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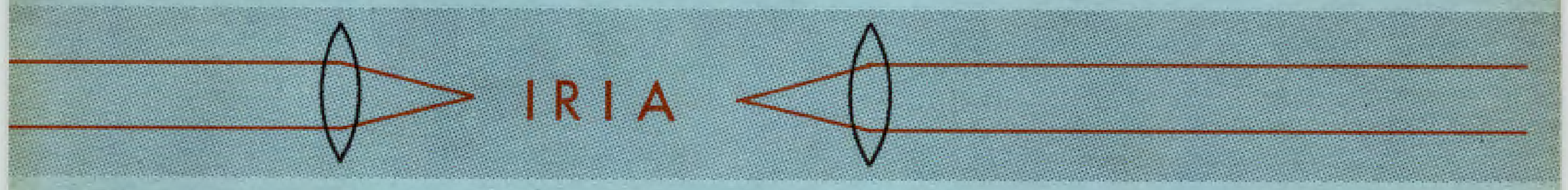
THE UNIVERSITY OF MICHIGAN
WILLOW RUN LABORATORIES

State-of-the-Art Report
OPTICAL MATERIALS FOR INFRARED INSTRUMENTATION



January 1959

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IRIA

State-of-the-Art Report

OPTICAL MATERIALS FOR INFRARED INSTRUMENTATION

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January 1959

THE UNIVERSITY OF MICHIGAN
WILLOW RUN LABORATORIES
ANN ARBOR, MICHIGAN

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PREFACE

The Infrared Information and Analysis Center (IRIA) at The University of Michigan is supported by a tri-service contract, Nonr 1224(12), administered by the Office of Naval Research, Physics Branch. University contract administration is provided to the Willow Run Laboratories by The University of Michigan Research Institute. A steering committee consisting of representatives of the three military services assists in the technical direction of the work. IRIA has the responsibility for the collection, analysis, and dissemination to authorized recipients, of all information concerning military infrared research and development.

The preparation of annotated bibliographies, state-of-the-art reports, and miscellaneous publications is one of the ways by which IRIA meets its responsibilities. Other ways in which IRIA performs its function are by preparing subject bibliographies, sponsoring symposia, and "consulting" with visitors.

Dr. Stanley S. Ballard and Dr. Kathryn A. McCarthy were consultants to The University of Michigan during the preparation of this report. Dr. Ballard is Professor of Physics and Chairman of the Physics Department of the University of Florida, Gainesville, Florida, and Dr. McCarthy is Assistant Professor of Physics at Tufts University, Medford, Massachusetts, and Research Fellow in Physical Metallurgy at Harvard University.

The authors would like to express their appreciation for the help given on this report by the many organizations and individuals who have contributed suggestions and cooperated by providing information and in some cases by supplying new data.

Lab. S.J.

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* Tables and figures for this chapter are listed on the inside back cover.
† Materials described in this chapter are listed on the inside back cover.

ABSTRACT

The properties of approximately fifty materials which are useful in optical instrumentation in the infrared portion of the electromagnetic spectrum are described and compared. Each material is discussed in detail in terms of its optical, chemical, thermal, and mechanical properties. Tables and figures are given so that the properties of the various materials can be readily compared.

CHAPTER 1

INTRODUCTION

The critical components of most optical instruments are the windows, lenses, and prisms. The properties of the optical materials from which these transmitting components are made are hence of primary importance to the designer of these instruments. Two or three decades ago, one who designed instruments intended to operate in the infrared part of the spectrum could choose from only a few materials. These were crystal quartz and fused silica, rock salt, fluorite, and perhaps some others. Since spectrometers were the chief infrared instruments then being designed, the available materials served the purpose rather satisfactorily. Of course, rock salt was troublesome because of its high water solubility; it was thus necessary to design the infrared spectrometer so that the optical system was filled with a thoroughly dry gas, or perhaps was evacuated. Such special precautions can be taken with laboratory instruments but are quite impractical for present-day field instruments which are used, for example, in military applications.

The rapid rise in the military application of infrared technology has come only during the last ten or fifteen years, starting with the later years of World War II. Concurrently, there has been a considerable improvement in optical materials, largely because of the development of methods for producing synthetic single crystals of some of the naturally occurring substances, and for growing, in suitably large sizes, synthetic crystals which did not exist appropriately in the natural state. Also, new types of glass have been developed with good transmission far enough into the infrared to make them practicable in certain types of instruments. A second factor bearing on the optical materials situation is the development of high-purity samples of a class of compounds and elements known as semiconductors. Some of these (for instance, galena — natural lead sulfide) have been known for many years, but others — such as high-purity germanium and silicon and the intermetallic compounds, consisting of elements from the second and sixth or third and fifth columns of the periodic table —are quite new. Examples of the so-called II-VI and III-V compounds are cadmium sulfide and indium antimonide, respectively.

It is the purpose of this report to present, in a fashion designed to be of maximum use to the worker in infrared instrumentation, all the currently available data on the optical, mechanical, thermal, and some chemical properties of about fifty materials of possible interest. In a field that is progressing as fast as this one, any report that is published will soon be partially out of date, since new data are being obtained all the time. The present collation of data is substantially complete as of the summer of 1958; it is a reference source and a basis for the addition of new information. The authors have a continuing interest in this field and hence desire to be informed of new data as they become available—such acts of cooperation on the part of the readers of this report will be greatly appreciated.

Wavelength Regions

The most important parameter, or "independent variable," with regard to optical materials is wavelength. Thus, wavelength will be the primary consideration in most of the discussions of the properties of these materials. In this connection one should know which wavelength regions are likely to be of the greatest practical interest. The answer depends, of course, on the intended use of the instrument. Infrared spectroscopists usually like to be able to work to as long wavelengths as possible, although there are certain regions of shorter wavelength which are of special interest (for example, the region of fundamental vibrations of diatomic molecules, so important to infrared spectrophotometric analysis). For years the infrared spectroscopist has used an instrument equipped with a rock salt prism and hence can work out to a wavelength of about 16 μ, although sometimes he employs prisms of fluorite or even crystal quartz in order to achieve higher dispersion and greater resolving power at shorter wavelengths. These considerations are well covered by articles in the scientific literature and will not be enlarged upon here. Rather, primary attention will be given to the military applications of infrared, which seem to be achieving more and more importance these days. From the point of view of the user of infrared military equipments, the wavelength-region situation is somewhat simpler. For one thing, it is rarely necessary to consider wavelengths longer than about 15 μ, whereas the infrared spectroscopist now works with prism instruments out to 50 μ, and with grating instruments to much longer wavelengths. Also, military instruments are usually designed to operate in a rather narrow spectral band, while the spectrometer covers as wide a range as possible. The spectral region in which one is interested for a specific application depends upon the nature of the target or other radiation sources to be detected or measured, on the nature of the intervening atmosphere, and on the type of detector to be used in the equipment. The interplay among these various items defines three major regions of interest for military purposes.

Due largely to the interaction of the factors of detector-sensitivity range and atmospheric absorption, three general wavelength regions are usually quoted for the military infrared. Different names are used by different persons for these regions, but some measure of acceptance has been found for the following: *near, intermediate,* and *far*. The near infrared region is sometimes called the lead sulfide region; the intermediate or middle infrared is sometimes referred to as the lead selenide region; and the far infrared is often called the thermal region, since detectors of the thermal type are ordinarily used at these longer wavelengths. In this context, the near infrared region extends from the red end of the visible — a wavelength of 0.75 μ — to about 2.7 μ. The latter wavelength is the location of the long-wavelength edge of one of the "windows" or regions of good transmission through the low-altitude atmosphere, and also is the wavelength at which lead sulfide cells begin to lose sensitivity and water vapor begins to absorb. It might be noted that in many actual instruments a cut-on filter is used to define the short-wavelength end of the pass band so as to exclude solar radiation, either direct or scattered. (The term "cut-on," referring to an abrupt increase in transmission, is used in the context of proceeding from shorter to longer wavelengths. A cut-on filter is also called a long-wavelength-pass filter.) Ordinarily a germanium filter, which has a sharp cut-on at 1.8 μ, is used. Alternatively, a silicon filter may be used, with a cut-on at about 1.2 μ, or an appropriate interference-type filter. In any case, such an instrument then operates in a rather narrow wavelength band determined by the filter at the short-wavelength end and the drop-off of detector sensitivity at the long-wavelength end.

The intermediate infrared region extends roughly from 3 to 6 μ. This wavelength region covers two atmospheric "windows": one of high transmission from 3.0 to 4.2 μ, and one of somewhat less transmission from 4.5 to about 5.3 μ. This is the region that contains the strong carbon dioxide absorption at 4.3 μ. Detectors used in the intermediate region include lead selenide, lead telluride, and indium antimonide.

The thermal or long-wavelength infrared region is normally taken as extending from 8 to 13 μ, and matches the large transmission window of the atmosphere between these wavelengths. There is an ozone absorption band at 9.6 μ, but otherwise this is a region of good transmission. At present there is no room-temperature detector of the quantum type that is operational in this region; hence a thermal type of detector such as a bolometer or thermocouple is commonly used. Objects at room temperature have their maximum of radiation at about 10 μ (corresponding to a blackbody at 300°K); therefore, this is the region most often employed in the detection of objects at or near ordinary room temperature.

It should be noted that at high altitudes (over 30,000 or 40,000 ft) the atmosphere absorbs very much less than it does near sea level. The effect of water vapor is negligible at these high altitudes, and carbon dioxide absorption is important only at strong bands such as the 4.3 μ band referred to above. Thus the designation of wavelength regions on the basis of atmospheric absorption is not appropriate for high-altitude air-to-air applications; nevertheless, it is convenient to retain the nomenclature just described.

Hierarchies to Judge the Suitability of a Material

Data are given in this report on a substantial number of physical properties, for the several materials covered. Some of these properties are of considerably more interest to the optical designer than are others. In fact, one can set up a hierarchy of properties, and a different hierarchy is appropriate for each different instrument usage. For example, infrared spectrometers (laboratory instruments) use optical materials chiefly as prisms and as absorption-cell windows. The most important property to consider in selecting a material for either of these uses is its transmission region. For a prism, the refractive index and dispersion are the next most important properties, and then homogeneity, freedom from birefringence, freedom from cold flow induced by clamping the component, etc. For absorption-cell windows, chemical resistance to the solvents used in preparing test samples is critical; refractive index is important only insofar as reflection losses are concerned. The strength of the material and its tendency to cold flow and to lose figure should also be considered.

For field applications the list of important properties is quite different, although again the transmission region is paramount. In order to avoid the potentially troublesome effects of reradiation from optical components to the detector in an instrument, particularly those used in a high-temperature environment, a material should always be chosen whose transmission region extends well beyond the spectral passband of the instrument. It is also desirable that the material have high internal transmittance or low absorption, so that the effect of re-emission is not significant. Single-crystal materials in general have excellent internal transmittance in their regions of good transmission. The glasses, however, may exhibit a general absorption of a few percent even in their high-transmission region. Other optical properties of importance are homogeneity and freedom from birefringence, which is of particular importance in field instruments since the light from the clear sky is partially polarized and unsuspected difficulties may arise if the optical components are somewhat birefringent. Among mechanical properties, strength (as expressed, for example, by Young's modulus, elastic limit, and ultimate tensile strength) is important to the mechanical designer, as is freedom from cold flow and from plastic deformation. It is desirable for a material to have a high surface hardness, especially when it is used for elements that are exposed to the outside environment. Note must be taken of the solubility of any materials used in components located where they are subjected to weather conditions. As to thermal properties, the softening point is of course a primary consideration for a material from which an irdome is to be made. Thermal expansion and thermal conductivity are important in any element that will be raised above the general ambient temperature. High resistance to thermal shock is desired in irdomes and other elements which may be considerably raised (or lowered) in temperature in a very short period of time. The designer is faced with a special problem with the optical crystals having rather large expansion coefficients: he may have trouble in matching their expansion to that of the metal mounting. Electrical properties are of interest in some considerations but in general are not as important as optical, mechanical, and thermal properties.

Types of Materials

Several different types of optical materials can be specified. The best known are the single crystals, both natural and artificial. These may in turn be subdivided into dielectrics and semiconductors. Dielectric single crystals comprise the largest class of materials covered in this report, although the development of the field of semiconductors is so rapid that these newer crystals may outnumber the older ones in the not-too-distant future. The special properties of semiconductors are discussed in a section at the end of this chapter. Glasses and plastics are treated separately in Chapter 5.

Some indication of the sizes of blanks available for the various materials is given in the "Notes" sections in Chapter 4. Of course, size availability is something that is subject to change as larger furnaces are constructed and other growing techniques are developed; therefore, the suppliers should be contacted in order to obtain up-to-date information. Also, in Chapter 4 reference may be made to the ease of working the material so as to produce the desired optical finish. In addition, references are made to special problems such as the toxicity of some of the crystals and the opacity that may result from solarization. This is not a treatise on optical manufacturing methods, however, so these notes should be thought of as only fragmentary and suggestive.

It is an unfortunate fact that very often it is inconvenient, if not impossible, to obtain single crystals in sizes sufficiently large to enable cutting out of the desired size components. In an effort to circumvent this difficulty, at least for flat plates or slightly curved windows, there has been research for several years on methods of making what might be called "compacts" or sintered plates of either the powdered crystal or aggregates of microcrystals. If an appropriately sized amount of such a powder or microcrystal complex is heated and pressed in a mold, perhaps under rather high pressure, it may be possible to make a window of suitably large diameter. The transmission of such a hot-pressed sample is expected to be inferior to that of the single crystal, due largely to scattering by the tiny crystalline units and the voids in the compacted mass. The pressing operation may be carried out with the sample in a vacuum to reduce the cloudy appearance of the pressed plate. Current development programs suggest that in the future it will be possible to obtain satisfactory sintered plates of crystals with such otherwise desirable characteristics as are possessed by, for example, magnesium oxide, magnesium fluoride, and barium fluoride.

The glasses comprise the other large group of optical materials. Optical glasses in general transmit as far into the infrared as the so-called water absorption band at about 2.8 μ. Practically all glasses show a deep absorption in this region, and most glasses do not recover substantial transmission beyond 3 μ. There has been considerable research and development among glass makers in adopting special formulas or other means for obtaining transmission out to 5 or 6 μ, so as to cover the intermediate infrared region. A brief description of some glasses which at least partially satisfy this requirement is given in Chapter 5. Certain infrared-transmitting materials such as fused silica, arsenic trisulfide, and amorphous selenium are glasses rather than crystals, but they are so different from the conventional types of silicate glass that it seems proper to treat them along with the crystalline materials in Chapter 4.

Finally, there are a number of plastics which exhibit transmission in the infrared region; some of them transmit out at least as far as 15 μ if they are thin enough. In most instrumentation applications, however, thin films of plastic cannot be used; therefore, interest centers in the plastics that have suitable transmission in thicknesses of a millimeter or more so that they are strong enough for use as windows. Even so, it may be necessary to back these films with a wire mesh or a metal spider in order to preserve the correct figure and provide mechanical strength — the obscuration from the small amount of opaque material thus placed in the field of view can ordinarily be tolerated. A brief discussion of some of the available and useful plastics is given in Chapter 5.

Semiconductors

Semiconductors form a class of materials with values of electrical resistivity at room temperature that are intermediate between those of good conductors and those of insulators (sometimes called dielectrics). An additional characteristic of a semiconductor is that in some temperature ranges it has a negative coefficient of resistivity.

The distinction between metals, semiconductors, and insulators on the basis of electrical resistive properties can be understood in terms of the so-called energy gap in solids; this is a measure of the energy difference between the valence and the conduction bands postulated in the band theory of solids. The dielectric or insulating materials discussed in this report have energy gaps generally greater than 6 electron volts (ev), and are considered to be insulators on the basis that the valence band, composed of all the energy levels below the forbidden band, is filled with electrons, and the conduction band, composed of all levels above the forbidden band, is empty. The semiconductors have smaller energy gaps, roughly 0.1 to 2 ev, and are insulators only at 0°K. At temperatures greater than 0°K they are not insulators because some electrons are transferred to the conduction band as a result of thermal excitation.

Most semiconductors are opaque in the visible region and begin to transmit in the infrared region. These materials absorb the incident photons when the photon energy is greater than the energy corresponding to the forbidden gap; when the photon energy is smaller than that of the gap, the photons are transmitted. Thus a long cut-on wavelength corresponds to a small energy gap, and vice versa. For example, germanium, with an energy gap of 0.7 ev, should cut on at 1.78 μ, whereas cadmium sulfide with an energy gap of 2.4 ev begins transmitting at the red end of the visible spectrum.

The cut-on wavelength of semiconductors is a function of temperature and of impurity content or resistivity, greater resistivity corresponding to greater purity. The transmittance of germanium as a function of temperature is given in Figure 4-16 of Chapter 4 and shows that the cut-on wavelength increases with increasing temperature; this behavior is the same for all semiconductors. The transmission spectrum of indium antimonide given in Figure 4-18a also demonstrates that, at wavelengths longer than the cut-on wavelength, the transmittance is nearly constant as a function of wavelength for samples with low impurity content; for samples with high impurity content, the transmittance is lower than it would be for a purer material.

A high melting point is a desirable property in an optical material. However, the problems of preparing semiconductors of the III-V and II-VI types are more severe when they have high melting points. Furthermore, the problems of fabricating optical elements from such intermetallic compounds are many, due primarily to their brittleness and softness.

The values given for various properties in this report are almost always those for single crystals of the material. Since single crystals of sufficient size are often not available, it may be necessary to use a polycrystalline sample for instrumentation purposes. Although data for polycrystalline materials are generally not quoted, Gibson has reported on a comparison of the transmission of single crystal and polycrystalline lead sulfide (see Chapter 4, Item 41); high absorption in the polycrystalline sample, not found in the single crystal, is attributed to scattering by the microcrystalline structure. Thus care must be taken in extrapolating from single-crystal data to obtain the properties of polycrystalline substances.

CHAPTER 2

DEFINITIONS, CONVERSION FACTORS, AND ABBREVIATIONS

Data on some sixteen different properties of optical materials are presented in Chapters 3 and 4. These properties are carefully defined in the present chapter, and some information is given on the variation of their values with temperature, wavelength, and material purity. Units in which the properties are usually reported in the literature are given, and other common units and conversion factors are described with the definitions. Additional comments regarding particular materials are presented in Chapter 4.

Since many references are given in this report, an abbreviated format has been used. The American Institute of Physics abbreviations for scientific journals are used; they are listed at the end of this chapter. Special abbreviations (also listed) are employed for books and reports referred to frequently.

The definitions of the properties described in this report are given below.

Specific Gravity

Specific gravity is a measure of the density of a material. It is the ratio of the density of a substance to the density of water, both at a temperature of 4°C. The values given in Chapter 4 are for room temperature, unless a temperature is specified. Specific gravity is a dimensionless quantity. The density of a material in the metric system (gm/cm^3) is numerically the same as its specific gravity. The density in the English system (lb/ft^3) is numerically 62.4 times the specific gravity.

Crystal Class

It is assumed that the reader is acquainted with the various crystal classes, which describe in an organized way the arrangements of the atoms in a crystal. Information about crystal classes is given in Chapters 1 and 3 of *Introduction to Solid-State Physics* (second edition), by C. Kittel, Chapter 1 of *Piezoelectricity* by W. G. Cady, and *Crystal Structures*, by R. W. G. Wyckoff.

Directions and planes within the crystals are specified in terms of Miller indices (pp. 33–34 of Kittel), where the direction or plane is indicated by three numbers, h, k, and l. The particular notation used in Chapters 3 and 4 of this report is as follows:

$(h\,k\,l)$ specifies a single plane with indices h, k, l;
$\{h\,k\,l\}$ specifies a family of planes all with indices h, k, l;
$[h\,k\,l]$ specifies a single direction with indices h, k, l;
$\langle h\,k\,l\rangle$ specifies a family of directions all with indices h, k, l.

In the cubic system, the crystal class of most of the optical materials dealt with in this report, a direction and a plane with the same Miller indices are mutually perpendicular. This is not true in other crystal systems.

Transmission

When light is incident on a dielectric boundary, part of the energy is reflected, part is absorbed, and part is transmitted. The optical absorption of a material is a function of its chemical and physical structure, and varies with wavelength and thickness.

There are losses due to reflection at the two surfaces, and also due to absorption within the material; the *external transmittance* is a measure of the sum of these two types of loss. It is the ratio of the intensity of the light which has passed through a material and is observable on the other side, to the intensity of the incident light. It is a pure number, less than unity, and is usually expressed as a percent. The ratio of the intensity of the light arriving at the second interface to that leaving the first interface is the *internal transmittance*. For a particular sample, the internal transmittance, which relates only to absorption losses, is larger than the external transmittance.

Sometimes absorption curves are given instead of transmission curves. The (internal) absorption is expressed in terms of an *absorption coefficient* α (also called absorption constant). It is defined by the relationship $\alpha t \equiv -\log_e I/I_0$, where I/I_0 represents the internal transmittance and t is the thickness. Thus, the units of absorption coefficient are reciprocal length, and the reciprocal of the absorption coefficient is the distance through which the intensity of radiation is reduced to $1/e$, or 36.8%, of its original value.

In Chapter 4, curves of external transmittance, internal transmittance, and absorption coefficient are presented. Long- and short-wavelength transmission cut-offs for samples 2 mm thick are given. In Chapter 4, the wavelength limits quoted are, where possible, those corresponding to an external transmittance of 10%. In some cases these "cut-offs" are sensitive functions of temperature and impurity content, as is particularly true for semiconductor materials.

Much of the information in Chapter 4 on the transmission of semiconductors is presented in terms of the absorption coefficient as a function of photon energy rather than wavelength. Photon energy is usually given in electron volts; 1 ev is the energy required to raise the potential of an electron one volt. The relationship of the energy of a photon to its wavelength is given by the equation $E = hc/\lambda$. For conversion from photon energy in electron volts to wavelength in microns, multiply the reciprocal of the photon energy in electron volts by 1.24; to convert from wavelength in microns to photon energy in electron volts, multiply the reciprocal of the wavelength in microns by 1.24.

Reflection Loss

It has been mentioned above that, when light is incident on an dielectric interface, part of it is reflected. The *reflection loss* is a ratio less than unity and is usually specified as a percentage of the original intensity. It is a function of the refractive index of the material, the polarization and angle of incidence of the light. Equations for single-surface reflection as a function of incident angle are given in most optics textbooks. The reflection loss of unpolarized light from one surface at normal incidence is given by $(n-1)^2/(n+1)^2$. For transparent substances, reflections from the second surface must also be considered. The external transmittance of a plane-parallel plate, taking into account multiple internal reflections, is $2n/(n^2+1)$. Reflection loss decreases as the angle of incidence increases. Reflection loss has been calculated, where possible, at the wavelengths 2, 4, and 10 μ, whichever one is warranted by the transmission spectrum. These values represent operation in the lead sulfide, the lead selenide, and the thermal spectral regions, respectively. In a few cases the reflection loss is given at a wavelength different from one of these three.

Refractive Index

The refractive index of a substance is the ratio of the speed of light *in vacuo* to the speed of light in that substance. Refractive index is a function both of wavelength and of the temperature of the sample, but is not strongly affected by the sample purity. Refractive index curves are presented in Chapter 3; tables of refractive index and values for the temperature coefficient of refractive index, dn/dT, are given in Chapter 4.

Dispersion

The dispersion of a substance is defined as the derivative of the refractive index with respect to wavelength, $dn/d\lambda$. Figure 3-3 shows the dispersion of several materials for purposes of comparison only — the information needed for any calculations of dispersion should be taken from the refractive-index data tables.

Reciprocal dispersion, or nu-value, is defined as

$$\frac{n_D - 1}{n_F - n_C}$$

where n_D, n_F, and n_C are the refractive indices at wavelengths of 0.589 μ, 0.656 μ, and 0.486 μ, respectively. Reciprocal dispersion is given in Chapter 4 for several materials.

Dielectric Constant

From the classical point of view, when two plane-parallel plates are separated by a distance that is small compared to the dimensions of the plates and the volume between the plates is evacuated, the application of a potential difference will set up a homogeneous electric field between the plates. The capacitance of this system is the ratio of the total surface charge to the potential difference between the plates. When the volume between the plates is filled with an insulating material, the charge on the plates remains the same, but the potential difference between the plates is lowered and the capacitance of the system is correspondingly increased. The *dielectric constant* of the insulating material is the ratio of the potential difference when the volume between the plates is evacuated, to the potential difference when the volume is filled with the insulating material. The values given in Table 3-1 and in Chapter 4 are the relative dielectric constants of the materials, that is, the ratios of the dielectric constants of the material to that of a vacuum. Dielectric constant is dimensionless; in certain crystals, it varies with direction.

Melting Temperature

Melting temperature is that temperature at which the phase of a material changes from solid to liquid. At atmospheric pressure some optical materials melt; some, such as cadmium sulfide, sublime; others, such as gallium arsenide, dissociate; and still others, such as the glasses, soften. Comments are made in Chapter 4 on the few materials for which the conditions for the change of phase are unusual. For certain of the newer binary compounds, phase diagrams are given. These phase diagrams are by no means complete, but are necessary for consideration of the growth conditions of these newer materials.

Thermal Conductivity

When heat flows at a uniform rate through a regularly shaped solid in a direction perpendicular to the faces of the solid, the quantity of heat that passes through a section of the face per unit time is proportional to the area of the section of the face and to the temperature gradient, that is, the difference in temperature per unit thickness in the direction of heat flow; the constant of proportionality is called *thermal conductivity*. The thermal conductivity of a solid is a function of the temperature and the purity of the solid; for most glasses, the thermal conductivity increases with increasing temperature; for most other optical materials, the thermal conductivity decreases with increasing temperature in a temperature range above 30°K.

The thermal conductivity is the same in all directions in a cubic crystal. In hexagonal crystals and tetragonal crystals, the thermal conductivity is dependent on the direction of the heat flow through the crystal; for these crystals two values of thermal conductivity are given: one, with the direction of the heat flow parallel to the *c*-axis, and the other, with the direction of heat flow perpendicular to the *c*-axis.

Three units of thermal conductivity are in common use, namely, cal/(cm sec C°), watt/(cm C°), and Btu in./(hr ft^2 F°). To convert thermal conductivity in cal/(cm sec C°) to watt/(cm C°), multiply the magnitude in cal/(cm sec C°) by 4.186; to convert thermal conductivity in cal/(cm sec C°) to Btu in./(hr ft^2 F°), multiply the magnitude in cal/(cm sec C°) by 1.442×10^{-3}.

Thermal Expansion

When a material is heated, its dimensions change; usually the dimensions increase with increasing temperature. The *linear coefficient of thermal expansion* is a measure of the proportional change in length of a given sample, and is defined as the change in length divided by the original length and the change in temperature. This coefficient increases with increasing temperature, but in the temperature ranges of practical interest the change in the coefficient is negligible. Marked changes occur when the crystals show a change in phase.

For simple cubic crystals the thermal expansion is the same in all directions. For hexagonal and tetragonal crystals, the thermal expansion is dependent on the direction of heat flow through the crystal; for these crystals two values of thermal expansion are given: one with the direction of heat flow parallel to the *c*-axis, and the other, with the direction of heat flow perpendicular to the *c*-axis. The coefficient is usually given in units of 1/C°; the value of the coefficient given in 1/C° should be multiplied by 5/9 to give its value in 1/F°.

Specific Heat

When heat is applied to a material, the temperature of the material increases. But the rate of increase is not the same for all materials. The specific heat capacity of a substance is defined as the amount of heat needed to increase the temperature of 1 gm of the substance 1°C. The *specific heat* of a material is defined as the ratio of its specific heat capacity to the specific heat capacity of water, with no phase change occurring. The specific heat capacity of water is (by definition) 1 cal/(gm C°), or 1 Btu/(lb F°). Thus, specific heat is a measure of the heat capacity of a substance relative to that of water; the specific heat is a pure number, and has the same value in both metric and English systems of units.

Specific heat is a function of temperature; however, in the temperature range in which optical materials are ordinarily used, the specific heat is nearly constant. The values of specific heat given in the tables of Chapter 4 were measured at constant pressure; the specific heat at constant volume, although of theoretical importance, is very difficult to measure but can be determined from the thermodynamic relationship for the difference of the two specific heats. This difference equals $TV\beta^2k^{-1}$, where T is the absolute temperature, V is the molar volume, β is the volume expansivity (equal to three times the linear coefficient of expansion), and k is the compressibility (the reciprocal of bulk modulus, defined in the discussion of elastic moduli). For the materials considered in this report, the difference between the two specific heats can be shown to be not greater than 2% of the specific heat quoted, in the temperature range in which they are commonly used.

Hardness

Hardness is a well-known physical property of materials, and numerous methods have been used to measure and specify it. The best way to describe hardness specifications is to describe these experimental procedures. Most of the hardness values given in Chapters 3 and 4 are Knoop numbers: A pyramidal diamond point is pressed into the sample with a known force, the indentation made is then measured and the Knoop value calculated. The point is so designed that the surface being tested is not work-hardened along the direction from which the hardness value is obtained. The Knoop number varies slightly with the indenter load and with temperature. The Knoop numbers vary from values as small as 4 for a soft material such as potassium bromide to values as high as 2000 for a hard material such as sapphire.

Moh values of hardness are arrived at by determining which materials can scratch other materials. Values on the Moh scale are given for a few materials in Chapter 3, where the Moh value is determined relative to a value of 1 for talc and 10 for diamond; the Knoop hardness for diamond is 7000.

Vickers values of hardness are determined by pressing a pyramidal diamond indenter into the material. The value is then determined by dividing the indenter load (in kilograms) by the pyramidal area of the indenter (in square millimeters). The hardness on the Vickers scale of several materials is given in Table 3-6.

Rockwell hardness and Brinell hardness values are not quoted in this report. Rockwell hardness is related to a specific measuring instrument; Brinell hardness values are analogous to Vickers values. The Brinell indenter is a section of a sphere.

Solubility

When a solid sample is placed in a solvent, the molecular or the crystalline structure may be broken down so that the solute (the sample) is dissolved by the solvent. *Solubility* is a measure of the amount of solute that can be "absorbed" by a given amount of solvent. It is usually given in terms of grams of solute per 100 gm of solvent. Water has been taken as the solvent, in Chapters 3 and 4. A material is said to be insoluble when its solubility is less than 10^{-3} gm per 100 gm of water.

Elastic Moduli

Hooke's law states that for *small* deformations the stress acting on a solid is proportional to the strain existing within it. The components of stress are linear functions of the components of strain; the constants of proportionality between the components of stress and the components of strain are called the ***elastic stiffness constants,*** or the elastic coefficients. These coefficients are designated by the quantities c_{hk}, where h and k have values from 1 to 6. For cubic crystals, there are 3 independent c_{hk}'s, namely, c_{11}, c_{12}, and c_{44}. For tetragonal crystals, such as titanium dioxide, there are 5 independent c_{hk}'s, namely, c_{11}, c_{12}, c_{13}, c_{33}, and c_{44}. For hexagonal crystals, such as crystal quartz and calcite, there are 6 independent c_{hk}'s, namely, c_{11}, c_{12}, c_{13}, c_{14}, c_{33}, and c_{44}.

The components of strain may alternatively be considered as linear functions of the components of stress; then, the constants of proportionality between the respective components are called ***elastic compliance constants*** and are denoted by s_{hk}'s, where h and k have values from 1 to 6. For cubic crystals, there are 3 independent s_{hk}'s, namely, s_{11}, s_{12}, and s_{44}. As in the case of c_{hk}'s, there are 5 independent s_{hk}'s for tetragonal crystals and 6 independent s_{hk}'s for hexagonal crystals.

For a cubic crystal, the equations below relate c_{hk} with s_{hk}:

$$s_{11} = \frac{(c_{11} + c_{12})}{(c_{11} + 2c_{12})\ (c_{11} - c_{12})}$$

$$s_{12} = \frac{-c_{12}}{(c_{11} + 2c_{12})\ (c_{11} - c_{12})}$$

$$s_{44} = \frac{1}{c_{44}}$$

In Chapter 4, c_{hk} values are given in preference to s_{hk} values, since the c_{hk}'s are of the same order of magnitude as the engineering moduli.

The elastic moduli in common engineering use are ***Young's modulus, modulus of rigidity*** (also called shear modulus), and ***bulk modulus*** (the reciprocal of compressibility). Young's modulus is concerned with that deformation of a body in which an applied force results in a change in length of the body; Young's modulus is defined as the ratio of stress to strain, where the stress is the force per unit area perpendicular to which the force is applied and the strain is the resulting fractional change in length. The modulus of rigidity is concerned with that deformation of a body in which an applied force results in a change in shape of the body; the modulus of rigidity is the ratio of the shearing stress to the shear strain, where the shearing stress is the force per unit area parallel to which the force is applied and the shear strain is the angle of shear in radians. Bulk modulus is concerned with that deformation of a body in which an applied force results in a change in volume of the body; bulk modulus is the ratio of the pressure applied to a body to the volume strain, where this strain is the resulting fractional decrease in volume of the body.

These three engineering moduli are related to the c_{hk}'s by the following equations:

$$\text{Young's modulus} = \frac{(c_{11} + 2c_{12})\ (c_{11} - c_{12})}{(c_{11} + c_{12})}$$

$$\text{Modulus of rigidity} = c_{44}$$

$$\text{Bulk modulus} = \frac{c_{11} + 2c_{12}}{3}$$

The values of Young's modulus quoted in Chapter 4 were determined in several ways. The preferred value is that obtained from measurements made in either tension or compression, where the experimental procedure conforms most closely to the elongation system indicated by the definition of Young's modulus. However, for most optical materials, such data are rare and difficult to obtain; many of these materials cleave when subjected to either tension or compression. Young's modulus may also be determined from measurements made with the sample bent in flexure. The values obtained in flexure are in general lower than those obtained in either tension or compression. This may be explained in a simple way by considering that plastic deformation in a sample loaded in flexure is probably initiated more easily than in a sample subjected to tension; thus the slope of the stress-strain curve for the sample bent in flexure is less than the slope of the stress-strain curve for the sample in tension.

A value of Young's modulus computed from the elastic coefficients is given in Chapter 4 only when there were no values in the literature based on tension, compression, or flexure measurements.

The modulus of rigidity is generally determined from measurements on rods strained in torsion. Such measurements on optical materials can be made only on samples that do not cleave easily. Thus most of the values of the modulus of rigidity given in Chapter 4 are computed from the elastic coefficients.

The bulk modulus is the reciprocal of the compressibility, and is generally determined from compressibility measurements. In the absence of experimental values, the bulk modulus was computed from the elastic coefficients.

In general, crystals are anisotropic with respect to their elastic properties; that is, the values of these moduli differ with direction in the crystal. A measure of the anisotropy of a cubic crystal is given by the ***anisotropy factor,*** A; it is defined as $2c_{44}/(c_{11} - c_{12})$. This factor equals unity for elastically isotropic materials, and for elastically anisotropic crystals has values either greater than or less than unity. It can be shown that, for those crystals with $A > 1$, such as germanium and silicon, Young's modulus has its maximum value along $<100>$ directions and a minimum value along $<111>$ directions; for crystals with $A < 1$, such as sodium chloride, Young's modulus has its maximum value along <111> directions and its minimum value along <100> directions. The variation in elastic properties with direction may be as great as 30% and should be considered in design problems.

The discussion of elastic properties given above is applicable only when the deformation of the crystal is small, that is, less than 1% in research studies and less than 2% for practical applications. When a crystal is deformed to such an extent that Hooke's law is no longer obeyed, the crystal is said to be plastically deformed. The *elastic limit* is used to indicate the stress above which plastic deformation occurs and below which Hooke's law is obeyed. For metals, the stress-strain curve shows an abrupt change; for most optical materials the stress-strain curve gradually changes from a straight line to a curve with decreasing slope. In the apparent absence of a unique departure from Hooke's law, an *apparent elastic limit* must be defined. For some crystals that were tested in flexure, an apparent elastic limit is quoted in Chapter 4; this limit is taken as that stress on the stress-strain curve where the slope is half the slope at the origin of the stress-strain curve.

A *modulus of rupture* is quoted in Chapter 4 for some materials. This value is strongly dependent upon the history of the particular sample and should be used only for approximate calculations. The presence of small cracks or barely macroscopic cleavages will change the apparent rupture strength by at least an order of magnitude. There are three materials that show a markedly different performance at stresses where rupture might be anticipated. The stress-strain curves of thallium bromide-iodide, thallium bromide-chloride, and silver chloride show rapid increases in slope at large deformations and appreciable cold flow, that is, marked increase in deformation with time; there is little information on such cold flow, but the available results indicate that at stresses beyond the apparent elastic limit many additional slip systems must be activated.

In Chapter 4, the elastic moduli of primary use to the engineer are given in units of pounds per square inch (psi), whereas those used more often in a physics context are given in dynes per square centimeter (dyne/cm^2). To convert stresses and moduli from psi to dyne/cm^2, multiply the magnitude in psi by 6.90×10^4; to convert from dyne/cm^2 to psi, multiply the magnitude in dyne/cm^2 by 1.45×10^{-5}.

Abbreviations Used for Scientific Journals

Acta. Cryst.	Acta Crystallographica
Ann. Physik	Annalen der Physik
Bell System Tech. J.	Bell System Technical Journal
Compt. rendus	Comptes rendus hebdomadaires des séances de l'académie des sciences
J. Am. Ceram. Soc.	Journal of the American Ceramic Society
J. Am. Chem. Soc.	Journal of the American Chemical Society
J. Appl. Phys.	Journal of Applied Physics
J. Opt. Soc. Am.	Journal of the Optical Society of America
J. Phys. Chem.	Journal of Physical Chemistry
J. Research NBS	Journal of Research of the National Bureau of Standards
Optik	Optik
Phil. Mag.	Philosophical Magazine
Phil. Mag. Suppl.	Supplement to Philosophical Magazine (also called Advances in Physics)
Phys. Rev.	Physical Review
Proc. Am. Acad. Arts Sci.	Proceedings of the American Academy of Arts and Sciences
Proc. Indian Acad. Sci.	Proceedings of the Indian Academy of Sciences
Proc. I.R.E.	Proceedings of the Institute of Radio Engineers
Proc. Phys. Soc.	Proceedings of the Physical Society (London)
Proc. Roy. Soc.	Proceedings of the Royal Society (London)
Rev. Mod. Phys.	Reviews of Modern Physics
Rev. Sci. Instr.	Review of Scientific Instruments
Z. Naturforschung	Zeitschrift für Naturforschung
Z. Physik	Zeitschrift für Physik
Z. physik. Chem.	Zeitschrift für physikalische Chemie

Abbreviations Used for Books and Reports

AIPH—American Institute of Physics Handbook
(McGraw-Hill Book Company, Inc., New York, 1957.)

ERDL—Proceedings of the Conference on Infrared Optical Materials, Filters, and Films
Held on 10 February 1955 at the Engineer Research and Development Laboratories, Fort Belvoir, Virginia.

Fan—Infrared Absorption in Semiconductors
H. Y. Fan, Reports on Progress in Physics, Vol. XIX, 1956, pp. 107–155 (The Physical Society, London).

HCP—Handbook of Chemistry and Physics
(Chemical Rubber Publishing Company, Cleveland, Ohio, 1957), 39th edition.

ICT—International Critical Tables
(McGraw-Hill Book Company, Inc., New York, 1929.)

Kohlrausch—Lehrbuch der praktischen Physik
Friedrich Kohlrausch, (B. G. Teubner, Leipzig, 1930).

Landolt—Physikalisch-Chemische Tabellen, Vol. I-IV,
Landolt-Börnstein, (Julius Springer, Berlin, 1923, 1927, 1931, 1935).

Moss—Photoconductivity in the Elements
T. S. Moss, (Butterworth and Company, Ltd., London, 1952).

SPT—Smithsonian Physical Tables
Prepared by W. E. Forsythe (The Smithsonian Institution, Washington, D. C., 1954), 9th edition.

Smakula—Physical Properties of Optical Crystals with Special Reference to Infrared
Alexander Smakula, (Office of Technical Services, U. S. Department of Commerce, Document No. 111,052 of October 1952).

Smith—The Detection and Measurement of Infra-Red Radiation
R. A. Smith, F. E. Jones, and R. P. Chasmar, (Oxford University Press, London and New York, 1957).

Sosman—The Properties of Silica
Robert B. Sosman, (The Chemical Catalog Company, Inc., New York, 1927).

Tutton—Crystallography and Practical Crystal Measurement
A. E. H. Tutton, (Macmillan and Company, Ltd., London, 1922).

Voigt—Lehrbuch der Kristallphysik
W. Voigt, (B. G. Teubner, Leipzig, 1910. Reprinted in U. S. A., Edwards Brothers, Inc., Ann Arbor, Michigan, 1946).

Von Hippel—Dielectric Materials and Applications
Arthur R. von Hippel, editor, (John Wiley & Sons, Inc., New York, 1954).

WADC-I—Infrared Window Studies, Part I
Conrad M. Phillipi and Niel F. Beardsley, WADC Technical Note 55-194, Aerial Reconnaissance Laboratory, Wright Air Development Center, June 1955.

WADC-II—Infrared Window Studies, Part II
Conrad M. Phillipi and Niel F. Beardsley, WADC Technical Note 55-194, Aerial Reconnaissance Laboratory, Wright Air Development Center, December 1956.

Welker and Weiss—Group III—Group V Compounds
H. Welker and H. Weiss, Solid-State Physics, Vol. 3, F. Seitz and D. Turnbull, editors, (Academic Press, Inc., New York, 1956).

Wooster—A Textbook on Crystal Physics
W. A. Wooster, (University Press, Cambridge, 1938).

CHAPTER 3

COMPARISONS OF PROPERTIES

A designer or engineer is usually faced with one of two problems in the choice of the proper optical materials to be used in an infrared instrumentation problem. He must either choose from among many materials an available one that represents a variety of compromises, or he must design an optical system using a specific material. The solution of the first of these problems is facilitated by a tabular reference source that permits rapid comparison of materials; the solution of the second problem requires detailed knowledge of the specific properties of a single material. This report presents data in two different ways, corresponding to the two problems just stated. Chapter 4 describes each material in detail, whereas this chapter gives a ready comparison of materials on the basis of certain properties. This comparison consists of figures of transmission region, refractive index, and dispersion, and tables of dielectric constant, melting or softening temperature, thermal conductivity, thermal expansion, specific heat, hardness, and solubility. The references for these data are given in Chapter 4. Values are listed in each table in order of increasing magnitude; where they are appropriate, familiar, but not necessarily optical, materials provide a level of reference.

Transmission Region

The choice of an optical material for a particular application is dependent primarily upon the transmission region of that material (Chapter 1). Figure 3-1 displays the transmission regions of most of the materials discussed in this report. Note that the abscissa is logarithmically graduated. The white bars represent the wavelength region in which a particular material transmits appreciably. The limiting wavelengths, for both high and low cut-off, have been chosen on a somewhat arbitrary basis, namely, as that wavelength at which a sample of 2-mm thickness has 10% external transmittance. Such a criterion is a compromise between window and filter usage, and its appropriateness must be judged whenever it is used. In some cases this criterion is insufficient; in Figure 3-1 the criterion has not always been adhered to. The criterion is inadequate in the consideration of semiconducting materials; in this instance, a purity and a temperature must also be specified. The available data were not sufficient to compare semiconductors in a more satisfactory manner — not enough measurements at room temperature have been made on samples of comparable purity to provide such a comparison. Room-temperature measurements on the materials described in Chapter 4 were used to determine the cut-off wavelengths.

Some semiconductors violate the criterion in another way. Materials such as indium antimonide have an external transmittance of less than 10% even in their most transparent regions; these are indicated with an asterisk (*). Although these materials may never be useful as lenses and prisms,

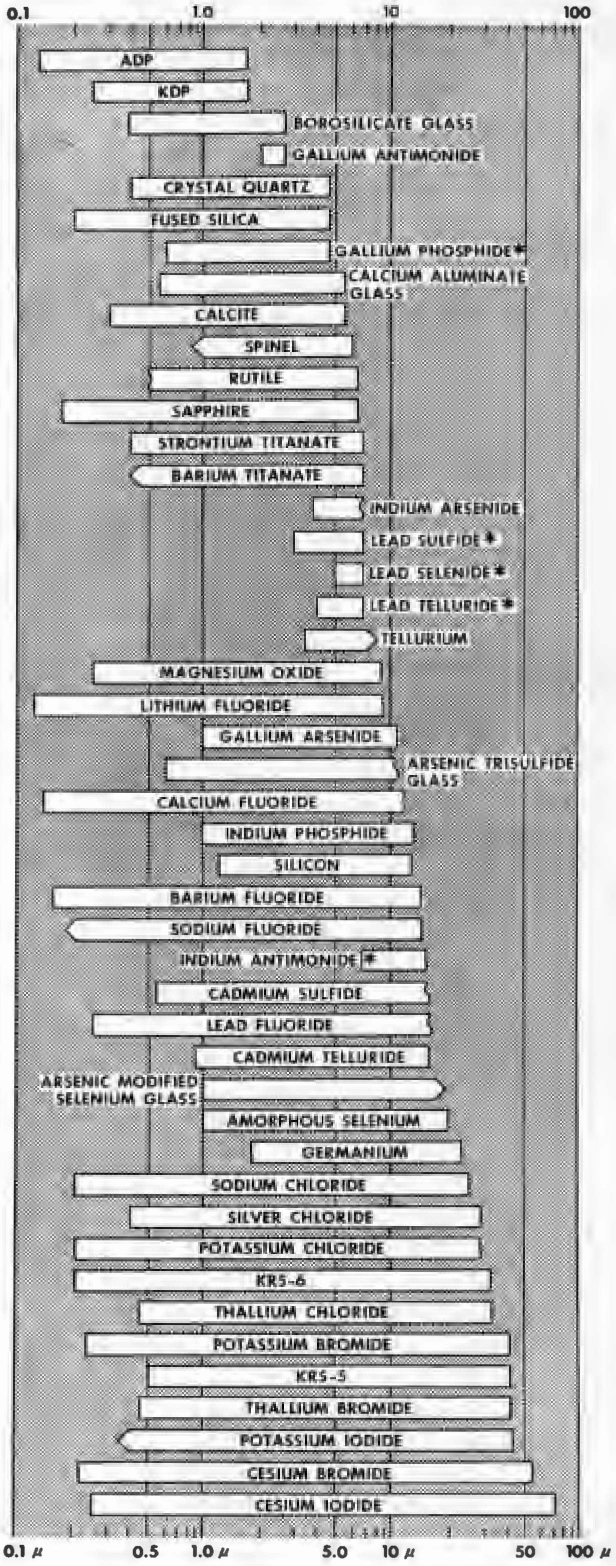


Fig. 3-1. Transmission regions. The limiting wavelengths, for both long and short cut-off, have been chosen as those wavelengths at which a sample 2 mm thick has 10% transmission. Materials marked with an asterisk (*) have a maximum external transmittance less than 10%.

they may perform admirably as filters in some applications. Thus they are included, and a qualitative judgment is made of their cut-off region.

Several different "endings" have been used for the bars of the chart; each has a specific meaning: A bar which has a straight, vertical ending indicates that the cut-off exists at the wavelength represented by the end of the bar *exactly* as defined above; a bar which ends in an S-shape represents a material which cuts off at *approximately* that wavelength; lastly, a bar ending in an angle indicates that the material transmits *at least* to that wavelength, and probably further. The measurements reported on materials in this last group have not been made to sufficiently long wavelengths to determine the cutoff.

Refractive Index

The refractive index of a material is extremely important in the design of all refracting optical elements. Figure 3-2 presents curves of refractive index *vs* wavelength and illustrates the range of the refractive indices of many of the materials described in this report. (Tables of refractive index as a function of wavelength are given in Chapter 4.) The figure provides a ready comparison of the indices of the several materials. For comparison, the refractive indices of standard optical glasses range from roughly 1.4 to 1.8.

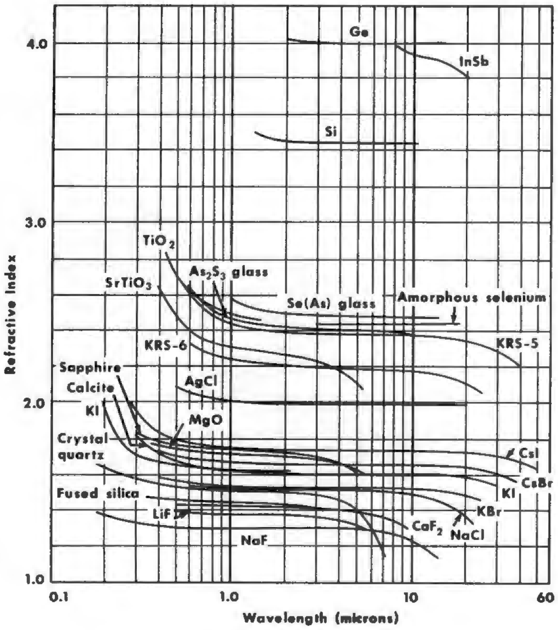


Fig. 3-2. Refractive index *vs* wavelength for several optical materials.

For crystals whose refractive index varies with direction, only the refractive index corresponding to the ordinary ray, n_o, has been plotted. The refractive indices of tellurium for both the ordinary and extraordinary rays have been omitted because of their extremely high values of approximately 6.237 and 4.789 respectively at 12 μ.

Dispersion

The data of Figure 3-2 are plotted in Figure 3-3 in a different form, which is more useful for some purposes; Figure 3-3 is a plot of the slopes of the curves of Figure 3-2 *vs* wavelength. The abscissa, representing wavelength, is graduated logarithmically from 0.1 to 40 μ. The ordinate is also graduated logarithmically, from 0.0001 to 0.1 per micron.

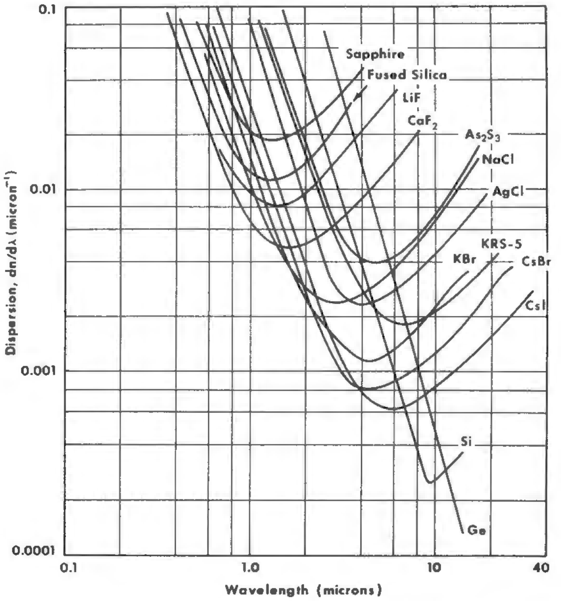


Fig. 3-3. Dispersion *vs* wavelength for several optical materials.

The wide spread of values for the different materials is again illustrated. Materials like calcium fluoride and lithium fluoride have been used as prisms for spectroscopic purposes in the wavelength region of about 1 to 8 μ because their relatively high dispersion makes them particularly suitable for this laboratory purpose. On the other hand, silicon and especially germanium exhibit comparatively low dispersion in the wavelength region around 10 μ. Thus, in this region they should be valuable as lens and deviating prism materials because of their relatively small chromatism.

One can define an "infrared dispersion," or "infrared nu-value," by selecting several infrared wavelengths analogous to the visible *C*, *D*, and *F* lines. However, the choice of these wavelengths is so dependent on the particular application that "infrared dispersion" has not been defined or used in this report. Rather, one can determine the dispersion in the desired wavelength interval from Figures 3-2 and 3-3, and, if more accuracy is required, calculate the dispersion from the refractive index tables of Chapter 4.

Dielectric Constant

Dielectric constant is defined in Chapter 2 in terms of the charge and potential difference associated with a plane parallel-plate condenser. The dielectric constant is a function of frequency and temperature, and these values are given in Table 3-1. Every attempt has been made to include measurements taken at microwave frequencies and to indicate such peculiarities as variation with orientation. The dielectric properties also depend upon purity (this is particularly true for semiconductors); thus, the purity of the sample measured is given, when available.

When the dielectric constant is measured with the electric field parallel to the *c*-axis (the optic axis), the measurement is identified with a superscript "*p*"; when the electric field is perpendicular to the optic axis, the measurement is identified with a superscript "*s*." For comparison, values are quoted for silica glass and mica; references are given for these substances since they do not appear elsewhere in the report.

TABLE 3-1. Dielectric Constant

Material	Dielectric Constant	Frequency (cps)	Temperature (°C)	Remarks
Fused silica (SiO_2)	3.78	10^2 to 10^{10}	25	
Silica glass	3.81	10^8	20	*HCP*, p. 2346
Crystal quartz (SiO_2)	4.27^p	10^7	17 to 22	
	4.34^s	10^7	17 to 22	
Potassium chloride (KCl)	4.64	10^6	29.5	
Potassium bromide (KBr)	4.90	10^2 to 10^{10}	25	
Potassium iodide (KI)	4.94	10^6	—	
Cesium iodide (CsI)	5.65	10^6	25	
Sodium chloride (NaCl)	5.90	10^2 to 10^{10}	25	
Amorphous selenium (Se)	6.00	10^2 to 10^{10}	25	
Sodium fluoride (NaF)	6.0	10^6	19	
Selenium crystal (Se)	6.0	10^2 to 10^{10}	—	
Cesium bromide (CsBr)	6.51	10^6	25	
Calcium fluoride (CaF_2)	6.76	10^5	—	
Sodium nitrate ($NaNO_3$)	6.85	10^5	19	
Mica, glass bonded, injection	6.9 to 9.2	10^6	room	*HCP*, p. 2344
Barium fluoride (BaF_2)	7.33	10^6	—	
Calcite ($CaCO_3$)	8.5^s	10^4	17 to 22	
	8.0^p	10^4	17 to 22	
Sapphire (Al_2O_3)	10.55^p	10^2 to 10^8	25	
	8.6^s	10^2 to 10^{10}	25	
Arsenic trisulfide glass (As_2S_3)	8.1	10^3 to 10^6	—	
Spinel ($MgO \cdot 3.5Al_2O_3$)	8 to 9	—	—	
Lithium fluoride (LiF)	9.00	10^2 to 10^{10}	25	
Magnesium oxide (MgO)	9.65	10^3 to 10^8	25	
Cadmium telluride (CdTe)	11.0	10^3 to 10^5	—	5.5×10^{13} carriers/cc
Silicon (Si)	13	10^{10}	—	
Silver chloride (AgCl)	12.3	—	room	
Germanium (Ge)	16.6	10^{10}	—	9.0 ohm-cm resistivity
Lead sulfide (PbS)	17.9	10^6	15	
Thallium bromide (TlBr)	30.3	10^3 to 10^7	25	
Thallium bromide-iodide (KRS-5)	32.5	10^2 to 10^7	25	
Thallium chloride (TlCl)	31.9	10^6	—	
Thallium bromide-chloride (KRS-6)	32	10^2 to 10^5	25	
Potassium dihydrogen phosphate (KDP)	44.5 to 44.3^s	10^2 to 10^5	—	
	21.4 to 20.2^p	10^2 to 10^8	—	
Ammonium dihydrogen phosphate (ADP)	56.4 to 55.9^s	10^2 to 10^8	—	
	16.4 to 13.7^p	10^2 to 10^{10}	—	
Titanium dioxide (TiO_2)	170^p	10^4 to 10^7	25	
	86^s	10^2 to 10^7	25	
Strontium titanate ($SrTiO_3$)	234	10^2 to 10^{10}	25	
Barium titanate ($BaTiO_3$)	1240 to 1200	10^2 to 10^8	25	

^{p} Dielectric constant measured parallel to *c*-axis

^{s} Dielectric constant measured perpendicular to *c*-axis

— Value not indicated.

Melting Temperature

The melting (or softening) temperature of optical materials, given in Table 3-2, is important in the preparation of the material and in the use of the material. Both the pressure and the temperature at which a material melts, dissociates, or softens should be known. Thus, the pressure at which the melting temperature was measured is stated when it is different from atmospheric pressure.

TABLE 3-2. Melting or Softening Temperature

Material	Temperature (°C)
Amorphous selenium (Se)	35*
Arsenic modified selenium glass; Se(As)	70*
Arsenic trisulfide glass (As_2S_3)	210*
Potassium dihydrogen phosphate (KDP)	252.6
Sodium nitrate ($NaNO_3$)	306.8
Gallium arsenide (GaAs)	400‡
Thallium bromide-iodide (KRS-5)	414.5
Thallium bromide-chloride (KRS-6)	423.5
Thallium chloride (TlCl)	430
Tellurium (Te)	449.7
Silver chloride (AgCl)	457.7
Thallium bromide (TlBr)	460
Gallium phosphide (GaP)	> 500
Indium antimonide (InSb)	523
Cesium iodide (CsI)	621
Cesium bromide (CsBr)	636
Gallium antimonide (GaSb)	720
Potassium iodide (KI)	723
Potassium bromide (KBr)	730
Potassium chloride (KCl)	776
Sodium chloride (NaCl)	801
Borosilicate crown glass	820*
Lead fluoride (PbF_2)	855
Lithium fluoride (LiF)	870
Calcite ($CaCO_3$)	894.4‡
Cadmium sulfide (CdS)	900†
Lead telluride (PbTe)	917
Germanium (Ge)	936
Indium arsenide (InAs)	942
Sodium fluoride (NaF)	980
Cadmium telluride (CdTe)	~ 1040
Indium phosphide (InP)	1050
Lead selenide (PbSe)	1065
Lead sulfide (PbS)	1114
Gallium arsenide (GaAs)	1238
Barium fluoride (BaF_2)	1280
Calcium fluoride (CaF_2)	1360
Silicon (Si)	1420
Crystal quartz (SiO_2)	< 1470
Barium titanate ($BaTiO_3$)	1600
Fused silica (SiO_2)	~ 1710
Titanium dioxide (TiO_2)	1825
Sapphire (Al_2O_3)	2030
Spinel ($MgO \cdot 3.5Al_2O_3$)	2030 to 2060
Strontium titanate ($SrTiO_3$)	2080
Magnesium oxide (MgO)	2800

* Softening temperature.
† Sublimation temperature.
‡ Dissociation temperature.

Thermal Conductivity

Thermal conductivity is defined in Chapter 2, and values are given in Table 3-3 for many of the materials discussed in this report. For crystals which exhibit anisotropy, the orientation of the heat flow with respect to the *c*-axis is noted; values are given for the heat flow parallel (*p*) and perpendicular (*s*) to the *c*–axis. The values are given in terms of 10^{-4} cal/(cm sec C°); for example, the thermal conductivity of arsenic trisulfide glass is 4.0×10^{-4} cal/(cm sec C°). For comparison, data (with references) are provided for diatomaceous earth and silver.

TABLE 3-3. Thermal Conductivity

Material	Thermal Conductivity (10^{-4} cal/(cm sec C°))	Temperature (°C)	Remarks
Diatomaceous earth	1.3	"ordinary"	*HCP*, p. 2255
Arsenic modified selenium glass; Se(As)	3.3	—	
Arsenic trisulfide glass (As_2S_3)	4.0	40	
Thallium bromide-iodide (KRS-5)	13	20	
Thallium bromide (TlBr)	14	43	
Lead sulfide (PbS)	16	—	
Thallium bromide-chloride (KRS-6)	17.1	56	
Thallium chloride (TlCl)	18	38	
Ammonium dihydrogen phosphate (ADP)	17^p	42	
	30^s	40	
Cesium bromide (CsBr)	23	25	
Cesium iodide (CsI)	27	25	
Silver chloride (AgCl)	27.5	22	
Fused silica (SiO_2)	28.2	41	
Potassium dihydrogen phosphate (KDP)	29^p	39	
	32^s	46	
Barium titanate ($BaTiO_3$)	32	room	Ceramic material
Calcite ($CaCO_3$)	132^p	0	
	111^s	0	
Potassium bromide (KBr)	115	46	
Tellurium (Te)	150	—	
Sodium chloride (NaCl)	155	16	
Potassium chloride (KCl)	156	42	
Crystal quartz (SiO_2)	255^p	50	
	148^s	50	
Calcium fluoride (CaF_2)	232	36	
Lithium fluoride (LiF)	270	41	
Barium fluoride (BaF_2)	280	13	
Titanium dioxide (TiO_2)	300^p	36	
	210^s	44	
Spinel ($MgO \cdot 3.5\ Al_2O_3$)	330	35	
Cadmium sulfide (CdS)	380	20	
Sapphire (Al_2O_3)	600^p	26	
	550^s	23	
Magnesium oxide (MgO)	600	20	
Indium antimonide (InSb)	850	20	
Germanium (Ge)	1400	20	*n*-type, 40 ohm-cm resistivity
Silicon (Si)	3090	40	*p*-type
Silver (Ag)	10060	18	*HCP*, p. 2254

^{p} Thermal conductivity measured with heat flow parallel to *c*-axis.

^{s} Thermal conductivity measured with heat flow perpendicular to *c*-axis.

— Value not indicated.

Thermal Expansion

The linear coefficient of thermal expansion, α, is defined in Chapter 2, and values for many materials are listed in Table 3-4. They are given in terms of 10^{-6}/C°; for example, the thermal expansion of silicon is 4.2 × 10^{-6}/C°.

For crystals which exhibit anisotropy, the orientation of the heat flow with respect to the *c*–axis is stated; values are quoted for heat flow parallel (*p*) and perpendicular (*s*) to the *c*–axis. Each value of thermal expansion is accompanied by the temperature range over which the measurement was made or by the average temperature of the range of the measurement. For comparison, data (with references) are given for invar, borosilicate crown glass, and copper.

Table 3-4. Linear Coefficient of Thermal Expansion

Material	Coefficient of Thermal Expansion 10^{-6}/C°	Average Temperature or Temperature Range (°C)	Remarks
Fused silica (SiO_2)	0.5	20 to 900	
Invar	0.9	20	*HCP*, p. 2062
Silicon (Si)	4.2	25	
Cadmium sulfide (CdS)	4.2	27 to 70	
Cadmium telluride (CdTe)	4.5	50	
Indium antimonide (InSb)	4.9	20 to 60	
Indium arsenide (InAs)	5.3	—	
Germanium (Ge)	5.5 to 6.1	25	
Gallium arsenide (GaAs)	5.7	—	
Spinel ($MgO \cdot 3.5\,Al_2O_3$)	5.9	40	
Sapphire (Al_2O_3)	6.7^{p}	50	
	5.0^{s}	50	
Borosilicate crown glass	9	22 to 498	*HCP*, p. 2065
Titanium dioxide (TiO_2)	9.19^{p}	40	
	7.14^{s}	40	
Strontium titanate ($SrTiO_3$)	9.4	—	
Crystal quartz (SiO_2)	7.97^{p}	0 to 80	
	13.37^{s}	0 to 80	
Sodium nitrate ($NaNO_3$)	12^{p}	50	
	11^{s}	50	
Magnesium oxide (MgO)	13.8	20 to 1000	
Copper (Cu)	14.09	–191 to 16	*HCP*, p. 2061
Tellurium (Te)	16.75	40	
Barium titanate ($BaTiO_3$)	19	10 to 70	Ceramic
	6.2^{p}	4 to 20	Single crystal
	15.7^{s}	4 to 20	Single crystal
Calcium fluoride (CaF_2)	24	20 to 60	
Arsenic trisulfide glass (As_2S_3)	24.6	33 to 165	
Calcite ($CaCO_3$)	25^{p}	0	
	-5.8^{s}	0	
Silver chloride (AgCl)	30	20 to 60	
Amorphous selenium (Se)	34	—	Estimated
Sodium fluoride (NaF)	36	room	
Potassium chloride (KCl)	36	20 to 60	
Lithium fluoride (LiF)	37	0 to 100	
Potassium iodide (KI)	42.6	40	
Potassium bromide (KBr)	43	20 to 60	
Sodium chloride (NaCl)	44	–50 to 200	
Cesium bromide (CsBr)	47.9	20 to 50	
Thallium bromide-chloride (KRS-6)	50	20 to 100	
Cesium iodide (CsI)	50	25 to 50	
Thallium bromide (TlBr)	51	20 to 60	
Thallium chloride (TlCl)	53	20 to 60	
Thallium bromide-iodide (KRS-5)	58	20 to 100	

^{p} Thermal expansion measured parallel to *c*-axis.

^{s} Thermal expansion measured perpendicular to *c*-axis.

— Value not indicated.

Specific Heat

Table 3-5 lists the specific heat of many of the materials described in this report. The specific heat is that measured at constant pressure, c_p, rather than at constant volume, c_v, although the numerical difference is negligible for most purposes. The temperature at which the measurement was made is given. It should be remembered that the specific heat of water is unity (by definition).

TABLE 3-5. Specific Heat

Material	Specific Heat	Temperature (°C)
Thallium bromide (TlBr)	0.045	20
Tellurium (Te)	0.0479	300
Cesium iodide (CsI)	0.048	20
Thallium bromide chloride (KRS-6)	0.0482	20
Lead sulfide (PbS)	0.050	—
Thallium chloride (TlCl)	0.052	0
Cesium bromide (CsBr)	0.063	20
Germanium (Ge)	0.074	0 to 100
Potassium iodide (KI)	0.075	−3
Barium titanate ($BaTiO_3$)	0.077	−98
Silver chloride (AgCl)	0.0848	0
Potassium bromide (KBr)	0.104	0
Potassium chloride (KCl)	0.162	0
Silicon (Si)	0.168	25
Titanium dioxide (TiO_2)	0.17	25
Sapphire (Al_2O_3)	0.18	25
Crystal quartz (SiO_2)	0.188	12 to 100
Calcite ($CaCO_3$)	0.203	0
Sodium chloride (NaCl)	0.204	0
Calcium fluoride (CaF_2)	0.204	0
Magnesium oxide (MgO)	0.209	0
Fused silica (SiO_2)	0.22	—
Sodium nitrate ($NaNO_3$)	0.247	0
Sodium fluoride (NaF)	0.26	0
Lithium fluoride (LiF)	0.373	10

— Value not indicated.

Hardness

Values of hardness for several materials are given in Table 3-6. Knoop values with the indenter aligned in either the <100> or the <110> direction are tabulated; the indenter load is given when it is known. When Knoop values were not available, Moh or Vickers values are quoted.

TABLE 3-6. Hardness

Material	Hardness (Knoop Number)	Direction	Indenter Load (gm)	Remarks
Potassium bromide (KBr)	5.9	<110>	200	
	7.0	<100>	200	
Potassium chloride (KCl)	7.2	<110>	200	
	9.3	<100>	200	
Silver chloride (AgCl)	9.5		200	
Thallium bromide (TlBr)	11.9	<110>	500	
	11.9	<100>	500	
Thallium chloride (TlCl)	12.8	<110>	500	
	12.8	<100>	500	
Sodium chloride (NaCl)	15.2	<110>	200	
	18.2	<100>	200	
Sodium nitrate ($NaNO_3$)	19.2	Perpendicular to cleavage planes	200	
Cesium bromide (CsBr)	19.5		200	
Thallium bromide-chloride (KRS-6)	29.9	<110>	500	
	38.5	<100>	500	
Thallium bromide-iodide (KRS-5)	40.2		200	Machined surface
	39.8	<100>	500	
	33.2	<110>	500	
Barium fluoride (BaF_2)	82		500	
Lithium fluoride (LiF)	102–113		600	Vacuum grown
Arsenic trisulfide glass (As_2S_3)	109		100	
Calcium fluoride (CaF_2)	158.3	<110>	500	
	158.3	<100>	500	
Fused silica (SiO_2)	461		200	
Strontium titanate ($SrTiO_3$)	595			
Magnesium oxide (MgO)	692	Perpendicular to cleavage planes	600	
Crystal quartz (SiO_2)	741	Perpendicular to z- and x-cut faces	500	
Titanium dioxide (TiO_2)	879	random	500	
Spinel ($MgO \cdot 3.5\ Al_2O_3$)	1140	random	1000	
Silicon (Si)	1150			7 (Moh Number)
Sapphire (Al_2O_3)	1370	random	1000	
Calcite ($CaCO_3$)				3 (Moh Number)
Cadmium telluride (CdTe)				43.5 (Vickers Scale)
Barium titanate ($BaTiO_3$)				200–580 (Vickers Scale) Single crystal

Solubility

Values of water solubility are given in Table 3-7, and the temperatures at which the measurements were made are noted. Some values of the solubility of these materials in other solvents are given in Chapter 4.

TABLE 3-7. Solubility

Material	Solubility (gm/100 gm water)	Temperature (°C)
Spinel ($MgO \cdot 3.5\ Al_2O_3$)	insoluble*	
Crystal quartz (SiO_2)	insoluble	
Fused silica (SiO_2)	insoluble	
Titanium dioxide (TiO_2)	insoluble	
Sapphire (Al_2O_3)	insoluble	
Silver chloride ($AgCl$)	insoluble	
Arsenic trisulfide glass (As_2S_3)	insoluble	
Amorphous selenium (Se)	insoluble	
Arsenic modified selenium glass; $Se(As)$	insoluble	
Tellurium (Te)	insoluble	
Cadmium sulfide (CdS)	insoluble	
Gallium arsenide ($GaAs$)	insoluble	
Germanium (Ge)	insoluble	
Indium arsenide ($InAs$)	insoluble	
Gallium antimonide ($GaSb$)	insoluble	
Tellurium (Te)	insoluble	
Lead selenide ($PbSe$)	insoluble	
Silicon (Si)	insoluble	
Cadmium telluride ($CdTe$)	insoluble	
Indium antimonide ($InSb$)	insoluble	
Magnesium oxide (MgO)	insoluble	
Calcite ($CaCO_3$)	0.0014	25
Calcium fluoride (CaF_2)	0.0017	26
Thallium bromide ($TlBr$)	0.05	25
Thallium bromide-iodide (KRS-5)	0.05	room
Barium fluoride (BaF_2)	0.17	10
Lithium fluoride (LiF)	0.27	18
Thallium bromide-chloride (KRS-6)	0.32	20
Thallium chloride ($TlCl$)	0.32	20
Sodium fluoride (NaF)	4.22	18
Ammonium dihydrogen phosphate (ADP)	22.7	0
Potassium dihydrogen phosphate (KDP)	33	25
Potassium chloride (KCl)	34.7	20
Sodium chloride ($NaCl$)	35.7	0
Cesium iodide (CsI)	44	0
Potassium bromide (KBr)	53.5	0
Sodium nitrate ($NaNO_3$)	73	0
Cesium bromide ($CsBr$)	124.3	25
Potassium iodide (KI)	127.5	0

* "Insoluble" means less than 10^{-3} gm/100 gm water at room temperature.

Young's Modulus

Values of Young's modulus for several materials are given in Table 3-8. The calculated values are obtained from the values of the elastic moduli by the method described in Chapter 2.

TABLE 3-8. Young's Modulus

Material	Young's Modulus (10^6 psi)	Remarks
Cesium iodide (CsI)	0.769	Measured in flexure
Thallium bromide-iodide (KRS-5)	2.3	Measured in flexure
Cesium bromide ($CsBr$)	2.3	Measured in flexure
Arsenic trisulfide glass (As_2S_3)	2.3	
Silver chloride ($AgCl$)	2.9	Measured in flexure
Thallium bromide-chloride (KRS-6)	3.0	Measured in flexure
Potassium bromide (KBr)	3.9	Measured in flexure
Thallium bromide ($TlBr$)	4.28	Calculated
Potassium chloride (KCl)	4.30	Measured in flexure
Potassium iodide (KI)	4.57	Calculated
Thallium chloride ($TlCl$)	4.60	Calculated
Barium titanate ($BaTiO_3$)	4.90	Single crystal
	16.50	Ceramic
Sodium chloride ($NaCl$)	5.80	Measured in flexure
Indium antimonide ($InSb$)	6.21	Calculated
Barium fluoride (BaF_2)	7.70	Measured in flexure
Gallium antimonide ($GaSb$)	9.19	Calculated
Lithium fluoride (LiF)	9.40	Measured in flexure Minimum value
Calcite ($CaCO_3$)	10.50[p]	
	12.80[s]	
Fused silica (SiO_2)	10.60	
Calcium fluoride (CaF_2)	11.0	Measured in flexure Minimum value
Crystal quartz (SiO_2)	11.1[s]	
	14.1[p]	
Germanium (Ge)	14.9	Calculated
Silicon (Si)	19.0	Calculated
Magnesium oxide (MgO)	36.1	Calculated
Sapphire (Al_2O_3)	50.0	

[p] Young's modulus measured parallel to *c*-axis.

[s] Young's modulus measured perpendicular to *c*-axis.

CHAPTER 4

DETAILED DESCRIPTIONS OF MATERIALS

1. Fused Silica (SiO_2)

Composition

An amorphous material variously called quartz glass, vitreous silica, fused quartz, or fused silica. It is prepared by melting chunks of pure crystal quartz in a suitable container or by a flame process in which powdered silica or a silicate is carried in a blow-torch-like flame and deposited on a cooled surface as pure amorphous SiO_2. Values of the physical properties of fused silica are in general quite different from those of crystal quartz.

Molecular Weight

60.06

Specific Gravity

2.202

(D. S. Hughes and C. Maurette, *J. Appl. Phys.*, Vol. 27, pp. 1184–1186, 1956)

Crystal Class

Not applicable.

Transmission

Long wavelength limit	4.5 μ
Short wavelength limit	0.2 μ

The transmission of fused silica is illustrated in Fig. 4-1. (*WADC-I*, p. 13)

Reflection Loss

6.3% for two surfaces, at a wavelength of 2 μ.

For a material with such a low refractive index, the reflection losses are small. It is difficult to find a suitable substance for thin-film coating that would substantially reduce these losses. A material of refractive index 1.2 would be optimum for coating fused silica.

Refractive Index

Values of refractive index at 24°C, for the wavelength range 0.34 to 3.5 μ, are given in Table 4-1. Values are taken from the original data of W. S. Rodney and R. J. Spindler, *J. Opt. Soc. Am.*, Vol. 44, pp. 677–679, 1954. See also *J. Research NBS*, Vol. 53, pp. 185–189, 1954. Data for shorter wavelengths are given in *AIPH*, p. 6–31; see p. 6–30 for references to other data.

Temperature coefficient of refractive index, $+1 \times 10^{-5}$/C° in the visible region. The value decreases somewhat for increasing wavelength, to 0.4×10^{-5}/C° at 3.5 μ

(Rodney and Spindler, *above ref.*, p. 189)

Dispersion

A graph of $dn/d\lambda$ *vs* λ is given in Fig. 3-3.

Dielectric Constant

3.78 in a frequency range from 100 cps to 2.5×10^{10} cps, at a temperature of 25°C.

(*von Hippel*, p. 311)

Softening Temperature

~1710°C.

(*Sosman*, p. 86)

Thermal Conductivity

2.82×10^{-3} cal/(cm sec C°) at 41°C.

(S. S. Ballard, K. A. McCarthy, and W. C. Davis, *Rev. Sci. Instr.*, Vol. 21, pp. 905–907, 1950)

Thermal Expansion

0.5×10^{-6}/C° in a temperature range from 20°C to 900°C.

(J. B. Saunders, *J. Research NBS*, Vol. 28, pp. 51–55, 1942)

Specific Heat

0.22

(*AIPH*, p. 3–83)

Hardness

Knoop number 461 for load of 200 gm.

(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 41, pp. 215–222, 1951)

Solubility

Insoluble in water, soluble in hydrofluoric acid, very slightly soluble in alkalis.

Elastic Moduli

Young's modulus, 1.06×10^{7} psi at 20°C.

(H. J. McSkimin, *J. Appl. Phys.*, Vol. 24, pp. 988–997, 1953)

Modulus of rigidity, 4.52×10^{6} psi at 20°C.

(McSkimin, *above ref.*)

Bulk modulus, 5.37×10^6 psi.
(Calculated from compressibility value given in *Sosman*, p. 431)

Notes

Fused silica has been used extensively for small windows, in the lead sulfide region of the spectrum. It is reported that even at a temperature of 420°C the material has lost only 3% in transmission. It cuts and grinds very well, and is otherwise quite suitable for many applications. In commercial-grade fused silica there is a strong absorption band at 2.8 μ. It is available in circular plates up to 18 in. in diameter with a minimum thickness of 1/16 in. and a maximum thickness of 3 in. Vycor, Corning Glass number 7905 (Corning Glass Works, Corning, New York) contains 96% silica, and has properties similar to fused silica – see discussion in Chapter 5. Corning commercial fused silica 7940, made by a different method, has a softening point of 1585°C, more than 100°C lower than other fused silicas, such as that prepared by General Electric Company, Cleveland, Ohio.

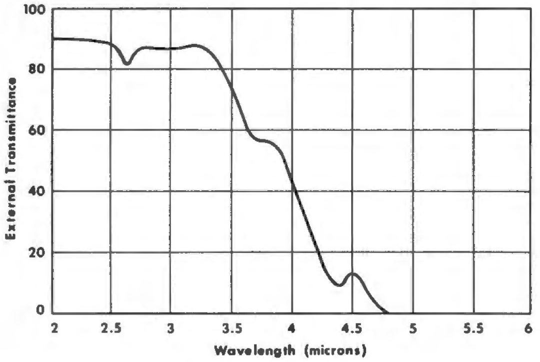


Fig. 4-1. The transmission of fused silica; thickness, 2.85 mm.

TABLE 4-1. The Refractive Index of Fused Silica at 24°C

Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index
0.34	1.47877	0.56	1.459561	1.50	1.444687
0.35	1.47701	0.57	1.459168	1.60	1.443492
0.36	1.47540	0.58	1.458794	1.70	1.442250
0.37	1.47393	0.59	1.458437	1.80	1.440954
0.38	1.47258	0.60	1.458096	1.90	1.439597
0.39	1.47135	0.61	1.457769	2.00	1.438174
0.40	1.470208	0.62	1.457456	2.10	1.436680
0.41	1.469155	0.63	1.457156	2.20	1.435111
0.42	1.468179	0.64	1.456868	2.30	1.433462
0.43	1.467273	0.65	1.456591	2.40	1.431730
0.44	1.466429	0.66	1.456324	2.50	1.429911
0.45	1.465642	0.67	1.456066	2.60	1.428001
0.46	1.464908	0.68	1.455818	2.70	1.425995
0.47	1.464220	0.69	1.455579	2.80	1.423891
0.48	1.463573	0.70	1.455347	2.90	1.421684
0.49	1.462965	0.80	1.453371	3.00	1.41937
0.50	1.462394	0.90	1.451808	3.10	1.41694
0.51	1.461856	1.00	1.450473	3.20	1.41440
0.52	1.461346	1.10	1.449261	3.30	1.41173
0.53	1.460863	1.20	1.448110	3.40	1.40893
0.54	1.460406	1.30	1.446980	3.50	1.40601
0.55	1.459973	1.40	1.445845		

2. Titanium Dioxide (TiO_2)

Composition

Single crystal; natural (rutile or titania), or synthetic.

Molecular Weight

79.90

Specific Gravity

4.25

(Linde Air Products Company, *technical pamphlet* by R. W. Kebler)

Crystal Class

Tetragonal

Transmission

Long wavelength limit 6.2 μ
Short wavelength limit ~ 0.43 μ

The transmission of titanium dioxide is illustrated in Fig. 4-2.

(Linde, *above ref.*)

Reflection Loss

30.0% for two surfaces for the ordinary ray, at a wavelength of 2 μ.

34.8% for two surfaces for the extraordinary ray, at a wavelength of 2 μ.

Refractive Index

Calculated values of refractive index for the wavelength range 0.436 to 1.53 μ, both n_o and n_e, are given in Table 4-2. Values are taken from J. R. DeVore, *J. Opt. Soc. Am.*, Vol. 41, pp. 416–419, 1951, and W. F. Parsons, private communication; the temperature at which the measurements were made is not given. The data of Parsons are for the wavelength region 2.0 to 5.5 μ; the other data are those of DeVore. Linde Air Products Company quotes these values for $\lambda = 0.5893$ μ: $n_e = 2.903$, $n_o = 2.616$. See also *Smakula*, p. 103, for refractive index data for natural rutile at 25°C.

Temperature coefficient of refractive index: for the range 25 to 110°C, $\sim 4 \times 10^{-5}$/C° for n_o, 9×10^{-5}/C° for n_e.

(*Smakula*, p. 103)

Dispersion

Reciprocal dispersion, or nu-value: 10.4 parallel to *c*-axis, 9.3 perpendicular to *c*-axis.

(Linde, *above ref.*)

Dielectric Constant

200 to 160 in a frequency range from 1×10^4 cps to 1×10^7 cps, at a temperature of 25°C with the field parallel to the *c*-axis.

87.3 to 85.8 in a frequency range from 100 cps to 1×10^7 cps, at a temperature of 25°C with the field perpendicular to the *c*-axis.

(*von Hippel*, p. 302)

Melting Temperature

1825°C

(Linde, *above ref.*)

Thermal Conductivity

3.0×10^{-2} cal/(cm sec C°) at 36°C for heat flow parallel to *c*-axis.

2.1×10^{-2} cal/(cm sec C°) at 44°C for heat flow perpendicular to *c*-axis.

(K. A. McCarthy and S. S. Ballard, *J. Opt. Soc. Am.*, Vol. 41, pp. 1062–1063, 1951)

Thermal Expansion

9.19×10^{-6}/C° at 40°C parallel to *c*-axis.

7.14×10^{-6}/C° at 40°C perpendicular to *c*-axis.

(Linde, *above ref.*)

Specific Heat

0.17 at 25°C

(Linde, *above ref.*)

Hardness

Knoop number 879 with indenter load of 500 gm measured in random directions, 792 with indenter load of 1000 gm also measured in random directions.

(Linde, *above ref.*)

Solubility

Insoluble in water, soluble in concentrated sulfuric acid.

Elastic Moduli

Notes

R. W. Kebler indicated in a private communication that a melting temperature of 1820 ± 20°C measured by J. Bunting (*J. Res. NBS* vol. 2, p. 719, 1933) is probably the best value and that new knoop hardness values have been obtained: 910 and 900 parallel and perpendicular, respectively, to the *c*-axis, with an indenter load of 100 gm. Rutile is available from the Linde Co., 30 East 42nd Street, New York 17, N. Y.

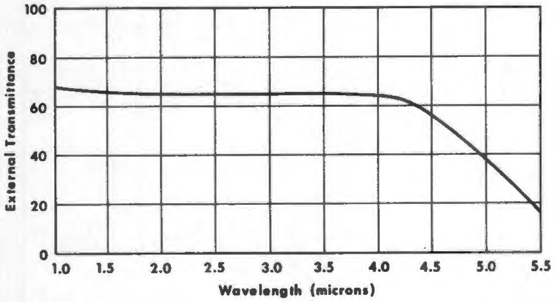


Fig. 4-2. The transmission of titanium dioxide; thickness, 6 mm.

TABLE 4-2. The Refractive Index of Titanium Dioxide

Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index
0.4358	2.853	0.6907	2.555	3.0000	2.380
0.4916	2.723	0.7082	2.548	3.5000	2.367
0.4960	2.715	1.0140	2.483	4.0000	2.350
0.5461	2.652	1.5296	2.451	4.5000	2.322
0.5770	2.623	2.0000	2.399	5.0000	2.290
0.5791	2.621	2.5000	2.387	5.5000	2.200

3. Sapphire (Al_2O_3)

Composition

Synthetic single crystal of corundum: pure Al_2O_3.

Molecular Weight

101.94

Specific Gravity

3.98

(Linde Air Products Company, *technical pamphlet* by R. W. Kebler)

Crystal Class

Hexagonal.

Transmission

Long wavelength limit	6.5 μ
Short wavelength limit	0.17 μ

The transmission of sapphire is illustrated in Fig. 4-3.

(Linde, *above ref.*)

Reflection Loss

12.0% for two surfaces for the ordinary ray, at a wavelength of 4 μ.

Refractive Index

Values of refractive index of synthetic sapphire for the ordinary ray, n_o, at 24°C, for the wavelength range 0.26 to 5.6 μ, are given in Table 4-3; the data are those of I. H. Malitson, F. V. Murphy, Jr., and W. S. Rodney, *J. Opt. Soc. Am.*, Vol. 48, pp. 72–73, 1958. Values of n_e are smaller than n_o by about 0.08, in the visible region.

The temperature coefficient of refractive index is positive but small.

(See Malitson, *above ref.*)

Dispersion

Reciprocal dispersion, or nu-value: 72.2

(Linde, *above ref.*)

A graph of $dn/d\lambda$ *vs* λ is given in Fig. 3-3.

Dielectric Constant

10.55 in a frequency range from 100 cps to 3×10^8 cps, at a temperature of 25°C with the field parallel to *c*-axis.

8.6 in a frequency range from 100 cps to 2.5×10^{10} cps at a temperature of 25°C with the field perpendicular to *c*-axis.

(*von Hippel*, p. 301)

Melting Temperature

2030°C

(Linde, *above ref.*)

Thermal Conductivity

6.0×10^{-2} cal/(cm sec C°) at 26°C, heat flow parallel to *c*-axis.

5.5×10^{-2} cal/(cm sec C°) at 23°C, heat flow perpendicular to *c*-axis.

(K. A. McCarthy and S. S. Ballard, *J. Opt. Soc. Am.*, Vol. 41, pp. 1062–1063, 1951)

Thermal Expansion

6.7 to 10^{-6}/C° at 50°C parallel to *c*-axis.

5.0×10^{-6}/C° at 50°C perpendicular to *c*-axis.

(Linde, *above ref.*)

Specific Heat

0.18 at 25°C

(Linde, *above ref.*)

Hardness

Knoop number 1370 with indenter load of 1000 gm measured in various random directions.

(Eastman Kodak Company, private communication)

Solubility

Insoluble in water, slightly soluble in acids and alkalis.

Elastic Moduli

Young's modulus, 5.0×10^7 psi, no temperature given.

The measurement was made in flexure; this value is the minimum value quoted.

(Linde, *above ref.*)

Bulk modulus, 3.0×10^5 psi.

(Linde, *above ref.*)

Modulus of rigidity, 2.15×10^7 psi.

The measurement was made in torsion; this value is the minimum value quoted.

(Linde, *above ref.*)

Modulus of rupture, 6.5×10^4 psi.

The maximum bending stress was measured; this value is the minimum value quoted.

(Linde, *above ref.*)

Notes

A loss of transmission of not more than 3% is encountered when the material is heated to 440°C. A fairly high emissivity (0.05) has been reported and may be significant in reradiation. It is also significant that it does not show the 2.8 μ water band. Since this material is very hard (often used as an abrasive), it must be ground and polished with diamond or boron-carbide abrasive; the techniques are therefore difficult and costly. (Note: the transmission of ruby is very similar to that of sapphire, but it cuts off, of course, in the red.) Blanks of sapphire are manufactured by the Linde Air Products Company, 30 E. 42nd St., New York 17, N. Y., that are large enough for 3-in.-diameter domes and hemispheres, and 5.5-in.-diameter windows. The aim is to be able to make 6-in. hemispheres. Sapphire has very high thermal conductivity at liquid nitrogen temperatures and below, so it can be used as a substrate for cooled cells.

Notes Added in Proof:

R. W. Kebler, in a private communication, indicates that knoop hardness values from 1525 to 2000 for different orientations were obtained by the Linde Co., using an indenter load of 100 gm. He also states that the elastic coefficients of sapphire have recently been measured (W. Myer and E. A. Heidemann, *Acta Cryst.* Vol. 2, pp. 1–7, 1959)

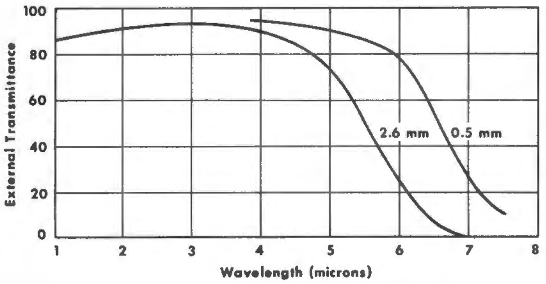


Fig. 4-3. The transmission of sapphire for two thicknesses.

TABLE 4-3. The Refractive Index of Sapphire, Ordinary Ray, at 24.0°C

Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index
0.26520	1.8336	0.64385	1.7655	2.4374	1.7278
0.28035	1.8243	0.706519	1.7630	3.2432	1.7044
0.28936	1.8195	0.85212	1.7588	3.2666	1.7036
0.29673	1.8159	0.89440	1.7579	3.303	1.7023
0.30215	1.8135	1.01398	1.7555	3.3293	1.7015
0.3130	1.8091	1.12866	1.7534	3.4188	1.6982
0.33415	1.8018	1.36728	1.7494	3.5078	1.6950
0.34662	1.7981	1.39506	1.7489	3.70	1.6875
0.361051	1.7945	1.52952	1.7466	4.258	1.6637
0.365015	1.7936	1.6932	1.7437	4.954	1.6266
0.39064	1.7883	1.70913	1.7434	5.1456	1.6151
0.404656	1.7858	1.81307	1.7414	5.349	1.6020
0.435834	1.7812	1.9701	1.7383	5.419	1.5973
0.54607	1.7708	2.1526	1.7344	5.577	1.5864
0.576960	1.7688	2.24929	1.7323		
0.579066	1.7687	2.32542	1.7306		

4. Magnesium Oxide (MgO)

Composition

Single crystal, natural (periclase or beta-magnesia), or synthetic.

Molecular Weight

40.32

Specific Gravity

3.576 at 25°C

(M. A. Durand, *Phys. Rev.*, Vol. 50, pp. 449–455, 1936)

Crystal Class

Cubic, sodium chloride structure; cleaves on {100} and {111} planes.

Transmission

Long wavelength limit 8.5 μ

Short wavelength limit 0.25μ

The transmission of magnesium oxide is illustrated in Fig. 4-4.

(Adapted from *Smith,* p. 356)

Reflection Loss

11.6% for two surfaces, at a wavelength of 4 μ.

Refractive Index

Values of refractive index at 23.3°C, for the wavelength range 0.36 to 5.35 μ, are given in Table 4-4. The data are taken from R. E. Stephens and I. H. Malitson, *J. Research NBS,* Vol. 49, pp. 249–252, 1952. The earlier measurements of J. Strong and B. T. Brice, *J. Opt. Soc. Am.*, Vol. 25, p. 207, 1935, are discussed.

Temperature coefficient of refractive index: about $1.4 \times 10^{-5}/\mathrm{C}^{\circ}$ for 20 to 40°C and 0.77 μ.

(A data table is given by Stephens and Malitson, *above ref.*, p. 249.)

Dispersion

Reciprocal dispersion, or nu-value: 53.5.

(Computed from the data of Stephens and Malitson)

Dielectric Constant

9.65 in a frequency range from 100 cps to 1×10^8 cps, at a temperature of 25°C.

(*von Hippel*, p. 301)

Melting Temperature

2800°C

(*HCP*, p. 555)

Thermal Conductivity

6×10^{-2} cal/(cm sec C°) at 20°C.

(K. A. McCarthy and C. A. Bruns, Tufts University, unpublished data)

Thermal Expansion

$13.8 \times 10^{-6}/\mathrm{C}^{\circ}$ in a temperature range from 20°C to 1000°C.

J. B. Austin, *J. Am. Ceram. Soc.*, Vol. 14, pp. 795–810, 1931)

Specific Heat

0.209 at 0°C

(*HCP*, p. 2090)

Hardness

Knoop number 692 with indenter load of 600 gm. Indentation made on cleavage plane with some cracks appearing.

(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 41, pp. 215–222, 1951)

Solubility

Insoluble in water, soluble in acids and ammonia salts.

Elastic Moduli

Young's modulus, 3.61×10^7 psi.

Calculated from elastic coefficients.

Modulus of rigidity, 2.24×10^7 psi.

Calculated from elastic coefficients.

Bulk modulus, 2.24×10^7 psi.

Calculated from elastic coefficients.

Elastic coefficients at 17°C

c_{11} 2.90×10^{12} dyne/cm^2

c_{12} 0.876×10^{12} dyne/cm^2

c_{44} 1.55×10^{12} dyne/cm^2

(M. A. Durand, *Phys. Rev.*, Vol. 50, pp. 449–455, 1936)

Anisotropy factor, 1.5

Notes

Pressed MgO can be worked like a ceramic material; a good surface can be obtained with a diamond wheel, belt grinder, and carborundum cloth. The crystal can be cut on a disc grinder with no lubricant. Hard work with an aluminum oxide finishing cloth is necessary to get a smooth finish. It can also be used without polishing if a perfect cleavage of the single crystal has been obtained. Some specimens show a little O-H absorption, probably due to water. The polished surfaces of optical components of MgO can be protected from attack by atmospheric moisture with evaporated coatings of SiO. MgO has a slippage plane that may affect the mechanical strength of certain optical components. It loses only about 3% transmission when heated to 440°C.

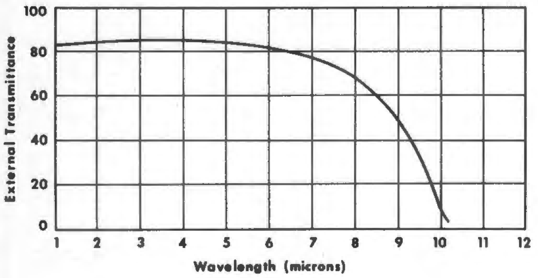


Fig. 4-4. The transmission of magnesium oxide; thickness, 0.67 mm.

TABLE 4-4. The Refractive Index of Magnesium Oxide at 23.3°C

Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index
0.36117	1.77318	1.97009	1.70885
0.365015	1.77186	2.24929	1.70470
1.01398	1.72259	2.32542	1.70350
1.12866	1.72059	3.3033	1.68526
1.36728	1.71715	3.5078	1.68055
1.52952	1.71496	4.258	1.66039
1.6932	1.71281	5.138	1.63138
1.7092	1.71258	5.35	1.62404
1.81307	1.71108		

5. Lithium Fluoride (LiF)

Composition

Single crystal, synthetic, grown in either air or vacuum. The measurements reported below are for both air-grown and vacuum-grown samples.

Molecular Weight

25.94

Specific Gravity

2.639 at 25°C

(C. A. Hutchison and H. L. Johnston, *J. Am. Chem. Soc.*, Vol. 62, p. 3165–3168, 1940)

Crystal Class

Cubic, sodium chloride structure; cleaves on {100} planes.

Transmission

Long wavelength limit 9 μ

Short wavelength limit 0.12 μ

The transmission of lithium fluoride is illustrated in Fig. 4-5.

(Adapted from *Smith*, p. 337)

Reflection Loss

4.4% for two surfaces, at a wavelength of 4 μ.

Lithium fluoride has the lowest refractive index of any of the common optical crystals; therefore, the reflection losses are small and are not easy to reduce because of the difficulty of finding a coating material of substantially lower refractive index.

Refractive Index

Values of refractive index at 23.6°C, for the wavelength range 0.5 to 6 μ, are given in Table 4-5; the data are from L. W. Tilton and E. K. Plyler, *J. Research NBS*, Vol. 47, pp. 25–30, 1951.

Temperature coefficient of refractive index at 30°C: -1.6×10^{-5}/C°.

(Tilton and Plyler, *above ref.*, p. 25)

Dispersion

Curves illustrating the variation with wavelength of the refractive index and the dispersion of lithium fluoride in the range of 0.5 to 11 μ are given in *Smith*, p. 339.

A graph of $dn/d\lambda$ *vs* λ is given in Fig. 3-3.

Dielectric Constant

9.00 in a frequency range from 100 cps to 1×10^{10} cps, at a temperature of 25°C.

9.11 in same frequency range, at a temperature of 80°C.

(*von Hippel*, p. 301)

Melting Temperature

870°C

(*HCP*, p. 549)

Thermal Conductivity

2.7×10^{-2} cal/(cm sec C°) at 41°C.

(S. S. Ballard, L. S. Combes, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 41, pp. 772–775, 1951)

Thermal Expansion

37×10^{-6}/C° in a temperature range from 0°C to 100°C for vacuum-grown material.

(Ballard, *above ref.*)

Specific Heat

0.373 at 10°C

(*HCP*, p. 2090)

Hardness

Knoop number 102 to 113 with indenter load of 600 gm, for vacuum-grown material.

(Ballard, *above ref.*)

Solubility

0.27 gm/100 gm water at 18°C, soluble in acids.

(*HCP*, p. 537.)

Elastic Moduli

Young's modulus, 9.4×10^6 psi.

The measurement was made in flexure; the minimum value measured is quoted.

(Ballard, *above ref.*)

Modulus of rigidity, 8.0×10^6 psi.

Calculated from elastic coefficients.

Bulk modulus, 9.0×10^6 psi.

Calculated from elastic coefficients.

Apparent elastic limit, 1.62×10^7 psi.

The measurement was made in flexure; the minimum value measured is quoted.

(Ballard, *above ref.*)

Modulus of rupture, 2.0×10^7 psi.

The measurement was made in flexure; the minimum value measured is quoted.

Elastic coefficients at room temperature

c_{11} 9.74×10^{11} dyne/cm^2

c_{12} 4.04×10^{11} dyne/cm^2

c_{44} 5.54×10^{11} dyne/cm^2

(H. B. Huntington, *Phys. Rev.*, Vol. 72, pp. 321–331, 1947)

Anisotropy factor, 1.9

Notes

When lithium fluoride is grown in a vacuum the absorption at 2.8 μ attributed to the H-F band disappears. Cylindrical castings 6 in. in diameter by 4 in. are available from the Harshaw Chemical Company. The cylinder is topped by a 120° cone. Optovac, Inc., North Brookfield, Mass., can supply crystals up to 4.75 in. in diameter. LiF and As_2S_3 should combine to give a satisfactory achromatic lens for the 2- to 5-μ region.

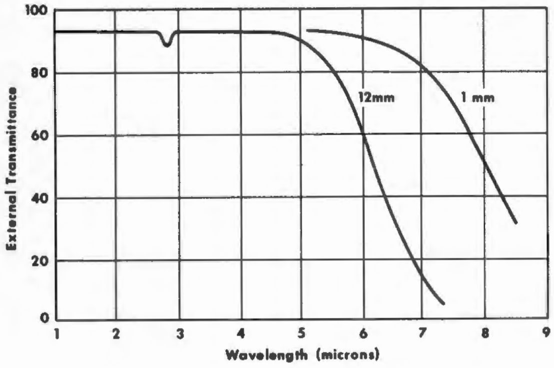


Fig. 4-5. The transmission of lithium fluoride for two thicknesses.

TABLE 4-5. The Refractive Index of Lithium Fluoride at 23.6°C

Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index
0.5	1.39430	2.4	1.37446	4.3	1.34319
0.6	1.39181	2.5	1.37327	4.4	1.34100
0.7	1.39017	2.6	1.37203	4.5	1.33875
0.8	1.38896	2.7	1.37075	4.6	1.33645
0.9	1.38797	2.8	1.36942	4.7	1.33408
1.0	1.38711	2.9	1.36804	4.8	1.33165
1.1	1.38631	3.0	1.36660	4.9	1.32916
1.2	1.38554	3.1	1.36512	5.0	1.32661
1.3	1.38477	3.2	1.36359	5.1	1.32399
1.4	1.38400	3.3	1.36201	5.2	1.32131
1.5	1.38320	3.4	1.36037	5.3	1.31856
1.6	1.38238	3.5	1.35868	5.4	1.31575
1.7	1.38153	3.6	1.35693	5.5	1.31287
1.8	1.38064	3.7	1.35514	5.6	1.30993
1.9	1.37971	3.8	1.35329	5.7	1.30692
2.0	1.37875	3.9	1.35138	5.8	1.30384
2.1	1.37774	4.0	1.34942	5.9	1.30068
2.2	1.37669	4.1	1.34740	6.0	1.29745
2.3	1.37560	4.2	1.34533		

6. Calcium Fluoride (CaF_2)

Composition

Single crystal, natural (fluorite), or synthetic.

Molecular Weight

78.08

Specific Gravity

3.179 at 25°C

(A. Smakula and V. Sils, *Phys. Rev.*, Vol. 99, pp. 1744–1746, 1955)

Crystal Class

Cubic, calcium fluoride structure; cleaves on {111} planes.

Transmission

Long wavelength limit 12.0 μ
Short wavelength limit 0.13 μ

The transmission of calcium fluoride is illustrated in Fig. 4-6.

(Adapted from *Smith,* p. 341)

Reflection Loss

5.6% for two surfaces, at a wavelength of 4 μ.

Refractive Index

Values of refractive index at 20°C, for the wavelength range 0.49 to 9.4 μ, are given in Table 4-6; data are taken from W. W. Coblentz, *J. Opt. Soc. Am.*, Vol. 4, pp. 441, 1920. Data from another source are given in *AIPH,* pp. 6–26, 6–27. Presumably, prisms of natural fluorite rather than synthetic CaF_2 were used in all these measurements.

Temperature coefficient of refractive index:
-9×10^{-6}/C° at 6.5 μ.

(Coblentz, *above ref.* See *Smakula,* p. 64 for additional data, and p. 75 for a graph.)

Dispersion

Curves illustrating the variation with wavelength of refractive index and of dispersion, in the range 0.5 to 9.5 μ, are given in *Smith,* p. 342.

A graph of $dn/d\lambda$ *vs* λ is given in Fig. 3-3.

Dielectric Constant

6.76 at a frequency of 1×10^5 cps.

(*AIPH,* p. 5–115)

Melting Temperature

1360°C

(*HCP,* p. 505)

Thermal Conductivity

2.32×10^{-2} cal/(cm sec C°) at 36°C.

(S. S. Ballard, K. A. McCarthy, and W. C. Davis, *Rev. Sci. Instr.*, Vol. 21, pp. 905–907, 1950.)

Thermal Expansion

24×10^{-6}/C° in a temperature range from 20°C to 60°C.

(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 41, pp. 215–222, 1951)

Specific Heat

0.204 at 0°C

(*HCP,* p. 2088)

Hardness

Knoop number 158.3 with indenter load of 500 gm; same result with indenter in both <100> and <110> direction.

(Combes, *above ref.*)

Solubility

0.0017 gm/100 gm water at 26°C, soluble in ammonia salt solutions.

(*HCP,* p. 505)

Elastic Moduli

Young's modulus, 1.1×10^7 psi.

The measurement was made in flexure; the minimum value measured is quoted.

(S. S. Ballard, L. S. Combes, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 42, pp. 684–685, 1952)

Modulus of rigidity, 4.9×10^6 psi.

Calculated from elastic coefficients.

Bulk modulus, 1.2×10^7 psi.

Calculated from elastic coefficients.

Apparent elastic limit, 5.3×10^3 psi.

The measurement was made in flexure; the minimum value measured is quoted.

(Ballard, *above ref.*)

Modulus of rupture, 5.3×10^3 psi.

The measurement was made in flexure; the minimum value measured is quoted.

Cold flow, none.

Elastic coefficients (no temperature given)

c_{11} 16.4×10^{11} dyne/cm^2
c_{12} 4.47×10^{11} dyne/cm^2
c_{44} 3.38×10^{11} dyne/cm^2

Anisotropy factor, 0.56

(*Voigt,* p. 744)

Notes

This material cuts nicely on a diamond saw, but is fragile on a diamond fine-grinding wheel. It is difficult to grind; very light "cuts" are recommended. Optovac, Inc., North Brookfield, Mass., can supply fluorite crystals up to 6.5 in. in diameter from stock, and 9-in.-diameter crystals can be produced.

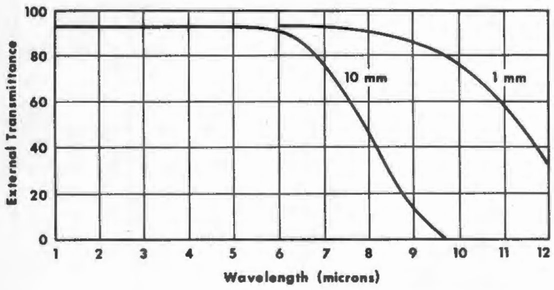


Fig. 4-6. The transmission of calcium fluoride for two thicknesses.

TABLE 4-6. The Refractive Index of Calcium Fluoride at 20°C

Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index
0.48615	1.43704	1.900	1.42439	3.4000	1.41487
0.58758	1.43388	1.9153	1.42431	3.5359	1.41376
0.58932	1.43384	1.9644	1.42407	3.8306	1.41119
0.65630	1.43249	2.0582	1.42360	4.000	1.40963
0.68671	1.43200	2.0626	1.42357	4.1252	1.40847
0.72818	1.43143	2.1608	1.42306	4.2500	1.40722
0.76653	1.43093	2.250	1.42258	4.4000	1.40568
0.88400	1.42980	2.3573	1.42198	4.6000	1.40357
1.0140	1.42884	2.450	1.42143	4.7146	1.40233
1.08304	1.42843	2.5537	1.42080	4.8000	1.40130
1.1000	1.42834	2.6519	1.42018	5.000	1.39908
1.1786	1.42789	2.700	1.41988	5.3036	1.39522
1.250	1.42752	2.750	1.41956	5.8932	1.38712
1.3756	1.42689	2.800	1.41923	6.4825	1.37824
1.4733	1.42642	2.880	1.41890	7.0718	1.36805
1.5715	1.42596	2.9466	1.41823	7.6612	1.35675
1.650	1.42558	3.0500	1.41750	8.2505	1.34440
1.7680	1.42502	3.0980	1.41714	8.8398	1.33075
1.8400	1.42468	3.2413	1.41610	9.4291	1.31605
1.8688	1.42454				

7. Arsenic Trisulfide Glass (As_2S_3)

Composition

Synthetic, amorphous (glass). Technical arsenious sulfide is purified by distillation at dark red heat. The sulfide can then be poured and molded. It is advisable to pass a stream of H_2S through the distillation.

(R. Frerichs, *J. Opt. Soc. Am.*, Vol. 43, p. 1153, 1953)

Molecular Weight

264.02

Specific Gravity

3.198

(American Optical Company, *Technical Data Sheets*)

Crystal Class

Not applicable.

Transmission

Long wavelength limit	$\sim 11\ \mu$
Short wavelength limit	$0.6\ \mu$

The transmission of arsenic trisulfide glass is illustrated in Fig. 7-1.

(Adapted from *Smith*, p. 356)

Reflection Loss

28.5% for two surfaces, at a wavelength of $10\ \mu$.

Coatings are available to reduce reflection loss to about 4% at a specific wavelength or at several wavelengths.

(American Optical Company)

Refractive Index

Values of refractive index at 25°C, for the wavelength range of 0.58 to $12\ \mu$, are given in Table 4-7; the indices were measured at the National Bureau of Standards.

(Malitson, Rodney, and King, *J. Opt. Soc. Am.*, Vol. 48, p. 633, 1958)

Dispersion

A graph of $dn/d\lambda$ *vs* λ is given in Fig. 3-3.

Dielectric Constant

8.1 in a frequency range of 10^3 to 10^6 cps.

(American Optical Company)

Softening Temperature

210°C

(American Optical Company)

Thermal Conductivity

4×10^{-4} cal/(cm sec C°) at 40°C (average).

(Measured at Tufts University for the American Optical Company)

Thermal Expansion

24.62×10^{-6}/C° in a temperature range from 33°C to 165°C

(American Optical Company)

Specific Heat

Hardness

Knoop number 109 with indenter load of 100 gm.

(L. S. Combes, Tufts University, unpublished data)

Solubility

Slightly more soluble than crown glass in water, soluble in alkalis, attacked by metallic mercury and concentrated mineral acids.

Elastic Moduli

Young's modulus, 2.30×10^6 psi

Modulus of rigidity, 9.4×10^5 psi

Modulus of rupture, 2.4×10^3 psi

(American Optical Company)

Notes

The properties of arsenic trisulfide glass vary with different batches. This difference is probably caused by various quantities of arsenic di- and penta-sulfide as well as free sulfur. For instance, the properties quoted in the Servo Corporation of America brochure TDS-R-4, "Servofrax Arsenic Trisulfide Glass," are somewhat different from those quoted here. There are currently two types of glass to be considered: type A and type S. Type S is the type usually used commercially and discussed here; type A has better visible-spectrum transmission, but poorer mechanical properties. Although it cracks rather easily under thermal strain, a sample window of arsenic trisulfide was subjected to a 500°C air blast on one side for more than 30 sec and did not crack. A 4.5-in. dome has traveled successfully at Mach 2.8 and has withstood 160 g without damage. Arsenic trisulfide is quite soft and brittle (although experiments are in progress to harden it somewhat), and can be pressed, sawed, ground and polished rather easily. The coefficient of expansion of arsenic trisulfide is similar to that of aluminum, so it can therefore be used in aluminum mounts quite satisfactorily. Silicon monoxide is often used as a coating for reducing reflection losses. Arsenic trisulfide glass is available from American Optical Company, Servo Corporation of America, New Hyde Park, N. Y., and Fraser Glass Company, Chicago 37, Ill.

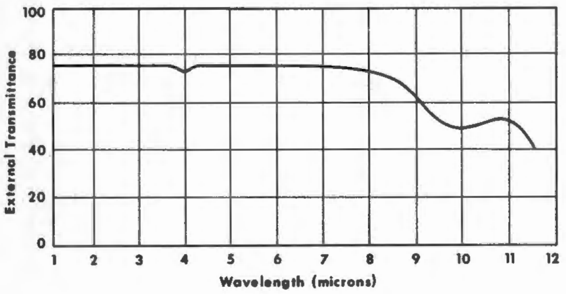


Fig. 4-7. The transmission of arsenic trisulfide glass; thickness, 5 mm.

TABLE 4-7. The Refractive Index of Arsenic Trisulfide Glass at 25°C

Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index
0.576960	2.66324	1.7006	2.43260
0.579016	2.66054	1.81308	2.42999
0.5876	2.65007	1.9701	2.42682
0.643857	2.59762	3.4188	2.41374
0.6678	2.58083	4.258	2.41013
0.69075	2.56697	5.138	2.40671
0.7065	2.55857	6.238	2.40221
0.85212	2.50611	6.692	2.40035
0.89440	2.49633	8.662	2.39035
1.01398	2.47568	9.724	2.38342
1.12866	2.46229	11.035	2.37365
1.395055	2.44379	11.475	2.36944
1.52952	2.43803	11.862	2.36577

8. Barium Fluoride (BaF_2)

Composition

Single crystal, synthetic.

Molecular Weight

175.36

Specific Gravity

4.83 at 20°C
(*HCP*, p. 491)

Crystal Class

Cubic, calcium fluoride structure.

Transmission

Long wavelength limit 15.0 μ
Short wavelength limit 0.15 μ

The transmission of barium fluoride is illustrated in Fig. 4-8.
(*WADC-I*, p. 16)

Reflection Loss

7.7% for two surfaces, at a wavelength of 0.6 μ.

Refractive Index

Values of refractive index at 25°C for the wavelength range of 0.25 to 11 μ are given in Table 4-8; the indices were measured at the National Bureau of Standards and are preliminary data.
(I. H. Malitson, private communication)

Dispersion

Reciprocal dispersion, or nu-value: 81.7.

Dielectric Constant

7.33 at a frequency of 2×10^6 cps.
(*AIPH*, p. 5-115)

Melting Temperature

1280°C
(*HCP*, p. 491)

Thermal Conductivity

28×10^{-3} cal/(cm sec C°) at 13°C.
(*AIPH*, p. 4-76)

Thermal Expansion

Specific Heat

Hardness

Knoop number 82 for 500-gm load.
(S. S. Ballard, L. S. Combes, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 42, pp. 684–685, 1952)

Solubility

0.17 gm/100 gm water at 10°C, soluble in acids and ammonium chloride.
(*HCP*, p. 491)

Elastic Moduli

Young's modulus, 7.7×10^6 psi.
The measurement was made in flexure.
(Ballard, *above ref.*)
Apparent elastic limit, 3.9×10^7 psi.
The measurement was made in flexure.
(Ballard, *above ref.*)
Modulus of rupture, 3.9×10^7 psi.
The measurement was made in flexure.
(Ballard, *above ref.*)

Notes

Barium fluoride can be obtained from the Harshaw Chemical Company, Cleveland, Ohio, in cylinders up to 6 in. in diameter by 3.7 in., topped by a 120° cone, and from Optovac Inc., North Brookfield, Mass., in sizes up to 2.5 in. in diameter. The material can be cut with a Norton diamond wheel at about 4000 rpm. Very, very light pressure should be applied to prevent cleavage.

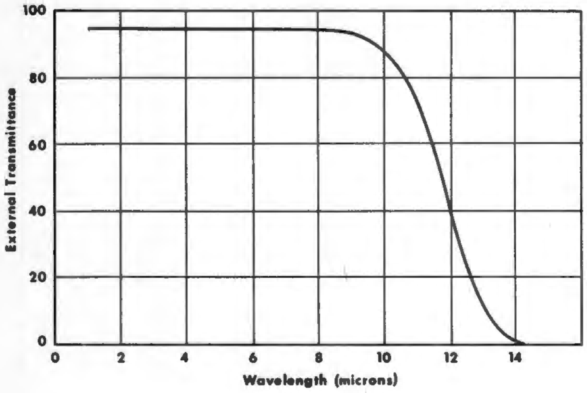


Fig. 4-8. The transmission of barium fluoride; thickness, 9.1 mm.

TABLE 4-8. The Refractive Index of Barium Fluoride at 25°C

Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index
0.2536	1.5122	1.01398	1.4685
0.28035	1.5067	1.12866	1.4678
0.28936	1.5039	1.36728	1.4668
0.29673	1.5019	1.52952	1.4662
0.30215	1.5005	1.681	1.4656
0.3130	1.4978	1.918	1.4649
0.32546	1.4952	1.9701	1.4647
0.33415	1.4936	2.1526	1.4641
0.34036	1.4926	2.32542	1.4636
0.34662	1.4916	2.576	1.4626
0.361051	1.4894	2.673	1.4624
0.365015	1.4889	3.2434	1.4602
0.404656	1.4844	3.422	1.4594
0.435834	1.4818	3.7067	1.4588
0.54607	1.4759	5.138	1.4501
0.576960	1.4748	5.3034	1.4491
0.579066	1.4747	5.343	1.4488
0.589262	1.4744	5.549	1.4474
0.64385	1.4730	5.7663	1.4459
0.65628	1.4728	6.16	1.4436
0.706519	1.4718	9.724	1.4209
0.767858	1.4708	11.035	1.4142

9. Sodium Chloride (NaCl)

Composition

Single crystal, natural (rock salt), or synthetic.

Molecular Weight

58.45

Specific Gravity

2.164 at 20°C

(H. L. Johnston and D. A. Hutchison, *Phys. Rev.*, Vol. 62, pp. 32–36, 1942)

Crystal Class

Simple cubic; cleaves on {100} planes.

Transmission

Long wavelength limit	26.0 μ
Short wavelength limit	0.21 μ

The transmission of rock salt is illustrated in Fig. 4-9.

(Adapted from *Smith*, p. 332)

Reflection Loss

7.5% for two surfaces, at a wavelength of 10 μ.

Refractive Index

Values of refractive index at 20°C, for the wavelength range 0.59 to 22.3 μ, are given in Table 4-9; data are taken from W. W. Coblentz, *J. Opt. Soc. Am.*, Vol. 4, p. 443, 1920. Data from other sources are given in *AIPH*, pp. 6-28 and 6-29. Presumably, prisms of natural rock salt rather than synthetic NaCl were used in all these measurements.

Temperature coefficient of refractive index:

-2.5×10^{-5}/C° at 9μ;

(Coblentz, *above ref.* See *Smakula*, pp. 69–70 for additional data, and p. 75 for a graph showing variation of dn/dT with wavelength.)

Dispersion

Curves illustrating the variation with wavelength of refractive index and of dispersion in the range 0.6 to 2.7 μ are given on p. 333 of *Smith*.

A graph of $dn/d\lambda$ *vs* λ is given in Fig. 3-3.

Dielectric Constant

5.90 in a frequency range from 100 cps to 2.5×10^{10} cps, at a temperature of 25°C.

6.35 to 5.97 in same frequency range, at a temperature of 85°C.

(*von Hippel*, p. 302)

Melting Temperature

801°C

(*HCP*, p. 605)

Thermal Conductivity

1.55×10^{-2} cal/(cm sec C°) at 16°C.

(*AIPH*, p. 4-76)

Thermal Expansion

44×10^{-6}/C° in a temperature range from −50°C to 200°C.

(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 41, pp. 215–222, 1951)

Specific Heat

0.204 at 0°C

(*HCP*, p. 2092)

Hardness

Knoop number 15.2 with indenter load of 200 gm; indenter in <110> direction.

Knoop number 18.2 with indenter load of 200 gm; indenter in <100> direction.

(*Combes*, above ref.)

Solubility

35.7 gm/100 gm water at 0°C, soluble in glycerine, slightly soluble in alcohol and liquid ammonia, insoluble in hydrochloric acid.

(*HCP*, p. 605)

Elastic Moduli

Young's modulus, 5.8×10^6 psi.

The measurement was made in flexure.

(*Combes*, above ref.)

Modulus of rigidity, 1.83×10^6 psi.

Calculated from elastic coefficients.

Bulk modulus, 3.54×10^6 psi.

Calculated from elastic coefficients.

Apparent elastic limit, 3.5×10^2 psi.

The measurement was made in flexure.

(*Combes*, above ref.)

Modulus of rupture, 5.7×10^2 psi.

The measurement was made in flexure.

(*Combes*, above ref.)

Elastic coefficients at room temperature

c_{11}	4.85×10^{11} dyne/cm²
c_{12}	1.23×10^{11} dyne/cm²
c_{44}	1.26×10^{11} dyne/cm²

(H. B. Huntington, *Phys. Rev.*, Vol. 72, pp. 321–331, 1947)

Anisotropy factor, 0.70

Notes

Sodium chloride polishes easily and, although hygroscopic, can be protected by evaporated coatings and plastics. Selenium films have been used successfully. It is available from the Harshaw Chemical Company, Cleveland, Ohio, in sizes that can be cut from a 12-in. diameter, 12-in. long cylinder, and from Optovac, Inc., North Brookfield, Mass., in sizes up to 8 in. in diameter.

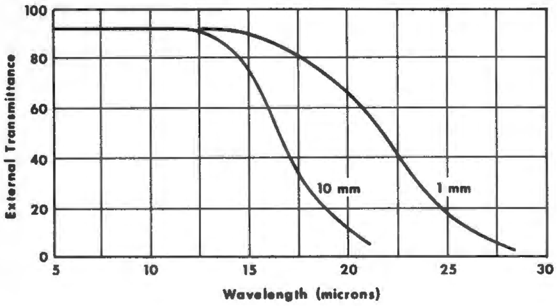


Fig. 4-9. The transmission of sodium chloride for two thicknesses.

TABLE 4-9. The Refractive Index of Sodium Chloride at 20°C

Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index
0.589	1.54427	1.6848	1.52764	7.22	1.51020
0.6400	1.54141	1.7670	1.52736	7.59	1.50850
0.6874	1.53930	2.0736	1.52649	7.6611	1.50822
0.7604	1.53682	2.1824	1.52621	7.9558	1.50665
0.7858	1.53607	2.2464	1.52606	8.04	1.5064
0.8835	1.53395	2.3560	1.52579	8.8398	1.50192
0.9033	1.53361	2.6505	1.52512	9.00	1.50100
0.9724	1.53253	2.9466	1.52466	9.50	1.49980
1.0084	1.53206	3.2736	1.52371	10.0184	1.49462
1.0540	1.53153	3.5359	1.52312	11.7864	1.48171
1.0810	1.53123	3.6288	1.52286	12.50	1.47568
1.1058	1.53098	3.8192	1.52238	12.9650	1.47160
1.1420	1.53063	4.1230	1.52156	13.50	1.4666
1.1786	1.53031	4.7120	1.51979	14.1436	1.46044
1.2016	1.53014	5.0092	1.51883	14.7330	1.45427
1.2604	1.52971	5.3009	1.51790	15.3223	1.44743
1.3126	1.52937	5.8932	1.51593	15.9116	1.44090
1.4874	1.52845	6.4825	1.51347	17.93	1.4149
1.5552	1.52815	6.80	1.51200	20.57	1.3735
1.6368	1.52781	7.0718	1.51093	22.3	1.3403

10. Silver Chloride (AgCl)

Composition

Single crystal, synthetic.

Molecular Weight

143.34

Specific Gravity

5.589 at 0°C
(P. W. Bridgman, *Proc. Am. Acad. Arts Sci.,* Vol. 74, pp. 21–25, 1940)

Crystal Class

Cubic, sodium chloride structure; does not cleave.

Transmission

Long wavelength limit 30.0 μ
Short wavelength limit 0.4 μ
The transmission of silver chloride is illustrated in Fig. 4-10.
(*Smith,* p. 343)

Reflection Loss

19.5% for two surfaces, at a wavelength of 10 μ

Refractive Index

Values of refractive index at 23.9°C, for the wavelength range 0.5 to 20.5 μ, are given in Table 4-10; the data are those of Tilton, Plyler, and Stephens, *J. Opt. Soc. Am.*, Vol. 40, pp. 540–543, 1950.

Temperature coefficient of refractive index: approximately -6.1×10^{-5}/C° at 0.61 μ.
(Tilton, *above ref.*)

Dispersion

Curves illustrating the variation with wavelength of refractive index and of dispersion, in the range 1 to 20 μ, are given in *Smith,* p. 343.

A graph of $dn/d\lambda$ *vs* λ is given in Fig. 3-3.

Dielectric Constant

12.3 at room temperature.
(A. Eucken and A. Büchner, *Z. Phys. Chem.,* Vol. 27B, pp. 321–349, 1934)

Melting Temperature

457.7°C
(H. C. Kremers, *J. Opt. Soc. Am.,* Vol. 37, pp. 337–341, 1947)

Thermal Conductivity

2.75×10^{-3} cal/(cm sec C°) at 22°C.
(K. A. McCarthy, Tufts University, unpublished data)

Thermal Expansion

30×10^{-6}/C° in a temperature range from 20°C to 60°C.
(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.,* Vol. 41, pp. 215–222, 1951)

Specific Heat

0.0848 at 0°C
(*HCP,* p. 2091)

Hardness

Knoop number 9.5 with indenter load of 200 gm.
(Combes, *above ref.*)

Solubility

Insoluble in water, ammonium hydroxide, sodium sulfite, and potassium cyanide.

Elastic Moduli

Young's modulus, 2.9×10^6 psi.
The measurement was made in flexure.
(Combes, *above ref.*)
Modulus of rigidity 1.03×10^6 psi.
The measurement was made in torsion.
(Combes, *above ref.*)
Bulk modulus, 6.39×10^6 psi.
Calculated from elastic coefficients.
Apparent elastic limit, 3.8×10^3 psi, for measurement made in flexure; 7.4×10^2 psi, for measurement made in torsion.
Elastic coefficients at room temperature

c_{11}	6.01×10^{11} dyne/cm^2
c_{12}	3.62×10^{11} dyne/cm^2
c_{44}	0.625×10^{11} dyne/cm^2

(D. L. Arenberg, *J. Appl. Phys.*, Vol. 21, p. 941, 1950)
Anisotropy factor, 0.53

Notes

Silver chloride is a colorless ductile solid with mechanical properties similar to those of lead. A sheet of it, when struck with a hard object, will give a clear metallic ring, but the same sheet will bend easily when finger pressure is applied. Silver chloride that is not extremely pure darkens when exposed to ultraviolet light; it can be protected by a thin film of silver sulfide. Silver chloride is extremely corrosive to metal. It admits of simple fusing to glass or silver by a permanent vacuum-type seal. It is available from the Harshaw Chemical Co., Cleveland, Ohio, in pieces up to a cylinder 3.75 in. in diameter by 5 or 6 in. The ingot can be rolled to give a large-area sheet of the desired thickness. Single crystals can be turned on a lathe, planed, and operated on generally like a plastic. To clean silver chloride, one can wash it first in water, then in 0.2 strength hypo solution. The crystal should be bathed in this a few seconds until the polish of the surface "cleans." If turning or scraping is necessary, one can rub lightly with water and emery paper.

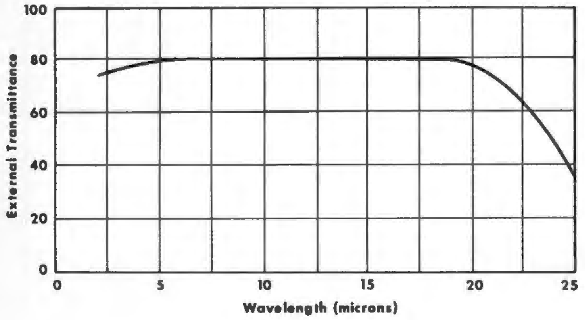


Fig. 4-10. The transmission of silver chloride; thickness, 5 mm.

TABLE 4-10. The Refractive Index of Silver Chloride at 23.9°C

Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index
0.5	2.09648	7.5	1.99021	14.5	1.95467
1.0	2.02239	8.0	1.99847	15.0	1.95113
1.5	2.01047	8.5	1.98661	15.5	1.94743
2.0	2.00615	9.0	1.98464	16.0	1.94358
2.5	2.00386	9.5	1.98255	16.5	1.93958
3.0	2.00230	10.0	1.98034	17.0	1.93542
3.5	2.00102	10.5	1.97801	17.5	1.93109
4.0	1.99983	11.0	1.97556	18.0	1.92660
4.5	1.99866	11.5	1.97297	18.5	1.92194
5.0	1.99745	12.0	1.97026	19.0	1.91710
5.5	1.99618	12.5	1.96742	19.5	1.91208
6.0	1.99483	13.0	1.96444	20.0	1.90688
6.5	1.99339	13.5	1.96133	20.5	1.90149
7.0	1.99185	14.0	1.95807		

11. Potassium Bromide (KBr)

Composition

Single crystal, synthetic.

Molecular Weight

119.01

Specific Gravity

2.75 at 23°C
(*Smakula*, p. 9)

Crystal Class

Cubic, sodium chloride structure; cleaves on {100} planes.

Transmission

Long wavelength limit 40 μ
Short wavelength limit 0.23 μ

The transmission of potassium bromide is illustrated in Fig. 4-11.
(E. K. Plyler, private communication)

Reflection Loss

8.4% for two surfaces, at a wavelength of 10 μ.

Refractive Index

Values of refractive index at 22°C, for the wavelength range 0.4 to 25 μ, are given in Table 4-11; the data are taken from Stephens, Plyler, Rodney, and Spindler, *J. Opt. Soc. Am.*, Vol. 43, pp. 111-112, 1953.

Temperature coefficient of refractive index: -4.0×10^{-5}/C°.
(Stephens, *above ref.*, p. 112)

Dispersion

A graph of $dn/d\lambda$ *vs* λ is given in Fig. 3-3.

Dielectric Constant

4.90 in a frequency range from 100 cps to 1×10^{10} cps, at a temperature of 25°C.

4.97 in same frequency range, at a temperature of 87°C.
(*von Hippel*, p. 301)

Melting Temperature

730°C
(*HCP*, p. 579)

Thermal Conductivity

1.15×10^{-2} cal/(cm sec C°) at 46°C.
(S. S. Ballard, K. A. McCarthy, and W. C. Davis, *Rev. Sci. Instr.*, Vol. 21, pp. 905–907, 1950)

Thermal Expansion

43×10^{-6} in a temperature range from 20°C to 60°C.
(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 41, pp. 215–222, 1951)

Specific Heat

0.104 at 0°C.
(*HCP*, p. 2091)

Hardness

Knoop number 5.9 in <110> direction with 200-gm indenter load.

Knoop number 7.0 in <100> direction with 200-gm indenter load.
(Combes, *above ref.*)

Solubility

53.48 gm/100 gm water at 0°C, slightly hygroscopic.
(*HCP*, p. 579)

Elastic Moduli

Young's modulus, 3.9×10^6 psi.
The measurement was made in flexure.
(Combes, *above ref.*)

Modulus of rigidity, 0.737×10^6 psi.
Calculated from elastic coefficients.

Bulk modulus, 2.18×10^6 psi.
Calculated from elastic coefficients.

Apparent elastic limit, 1.6×10^2 psi.
The measurement was made in flexure.
(Combes, *above ref.*)

Modulus of rupture, 4.8×10^2 psi.
The measurement was made in flexure.
(Combes, *above ref.*)

Elastic coefficients at room temperature
c_{11} 3.45×10^{11} dyne/cm^2
c_{12} 0.54×10^{11} dyne/cm^2
c_{44} 0.508×10^{11} dyne/cm^2
(H. B. Huntington, *Phys. Rev.*, Vol. 72, pp. 321–331, 1947)

Anisotropy factor, 0.35

Notes

Potassium bromide is grown in the same form as sodium chloride, but sometimes multiple crystals result. It can be obtained from the Harshaw Chemical Company, Cleveland, Ohio, in sizes up to a 12-in.-diameter cylinder 12 in. long, and from Optovac Inc., North Brookfield, Mass., in sizes up to 6 in. in diameter. Very pure samples have been obtained, but they cleave.

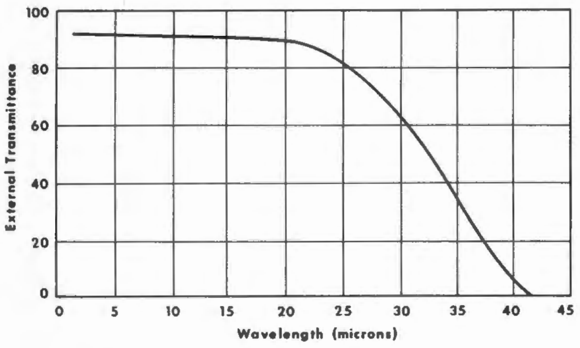


Fig. 4-11. The transmission of potassium bromide; thickness, 4.0 mm.

TABLE 4-11. The Refractive Index of Potassium Bromide at 22°C

Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index
0.404656	1.589752	6.238	1.53288
0.435835	1.581479	6.692	1.53225
0.486133	1.571791	8.662	1.52903
0.508582	1.568475	9.724	1.52695
0.546074	1.563928	11.035	1.52404
0.587562	1.559965	11.862	1.52200
0.643847	1.555858	14.29	1.51505
0.706520	1.552447	14.98	1.51280
1.01398	1.54408	17.40	1.50390
1.12866	1.54258	18.16	1.50076
1.36728	1.54061	19.01	1.49703
1.7012	1.53901	19.91	1.49288
2.44	1.53733	21.18	1.48655
2.73	1.53693	21.83	1.48311
3.419	1.53612	23.86	1.47140
4.258	1.53523	25.14	1.46324

12. Thallium Bromide-Iodide; KRS-5 (TlBr-TlI)

Composition

This synthetic mixed crystal, also called thallium bromoiodide (TlBr,I) and usually designated by the code name KRS-5, contains about 42 mole percent thallium bromide and 58 mole percent thallium iodide. The percentages corresponding to the minimum freezing temperature of the binary system are 45.7 and 54.3, respectively, and this is the composition which should give highest optical homogeneity.

(Smakula, Kalnajs, and Sils, *J. Opt. Soc. Am.*, Vol. 43, pp. 698–701, 1953)

Molecular Weight

Not applicable.

Specific Gravity

7.371 at 16°C

(*Smakula*, p. 11; for the 42%–58% material)

Crystal Class

Cubic; does not cleave along a crystal direction, but may break apart in a conchoidal fracture.

Transmission

Long wavelength limit 40 μ
Short wavelength limit 0.5 μ
The transmission of KRS-5 is illustrated in Fig. 4-12.
(E. K. Plyler, private communication)

Reflection Loss

28.4% for two surfaces, at a wavelength of 10 μ.

Refractive Index

Values of refractive indices at 25°C, for the wavelength range of 0.54 to 40 μ, are given in Table 4-12; these are the calculated data of W. S. Rodney and I. H. Malitson, *J. Opt. Soc. Am.*, Vol. 46, pp. 956–961, 1956. Data are given in the reference for temperatures of 19°C and 31°C also. A comparison is given of their new data, taken with the 45.7–54.3 mole percent mixed crystal, with the older data taken with 42–58 crystal material by Tilton, Plyler, and Stephens, *J. Research NBS*, Vol. 43, pp. 81–86, 1949.

Temperature coefficient of refractive index: varies from -23.5×10^{-5}/C° at 10 μ to -15.4×10^{-5}/C° at 40 μ.

(Rodney and Malitson, *above ref.* Data and a graph are given, for the region 0.6 to 40 μ.)

Dispersion

A graph of $dn/d\lambda$ *vs* λ is given in Fig. 3-3.

Dielectric Constant

32.9 to 32.5 in a frequency range from 100 cps to 1×10^7 cps, at a temperature of 25°C.

(*von Hippel*, p. 302; measurements made on 42% TlBr, 58% TlI material)

Melting Temperature

414.5°C

(A. Smakula, unpublished data)

Thermal Conductivity

1.3×10^{-3} cal/(cm sec C°) at 20°C

(*AIPH*, p. 4–76)

Thermal Expansion

58×10^{-6}/C° in a temperature range from 20°C to 100°C.

(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 41, pp. 215–222, 1951)

Specific Heat

Hardness

Knoop number 40.2 with indenter load of 200 gm on machined surface.

33.2 with indenter load of 500 gm, long axis of indenter in <110> direction.

39.8 with indenter load of 500 gm, long axis of indenter in <100> direction.

(Combes, *above ref.*)

Solubility

0.05 gm/100 gm water at room temperature.

(A. Smakula, *J. Opt. Soc. Am.*, Vol. 45, pp. 1086–1087, 1955)

Elastic Moduli

Young's modulus, 2.3×10^6 psi.

The measurement was made in flexure.

(Combes, *above ref.*, and *J. Opt. Soc. Am.*, Vol. 42, pp. 65–66, 1952)

Modulus of rigidity, 0.840×10^6 psi.

The measurement was made in torsion.

(Combes, *above ref.*)

Bulk modulus, 2.87×10^6 psi.
Calculated from elastic coefficients.
Apparent elastic limit, 3.8×10^3 psi.
The measurement was made in flexure; the minimum value quoted is measured.
(Combes, *above ref.*)
Modulus of rupture, 1.81×10^4 psi.
The measurement was made in flexure.
(Combes, *above ref.*)
Elastic coefficients at room temperature
c_{11} 3.31×10^{11} dyne/cm^2
c_{12} 1.32×10^{11} dyne/cm^2
c_{44} 0.579×10^{11} dyne/cm^2
(D. L. Arenberg, based on measurements made at Naval Research Laboratory, 1948–1949)
Anisotropy factor, 0.582

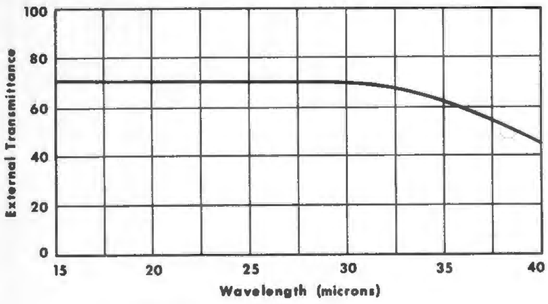


Fig. 4-12. The transmission of KRS-5; thickness, 5.15 mm.

Notes

KRS-5 has a waxy quality somewhat similar to that of silver chloride. It has often shown polarization properties due to strain birefringence. The modern compositions, however, show little, if any, of this effect. The thallium salts are somewhat toxic, so KRS-5 should be handled with care. It has a serious tendency to cold flow and change its shape with time; this is a result of plastic memory, or the gradual relief of strains. The proper annealing technique is not yet well understood, and even that would not completely eliminate the problem. It can be cut with a diamond saw very slowly. Then aloxite and crocus polishing cloths can be used. The refractive index of KRS-5 is not always uniform and sometimes appears as a gradient. If the composition corresponding to the minimum melting point is chosen, the change in refractive index should be less than 10^{-5}.

TABLE 4-12. The Refractive Index of KRS-5, Thallium Bromide-Iodide, at 25°C

Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index
0.540	2.68059	13.0	2.36371	27.0	2.30676
1.00	2.44620	14.0	2.36101	28.0	2.30098
1.50	2.40774	15.0	2.35812	29.0	2.29495
2.00	2.39498	16.0	2.35502	30.0	2.28867
3.00	2.38574	17.0	2.35173	31.0	2.28212
4.00	2.38204	18.0	2.34822	32.0	2.27531
5.00	2.37979	19.0	2.34451	33.0	2.26823
6.00	2.37797	20.0	2.34058	34.0	2.26087
7.00	2.37627	21.0	2.33643	35.0	2.25322
8.00	2.37452	22.0	2.33206	36.0	2.24528
9.00	2.37267	23.0	2.32746	37.0	2.23705
10.0	2.37069	24.0	2.32264	38.0	2.22850
11.0	2.36854	25.0	2.31758	39.0	2.21965
12.0	2.36622	26.0	2.31229	40.0	2.21047

13. Cesium Bromide (CsBr)

Composition

Single crystal, synthetic.

Molecular Weight

212.83

Specific Gravity

4.44
(*HCP*, p. 511)

Crystal Class

Cubic, cesium chloride structure.

Transmission

Long wavelength limit	55.0 μ
Short wavelength limit	0.22 μ

The transmission of cesium bromide is illustrated in Fig. 4-13.
(E. K. Plyler, private communication)

Reflection Loss

11.6% for two surfaces, at a wavelength of 10 μ.

Refractive Index

Values of refractive indices at 27°C are given in Table 4-13, for the wavelength range 0.5 to 39 μ; the data are those of W. S. Rodney and R. J. Spindler, *J. Research NBS*, Vol. 51, pp. 123–126, 1953.

Temperature coefficient of refractive index:
$+7.9 \times 10^{-5}$/C°; average value for two samples of different origin.
(Rodney and Spindler, *above ref.*, p. 124)

Dispersion

A graph of $dn/d\lambda$ *vs* λ is given in Fig. 3-3.

Dielectric Constant

6.51 at a frequency of 2×10^6 cps, temperature not given.
(*AIPH*, p. 5–115)

Melting Temperature

636°C
(*HCP*, p. 511)

Thermal Conductivity

2.3×10^{-3} cal/(cm sec C°) at 25°C.
(*AIPH*, p. 4-76)

Thermal Expansion

47.9×10^{-6}/C° in a temperature range from 20°C to 50°C.
(L. S. Combes, Tufts University, unpublished)

Specific Heat

0.063 at 20°C
(K. K. Kelley, *Bureau of Mines Bulletin* No. 371, p. 65, 1934)

Hardness

Knoop number 19.5 for indenter load of 200 gm
(S. S. Ballard, L. S. Combes, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 42, pp. 65–66, 1952)

Solubility

124.3 gm/100 gm water at 25°C, soluble in acid.
(*HCP*, p. 511)

Elastic Moduli

Young's modulus, 2.3×10^6 psi.
The measurement was made in flexure.
(Ballard, *above ref.*)

Apparent elastic limit, 12.2×10^2 psi.
The measurement was made in flexure.
(Ballard, *above ref.*)

Modulus of rupture, 23.9×10^2 psi.
The measurement was made in flexure.
(Ballard, *above ref.*)

Notes

Samples are available from the Harshaw Chemical Company, Cleveland, Ohio, in sizes up to a cylinder 7.5 in. in diameter by 4 in. long, with a 90° apex cone.

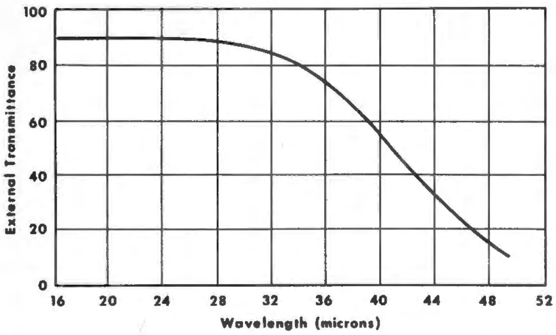


Fig. 4-13 The transmission of cesium bromide; thickness, 5.10 mm.

TABLE 4-13. The Refractive Index of Cesium Bromide at 27°C

Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index
0.5	1.70896	14.0	1.65651	27.0	1.62146
1.0	1.67793	15.0	1.65468	28.0	1.61764
2.0	1.67061	16.0	1.65272	29.0	1.61365
3.0	1.66901	17.0	1.65062	30.0	1.60947
4.0	1.66813	18.0	1.64838	31.0	1.60510
5.0	1.66737	19.0	1.64600	32.0	1.60053
6.0	1.66659	20.0	1.64348	33.0	1.59576
7.0	1.66573	21.0	1.64080	34.0	1.59078
8.0	1.66477	22.0	1.63798	35.0	1.58558
9.0	1.66370	23.0	1.63500	36.0	1.58016
10.0	1.66251	24.0	1.63186	37.0	1.57450
11.0	1.66120	25.0	1.62856	38.0	1.56860
12.0	1.65976	26.0	1.62509	39.0	1.56245
13.0	1.65820				

14. Cesium Iodide (CsI)

Composition

Single crystal, synthetic.

Molecular Weight

259.83

Specific Gravity

4.526

(A. Smakula and V. Sils, *Phys. Rev.*, Vol. 99, pp. 1744–1746, 1955)

Crystal Class

Cubic, cesium chloride structure.

Transmission

Long wavelength limit	70 μ
Short wavelength limit	0.24 μ

The transmission of cesium iodide is illustrated in Fig. 4-14.

(E. K. Plyler and N. Acquista, *J. Opt. Soc. Am.*, Vol. 48, pp. 668–669, 1958, and Vol. 43, p. 978, 1953)

Reflection Loss

13.6% for two surfaces, at a wavelength of 10 μ.

Refractive Index

Values of refractive index at 24°C, for the wavelength range 0.28 to 50 μ, are given in Table 4-14; the data are those computed by W. S. Rodney from his measurements; see *J. Opt. Soc. Am.*, Vol. 45, pp. 987–992, 1955.

Temperature coefficient of refractive index: approximately -9 to -8×10^{-5}/C° for the wavelength range 10 to 50 μ.

(W. S. Rodney, *above ref.*, p. 991; values are given over the wavelength range 0.3 to 50 μ)

Dispersion

A graph of $dn/d\lambda$ *vs* λ is given in Figure 3-3.

Dielectric Constant

5.65 at a frequency of 1×10^6 cps, at 25°C.

(*AIPH*, p. 5–115)

Melting Temperature

621°C

(*HCP*, p. 513)

Thermal Conductivity

2.7×10^{-3} cal/(cm sec C°) at a temperature of 25° C.

(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.* Vol. 41, pp. 215–222, 1951)

Thermal Expansion

50×10^{-6}/C° in a temperature range from 25° to 50°C.

(Ballard, *above ref.*)

Specific Heat

0.048 at 20°C

(K. K. Kelley, *Bureau of Mines Bulletin* No. 371, p. 65, 1934)

Hardness

Solubility

44 gm/100 gm water at 0°C; 160 gm/100 gm water at 61°C, slightly hygroscopic, soluble in alcohol.

(*HCP*, p. 513)

Elastic Moduli

Young's modulus, 7.69×10^5 psi.

The measurement was made in flexure.

(Ballard, *above ref.*)

Apparent elastic limit, 8.1×10^2 psi.

The measurement was made in flexure.

(Ballard, *above ref.*)

Notes

Samples are available from the Harshaw Chemical Company, Cleveland, Ohio, in sizes up to a cylinder 5.5 in. in diameter by 4 in., with a 90° apex cone.

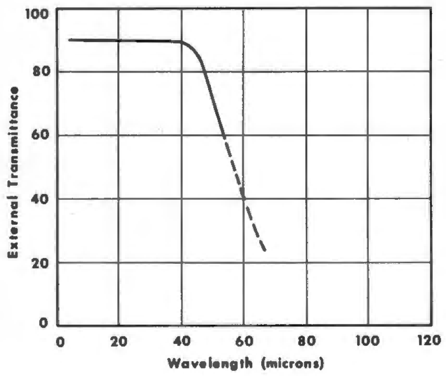


Fig. 4-14. The transmission of cesium iodide; thickness, 5 mm.

TABLE 4-14. The Refractive Index of Cesium Iodide at 24°C

Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index
0.500	1.80635	17.0	1.73190	34.0	1.69717
1.00	1.75721	18.0	1.73056	35.0	1.69427
2.00	1.74616	19.0	1.72913	36.0	1.69127
3.00	1.74400	20.0	1.72762	37.0	1.68815
4.00	1.74305	21.0	1.72602	38.0	1.68493
5.00	1.74239	22.0	1.72435	39.0	1.68159
6.00	1.74181	23.0	1.72258	40.0	1.67814
7.00	1.74122	24.0	1.72073	41.0	1.67457
8.00	1.74059	25.0	1.71880	42.0	1.67088
9.00	1.73991	26.0	1.71677	43.0	1.66707
10.0	1.73916	27.0	1.71465	44.0	1.66312
11.0	1.73835	28.0	1.71244	45.0	1.65905
12.0	1.73746	29.0	1.71014	46.0	1.65485
13.0	1.73650	30.0	1.70774	47.0	1.65051
14.0	1.73547	31.0	1.70525	48.0	1.64602
15.0	1.73436	32.0	1.70266	49.0	1.64139
16.0	1.73317	33.0	1.69996	50.0	1.63662

15. Arsenic-Modified Selenium Glass Se(As)

Composition

Arsenic-modified selenium glass consists of 92% selenium and 8% arsenic. The addition of arsenic to selenium provides a cross-linked structure which causes the material to have a higher softening point and reduces the tendency of the material to crystallize. At one time the material was formed from 80% selenium and 20% arsenic triselenide. This is equivalent to the 92%–8% selenium-arsenic glass.

(See W. F. Parsons, *ERDL* pp. 47–57; private communication)

Molecular Weight

Not applicable.

Specific Gravity

Crystal Class

Not applicable; the material can be considered a selenium-like material with its chain-like structure cross-linked with the arsenic.

(*ERDL, above ref.*)

Transmission

Long wavelength limit 19.0 μ
Short wavelength limit 1 μ

The transmission of selenium glass is illustrated in Fig. 4-15.

(C. D. Salzberg and J. J. Villa, *J. Opt. Soc. Am.*, Vol. 47, p. 244, 1957)

Reflection Loss

30.5% for two surfaces, at a wavelength of 10 μ.

Refractive Index

Values of refractive index of arsenic-modified selenium glass at 27°C, for the wavelength range 1 to 14 μ, are given in Table 4-15.

(Salzberg and Villa, *above ref.*)

Dispersion

Dielectric Constant

The bulk electrical conductivity is estimated to be less than 10^{-10} ohm-cm.

(Eastman Kodak Company, *Technical Data Sheets*)

Softening Temperature

~70°C

Lenses of this material have withstood this temperature for long periods of time with no change in power; domes or thin lenses show no deterioration at 65°C after 15 hours.

(Eastman Kodak Company, *above ref.*)

Thermal Conductivity

3.3×10^{-4} cal/(cm sec C°)

(Eastman Kodak Company, *above ref.*)

Thermal Expansion

34×10^{-6}/C° estimated.

(Eastman Kodak Company, *above ref.*)

Specific Heat

Hardness

Solubility

Insoluble

Elastic Moduli

The breaking strength of cylindrical rods is 1500–2400 psi. Experimental hyper-hemispherical domes about ¼ in. thick successfully withstand exploding pressure of 25 psi.

(Eastman Kodak Company, *above ref.*)

Notes

For a glass, this material shows unusual deformation properties; it tends to soften and flow because of the relative motion of the chains of selenium atoms. An unloaded glass sample is free from viscous flow up to temperatures of 70°C. Above 70°C, the glass flows quite easily. Thus, particular care must be taken in machining. This glass shows a strong absorption at 12.7 μ. It makes good optical contact with lead sulfide although the thermal conductivities are different, and they will separate unless "potted" plastically. The glass is available from the Eastman Kodak Company, Rochester, N. Y. An 8-in. 210° hyperhemispherical dome ¼ in. thick has been made by the Eastman Kodak Company.

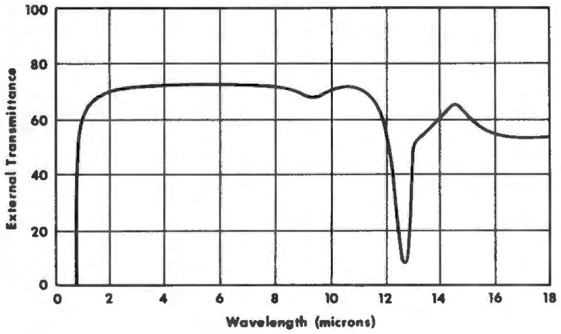


Fig. 4-15. The transmission of arsenic-modified selenium glass; thickness unknown.

TABLE 4-15. The Refractive Index of Arsenic-Modified Selenium Glass at 27°C

Wave-length (μ)	Refractive Index Prism *a*	Refractive Index Prism *b*	Wave-length (μ)	Refractive Index Prism *a*	Refractive Index Prism *b*
1.0140	2.5774	2.5783	7.00	2.4778	2.4787
1.1286	2.5554	2.5565	7.50		2.4784
1.3622	2.5285	2.5294	8.10	2.4772	2.4778
1.5295	2.5173	2.5183	8.50		2.4775
1.7012	2.5089	2.5100	9.10	2.4765	2.4771
2.1526	2.4950	2.4973	9.50		2.4768
3.00	2.4861	2.4882	10.00	2.4756	2.4767
3.4188	2.4841	2.4858	10.50		2.4759
4.00	2.4825	2.4835	11.00	2.4752	2.4758
4.50		2.4822	11.50		2.4753
5.00	2.4803	2.4811	12.00		2.4749
5.50		2.4804	13.00		2.4760[*sic*]
6.00	2.4789	2.4798	13.50		2.4748
6.50		2.4792	14.00		2.4743

16. Germanium (Ge)

Composition

Single crystal, synthetic; atomic number 32.
The energy gap is approximately 0.7 ev.

Atomic Weight

72.60
(G. L. Pearson and W. H. Brattain, *Proc. IRE,* Vol. 43, pp. 1794–1806, 1955)

Specific Gravity

5.327 at 25°C
(A. Smakula and V. Sils, *Phys. Rev.*, Vol. 99, pp. 1744–1746, 1955)

Crystal Class

Cubic, diamond structure.

Transmission

Long wavelength limit	23.0 μ
Short wavelength limit	1.8 μ

The transmission of germanium is illustrated in Figs. 4-16a and 4-16b.
(*WADC-II,* p. 47)

Reflection Loss

52.9% for two surfaces, at a wavelength of 10 μ.

Refractive Index

Values of refractive index at 27°C, for the wavelength range 2 to 16 μ, are given in Table 4-16; the data are those of C. D. Salzberg and J. J. Villa, *J. Opt. Soc. Am.*, Vol. 48, p. 579, 1958. The resistivity of the germanium sample is about 50 ohm-cm. (These data are about 5 parts in the third decimal place lower than those reported by H. B. Briggs, *Phys. Rev.*, Vol. 77, p. 287, 1950.) The authors report corrections to their original measurements (*J. Opt. Soc. Am.*, Vol. 47, pp. 244–246, 1957) and also report refractive indices of polycrystalline germanium which differ from those of the single crystal by only a few parts in the fourth decimal place.

Dispersion

A graph of $dn/d\lambda$ *vs* λ is given in Figure 3-3.

Dielectric Constant

16.6 at a frequency of 9.37×10^9 cps for a sample that has a resistivity of 9.0 ohm-cm. (University of Pennsylvania, *Quarterly Progress Report* Number 4, Contract AF 33(616)-78, June 1953)

Melting Temperature

936°C
(Pearson and Brattain, *above ref.*)
942°C
(A. Smakula, private communication)

Thermal Conductivity

0.14 cal/(cm sec C°) at 20°C
(K. A. McCarthy and S. S. Ballard, *Phys. Rev.*, Vol. 99, p. 1104, 1955)

Thermal Expansion

5.5×10^{-6}/C° at 25°C
(M. E. Fine, *J. Appl. Phys.*, Vol. 24, pp. 338–340, 1953)
6.1×10^{-6}/C° at 25°C
(Pearson and Brattain, *above ref.*)

Specific Heat

0.074 in a temperature range from 0°C to 100°C
(Pearson and Brattain, *above ref.*)

Hardness

Solubility

Insoluble in water, soluble in hot sulfuric acid and aqua regia, etched in CP-4
(*HCP,* p. 531)

Elastic Moduli

Young's modulus, 1.49×10^7 psi.
Calculated from elastic coefficients.
Modulus of rigidity, 9.73×10^6 psi.
Calculated from elastic coefficients.
Bulk modulus, 1.12×10^7 psi.
(Pearson and Brattain, *above ref.*)
Elastic coefficients at 20°C

c_{11}	1.29×10^{12} dyne/cm^2
c_{12}	4.83×10^{11} dyne/cm^2
c_{44}	6.71×10^{11} dyne/cm^2

(H. J. McSkimin, *J. Appl. Phys.*, Vol. 24, pp. 988–997, 1953)
Anisotropy factor, 1.66

Notes

Germanium can be used as an optical material both as a single crystal and in polycrystalline form. It is hard and brittle at room temperature and tends to fracture during fabrication. Its chemical inertness makes it useful for optical applications although its electrical properties are affected by moisture, etc. It should have a purity corresponding to 16 – 30 ohm-cm to be useful. It can be coated with silicon monoxide in the region out to about 5 μ, and zinc sulfide for the 8- to 13-μ region. There is usually an absorption band observed at 11.6 μ; this is due to Ge-O stretching superimposed on a weak lattice band vibration. Germanium becomes opaque at about 125° C.

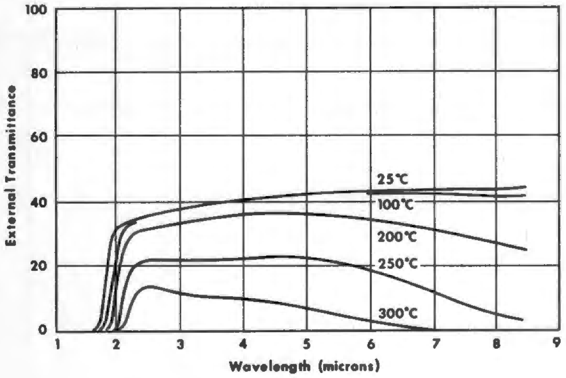


Fig. 4-16a. The transmission of germanium for several temperatures; thickness, 1.15 mm; resistivity, 30 ohm-cm.

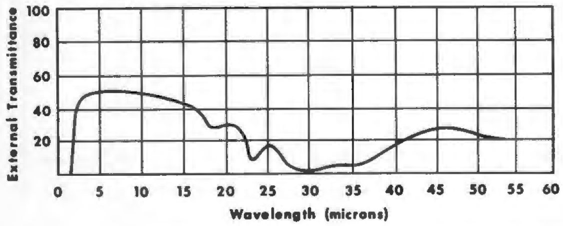


Fig. 4-16b. The transmission of germanium; thickness, 2 mm.

TABLE 4-16. The Refractive Index of Germanium at 27°C

Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index
2.0581	4.1016	4.866	4.0170
2.1526	4.0919	6.238	4.0094
2.3126	4.0786	8.66	4.0043
2.4374	4.0708	9.72	4.0034
2.577	4.0609	11.04	4.0026
2.7144	4.0552	12.20	4.0023
2.998	4.0452	13.02	4.0021
3.3033	4.0369	14.21	4.0015*
3.4188	4.0334	15.08	4.0014*
4.258	4.0216	16.00	4.0012*

* Original measurements

17. Silicon (Si)

Composition

Single crystal, synthetic; atomic number 14.
The energy gap is approximately 1.1 ev.

Atomic Weight

28.09
(*AIPH*, p. 7–9)

Specific Gravity

2.329 at 25°C
(A. Smakula and V. Sils, *Phys. Rev.*, Vol. 99, pp. 1744–1746, 1955)

Crystal Class

Cubic, diamond structure.

Transmission

Long wavelength limit	15.0 μ
Short wavelength limit	1.2 μ

The transmission of silicon is illustrated in Fig. 4-17a. The curves illustrate the transmissions for a coated and an uncoated sample of the material. The measurements were made at a temperature of 38°C.
(Texas Instruments Incorporated, *Technical Data Sheet*)

The variation of transmission with temperature is illustrated in Fig. 4-17b.
(*WADC-II*, p. 48)

Reflection Loss

46.1% for two surfaces, at a wavelength of 10 μ.

Refractive Index

Values of refractive index at 26°C, for the wavelength range 1.4 to 11 μ, are given in the Table 4-17; the data are those of C. D. Salzberg and J. J. Villa, *J. Opt. Soc. Am.*, Vol. 47, pp. 244–246, 1957. The purity of the silicon sample is not specified. These data are about 5 parts in the third decimal place lower than those reported by H. B. Briggs, *Phys. Rev.*, Vol. 77, p. 287, 1950.

Dispersion

A graph of $dn/d\lambda$ *vs* λ is given in Figure 3-3.

Dielectric Constant

13 at a frequency of 9.37×10^9 cps.
(Preliminary Data, University of Pennsylvania, *Quarterly Progress Report,* Number 4, Contract AF 33 (616)-78, June 1953)

Melting Temperature

1420°C
(Pearson and Brattain, *Proc. I.R.E.*, Vol. 43, pp. 1794–1806, 1955)

Thermal Conductivity

0.39 cal/(cm sec C°) at 40°C (p-type material)
(A. D. Stuckes and R. P. Chasmar, "Report of the Meeting on Semi-Conductors," *Physical Society, London,* p. 123, April 1956)

Thermal Expansion

4.15×10^{-6}/C° in a temperature range from 10°C to 50°C.
(M. E. Straumanis and E. Z. Aka, *J. Appl. Phys.*, Vol. 23, pp. 330-334, 1952)
4.2×10^{-6}/C° at 25°C
(Pearson and Brattain, *above ref.*)

Specific Heat

0.168 at 25°C
(*AIPH*, p. 4–41)
0.181 in a temperature range for 0° to 100°C
(Pearson and Brattain, p. 1804, *above ref.*)

Hardness

Knoop number 1150
Moh 7
(Texas Instruments, Inc., *above ref.*)

Solubility

Insoluble in water, insoluble in acids, including hydrofluoric acid, but soluble in hydrofluoric and nitric acid mixture.
(*HCP*, p. 599)

Elastic Moduli

Young's modulus, 1.90×10^7 psi.
Calculated from elastic coefficients.
Modulus of rigidity, 1.16×10^7 psi.
Calculated from elastic coefficients.
Bulk modulus, 1.48×10^7 psi.
(Pearson and Brattain, *above ref.*)
Elastic coefficients at room temperature

c_{11}	1.67×10^{12} dyne/cm²
c_{12}	0.65×10^{12} dyne/cm²
c_{44}	0.80×10^{12} dyne/cm²

(W. P. Binnie, *Phys. Rev.*, Vol. 103, pp. 579–580, 1957)
Anisotropy factor, 1.57

Notes

The physical and chemical properties of silicon are very similar to those of germanium. Optical-grade silicon (impurity content less than 10^8/cc) has high resistance to thermal and mechanical shocks. One sample which was heated to 400°C and quenched in ice water remained unaffected. It can be used as an irdome if aerodynamic heating does not take the skin temperature above 300°C.

Domes of 6-in. diameter, 0.14-in. thick, have been "hogged out," although it is possible they can be hot-formed since a plastic region appears at about 1000°C. Simple (aspheric) lens systems are possible, and work is being continued on casting and combining or "sticking together" elements.

Silicon can be ground on Blanchards; diamond curve generators can be used; and normal pitches and polishing compounds are acceptable, although operations take one and one-half times as long as those with quartz. Silicon monoxide can be used as a low reflectance coating at relatively short wavelengths. Silicon dioxide usually overcoats, and the combination is stable. At longer wavelength zinc sulfide ($n = 2.2$ at 10 μ) can be used as a coating. Both should be vacuum-evaporated.

An absorption band usually occurs at 9 μ, but this is due to a Si-O stretching (from the coating or "poisoning") superimposed on a weak lattice vibration. Silicon is available from Texas Instruments Inc., Dallas, Texas; Raytheon Manufacturing Co., Waltham, Mass.; and Baird-Atomic Inc., Cambridge, Mass.

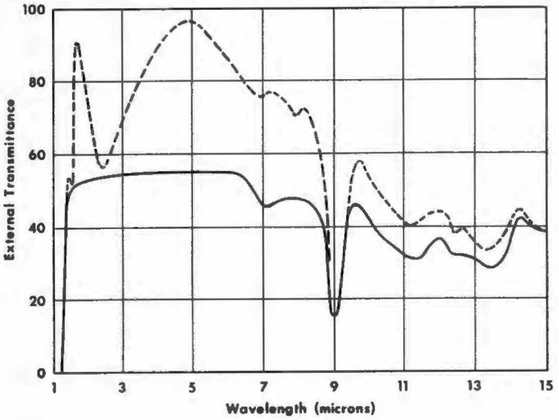


Fig. 4-17a. The transmission of silicon; thickness, 2.5 mm. Dashed curve is for a coated sample.

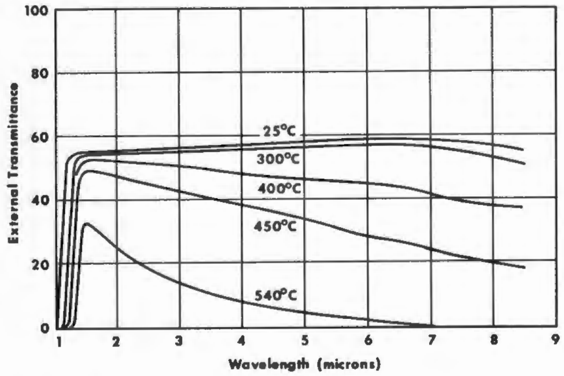


Fig. 4-17b. The transmission of silicon for several temperatures; thickness, 5.89 mm; resistivity, at least 5 ohm-cm.

TABLE 4-17. The Refractive Index of Silicon at 26°C

Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index
1.3570	3.4975	3.50	3.4284
1.3673	3.4962	4.00	3.4255
1.3951	3.4929	4.258	3.4242
1.5295	3.4795	4.50	3.4236
1.6606	3.4696	5.00	3.4223
1.7092	3.4664	5.50	3.4213
1.8131	3.4608	6.00	3.4202
1.9701	3.4537	6.50	3.4195
2.1526	3.4476	7.00	3.4189
2.3254	3.4430	7.50	3.4186
2.4373	3.4408	8.00	3.4184
2.7144	3.4358	8.50	3.4182
3.00	3.4320	10.00	3.4179
3.3033	3.4297	10.50	3.4178
3.4188	3.4286	11.04	3.4176

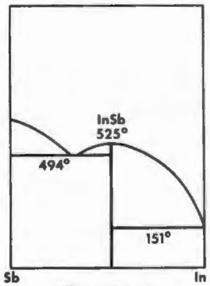
18. Indium Antimonide (InSb)

Composition

Indium antimonide has a metallic appearance; it can be used as an optical material in its single crystal form. The crystal can be prepared by melting the components together in a furnace since the vapor pressure is small at the melting point. The crystal can then be grown, for example, by the Kyropoulos method. The optical energy gap is 0.167 ev.

(Data taken from H. Welker, *Physica,* Vol. 20, p. 893, 1954; *Welker and Weiss;* F. Oswald and R. Schade, *Z. Naturforschung,* Vol. 9a, p. 611, 1954)

The phase diagram below comes from Welker and Weiss.



Phase Diagram

Molecular Weight

237

Specific Gravity

5.78

(L. H. DeVaux and F. A. Pizzarello, *Phys. Rev.,* Vol. 102, p. 85, 1956)

Crystal Class

Zinc blende; cleaves along {110} planes.

(*Welker and Weiss*)

Transmission

Long wavelength limit 16 μ
Short wavelength limit 7 μ

The transmission of indium antimonide is illustrated in Fig. 4–18a.

(M. Tanenbaum and H. B. Briggs, *Phys. Rev.,* Vol. 91, p. 1561, 1953)

The curves also illustrate the change in transmission as a function of sample purity. The absorption coefficient is plotted in Fig. 4–18b.

(Oswald and Schade, *above ref.*)

Reflection Loss

53.2% for two surfaces, at a wavelength of 10 μ.

Refractive Index

The average value for refractive index for the wavelength region 7 to 15 μ is 3.5.

(R. G. Breckenridge *et al., Phys. Rev.,* Vol. 96, p. 571, 1954)

Curves of refractive index *vs* wavelength and absorption constant *vs* wavelength are given in Fig. 4-18b. Values of refractive index for a sample with carrier concentration 2×10^{16}/cc for the wavelength region 7.87 to 22.20 μ are given in Table 4–18.

Dispersion

Dielectric Constant

Melting Temperature

523°C

(Breckenridge, *above ref.*)

Thermal Conductivity

8.5×10^{-2} cal/(cm sec C°) at 20°C.

(G. Busch and M. Schneider, *Physica,* Vol. 20, p. 1084, 1954)

Thermal Expansion

4.9×10^{-6}/C° from 20° to 60°C

(R. F. Potter, *Phys. Rev.,* Vol. 103, p. 47, 1956)

Specific Heat

Hardness

Solubility

Insoluble

Elastic Moduli

Young's modulus, 6.21×10^6 psi.
Calculated from elastic coefficients
Modulus of rigidity, 4.45×10^6 psi.
Calculated from elastic coefficients.
Bulk modulus, 6.28×10^6 psi.
Calculated from elastic coefficients.
Elastic coefficients at 27°C
c_{11} 6.472×10^{11} dyne/cm^2
c_{12} 3.265×10^{11} dyne/cm^2
c_{44} 3.071×10^{11} dyne/cm^2
(R. F. Potter, *above ref.*)
Anisotropy factor, 1.91

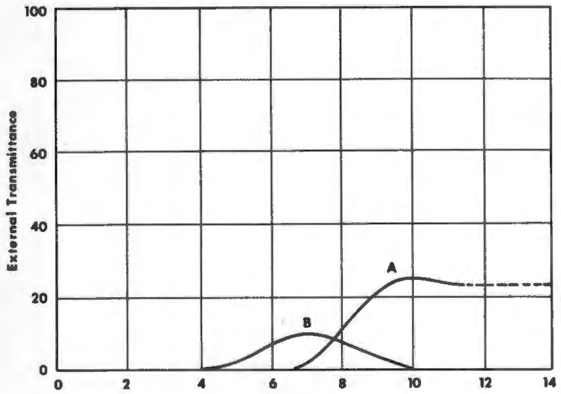


Fig. 4-18a. The transmission of indium antimonide; thickness, 0.007 inch; resistivity of A, 7×10^{-3} ohm-cm; resistivity of B, 2.5×10^{-4} ohm-cm.

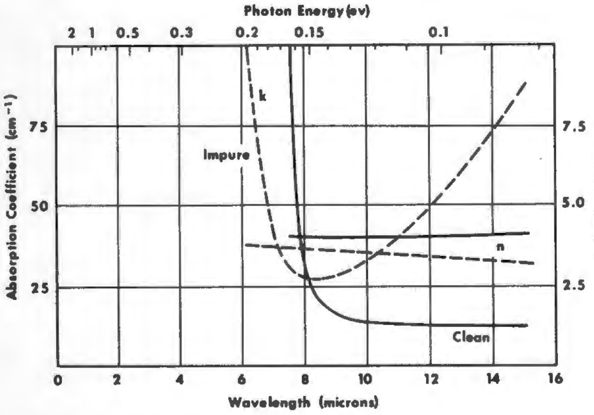


Fig. 4-18b. Absorption coefficient and refractive index of indium antimonide; resistivity of "clean," 2×10^{-2} ohm-cm; resistivity of "impure," 10^{-3} ohm-cm.

Notes

Indium antimonide is soft and brittle. To cut it, one may use a diamond wheel with care. To polish, lap in a manner very similar to that used for silicon and germanium. Samples of indium antimonide are available from Ohio Semiconductors, Columbus, Ohio, in sizes up to 0.125×0.375 in. with thickness from 0.03 to 0.01 in. Samples as large as 1.25×0.875 in. have been grown. InSb has a large Faraday effect. It can be used for filters (particularly in atmospheric heat measurements); it "cuts on" at about 7 μ; it can be antireflection coated with $PbCl_2$ for the 8- to 13-μ window.

TABLE 4-18. Refractive Index of Indium Antimonide (Carrier Concentration, 2.0×10^{16}/cc)

Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index
7.87	4.00	15.13	3.88
8.00	3.99	15.79	3.87
9.01	3.96	16.96	3.86
10.06	3.95	17.85	3.85
11.01	3.93	18.85	3.84
12.06	3.92	19.98	3.82
12.98	3.91	21.15	3.81
13.90	3.90	22.20	3.80

19. Selenium (Se)

Composition

Selenium can exist in various allotropic forms. The trigonal, or crystalline, form is the most stable. (It has the same structure as tellurium, but with different lattice constants.) The amorphous (or vitreous) form is fairly stable below 50°C but converts to the trigonal form at higher temperatures. The chain structure found in trigonal selenium is also found in the amorphous (and liquid) form. The structure of selenium causes its anisotropic properties. The material can be prepared by condensation of vapor, but obtaining large single crystals is difficult. Needles form along the *c*-axis. Siemens-Schukert Laboratory at Pretzfeld, Germany, obtained one which, when polished, measured 8 mm × 1.8 mm × 0.19 mm.

(R. S. Caldwell, *Special Report,* Contract DA 36-039-SC-71131, Department of Physics, Purdue University, January 1958)

Atomic Weight

78.96

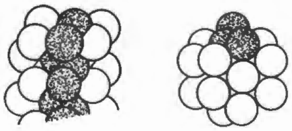
Specific Gravity

4.82, trigonal form
4.26, amorphous form
(*Moss,* p. 185)

Crystal Class

Trigonal or amorphous. The trigonal form has the structure shown in the accompanying diagram. The diagram is from von Hippel, *Tech. Report* Number 8, Laboratory for Technical Research, Massachusetts Institute of Technology. A spiral chain is formed where the spirals are arranged in hexagons. The spirals chain around the *c*-axis. The structure is trigonal and cleaves parallel to the *c*-axis.

(Caldwell, *above ref.* and Landolt-Börnstein)



Transmission

Long wavelength limit 20 μ
Short wavelength limit 1 μ

The transmission of amorphous selenium is illustrated in Fig. 4-20.

(Adapted from R. S. Caldwell, *above ref.* pp. 46, 84.)

Reflection Loss

29.7% for two surfaces, at a wavelength of 10 μ.

The data above are computed for amorphous selenium. For crystal selenium, the values are 36.2% and 48% for *E* parallel and perpendicular to *c*-axis, respectively.

Refractive Index

Trigonal selenium; for *E* perpendicular to *c*, *n* is 2.78 from 9 to 23 μ at 27°C; for *E* parallel to *c*, *n* is 3.58 ± 0.02 from 9 to 23 μ.

(R. S. Caldwell, *above ref.,* p. 43)

Amorphous selenium; *n* is 2.44 to 2.46 at 2.5 μ.

(E. W. Saker, *Proc. Phys. Soc.,* Vol. B65, p. 785, 1952)

n varies from 2.42 to 2.38 between 5 and 15 μ.

(L. Henry, *Compt. rend,* Vol. 237, p. 148, 1953)

Liquid selenium has a refractive index of 2.44 from 30 to 152 μ.

(Saker, *above ref.*)

Dispersion

Dielectric Constant

6.00 in a frequency range from 10^2 to 10^{10} cps at 25°C for amorphous selenium.

(*von Hippel,* p. 313)

Softening Temperature

35°C

(*ERDL, above ref.*)

Thermal Conductivity

Thermal Expansion

Specific Heat

Hardness

Solubility

Elastic Moduli

Notes

Solid selenium exists in four modifications at room temperature: amorphous, alpha monoclinic, beta monoclinic, and hexagonal. Selenium can be molded, ground, and polished readily. It has a tendency to crystallize at room temperature. Even though it melts at about 36°C, it softens some at lower temperatures, and this results in sagging.

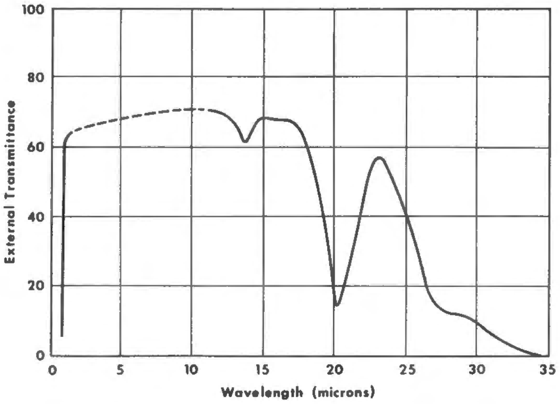


Fig. 4-19. The transmission of amorphous selenium; thickness, 1.69 mm.

20. Tellurium (Te)

Composition

Tellurium is an element belonging to the sixth group of the periodic table. It is found in nature, mainly in tellurides of gold and some other metals. It has a metallic appearance and forms a single crystal which is anisotropic in many properties. Tellurium has an optical energy gap of 0.37 ev. Tellurium can be grown by the Czochralski and Kyropoulos methods and by vacuum distillation. Crystals 1.5 cm in diameter by 4 or 5 cm long (*c*-axis) have been grown.

(R. S. Caldwell, *Special Report*, Contract DA 36-039-SC-71131, Purdue University, Department of Physics, Jan. 1958)

Caldwell also reports that a conducting surface forms as a result of many grinding and polishing operations.

Atomic Weight

127.61

Specific Gravity

6.24 at 20°C
(*HCP*, p. 383)

Crystal Structure

The structure is identical with that of trigonal selenium, but with different lattice parameters.

Transmission

Long wavelength limit	$> 8.0\ \mu$
Short wavelength limit	$3.5\ \mu$

The transmission of tellurium is illustrated in Fig. 4-20. The data are replotted from the curves of Loferski, *Phys. Rev.*, Vol. 93, p. 707, 1954.

Reflection Loss

68.8% for E parallel to *c*-axis, at a wavelength of 12 μ.
60% for E perpendicular to *c*-axis, at a wavelength of 12 μ.

Refractive Index

Values of the refractive index are given in Table 4-20 for *E* perpendicular and parallel to the *c*-axis, from 4.0 to 14.0 μ.

(Caldwell, *above ref.*)

The author comments that the values are higher by 0.03 for *E* perpendicular to *c* and lower for E parallel to *c* by 0.06 than the values given by P. A. Hartwig and J. J. Loferski (*J. Opt. Soc. Am.*, Vol. 44, p. 17, 1954). The data of Hartwig and Loferski may be in error because of an averaging effect of the orientation of the *c*-axis in their prism.

Dispersion

Dielectric Constant

Melting Point

449.7°
(R. Machol and E. F. Westrum, Jr., *J. Phys. Chem.*, Vol. 62, p. 361, 1958)

Thermal Conductivity

1.5×10^{-2} cal/(cm sec C°)
(H. J. Goldsmid, *Proc. Phys. Soc.*, Vol. 67B, p. 360, 1954)

Thermal Expansion

16.75 at 40°C
(*HCP*, p. 2061)

Specific Heat

4.79×10^{-2} at 300°C
(E. F. Westrum, Jr., private communication)

Hardness

Elastic Moduli

Solubility

Insoluble

(N. V. Sidgwich, *Chemical Elements and Their Compounds,* Clarendon Press, 1951)

Elastic Moduli

Notes

Single crystals of tellurium are hard to grow; a polycrystalline ingot usually forms from the melt. Large (2 mm × 2 mm × 10 mm) crystals can be grown rather well from the vapor phase. A hexagonal crystal symmetry results and cleavage occurs parallel to the *c*-axis. It is difficult to cleave or cut in other directions because the crystal will fracture. When Te is ground, a conducting layer tends to form on its surface; this layer can be removed by chemical etching although this does not leave an optical surface. Optical polishing can probably be accomplished without this effect; thin layers of tellurium have been made that have a good optical finish.

TABLE 4-20. The Refractive Indices of Tellurium

Wavelength (μ)	Index of Refraction $E \perp c$	$E \parallel c$	Wavelength (μ)	Index of Refraction $E \perp c$	$E \parallel c$
4.0	4.929	6.372	9.0	4.802	6.253
5.0	4.864	6.316	10.0	4.796	6.246
6.0	4.838	6.286	12.0	4.789	6.237
7.0	4.821	6.270	14.0	4.785	6.230
8.0	4.809	6.257			

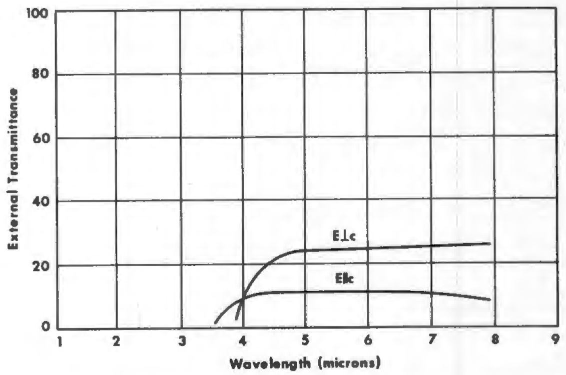


Fig. 4-20. The transmission of tellurium for two polarizations; thickness, 0.85 mm.

21. Crystal Quartz (SiO_2)

Composition

Natural crystal; pure SiO_2.

Molecular Weight

60.06

Specific Gravity

2.648 at 25°C

(A. Smakula and V. Sils, *Phys. Rev.*, Vol. 99, pp. 1744–1746, 1956)

Crystal Class

Hexagonal (birefringent).

Transmission

Long wavelength limit 4.5 μ

Short wavelength limit 0.4 μ

The transmission of crystal quartz is illustrated in Fig. 4-21.

(Adapted from *Smith*, p. 330)

Reflection Loss

8.2% for two surfaces for the ordinary ray, at a wavelength of 2 μ.

Refractive Index

Values of refractive index at 18°C or 20°C, for both the ordinary and the extraordinary rays and for the wavelength range 0.18 to 4.2 μ, are given in Table 4-21. The data are taken from *AIPH*, pp. 6-23 to 6-25.

Temperature coefficient of refractive index: approximately $-0.55 \times 10^{-5}/C°$ for the ordinary ray and $-0.65 \times 10^{-5}/C°$ for the extraordinary ray; both for approximately 60°C and in the red ($\lambda = 0.64\ \mu$). See *Smakula*, pp. 73–74 for data table, and pp. 75 and 76 for graphs.

Dispersion

Curves illustrating, for the ordinary ray, the variation with wavelength of refractive index and dispersion, in the range of 0.5 to 6 μ, are given in *Smith*, p. 330.

Dielectric Constant

4.34 at a frequency of 3×10^7 cps in a temperature range 17°C to 22°C, perpendicular to *c*-axis.

4.27 at a frequency of 3×10^7 cps in a temperature range 17°C to 22°C, parallel to *c*-axis.

(*HCP*, p. 2341)

Melting Temperature

Below 1470°C

(*HCP*, p. 559)

Transition from the alpha to the beta form is at 575°C.

(C. J. Smithells, *Metals Reference Book*, Second Edition, p. 859, Interscience Publishers Inc., 1955)

Thermal Conductivity

2.55×10^{-2} cal/(cm sec C°) at 50°C, heat flow parallel to *c*-axis.

1.48×10^{-2} cal/(cm sec C°) at 50°C, heat flow perpendicular to *c*-axis.

(*ICT*, Vol. 5, p. 106)

For values from 100°C to 475° C, see W. J. Knapp, *J. Am. Ceram. Soc.*, Vol. 26, p. 48, 1943.

Thermal Expansion

$7.97 \times 10^{-6}/C°$ parallel to *c*-axis, in a temperature range from 0°C to 80°C.

$13.37 \times 10^{-6}/C°$ perpendicular to *c*-axis, in a temperature range from 0°C to 80°C.

(*HCP*, p. 2063)

Specific Heat

0.188 in a temperature range from 12°C to 100°C

(*HCP*, p. 2104)

Hardness

Knoop number 741 with indenter load of 500 gm; no difference noted from indentations made randomly perpendicular to *x*-cut and *z*-cut faces.

(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 41, pp. 215–222, 1951)

Solubility

Insoluble in water

(*HCP*, p. 599)

Elastic Moduli

Young's modulus, at room temperature

11.1×10^6 psi, perpendicular to *c*-axis.

14.1×10^6 psi, parallel to *c*-axis.

(*Sosman*, p. 464)

Bulk modulus at 25°C, 5.28×10^6 psi

(*ICT*, Vol. III, p. 50)

Elastic coefficients at 35°C

c_{11}	8.675×10^{11} dyne/cm^2
c_{12}	0.687×10^{11} dyne/cm^2
c_{44}	5.786×10^{11} dyne/cm^2
c_{14}	1.796×10^{11} dyne/cm^2
c_{13}	1.13×10^{11} dyne/cm^2
c_{33}	10.68×10^{11} dyne/cm^2

(J. V. Atanasoff and P. J. Hart, *Phys. Rev.*, Vol. 59, pp. 85–96, 1941; corrected values, A. W. Lawson, *Phys. Rev.*, Vol. 59, pp. 838–839, 1941)

Notes

Crystal quartz is of little interest in modern infrared techniques. Historically, the material was of interest until synthetic fused silica was available. Quartz crystals crack easily when heated, in contrast to fused silica. Small synthetic crystals are being grown by the Brush Development Corp. of Cleveland, Ohio.

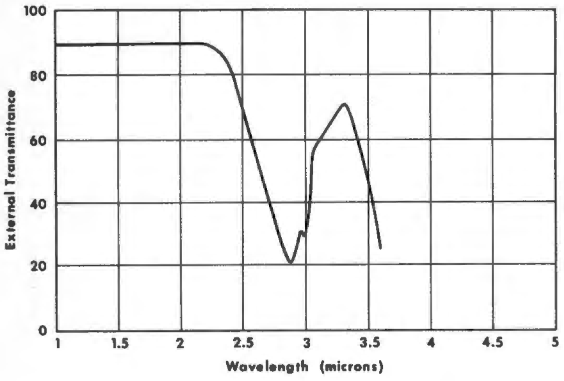


Fig. 4-21. The transmission of crystal quartz for the ordinary ray; thickness, 10 mm.

TABLE 4-21. The Refractive Indices of Crystal Quartz

Wavelength (μ)	Refractive Index	
	(ordinary ray)	(extraordinary ray)
0.185	1.65751	1.68988
0.198	1.65087	1.66394
0.231	1.61395	1.62555
0.340	1.56747	1.57737
0.394	1.55846	1.56805
0.434	1.55396	1.56339
0.508	1.54822	1.55746
0.5893	1.54424	1.55335
0.768	1.53903	1.54794
0.8325	1.53773	1.54661
0.9914	1.53514	1.54392
1.1592	1.53283	1.54152
1.3070	1.53090	1.53951
1.3958	1.52977	1.53832
1.4792	1.52865	1.53716
1.5414	1.52781	1.53630
1.6815	1.52583	1.53422
1.7614	1.52468	1.53301
1.9457	1.52184	1.53004
2.0531	1.52005	1.52823
2.30	1.51561	
2.60	1.50986	
3.00	1.49953	
3.50	1.48451	
4.00	1.46617	
4.20	1.4569	
5.00	1.417	
6.45	1.274	
7.0	1.167	

22. Calcite ($CaCO_3$)

Composition

Natural single crystal, sometimes called Iceland Spar.

Molecular Weight

100.09

Specific Gravity

2.7102 at 20°C
(*ICT*, Vol. III, p. 44)

Crystal Class

Hexagonal.

Transmission

Long wavelength limit 5.5 μ
Short wavelength limit 0.3 μ
The transmission of calcite is illustrated in Fig. 4-22.
(Nyswander, *Phys. Rev.*, Vol. 28, p. 291, 1909)

Reflection Loss

10.6% for two surfaces for the ordinary ray, at a wavelength of 2 μ.

Refractive Index

Values of refractive index at 18°C or 20°C, for both the ordinary and the extraordinary ray and for the wavelength range 0.2 to 3.3 μ, are given in Table 4-22. The data are taken from *Smakula*, pp. 97–98. See also *SPT*, p. 521.

Temperature coefficient of refractive index: approximately $0.21 \times 10^{-5}/C°$ for ordinary ray and $1.18 \times 10^{-5}/C°$ for extraordinary ray; both for around 61.5°C and the red ($\lambda = 0.64$ μ). See *Smakula*, p. 72 for data table, and pp. 75 and 76 for graphs.

Dispersion

Reciprocal dispersion, or nu-value: about 47.

Dielectric Constant

8.5 perpendicular to the *c*-axis, 8.0 parallel to the *c*-axis at 10^4 cps, 17 to 22°C.
(*HCP*, p. 2341)

Melting Temperature

1339°C at a pressure of 102.5 atm. Decomposes at 894.4°C.
(*HCP*, p. 503)

Thermal Conductivity

1.32×10^{-2} cal/(cm sec C°) at 0°C with heat flow parallel to *c*-axis.
1.11×10^{-2} cal/(cm sec C°) at 0°C with heat flow perpendicular to *c*-axis.
(*Landolt-Börnstein*, Vol. 1, p. 711, 1927)

Thermal Expansion

$25 \times 10^{-6}/C°$ at 0°C parallel to *c*-axis.
$-5.8 \times 10^{-6}/C°$ at 0°C perpendicular to *c*-axis.
(*Tutton*, Vol. II, p. 1329)

Specific Heat

0.203 at 0°C
(*HCP*, p. 2088)

Hardness

Moh 3
(*SPT*, p. 227)

Solubility

1.4×10^{-3} gm/100 gm water at 25°C.
(*HCP*, p. 503)

Elastic Moduli

Young's modulus
10.5×10^6 psi, parallel to *c*-axis.
12.8×10^6 psi, perpendicular to *c*-axis.
(*Voigt*, p. 754)
Bulk modulus at 0°C, 18.8×10^6 psi.
(*Smakula*, p. 28)
Elastic coefficients

c_{11}	13.71×10^{11} dyne/cm^2
c_{12}	4.56×10^{11} dyne/cm^2
c_{13}	4.51×10^{11} dyne/cm^2
c_{14}	-2.08×10^{11} dyne/cm^2
c_{33}	7.97×10^{11} dyne/cm^2
c_{44}	3.42×10^{11} dyne/cm^2

The data are computed from Voigt's data (p. 754), which are given in gm/cm^2. They agree with the values of J. Bhimasenachar, *J. Ind. Acad. Sci.*, Vol. 22A, p. 203, 1945.

Notes

Calcite is important historically. Its birefringent properties are well known, and although they are important academically they are disadvantageous for most instrument problems.

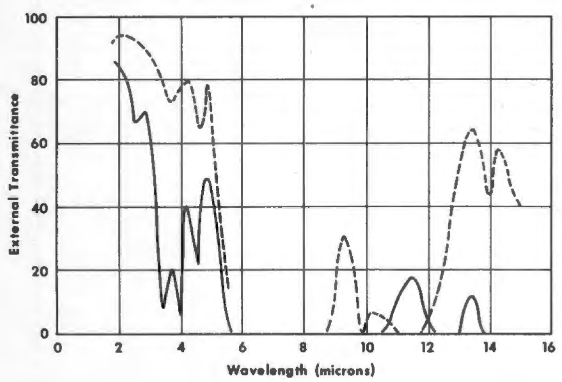


Fig. 4-22. The transmission of calcite for the ordinary ray (——) and for the extraordinary ray (- - - -); thickness, 1 mm.

TABLE 4-22. The Refractive Indices of Calcite (From 0.198 to 0.795 μ taken at 18°C; from 0.8007 to 3.324, at 20°C)

Wavelength	Refractive Index		Wavelength	Refractive Index	
(μ)	n_o	n_e	(μ)	n_o	n_e
0.200	1.90284	1.57649	1.422	1.63590	—
0.303	1.71959	1.51365	1.497	1.63457	1.47744
0.410	1.68014	1.49640	1.609	1.63261	—
0.508	1.66527	1.48956	1.682	1.63127	—
0.643	1.65504	1.48490	1.749	—	1.47638
0.706	1.65207	1.48353	1.761	1.62974	—
0.801	1.64869	1.48216	1.849	1.62800	—
0.905	1.64578	1.48098	1.909	—	1.47573
1.042	1.64276	1.47985	1.946	1.62602	—
1.159	1.64051	1.47910	2.053	1.62372	—
1.229	1.63926	1.47870	2.100	—	1.47492
1.307	1.63789	1.47831	2.172	1.62099	—
1.396	1.63637	1.47789	3.324	—	1.47392

23. Sodium Fluoride (NaF)

Composition

Single crystal, synthetic.

Molecular Weight

42.00

Specific Gravity

2.79 at 20°C
(*ICT*, Vol. I, p. 150)

Crystal Class

Cubic; cleaves on {100} planes.
Sometimes appears in tetragonal form.

Transmission

Long wavelength limit 15.0 μ
Short wavelength limit < 0.19 μ
The transmission of sodium fluoride is illustrated in Fig. 4-23.
(S. S. Ballard, private communication)

Reflection Loss

3.6% for two surfaces, at a wavelength of 4 μ.

Refractive Index

Values of refractive index at 18°C or 20°C, for the wavelength range 0.2 to 24 μ, are given in Table 4-23. The data are taken from *Smakula*, pp. 88–89.

Temperature coefficient of refractive index: -1.6×10^{-5}/C° at 0.55 μ and 3.5 μ; -0.7×10^{-5}/C° at 8.5 μ, for the temperature range 18 to 80°C. See *Smakula*, p. 67.

Dispersion

Reciprocal dispersion or nu-value: about 107.

Dielectric Constant

6.0 at a frequency of 2×10^6 cps, at 19°C.
(*AIPH*, p. 5–117)

Melting Temperature

980°C tetragonal form to 997°C cubic form.
(*HCP*, p. 607)

Thermal Conductivity

Thermal Expansion

36×10^{-6}/C° at room temperature.
(*Wooster*, p. 33)

Specific Heat

0.26 at 0°C
(*ICT*, Vol. V, p. 100)

Hardness

Solubility

4.22 gm/100 gm water at 18°C.
(*HCP*, p. 607)

Elastic Moduli

Notes

Sodium fluoride transmits in about the same region as calcium fluoride and lithium fluoride, but it is less useful mechanically. It has some significance, however, in cases where a remarkably low refractive index is needed. It may also be easily evaporated as a thin film and can be used for reflection-reducing coatings.

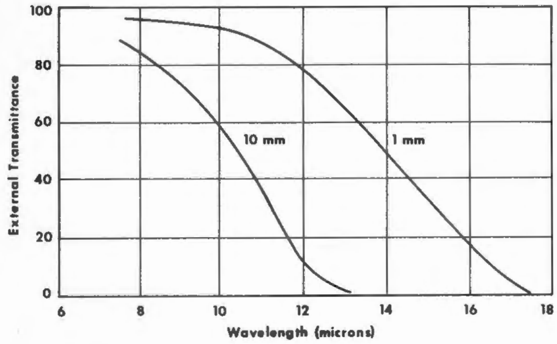


Fig. 4-23. The transmission of sodium fluoride for two thicknesses.

TABLE 4-23. The Refractive Index of Sodium Fluoride (Data from 0.186 μ to 1.083 μ taken at 20°C; from 1.27 μ to 24.0 μ, at 18°C)

Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index
0.186	1.3930	0.811	1.32272	8.1	1.269
0.199	1.3805	0.912	1.32198	9.1	1.262
0.203	1.3772	1.014	1.32150	10.3	1.233
0.302	1.34232	2.0	1.317	11.3	1.209
0.405	1.33194	3.1	1.313	12.5	1.180
0.486	1.32818	4.1	1.308	13.8	1.142
0.546	1.32640	5.1	1.301	15.1	1.093
0.589	1.32549	6.1	1.292	16.7	1.034
0.707	1.32372	7.1	1.281	17.3	1.000

24. Spinel ($MgO{\cdot}3.5Al_2O_3$)

Composition

Single crystal, synthetic.

Molecular Weight

356.74

Specific Gravity

3.61
(Linde Air Products Company, *Technical Data Sheets*)

Crystal Class

Cubic; does not cleave.

Transmission

Long wavelength limit 6.0 μ
Short wavelength limit < 0.9 μ
The transmission of spinel is illustrated in Figure 4-24.
(Linde, *above ref.*)

Reflection Loss

13.2% for two surfaces, at a wavelength of 0.6 μ.

Refractive Index

The following values are given by the Linde Air Products Company:

Wavelength (μ)	Refractive Index
0.4861	1.736
0.5893	1.727
0.6563	1.724

Dispersion

Reciprocal dispersion, or nu-value: 60.6

Dielectric Constant

8 to 9
(Linde, *above ref.*)

Melting Temperature

2030 to 2060°C
(Linde, *above ref.*)

Thermal Conductivity

3.3×10^{-2} cal/(cm sec C°) at 35°C.
(K. A. McCarthy and S. S. Ballard, *J. Opt. Soc. Am.*, Vol. 41, pp. 1062–3, 1951)

Thermal Expansion

5.9×10^{-6}/C° at 40°C
(Linde, *above ref.*)

Specific Heat

Hardness

Knoop hardness, 1140 with a load of 100 gm. Indenter set at random directions.
Moh 8
(Linde, *above ref.*)

Solubility

Insoluble in water; not attacked by common acids and NaOH; slightly etched by HF after 65 days at room temperature.
(Linde, *above ref.*)

Elastic Moduli

Notes

The mixture ratio 1:3.5, magnesium oxide to aluminum dioxide, is not unique; other ratios which exist seem to give essentially the same physical properties. The 1:3.5 mixture has been an easy one from which to grow gem stones, and is usually homogeneous where other compositions may exhibit concentration gradients. Spinel is available from the Linde Co., 30 East 42nd Street, New York 17, N. Y.

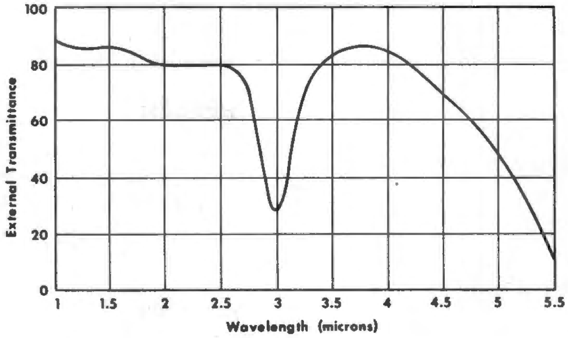


Fig. 4-24. The transmission of spinel; thickness, 5.4 mm.

25. Barium Titanate ($BaTiO_3$)

Composition

Synthetic single crystal; yellowish; currently grown by the Remeika method. A ceramic (noncrystalline) type of material is often used in transducers.

Molecular Weight

232.96

Specific Gravity

5.90, single crystal.

(Private communication, C. Hilsum, Services Electronics Research Laboratory, Baldock, England)

Crystal Class

Orthorhombic between −70°C and 5°C.
Tetragonal between ~5°C and 120°C.
Cubic above ~120°C.

Transmission

Long wavelength limit	6.9 μ
Short wavelength limit	<0.5 μ

The transmission of barium titanate is illustrated in Fig. 4-25

(C. Hilsum, *J. Opt. Soc. Am.*, Vol. 45, p. 771, 1955)

Reflection Loss

29.0% for two surfaces, in the infrared.

(See refractive index)

Refractive Index

About 2.40 throughout the visible and infrared, at room temperature.

(Hilsum, *above ref.*)

For variation with temperature, especially near the Curie point, see W. J. Mertz, *Phys. Rev.*, Vol. 76, pp. 1221–1225, 1949

Dispersion

Dielectric Constant

1240 decreasing to 100 in a frequency range from 100 cps to 2.5×10^{10} cps at a temperature of 25°C.

1240 to 1100 in a frequency range from 100 cps to 3×10^{8} cps.

(*von Hippel,* p. 305)

Melting Temperature

All components of $BaTiO_3$ are solid up to temperatures of 1600°C.

(A. von Hippel, *Rev. Mod. Phys.*, Vol. 22, pp. 221–237, 1950)

Thermal Conductivity

3.2×10^{-3} cal/(cm sec C°) at room temperature (ceramic).

(K. A. McCarthy and S. S. Ballard, *Phys. Rev.*, Vol. 90, p. 375, 1953)

Thermal Expansion

For ceramic

1.6×10^{-5}/C° in a temperature range −80°C to −20°C.
1.9×10^{-5}/C° in a temperature range 10°C to 70°C.
1.3×10^{-5}/C° in a temperature range 120°C to 180°C.
(von Hippel, *above ref.*)

For single crystal

6.2×10^{-6}/C° parallel to *c*-axis in a temperature range 4°C to 20°C.
15.7×10^{-6}/C° perpendicular to *c*-axis.
(A. Smakula, private communication)

Specific Heat

0.077 at −98°C

(J. T. Last, *Phys. Rev.*, Vol. 105, pp. 1740–1750, 1957)

Hardness

Vickers 200–580 for single crystal.

(C. Hilsum, private communication)

Solubility

Elastic Moduli

Young's modulus (single crystal), 4.9×10^{6} psi.
(C. Hilsum, private communication)

Young's modulus (ceramic), 1.65×10^{7} psi at 20°C.
(*AIPH*, p. 3–96)

Modulus of rigidity (single crystal), 1.83×10^{7} psi.
Calculated from elastic coefficients, assuming cubic symmetry.

Bulk modulus (single crystal), 2.35×10^{7} psi.
Calculated from elastic coefficients, assuming cubic symmetry.

Elastic coefficients (single crystal) at room temperature

c_{11} 2.06×10^{12} dyne/cm^2
c_{12} 1.40×10^{12} dyne/cm^2
c_{44} 1.26×10^{12} dyne/cm^2
(W. L. Bond, W. P. Mason, and H. J. Mc Skimin, *Phys. Rev.*, Vol. 82, pp. 442–443, 1951)

Anisotropy factor, assuming cubic symmetry, 3.82.

Elastic compliances (single tetragonal crystal) at 25°C

s_{11} 7.25×10^{-12} cm^2/dyne
s_{33} 10.8×10^{-12} cm^2/dyne
s_{12} -3.15×10^{-12} cm^2/dyne
s_{13} -3.26×10^{-12} cm^2/dyne
s_{44} 12.4×10^{-12} cm^2/dyne

Elastic compliances (ceramic crystal) at 25°C

s_{11} 8.18×10^{-12} cm^2/dyne
s_{33} 6.76×10^{-12} cm^2/dyne
s_{12} -2.98×10^{-12} cm^2/dyne
s_{13} -1.95×10^{-12} cm^2/dyne
s_{44} 18.3×10^{-12} cm^2/dyne
(D. Berlincourt and H. Jaffe, *Phys. Rev.*, Vol. 111, pp. 143–148, 1958)

Notes

Barium titanate is well known for its electrical properties. Because of its transmission properties, it has application for immersion lenses.

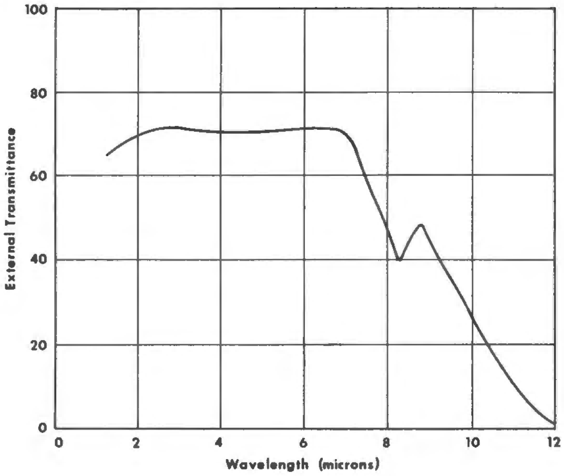


Fig. 4-25. The transmission of barium titanate; thickness, 0.094 mm.

26. Strontium Titanate ($SrTiO_3$)

Composition

Synthetic crystal; clear, colorless.

Molecular Weight

183.53

Specific Gravity

5.122 at 20°C

(S. B. Levin, N. J. Field, F. W. Plock, and L. Merker, *J. Opt. Soc. Am.*, Vol. 45, pp. 737–739, 1955)

Crystal Class

Cubic, perovskite type; does not cleave; exhibits conchoidal fracture.

Transmission

Long wavelength limit	6.8 μ
Short wavelength limit	0.39 μ

The transmission of strontium titanate is illustrated in Fig. 4-26.

(Levin, *above ref.;* W. F. Parsons, private communication. The 3.7-mm-thick sample was measured by Parsons.)

Reflection Loss

29.0% for two surfaces, at a wavelength of 0.6 μ.

Refractive Index

Values of refractive index of strontium titanate are given in Table 4-26. The data are taken from Levin, *above ref.*, and from W. F. Parsons, private communication. The data of Levin are for a 19° 55′ prism at approximately 21°C. The data of Parsons were measured at 26°C for a 22° 58′ 06″ prism. The data of Levin extend from 0.4046 to 0.6907 μ, and those of Parsons from 1.0140 to 5.3034 μ. Other data appear in the article by Levin, and AIPH p. 6–26.

Dispersion

Reciprocal dispersion, or nu-value: 12.6

Dielectric Constant

306 in a frequency range from 100 cps to 1×10^5 cps at 25°C.

(A. Linz, Jr., *Phys. Rev.*, Vol. 91, p. 753, 1953)

234 to 230 in a frequency range from 100 cps to 1×10^{10} cps at 25°C.

(*von Hippel*, p. 305)

Melting Temperature

2080°C.

(C. D. Salzberg, private communication)

Thermal Conductivity

Thermal Expansion

Approximately 9.4×10^{-6}/C°.

(A. Linz, *Data Sheets*. The National Lead Company)

Specific Heat

Hardness

Knoop number 595

(Levin, *above ref.*)

Moh 6 to 6.5

(Linz, *above ref.*)

Solubility

Elastic Moduli

Notes

Strontium titanate is of interest for special applications like immersion lenses. The single crystals can be ground with 220 carborundum on a lead lap, then by finer compounds like Linde "A" on a 50-50 tin-lead lap.

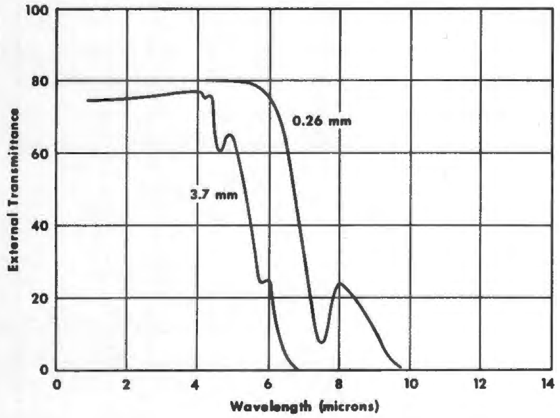


Fig. 4-26. The transmission of strontium titanate for two thicknesses.

TABLE 4-26. The Refractive Index of Strontium Titanate

Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index
0.4046	2.6466	1.3622	2.2922	3.3033	2.2181
0.4861	2.4890	1.5295	2.2850	3.5078	2.2088
0.5893	2.4069	1.6606	2.2799	4.2566	2.1695
0.6563	2.3788	1.7092	2.2782	5.1380	2.1123
0.6907	2.3666	2.1526	2.2626	5.1472	2.1120
1.0140	2.3148	2.4374	2.2527	5.3034	2.1005
1.1286	2.3056				

27. Thallium Bromide-Chloride; KRS-6 (TlBr-TlCl)

Composition

This synthetic mixed crystal, also called thallium bromochloride and usually designated by the code name KRS-6, contains about 40 mole percent thallium bromide and 60% thallium chloride.

Molecular Weight

Not applicable.

Specific Gravity

7.192 at 16°C, for the 40-60% material.
(*Smakula,* p. 11)

Crystal Class

Cubic, cesium chloride structure; does not cleave.

Transmission

Long wavelength limit	34.0 μ
Short wavelength limit	0.21 μ

The transmission of KRS-6 is illustrated in Fig. 4-27; the curve is adapted from transmission curves for two wavelength ranges given by E. K. Plyler, *J. Research NBS,* Vol. 41, p. 128, 1948.

Reflection Loss

24.2% for two surfaces, at a wavelength of 10 μ.

Refractive Index

Values of refractive index at room temperature, for the wavelength range 0.6 to 24 μ, are given in Table 4-27. The data are taken from G. Hettner and G. Leisegang, *Optik,* Vol. 3, p. 305, 1948. The composition of the KRS-6 used was 44.4% TlBr, 55.6% TlCl.

Dispersion

Curves illustrating the variation with wavelength of refractive index and of dispersion, in the range 0.6 to 24 μ, are given in *Smith,* p. 349.

Dielectric Constant

32.9 to 31.8 in a frequency range from 100 cps to 1×10^5 cps, at a temperature of 25°C.
(*von Hippel,* p. 302)

Melting Temperature

423.5°C
(*Smakula,* p. 54)

Thermal Conductivity

17.1×10^{-4} cal/(cm sec C°) at 56°C.
(S. S. Ballard, K. A. McCarthy, and W. C. Davis, *Rev. Sci. Instr.,* Vol. 21, pp. 905–907, 1950)

Thermal Expansion

50×10^{-6}/C° in a temperature range from 20°C to 100°C.
(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt., Soc. Am.,* Vol. 41, pp. 215–222, 1951)

Specific Heat

0.0482 at 20°C
Calculated from the values for thallium bromide and thallium chloride.

Hardness

Knoop number 29.9 with indenter load of 500 gm, long axis of indenter in <110> direction.
Knoop number 38.5 with indenter load of 500 gm, long axis of indenter in <100> direction.
(Combes, *above ref.*)

Solubility

0.32 gm/100 gm water at 20°C. The solubility of a mixed crystal is that of the more soluble component, in this case TlCl.
(*Smakula,* p. 17)

Elastic Moduli

Young's modulus, 3.0×10^6 psi.
The measurement was made in torsion.
(Combes, *above ref.*)
Modulus of rigidity, 1.23×10^6 psi.
The measurement was made in torsion.
(Combes, *above ref.*)
Bulk modulus, 3.31×10^6 psi.
Calculated from elastic coefficients.
Apparent elastic limit, 3.05×10^3 psi.
The measurement was made in torsion.
(Combes, *above ref.*)
Elastic coeffcients at room temperature

c_{11}	3.85×10^{11} dyne/cm^2
c_{12}	1.49×10^{11} dyne/cm^2
c_{44}	0.737×10^{11} dyne/cm^2

(D. L. Arenberg, based on measurements made at the Naval Research Laboratory, 1948–1949)
Anisotropy factor, 0.62.

Notes

KRS-6 has not been given very much attention because of the greater usefulness of KRS-5, which covers about the same transmission range and does it better. KRS-6 is almost unavailable.

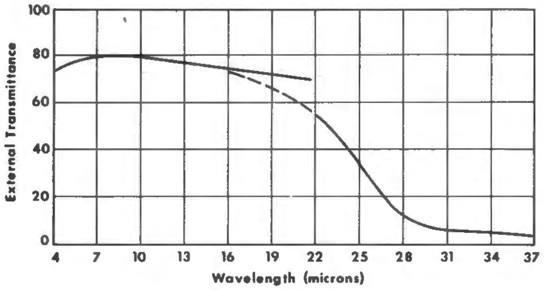


Fig. 4-27. The transmission of KRS-6; thickness, 6 mm.

TABLE 4-27. The Refractive Index of Thallium Bromide-Chloride

Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index
Na-D	2.3367	2.0	2.2059	11.0	2.1723
0.6	2.3294	2.2	2.2039	12.0	2.1674
0.7	2.2982	2.4	2.2024	13.0	2.1620
0.8	2.2660	2.6	2.2011	14.0	2.1563
0.9	2.2510	2.8	2.2001	15.0	2.1504
1.0	2.2404	3.0	2.1990	16.0	2.1442
1.1	2.2321	3.5	2.1972	17.0	2.1377
1.2	2.2255	4.0	2.1956	18.0	2.1309
1.3	2.2212	4.5	2.1942	19.0	2.1236
1.4	2.2176	5.0	2.1928	20.0	2.1154
1.5	2.2148	6.0	2.1900	21.0	2.1067
1.6	2.2124	7.0	2.1870	22.0	2.0976
1.7	2.2103	8.0	2.1839	23.0	2.0869
1.8	2.2086	9.0	2.1805	24.0	2.0752
1.9	2.2071	10.0	2.1767		

28. Potassium Chloride (KCl)

Composition

Single crystal, natural (sylvite), or synthetic.

Molecular Weight

74.55

Specific Gravity

1.9865 at 28°C
(D. A. Hutchison, *Phys. Rev.*, Vol. 66, pp. 144–148, 1948)

Crystal Class

Cubic, sodium chloride structure; cleaves on {100} planes.

Transmission

Long wavelength limit	30.0 μ
Short wavelength limit	0.21 μ

The transmission of potassium chloride is illustrated in Fig. 4-28.
(E. K. Plyler, private communicaton)

Reflection Loss

6.8% for two surfaces, at a wavelength of 10 μ.

Refractive Index

Refractive index data are given in the following papers: (a) For the wavelength range 0.589 to 17.6 μ, F. Paschen, *Ann. Physik,* Vol. 26, p. 120, 1908; (b) for the wavelength range 18.2 to 28.8 μ, H. W. Hohls, *Ann. Physik,* Vol. 29, p. 433, 1937; (c) for the wavelength range 0.19 to 23.0 μ, *Kohlrausch,* Vol. II, p. 528.

Temperature coefficient of refractive index varies from about -2.75×10^{-5}/C° at 10 μ to -0.5×10^{-5}/C° at 20 μ. See *Smakula,* data table, p. 66, and graph, p. 75.

Dispersion

Dielectric Constant

4.64 at a frequency of 10^6 cps, at 29.5°C.
(*AIPH*, p. 5–116)

Melting Temperature

776°C
(*HCP*, p. 579)

Thermal Conductivity

1.56×10^{-2} cal/(cm sec C°) at 42°C.
(S. S. Ballard, K. A. McCarthy, and W. C. Davis, *Rev. Sci. Instr.*, Vol. 21, pp. 905–907, 1950)

Thermal Expansion

36×10^{-6}/C° in a temperature range from 20°C to 60°C.
(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 41, pp. 215–222, 1951)

Specific Heat

0.162 at 0°C
(*HCP*, p. 2091)

Hardness

Knoop number 7.2 in <110> direction with 200 gm indenter load.
Knoop number 9.3 in <100> direction with 200 gm indenter load.
(Combes, *above ref.*)

Solubility

34.7 gm/100 gm water at 20°C.
(*HCP*, p. 579)

Elastic Moduli

Young's modulus, 4.3×10^6 psi.
The measurement was made in flexure.
(Combes, *above ref.*)
Modulus of rigidity, 0.906×10^6 psi.
Calculated from elastic coefficients.
Bulk modulus, 2.52×10^6 psi.
Calculated from elastic coefficients.
Apparent elastic limit, 3.3×10^2 psi.
The measurement was made in flexure.
(Combes, *above ref.*)
Modulus of rupture, 6.4×10^2 psi.
The measurement was made in flexure.
(Combes, *above ref.*)
Elastic coefficients

c_{11}	3.98×10^{11} dyne/cm²
c_{12}	0.62×10^{11} dyne/cm²
c_{44}	0.625×10^{11} dyne/cm²

(J. K. Galt, *Phys. Rev.*, Vol. 73, pp. 1460–1462, 1948)
Anisotropy factor, 0.372.

Notes

Natural potassium chloride was once important because it was available as a crystal. It is of little use now since commercial KBr is available and has a somewhat greater wavelength range. Potassium chloride is grown in the same form as sodium chloride, but sometimes multiple crystals instead of a single crystal ingot result; therefore, the large-size prisms are somewhat rare and more expensive. Crystals 12 in. in diameter by 12 in. long are available from the Harshaw Chemical Co., Cleveland, Ohio, and sizes up to 8 in. in diameter from Optovac, Inc., North Brookfield, Mass.

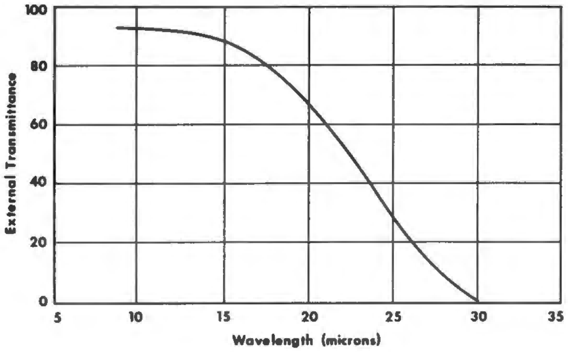


Fig. 4-28. The transmission of potassium chloride; thickness, 5.30 mm.

29. Thallium Chloride (TlCl)

Composition

Single crystal, synthetic.

Molecular Weight

239.85

Specific Gravity

7.018 at 25°C

(A. Smakula and V. Sils, *Phys. Rev.*, Vol. 99, pp. 1744–1746, 1955)

Crystal Class

Cubic, cesium chloride structure.

Transmission

Long wavelength limit 34.0 μ

Short wavelength limit 0.44 μ

The transmission of TlCl near its long wavelength limit is illustrated in Fig. 4-29.

(E. K. Plyler, *J. Research NBS*, Vol. 41, p. 128, 1948)

Reflection Loss

21.8% for two surfaces, at a wavelength of 10 μ.

Refractive Index

A few data for the visible region are quoted in *Smakula*, p. 90; they are taken from F. W. Barth, *Am. Mineral.*, Vol. 14, p. 358, 1929.

Wavelength (μ)	Refractive Index
0.436	2.400
0.546	2.720
0.578	2.253
0.589	2.247
0.650	2.223
0.750	2.198

Dispersion

Dielectric Constant

31.9 at a frequency of 2×10^6 cps, temperature not given.

(*AIPH*, pp. 5–117)

Melting Temperature

430°C

(*HCP*, p. 621)

Thermal Conductivity

1.8×10^{-3} cal/(cm sec C°) at 38°C.

(K. A. McCarthy and S. S. Ballard, *J. Opt. Soc. Am.*, Vol. 41, pp. 1062–1063, 1951)

Thermal Expansion

53×10^{-6}/C° in a temperature range from 20°C to 60°C.

(G. Jones and F. C. Jelen, *J. Am. Chem. Soc.*, Vol. 57, pp. 2532–2536, 1935)

Specific Heat

0.0520 at 0°C

(*HCP*, p. 3092)

Hardness

Knoop number 12.8 with 500-gm indenter load in both <100> and <110> directions.

(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 41, pp. 215–222, 1951)

Solubility

0.32 gm/100 gm water at 20°C.

(*HCP*, p. 621)

Elastic Moduli

Young's modulus, 4.60×10^6 psi.

Calculated from elastic coefficients.

Modulus of rigidity, 1.10×10^6 psi.

Calculated from elastic coefficients.

Bulk modulus, 3.42×10^6 psi.

Calculated from elastic coefficients.

Elastic coefficients at room temperature

c_{11} 4.01×10^{11} dyne/cm^2

c_{12} 1.53×10^{11} dyne/cm^2

c_{44} 0.760×10^{11} dyne/cm^2

(D. L. Arenberg, based on measurements made at Naval Research Laboratory, 1948–1949)

Anisotropy factor, 0.657.

Notes

Thallium chloride can be cut easily on a diamond saw (melted beeswax is used as a "lubricant" while it is being sawed). It is difficult to grind to dimension since the material flows to the edge and fills the grinding wheel. Thin strips bend like lead.

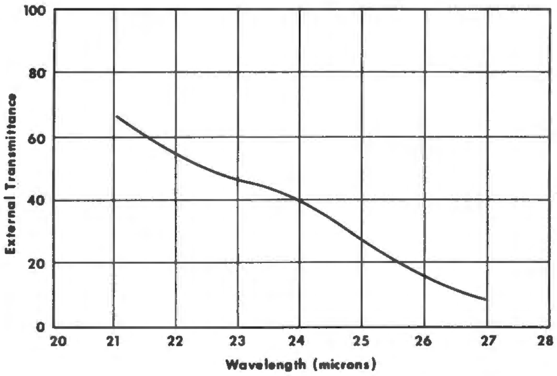


Fig. 4-29. The transmission of thallium chloride; thickness, 6 mm.

30. Thallium Bromide (TlBr)

Composition

Single crystal, synthetic

Molecular Weight

284.31

Specific Gravity

7.453 at 25°C

(A. Smakula and V. Sils, *Phys, Rev.*, Vol. 99, pp. 1744–1746, 1955)

Crystal Class

Cubic, cesium chloride structure.

Transmission

Long wavelength limit 40.0 μ
Short wavelength limit 0.44 μ

The transmission of TlBr at the longer wavelengths is illustrated in Fig. 4-30.

(E. K. Plyler, *J. Research NBS*, Vol. 41, p. 128, 1948)

Reflection Loss

29.0% for two surfaces, at a wavelength of 0.6 μ.

Refractive Index

A few values of refractive index in the visible region are quoted in *Smakula*, p. 90; they are taken from the work of F. W. Barth, *Am. Mineral.*, Vol. 14, p. 358, 1929.

Wavelength (μ)	Refractive Index
0.438	2.652
0.546	2.452
0.578	2.424
0.589	2.418
0.650	2.384
0.750	2.350

Dispersion

Reciprocal dispersion, or nu-value: approximately 80.

Dielectric Constant

30.3 in the frequency range 10^3 to 10^7 cps, at 25°C.

(*von Hippel*, p. 302)

Melting Temperature

460°C

(*HCP*, p. 621)

Thermal Conductivity

1.4×10^{-3} cal/(cm sec C°) at 43°C.

(K. A. McCarthy and S. S. Ballard, *J. Opt. Soc. Am.*, Vol. 41, pp. 1062–1063, 1951)

Thermal Expansion

51×10^{-6}/C°, in a temperature range from 20°C to 60°C.

(G. Jones and F. G. Jelen, *J. Am. Chem. Soc.*, Vol. 57, pp. 2532–2536, 1935)

Specific Heat

0.045 at 20°C

(K. K. Kelley, *Bureau of Mines Bulletin* No. 371, p. 51, 1934)

Hardness

Knoop number 11.9 with 500–gm indenter load in both <100> and <110> directions.

(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 41, pp. 215–222, 1951)

Solubility

0.05 gm/100 gm water at 25°C.

(*HCP*, p. 621)

Elastic Moduli

Young's modulus, 4.28×10^6 psi.
Calculated from elastic coefficients.
Modulus of rigidity, 1.10×10^6 psi.
Calculated from elastic coefficients.
Bulk modulus, 3.26×10^6 psi.
Calculated from elastic coefficients.
Elastic coefficients at room temperature
c_{11} 3.78×10^{11} dyne/cm^2
c_{12} 1.48×10^{11} dyne/cm^2
c_{44} 0.756×10^{11} dyne/cm^2
(D. L. Arenberg, based on measurements made at Naval Research Laboratory, 1948–1949)
Anisotropy factor, 0.657.

Notes

Thallium bromide can be ground without cracking or chipping although the edges turn over. A very small amount at a time should be ground. It bends like lead.

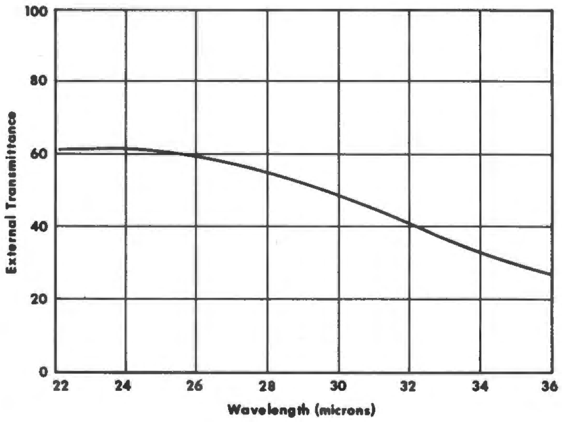


Fig. 4-30. The transmission of thallium bromide; thickness, 6 mm.

31. Sodium Nitrate ($NaNO_3$)

Composition

Single crystal, natural and synthetic.

Molecular Weight

85.01

Specific Gravity

2.261
(*HCP*, p. 609)

Crystal Class

Rhombohedral

Transmission

Reflection Loss

Refractive Index

Values of refractive index at room temperature for the wavelength range from 0.434 to 0.668 μ are given in Table 4-31. The data are taken from *ICT*, Vol. III, p. 26.

Dispersion

Reciprocal dispersion or nu-value: 28.5.

Dielectric Constant

6.85 at a frequency of 2×10^5 cps at 19°C.
(*AIPH*, p. 5–117)

Melting Temperature

306.8°C
(*HCP*, p. 609)

Thermal Conductivity

Thermal Expansion

12×10^{-6}/C° at 50°C, parallel to *c*-axis.
11×10^{-6}/C° at 50°C, perpendicular to *c*-axis.
(Landolt, p. 2217)

Specific Heat

0.247 at 0°C.
(*HCP*, p. 2092)

Hardness

Knoop number 19.2 with indenter load of 200 gm with indenter perpendicular to cleavage planes.
(L. S. Combes, S. S. Ballard, and K. A. McCarthy, *J. Opt. Soc. Am.*, Vol. 41, pp. 215–222, 1951)

Solubility

73 gm/100 gm water at 0°C.
180 gm/100 gm water at 100°C.
(*HCP*, p. 609)

Elastic Moduli

Bulk modulus, 2.6×10^{11} dyne/cm²
(*ICT*, Vol. III, p. 50)

Elastic coefficients

c_{11} 8.67×10^{11} dyne/cm²
c_{33} 3.74×10^{11} dyne/cm²
c_{44} 2.13×10^{11} dyne/cm²
c_{12} 1.63×10^{11} dyne/cm²
c_{13} 1.60×10^{11} dyne/cm²
c_{14} 0.82×10^{11} dyne/cm²
(J. Bhimasenachar, *Proc. Ind. Acad. Sci.*, Vol. 22A, pp. 199–208, 1945)

TABLE 4-31. The Refractive Indices of Sodium Nitrate at Room Temperature

Wavelength (μ)	Refractive Index		Wavelength (μ)	Refractive Index	
	(ordinary ray)	(extraordinary ray)		(ordinary ray)	(extraordinary ray)
0.434	1.6126	1.340	0.578	1.5860	1.336
0.436	1.6121	1.340	0.589	1.5848	1.336
0.486	1.5998	1.338	0.656	1.5791	1.334
0.501	1.5968	1.337	0.668	1.5783	1.334
0.546	1.5899	1.336			

32. Potassium Iodide (KI)

Composition

Single crystal, synthetic.

Molecular Weight

166.02

Specific Gravity

3.13
(*HCP*, p. 582)

Crystal Class

Cubic, cleaves on <100> planes.

Transmission

Long wavelength limit 42.0 μ
Short wavelength limit <0.38 μ
The transmission of potassium iodide is illustrated in Fig. 4-32.
(J. Strong, *Phys. Rev.*, Vol. 38, p. 1818, 1931)

Reflection Loss

10.6% for two surfaces, at a wavelength of 12 μ.

Refractive Index

Values of refractive index at 20°C for the wavelength range from 0.248 μ to 1.083 μ and at 38°C from 1.18 μ to 29.0 μ are given in Table 4-32. The data are taken from J. Strong, *above ref.*
(*Smakula*, p. 82)

The temperature coefficient of refractive index at 0.546 μ is -5.0×10^{-5}/C°.
(*Smakula*, p. 65)

Dispersion

The dispersion of potassium iodide is given in Fig. 3-3.
(H. W. Hohls, *Ann. Physik*, Vol. 29, p. 433, 1937)

Dielectric Constant

4.94 at a frequency of 2×10^6 cps.
(*AIPH*, p. 5–116)

Melting Temperature

723°C
(*HCP*, p. 571)

Thermal Conductivity

Thermal Expansion

42.6×10^{-6}/C° at 40°C.
(*ICT*, Vol. III, pp. 43–44)

Specific Heat

0.75 at −3°C.
(W. T. Berg and J. A. Morrison, *Proc. Roy. Soc.*, Vol. *A*242, pp. 467–477, 1957)

Hardness

Solubility

127.5 gm/100 gm water at 0°C.
208 gm/100 gm water at 100°C.
(*HCP*, p. 583)

Elastic Moduli

Young's modulus, 4.57×10^6 psi.
Calculated from elastic coefficients.
Modulus of rigidity, 0.90×10^6 psi.
Calculated from elastic coefficients.
Bulk modulus, 1.24×10^8 psi.
(*ICT*, Vol. III, p. 50)
Elastic coefficients

c_{11}	3.32×10^{11} dyne/cm^2
c_{12}	0.578×10^{11} dyne/cm^2
c_{44}	0.620×10^{11} dyne/cm^2

(P. W. Bridgman, *Proc. Am. Acad. Arts Sci.*, Vol. 64, p. 305, 1929)
Anisotropy factor, 0.451.

Notes

Potassium iodide is valuable as a prism material, but is too hygroscopic and soft for field use. It is available from the Harshaw Chemical Co., Cleveland, Ohio, in cylindrical ingots 7.5 in. in diameter by 5 in., with a 90° apex cone.

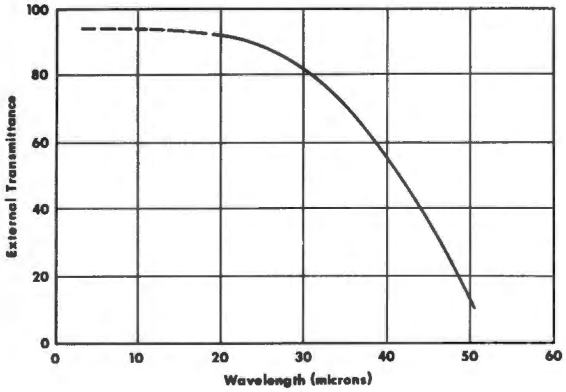


Fig. 4-32. The transmission of potassium iodide; thickness, 0.83 mm.

TABLE 4-32. Refractive Index of Potassium Iodide (From 0.248 through 1.083 µ at 20°C, and from 1.18 through 29.0 µ at 38°C)

Wave-length (µ)	Refractive Index	Wave-length (µ)	Refractive Index	Wave-length (µ)	Refractive Index
0.302	1.82769	8.84	1.6218	21	1.5930
0.405	1.71843	10.02	1.6201	22	1.5895
0.546	1.67310	11.79	1.6172	23	1.5858
0.768	1.6494	12.97	1.6150	24	1.5819
1.014	1.6396	14.14	1.6127	25	1.5775
2.36	1.6295	15.91	1.6085	26	1.5729
3.54	1.6275	18.10	1.6030	27	1.5681
4.13	1.6268	19	1.5997	28	1.5629
5.89	1.6252	20	1.5964	29	1.5571
7.66	1.6235				

33. Ammonium Dihydrogen Phosphate (ADP) and Potassium Dihydrogen Phosphate (KDP)

Composition

Synthetic single crystals: $NH_4H_2PO_4$ and KH_2PO_4.

Molecular Weight

ADP, 115.04
KDP, 136.09

Specific Gravity

Crystal Class

Transmission

Long wavelength limit ADP, 1.70 μ; KDP, 1.70 μ
Short wavelength limit ADP, 0.125 μ; KDP, 0.250 μ
The transmissions of ADP and KDP are illustrated in Fig. 4-33.
(R. C. McDonough, private communication)

Reflection Loss

ADP: 10.5% for two surfaces, at a wavelength of 0.7 μ.
KDP: 8.0% for two surfaces, at a wavelength of 0.59 μ.

Refractive Index

ADP: a few values of refractive index in the visible are given below. These were measured by the National Bureau of Standards under Contract N8onr-60801, for the Office of Naval Research. The data were measured at 20.5°C.

Wavelength (μ)	Refractive Index (ordinary ray)	Refractive Index (extraordinary ray)	Wavelength (μ)	Refractive Index (ordinary ray)	Refractive Index (extraordinary ray)
0.4062	1.49141	1.53973	0.5893	1.47869	1.52418
0.4340	1.48809	1.53583	0.6563	1.47633	1.52097
0.4861	1.48408	1.53098	0.7065	1.47489	1.51890

KDP: the refractive indices (from the same source) are 1.5095 and 1.4684 for the ordinary and extraordinary rays, respectively, at 0.5893 μ.

Dispersion

Reciprocal dispersion or nu-value for ADP: 60.

Dielectric Constant

ADP: 56.4 to 55.9 with the electric field perpendicular to the *c*-axis, in a frequency range of 10^2 to 10^8 cps.

16.4 to 13.7 with the electric field parallel to the *c*-axis, in a frequency range of 10^2 to 10^{10} cps.

KDP: 44.5 to 44.3 with the electric field perpendicular to the *c*-axis, in a frequency range of 10^2 to 10^8 cps.

21.4 to 20.2 with the electric field parallel to the *c*-axis, in a frequency range of 10^2 to 10^8 cps.

(*von Hippel*, p. 487)

Melting Temperature

KDP, 252.6°C.
(*HCP*, p. 585)

Thermal Conductivity

ADP: 1.7×10^{-3} cal/(cm sec C°) at 42°C, heat flow parallel to *c*-axis.

3.0×10^{-3} cal/(cm sec C°) at 40°C, heat flow perpendicular to *c*-axis.

KDP: 2.9×10^{-3} cal/(cm sec C°) at 39° C, heat flow parallel to *c*-axis.

3.2×10^{-3} cal/(cm sec C°) at 46°C, heat flow perpendicular to *c*-axis.

(K. A. McCarthy and Stanley S. Ballard, *J. Opt. Soc. Am.*, Vol. 41, p. 1063, 1951)

Thermal Expansion

Specific Heat

Hardness

Solubility

ADP: 22.7 gm/100 gm water at 0°C, insoluble in alcohol and acetone.
173.2 gm/100 gm water at 100°C.
(*HCP*, p. 487)
KDP: 33 gm/100 gm water at 25°C, insoluble in alcohol.
(*HCP*, p. 585)

Elastic Moduli

Notes

ADP and KDP are known for their electro-optical properties. The literature refers to extremely large samples that have been grown.

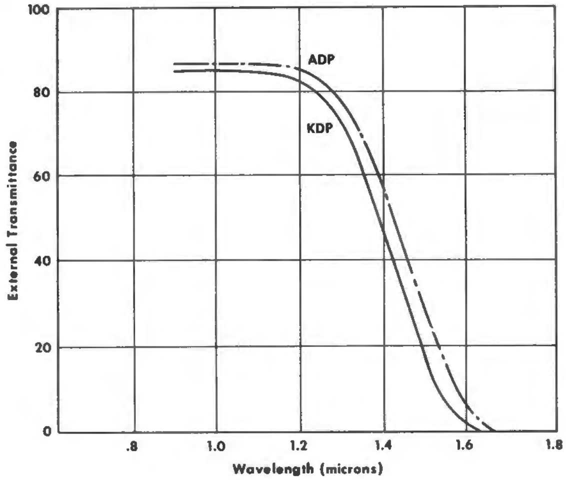


Fig. 4-33. The transmission of ADP and KDP; thicknesses, 7.8 mm. and 12.5 mm, respectively.

34. Lead Fluoride (PbF_2)

Composition

Synthetic single crystal.

Molecular Weight

245.21

Specific Gravity

8.24 at 20°C.
(*HCP*, p. 545)

Crystal Class

Cubic.

Transmission

Long wavelength limit ~ 17 μ
Short wavelength limit 0.25 μ
The transmission of lead fluoride is illustrated in Fig. 4-34.
(D. A. Jones, R. V. Jones, and R. W. H. Stevenson, *Proc. Phys. Soc.*, Vol. 65B, p. 906, 1952)

Reflection Loss

13.8% for two surfaces, at a wavelength of 10 μ.

Refractive Index

1.76 for "yellow light."
(Jones, *above ref.*)

Dispersion

High dispersion is quoted by Jones, *above ref.*

Dielectric Constant

Melting Temperature

855°C
(*HCP*, p. 545)

Thermal Conductivity

Thermal Expansion

Specific Heat

Hardness

Solubility

Elastic Moduli

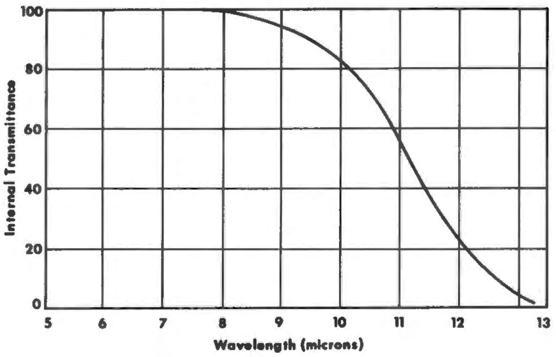


Fig. 4-34. The transmission of lead fluoride; thickness, 10 mm. Internal transmittance is given.

35. Cadmium Sulfide (CdS)

Composition

Single yellow crystal, synthetic. Prepared in three ways:

(1) Chemical reaction of heated cadmium metal and hydrogen sulfide in a tube furnace.
(R. Frerichs, *Phys. Rev.*, Vol. 72, pp. 594–601, 1947)

(2) Static resublimation process in which cadmium sulfide is heated in an atmosphere of hydrogen sulfide.
(D. C. Reynolds and S. J. Czyzak, *Phys. Rev.*, Vol. 79, p. 543, 1950)

(3) Growth in graphite boat by slow freezing at a rate of 0.5 in./hr.
(Eagle Picher Co., private communication)

The energy gap is 2.4 ev.
(W. C. Dunlap Jr., *An Introduction to Semiconductors*, John Wiley & Sons, Inc., New York, 1957.)

Molecular Weight

144.48

Specific Gravity

4.82 at 20°C
(*HCP*, p. 501)

Crystal Class (UNIAXIAL)

Zinc blende.

Transmission Limits

Long wavelength 16 μ
Short wavelength 0.52 μ

The transmission of cadmium sulfide is illustrated in Fig. 4-35.
(Eagle Picher Co., private communication)

Reflection Loss

12.9% for two surfaces, at a wavelength of 1.5 μ.

Refractive Index

Values of the refractive index of single crystal cadmium sulfide are given in Table 4-35. The data are taken from a curve of measured values and values calculated by the Cauchy dispersion formula. No information was available on the temperature and purity of the specimen.
(S. J. Czyzak *et al.*, "The Study of Properties of Single Crystals," University of Detroit, October 1955)

Dispersion

Dielectric Constant

Melting Temperature

1500°C ± 25°C at a pressure of 100 atm.
(Eagle Picher Co., private communication)

1475°C ± 15°C at a pressure of 150 psi.
(A. Addamiano, *J. Phys. Chem.*, Vol. 61, p. 1253, 1957)

Sublimes at 900°C.

Thermal Conductivity

3.8×10^{-2} cal/(cm sec C°) at 14°C.
(K. A. McCarthy and E. A. Bray, Tufts University, unpublished data)

Thermal Expansion

4.2×10^{-6}/C° in a temperature range from 27°C to 70°C.
(K. A. McCarthy and W. J. Little, Tufts University, unpublished data)

Specific Heat

Hardness

Knoop number 122 ± 4 for indenter load of 25 gm.
(Eagle Picher Co., private communication)

Solubility

Insoluble.

Elastic Moduli

Notes

Cadmium sulfide works nicely. It polishes like a metal, does not strain on cutting, and can probably be cut with a diamond saw. Polishing can be done with silicon carbide paper, distilled water, and levigated alumina. Rouge can be used as a final polish. Polycrystalline ingots have been obtained, with some single crystallites as large as 0.25 × 0.25 × 0.125 in.

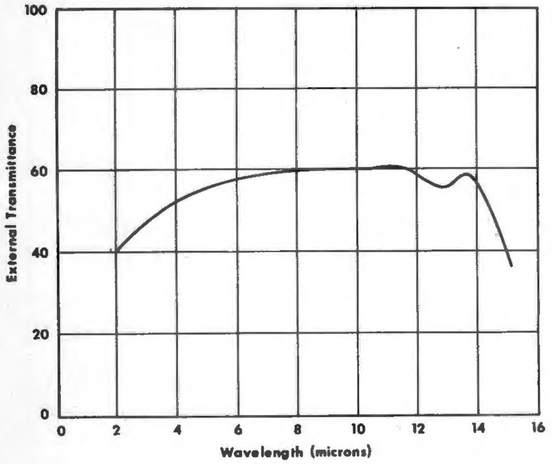


Fig. 4-35. The transmission of cadmium sulfide; thickness, 3.9 mm. The "dip" at about 13 μ is probably due to impurity content; the gradual decrease from 6 to 2 μ is due to scattering from a poorly polished sample.

TABLE 4-35. The Refractive Index of Cadmium Sulfide

Wavelength (μ)	Refractive Index	Wavelength (μ)	Refractive Index
0.6	2.500	1.1	2.315
0.7	2.425	1.2	2.300
0.8	2.370	1.3	2.301*
0.9	2.345	1.4	2.300*
1.0	2.330	1.5	2.295*

* Calculated from the Cauchy dispersion formula; the values deviate from measured values, in the region where they can be compared, by 0.01 to 0.02.

36. Gallium Arsenide (GaAs)

Composition

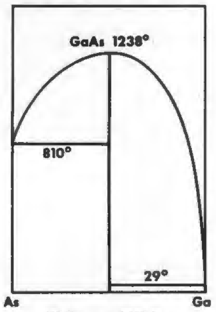
The phase diagram is shown below. Gallium arsenide is extremely similar to indium arsenide in many properties and in preparation. Zone-refining techniques work well, and crystals can be pulled, e.g., by the Kyropoulos method.

(Philco Corp., *Quarterly Progress Report* 2120-3)

The optical energy gap is 1.35 ev.

(F. Oswald and R. Schade, *Z. Naturforschung*, Vol. 9a, p. 611, 1954)

Phase Diagram



Welker and Weiss

Molecular Weight

144.63

Specific Gravity

Crystal Class

Zinc blende.

(*Welker and Weiss*)

Transmission

Long wavelength limit	11 μ
Short wavelength limit	1 μ

The transmission of gallium arsenide is illustrated in Fig. 4-36a.

(Philco Corp., *Quarterly Progress Report* 2120-4)

The absorption coefficient is plotted as a function of wavelength in Fig. 4-36b.

(Oswald and Schade, *above ref.*)

Reflection Loss

45% for two surfaces, at a wavelength of 12 μ.

Refractive Index

Values of refractive index for the wavelength region 1 to 13 μ are plotted in Fig. 4-36b. The purity of the sample was not specified. Values are tabulated in Table 4-36.

(Luther C. Barcus, private communication. See also L. C. Barcus, A. Perlmutter, and J. Callaway, *Phys. Rev.*, Vol. 111, p. 167, 1958)

Dispersion

Dielectric Constant

11.06 ± 0.14 for the high-frequency dielectric constant.

(L. C. Barcus, *above ref.*)

Melting Point

1238°C

(*Welker and Weiss*).

Gallium arsenide dissociates at about 400°C.

(R. Barrie, F. A. Cunnell, J. T. Edmond, and I. M. Ross, *Physica*, Vol. 20, p. 1087, 1954)

Thermal Conductivity

Thermal Expansion

5.7×10^{-6}/C°, temperature not specified.

(*Welker and Weiss*)

Specific Heat

Hardness

Solubility

Insoluble.

Elastic Moduli

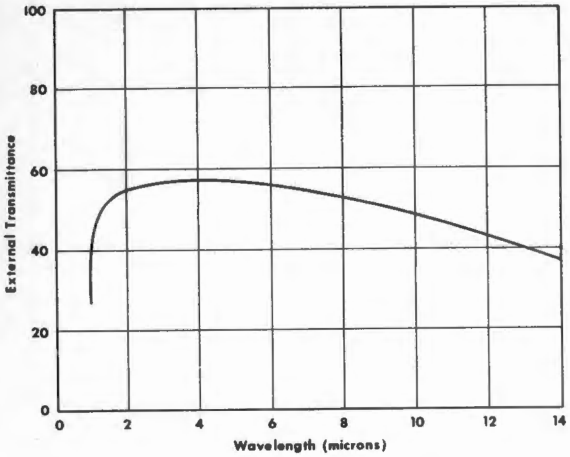


Fig. 4-36a. The transmission of gallium arsenide; thickness, 0.81 mm; resistivity, about 0.02 ohm-cm.

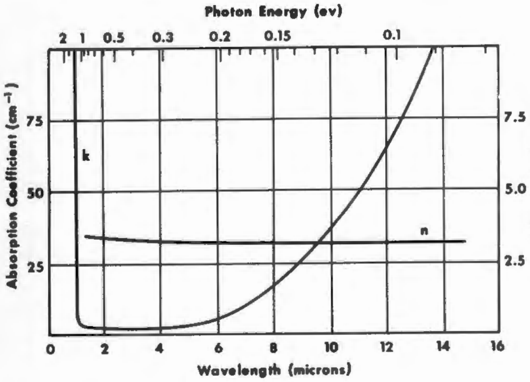


Fig. 4-36b. Absorption coefficient and refractive index of gallium arsenide; resistivity, 10^{-3} ohm-cm.

TABLE 4-36. The Refractive Index of Gallium Arsenide (Temperature and purity are not given)

Wavelength (μ)	Refractive Index
0.78 ± 0.01	3.34 ± 0.04
8.0 ± 0.05	3.34 ± 0.04
10.0 ± 0.05	3.135 ± 0.04
11.0 ± 0.05	3.045 ± 0.04
13.0 ± 0.05	2.97 ± 0.04
13.7 ± 0.05	2.895 ± 0.04
14.5 ± 0.05	2.82 ± 0.04
15.0 ± 0.05	2.73 ± 0.04
17.0 ± 0.05	2.59 ± 0.04
19.0 ± 0.05	2.41 ± 0.04
21.9 ± 0.1	2.12 ± 0.04

37. Indium Arsenide (InAs)

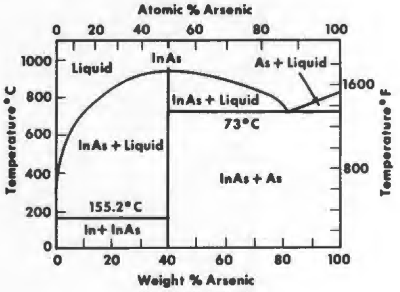
Composition

The phase diagram for InAs is shown below. The material has an appreciable vapor pressure at its melting point, but even so it tends to form stoichiometric proportions. The material is prepared by zone melting in an enclosed boat with carefully measured constituents (so that the melt is of stoichiometric proportions when the more volatile component has saturated vapor). Special care must also be used in pulling the crystal.

(Welker and Weiss)

The optical energy gap is 0.33 ev.

(F. Oswald and R. Schade, *Z. Naturforschung*, Vol. 9a, p. 611, 1954)



PHASE DIAGRAM

Molecular Weight

189.73

Specific Gravity

Crystal Class

Zinc blende.

(T. S. Liu and E. A. Peretti, *Trans. Am. Soc. Metals*, Vol. 45, p. 677, 1953)

Transmission

Long wavelength limit ~7.0 μ

Short wavelength limit 3.8 μ

The absorption of indium arsenide is illustrated in Fig. 4-37.

(Oswald and Schade, *above ref.*)

Reflection Loss

47% for two surfaces, at a wavelength of 6 μ.

Refractive Index

Values of refractive index for the wavelength region 3.8 to 15 μ for a sample with a resistivity of 10^{-3} ohm-cm are plotted in Fig. 4-37. The data are those of Oswald and Schade, *above ref.*

Dispersion

Dielectric Constant

Melting Point

942°C

(R. M. Talley and D. Enright, *Phys. Rev.*, Vol. 94, p. 1431, 1954)

Thermal Conductivity

Thermal Expansion

5.3×10^{-6}/C°, temperature not specified.

(*Welker and Weiss*)

Specific Heat

Hardness

Solubility

Insoluble

Elastic Moduli

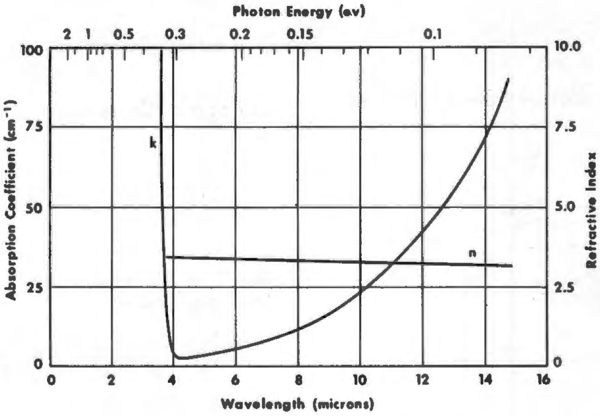


Fig. 4-37. Absorption coefficient and refractive index of indium arsenide; resistivity, 10^{-8} ohm-cm.

38. Gallium Antimonide (GaSb)

Composition

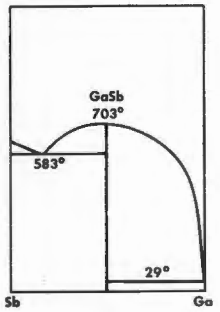
Gallium antimonide is similar in composition and preparation to indium antimonide. The main difficulty in the preparation of the material is obtaining sufficiently pure gallium. "As yet there has been no evidence that a deviation from stoichiometry in the case of gallium antimonide occurs . . . . One always obtains a conducting compound possessing a specific resistivity of 0.08 ohm-cm . . . ."

(*Welker and Weiss*)

The specific resistivity of the material cannot be increased by zone melting. The optical energy gap is 0.68 ev.

(F. Oswald and R. Schade, *Z. Naturforschung,* Vol. 9a, p. 611, 1954)

The phase diagram given below is from Welker and Weiss.



Molecular Weight

191.48

Specific Gravity

Crystal Class

Zinc blende.

(R. F. Blunt, W. R. Hosler, and H. P. R. Frederikse, *Phys. Rev.*, Vol. 96, p. 576, 1954)

Transmission

Long wavelength limit ~2.5 μ

Short wavelength limit 2.0 μ

The transmission of gallium antimonide is illustrated in Fig. 4-38a.

(D. F. Edwards, The University of Michigan, Willow Run Laboratories, private communication)

Reflection Loss

49.7% for two surfaces, at a wavelength of 4 μ.

Refractive Index

Values of refractive index for a sample with a resistivity of 0.08 ohm-cm and a carrier mobility of 650 $\text{cm}^2/(\text{v sec})$ in the wavelength region 1 to 16 μ have been plotted in Fig. 4-38b.

(Oswald, *above ref.*)

The data of Table 4-38 are for a 10.8° prism of a sample with 7.5×10^{16} carriers/cc at room temperature.

(D. F. Edwards, private communication)

Dielectric Constant

Melting Temperature

720°C

(H. Welker, *Physica,* Vol. 20, p. 893, 1954)

Thermal Conductivity

Thermal Expansion

Specific Heat

Hardness

Solubility

Insoluble

Elastic Moduli

Young's modulus, 9.19×10^6 psi.
Calculated from elastic coefficients.

Modulus of rigidity, 6.28×10^6 psi.
Calculated from elastic coefficients.

Bulk modulus, 8.19×10^6 psi.
Calculated from elastic coefficients.

Elastic coefficients

c_{11}	8.849×10^{11} dyne/cm^2
c_{12}	4.037×10^{11} dyne/cm^2
c_{44}	4.325×10^{11} dyne/cm^2

(Philco 2120–3; the values were supplied by H. P. R. Frederikse, *NBS*)

Anisotropy factor, 1.79.

TABLE 4-38. Index of Refraction of Gallium Antimonide

Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index	Wave-length (μ)	Refractive Index
1.8	3.820	2.1	3.780	2.4	3.755
1.9	3.802	2.2	3.764	2.5	3.749
2.0	3.789	2.3	3.758		

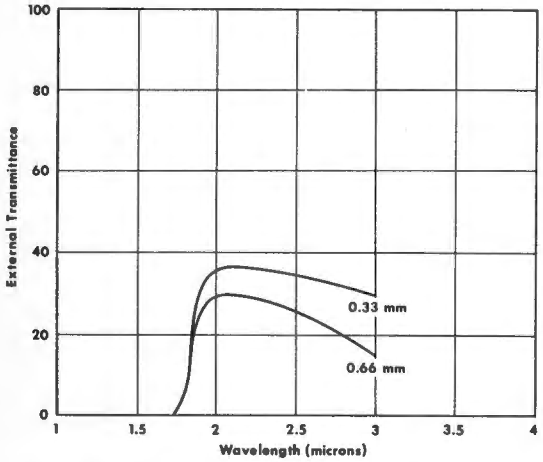


Fig. 4-38a. The transmission of gallium antimonide for two thicknesses.

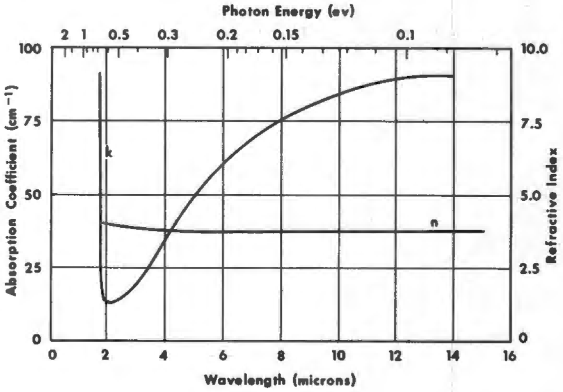


Fig. 4-38b. Absorption coefficient and refractive index of gallium antimonide; resistivity, 0.08 ohm-cm.

39. Gallium Phosphide (GaP)

Composition

Synthetic single crystal. A 1.5-in. ingot was obtained by growth in a temperature gradient (150°C/in., 1100°C mean temperature) for 1 week under a phosphorus vapor pressure of 1 atm. The energy gap is 2.25 ev.

(Philco Corp. *Quarterly Progress Report* 2120–3)

Molecular Weight

100.70

Specific Gravity

Crystal Class

Zinc blende.

Transmission

Long wavelength limit	4.5 μ
Short wavelength limit	0.6 μ

The absorption of gallium phosphide is illustrated in Fig. 4-39.

(F. Oswald, *Z. Naturforschung*, Vol. 10a., p. 927, 1955)

It is also reported that a 0.5-mm slightly impure sample exhibited 10% external transmittance from 1 to 12 μ and a 1.0-mm thick purer sample (5×10^4 ohm-cm) exhibited absorption coefficients of 6 cm^{-1} at 2 μ, 11 cm^{-1} at 3 μ, and 17 cm^{-1} at 4 μ.

(Philco Corp. *Quarterly Progress Report* 2120–5)

Reflection Loss

40% for two surfaces, at a wavelength of 2 μ.

Refractive Index

Values of refractive index for the wavelength region 0.5 to 15 μ are plotted in Fig. 4-39. The refractive index has been calculated by other investigators (Philco, *above ref.*) to be 1.7 at 2 μ and 1.4 at 3 μ and 4 μ.

(Philco 2120, Reports 1 through 5)

Dispersion

Dielectric Constant

Melting Point

Above 500°C.

Thermal Conductivity

Thermal Expansion

Specific Heat

Solubility

Elastic Moduli

c_{11} 14.7×10^{11} dyne/cm^2

(Calculated by Wood, Philco 2120–3)

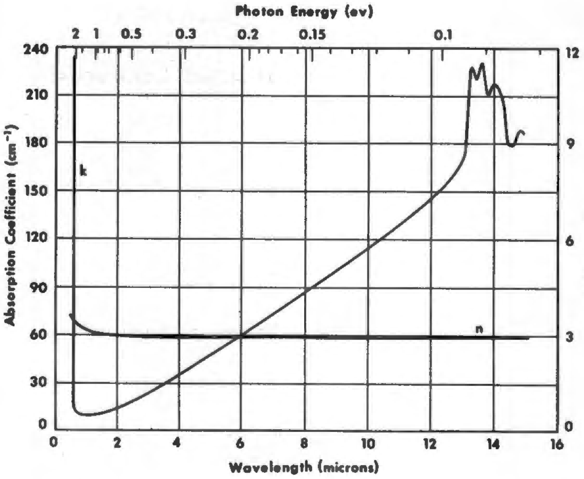


Fig. 4-39. Absorption coefficient and refractive index of gallium phosphide.

40. Indium Phosphide (InP)

Composition

Indium phosphide can be prepared by fusing together the pure elements and using a Kyropoulos crystal-growing technique. Two values for the optical energy gap can be found: 1.20 ev (F. A. Cunnell, J. T. Edmond, J. C. Richards, *Proc. Phys. Soc.*, Vol. 67B, p. 849, 1954); 1.25 ev (F. Oswald and R. Schade, *Z. Naturforschung*, Vol. 9a, p. 611, 1954).

Molecular Weight

145.80

Specific Gravity

Crystal Class

Zinc blende.
(*Welker and Weiss*)

Transmission

Long wavelength limit	14 μ
Short wavelength limit	1 μ

The absorption coefficient of indium phosphide is illustrated in Fig. 4-40.
(Oswald and Schade, *above ref.*)

It was also reported that a 4.5-mm sample has 60% transmission from 1 to 12 μ.
(Harman, 1952 Washington meeting of the Electrochemical Society)

Reflection Loss

43.2% for two surfaces, at a wavelength of 12 μ.

Refractive Index

The refractive index of indium phosphide is plotted in Fig. 4-40.
(Oswald and Schade, *above ref.*)

Dispersion

Dielectric Constant

Melting Point

1050°C
(Cunnell, *above ref.*)
1070°C
(H. Welker, *Physica*, Vol. 20, p. 893, 1954)

Thermal Conductivity

Thermal Expansion

Specific Heat

Solubility

Elastic Moduli

c_{11} 10.7 × 10^{11} dynes/cm^2.
(Predicted by Charles Wood in Philco Corp. *Quarterly Progress Report* 2130–3, Appendix A, January 1958)

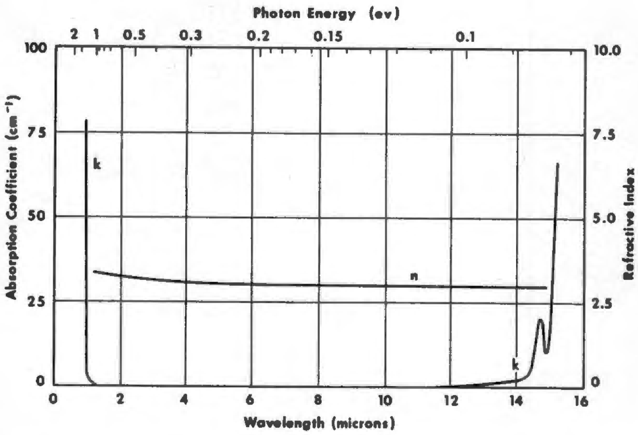


Fig. 4-40. Absorption coefficient and refractive index of indium phosphide.

41. Lead Sulfide (PbS)

Composition

Natural (galena), synthetic crystals, and thin films generated by evaporation or chemical deposition. The crystals can be grown by the Bridgman-Stockbarger technique. Sizes as large as a few centimeters are available. The energy gap is 0.34 ev.

Molecular Weight

239.28

Specific Gravity

7.5
(*HCP*, p. 547)

Crystal Class

Cubic, sodium chloride structure.
(R. A. Smith, *Phil. Mag. Suppl.*, Vol. 2, p. 321, 1953)

Transmission

Long wavelength limit	7.0 μ
Short wavelength limit	3.0 μ

The transmission of lead sulfide has been measured by several investigators. The transmission of thin films is lower than the single crystal value by a factor of about 10^2, apparently because of the microcrystalline structure of the film or impurities in the microcrystals. The transmission of the material is also affected by its state of polish. The transmission of a single crystal of galena of unknown origin is illustrated in Fig. 4-41a. The absorption coefficient minimum for this sample was 6 cm^{-1} at 4 μ. The absorption for several temperatures is plotted in Fig. 4-41b. X-ray analysis showed no detectable impurities. For other measurements see M. A. Clark and R. J. Cashman, *Phys. Rev.*, Vol. 85, p. 1043, 1952; D. G. Avery, *Proc. Phys. Soc.*, Vol. 64B, p. 1087, 1951; *ibid.*, Vol. 66B, p. 134, 1953; and A. F. Gibson, *Proc. Phys. Soc.*, Vol. 65B, pp. 378–388, 1952.

Reflection Loss

54% for two surfaces, at a wavelength of 3 μ.

Refractive Index

Values of refractive index for the wavelength region of 0.5 to 3.0 μ of lead sulfide have been reported by D. G. Avery, *Proc. Phys. Soc.*, Vol. 66B, p. 134, 1953. His values are for measurements made on several cleaved samples and one polished sample, and for two different types of polishing. Avery quotes 4.10 ± 0.06 for all samples at 3.0 μ and 4.0 ± 0.1 at 1.0 μ.

Dispersion

Dielectric Constant

17.9 at a frequency of 10^6 cps and temperature of 15°C.
(*HCP*, p. 2341)

Melting Temperature

1114°C

Thermal Conductivity

16×10^{-4} cal/(cm sec C°)
(H. J. Goldsmid, *Proc. Phys. Soc.*, Vol. 67B, p. 360, 1954)

Thermal Expansion

Specific Heat

0.050
(Goldsmid, *above ref.*)

Hardness

Solubility

Elastic Moduli

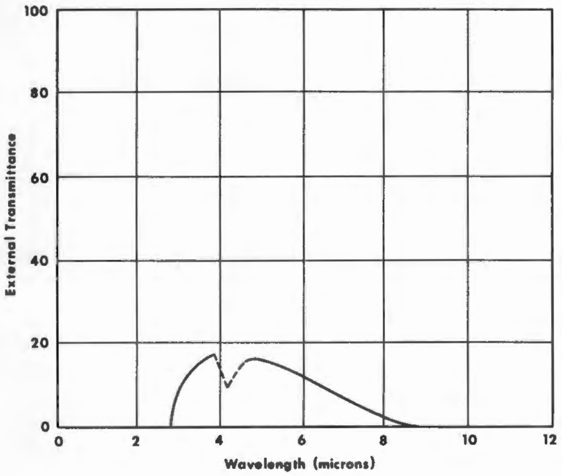


Fig. 4-41a. The transmission of lead sulfide; thickness unknown; no detectable impurity by x-ray analysis.

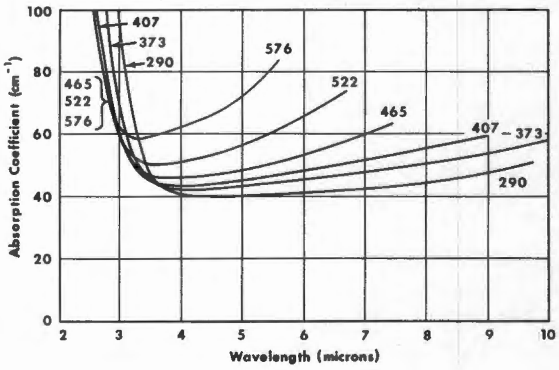


Fig. 4-41b. The absorption coefficient of n-type lead sulfide for several temperatures; temperatures are given in °K; purity unknown.

42. Lead Selenide (PbSe)

Composition

Single crystal or thin film. Can be grown by the Bridgman-Stockbarger technique in the absence of oxygen. Has a gray metallic appearance and an optical energy gap of 0.5 ev.

Molecular Weight

286.17

Specific Gravity

8.10 at 15°C
(*HCP*, p. 547)

Crystal Class

Cubic, sodium chloride structure.
(R. A. Smith, *Phil. Mag. Suppl.*, Vol. 2, p. 321, 1953)

Transmission

Long wavelength limit	7 μ
Short wavelength limit	5 μ

The absorption of p-type lead selenide at several temperatures is illustrated in Fig. 4-42.
(Adapted from A. F. Gibson, *Proc. Phys. Soc.*, Vol. 65B, p. 378, 1952)

Reflection Loss

56.8% for two surfaces, at a wavelength of 2 μ.

Refractive Index

Values of refractive index for surfaces prepared by different polishing techniques and for cleavage faces have been measured. Also, the real and imaginary parts of the dielectric constant are given by D. G. Avery, *Proc. Phys. Soc.*, Vol. 66B, pp. 134–140, 1953. He shows that the index of refraction varies from about 3.5 to 4.5 in the region of 1.0 to 2.2 μ and from 4.5 to 4.6 in the region of 2.2 μ to 3.5μ .

Dispersion

Dielectric Constant

Melting Temperature

1065°C
(*HCP*, p. 547)

Thermal Conductivity

100 × 10^{-4} cal/(cm sec C°)
(*AIPH*, p. 4–76)

Thermal Expansion

Specific Heat

Hardness

Solubility

Insoluble

Elastic Moduli

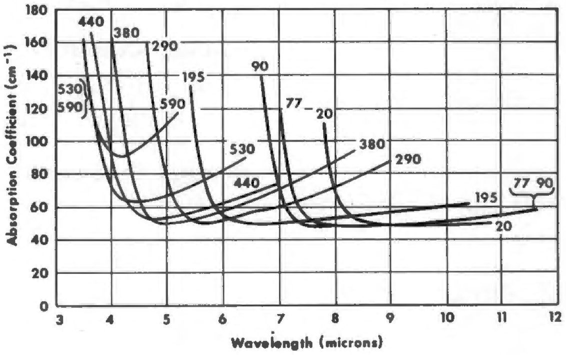


Fig. 4-42. The absorption coefficient of lead selenide for several temperatures; temperatures are given in °K; thickness, 0.68 mm; purity unknown.

43. Lead Telluride (PbTe)

Composition

Synthetic single crystal or thin film. The material has a metallic appearance, can be grown by the Bridgman-Stockbarger method, and has an optical energy gap of 0.6 ev.

(R. A. Smith, *Phil. Mag. Suppl.*, Vol. 2, p. 321, 1953)

Molecular Weight

334.82

Specific Gravity

8.16

(*HCP*, p. 547)

Crystal Class

Cubic; sodium chloride structure.

Transmission

Long wavelength limit 7 μ

Short wavelength limit 4 μ

The transmission of lead telluride is illustrated in Fig. 4-43.

(M. A. Clark and R. J. Cashman, *Phys. Rev.*, Vol. 85, p. 1043, 1952)

The absorption coefficient for several temperatures is plotted by A. F. Gibson, *Proc. Phys. Soc.*, Vol. 65B, p. 383, 1952.

Reflection Loss

63% for two surfaces, at a wavelength of 2 μ.

Refractive Index

The refractive index obtained for surfaces with different polish has been reported. It varies from about 4.1 to 5.2 from 1.0 to 2.0 μ and from 5.2 to 5.3 from 2.0 to 3.5 μ.

(D. G. Avery, *Proc. Phys. Soc.*, Vol. 66B, p. 134, 1953)

Avery has also reported the real and imaginary parts of the dielectric constant in the same article. He reports the refractive index is 5.35 ± 0.10 at 3 μ.

Dispersion

Dielectric Constant

Melting Temperature

917°C

(*HCP*, p. 547)

Thermal Conductivity

120×10^{-4} cal/(cm sec C°)

(*AIPH*, p. 4–76)

Thermal Expansion

Specific Heat

Hardness

Solubility

Elastic Moduli

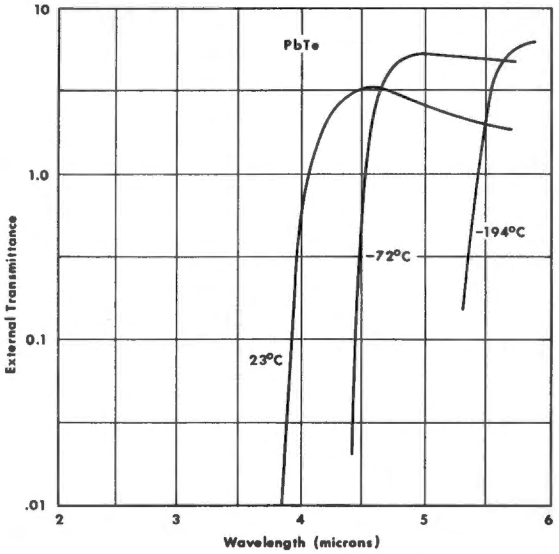


Fig. 4-43. The transmission of a lead telluride layer for three temperatures; thickness, 0.11 mm.

44. Cadmium Telluride (CdTe)

Composition

Single crystal; synthetic. The preparation of the crystal is somewhat difficult because of the high dissociation pressure of cadmium. Cadmium vapor "soaking" has been tried to obtain stoichiometry and maximum transmission.

(E. H. Lougher, Battelle Memorial Institute, private communication)

The energy gap is about 1.5 ev.

Molecular Weight

240.02

Specific Gravity

Crystal Class

Zinc blende; exhibits {110} cleavage.

Transmission

Long wavelength limit 15 μ
Short wavelength limit 0.9 μ

The transmission of cadmium telluride is about 63% from 2 to 15 μ for a 5-mm sample that has a purity corresponding to 10^{15} carriers/cc.

(T. S. Shilliday, Battelle Memorial Institute, private communication)

Reflection Loss

32% for two surfaces, at a wavelength of 10 μ.

Refractive Index

2.56 at 10 μ for a purity corresponding to 10^{15} carriers/cc.

(Shilliday, *above ref.*)

Dispersion

Dielectric Constant

11.0 for a sample with 5.5×10^{13} carriers/cc in a frequency range of 1 to 10^5 cps.

(D. deNobel and D. Hoffman, *Physica*, Vol. 22, p. 252, 1956)

6.55 for a sample with 10^{15} carriers/cc, calculated from the refractive index.

(Shilliday, *above ref.*)

Melting Temperature

Cadmium telluride has a simple phase diagram. One compound has a 1:1 ratio of cadmium to tellurium; its melting point is between 1041°C and 1050°C.

(J. Mellor, *A Comprehensive Treatment on Inorganic and Theoretical Chemistry,* Longmans, Green and Co., London, Vol. II, p. 51, 1931; *ICT II,* p. 430)

Thermal Conductivity

Thermal Expansion

4.5×10^{-6}/C° at 50°C.
5.9×10^{-6}/C° at 600°C.

(Shilliday, *above ref.*)

Specific Heat

Hardness

Vickers number 43.5 at room temperature.

(Shilliday, *above ref.*)

Solubility

Probably insoluble; no deterioration in transmittance and no observable corrosion of the sample after it had been exposed to 95% relative humidity at 49°C for 360 hr.

(Shilliday, *above ref.*)

Elastic Moduli

Modulus of rupture, 850 psi.

(Shilliday, *above ref.*)

Notes

Generally, the same cutting and polishing techniques used for silicon and germanium can be used for cadmium telluride.

45. Magnesium Fluoride (MgF_2)

NOTE: As this report was being published an important paper on the properties of single-crystal magnesium fluoride appeared (A. Duncanson and R. W. Stevenson, *Proc. Phys. Soc.*, Vol. 72, p. 1001–1006, 1958). Thus, this data sheet is out of place; it follows the semiconductors rather than being with the other dielectric crystals.

Composition

Single crystal, synthetic; faint violet color. The Stockbarger crystal-growing technique can be used. Vacuum drying is carried out for 24 to 48 hr before heating; the maximum furnace temperature should be kept only slightly above the melting point, otherwise the material hydrolyzes. The vacuum used to prepare the material described was 1–2 μ of Hg and the growth rate 1 mm/hr.

(Duncanson and Stevenson, *above ref.*)

Molecular Weight

62.32

Specific Gravity

3.1766 ± 0.0002 at 18°C.

(Duncanson and Stevenson, *above ref.*)

Crystal Class

SnO_2 type, tetragonal; cleaves parallel to *a*- and *c*-axes and conchoidally.

(Duncanson and Stevenson, *above ref.*)

Transmission

Long wavelength limit 7.5 μ

Short wavelength limit 0.11 μ

MgF_2 is quoted as transparent in the infrared to 7.5 μ with the absorption coefficient rising to 1 cm^{-1} at 7.3 μ. The transmission in the ultraviolet is good to about 0.11 μ; a 1.9-mm thick sample had an external transmittance of 7% at 0.11 μ.

(Duncanson and Stevenson, *above ref.*)

Reflection Loss

4.8% for two surfaces in the visible.

MgF_2 has application as a reststrahlen material with properties intermediate between those of LiF and NaF.

(Duncanson and Stevenson, *above ref.*)

Refractive Index

Values of refractive index between 0.4046 and 0.7065 μ are given for the ordinary and extraordinary rays in the reference of Duncanson and Stevenson. A few representative values are given below.

Wavelength (μ)	Refractive Index Ordinary Ray	Refractive Index Extraordinary Ray
0.404656	1.38359	1.39566
0.58937	1.37770	1.38950
0.706525	1.37599	1.38771

Temperature coefficient of refractive index:
0.19×10^{-5}/C° for the ordinary ray at 0.7065 μ

Dispersion

The reciprocal dispersions or nu-values are 105.4 for the ordinary ray and 104.4 for the extraordinary ray. Other values are given by Duncanson and Stevenson. They are obtained by differentiating the Hartmann formula.

Dielectric Constant

4.87 at frequencies between 9.5×10^4 and 4.2×10^7 cps measured parallel to the *c*-axis.

5.45 for the same frequency range measured perpendicular to the *c*-axis.

(Duncanson and Stevenson, *above ref.*)

Thermal Expansion

18.8×10^{-6}/C° parallel to the *c*-axis.

13.1×10^{-6}/C° perpendicular to the *c*-axis.

(Duncanson and Stevenson, *above ref.*)

Thermal Conductivity

Melting Temperature

1255 ± 3°C

(Duncanson and Stevenson, *above ref.*)

Solubility

0.0076 gm/100 gm water at 18°C

(*HCP*, p. 552)

Hardness

Elastic Moduli

Notes

Although good cleavages have occasionally been obtained, conchoidal fracture is more common. Ground surfaces have been polished on pitch laps with rouge, but beeswax with putty powder appears to give a higher polish more rapidly.

CHAPTER 5

GLASSES AND PLASTICS

Many plastics and some special glasses show substantial transmission in the infrared region. They may be selected for use in infrared instrumentation because of such considerations as lower cost and better availability in larger sizes than the single-crystal materials. Chapter 4 contains data sheets on several glasses (i.e., amorphous rather than crystalline materials) that are fairly well standardized. Other glasses are under development, but it did not seem practicable to treat them in Chapter 4 because definite data cannot yet be given for many of their properties. Thus they are discussed in a different manner in the present chapter. Plastics also are not amenable to the more detailed type of treatment and are included in this chapter.

Glasses

Most optical glasses transmit into the infrared only to a wavelength of about 2.7 μ and then a strong absorption sets in. In general, these glasses are not useful at longer wavelengths. Thus they are applicable only as far as the near-infrared region, and even for some equipments using lead sulfide cells, their cut-off comes at so short a wavelength that valuable energy is lost by absorption. There are special glasses, such as Corning No. 0160, that do not demonstrate a deep "water band" absorption at 2.8 μ and have a slower drop-off of transmission in the region 3 to 4 μ, as shown in Figure 5-1; such a glass may be preferred for windows in near-infrared equipments.

Although fused silica (also called fused quartz and quartz glass) is really a glass and not a crystalline material, it is in such common use that its properties are given in detail in Chapter 4, along with the other major infrared optical materials. Fused silica can be used throughout the near infrared, but only partially into the intermediate infrared, since its useful transmission limit in a 2-mm thickness is at about 4.5 μ, whereas intermediate-infrared equipments should possess good transmission to 5.5 or preferably 6 μ. Corning's Vycor (No. 7900) is a special high-silica glass, and its optical grade gives a performance comparable to that of fused silica out to a wavelength of 3.3 μ (see Figure 5-1). In considering the selection of a glass for a window or lens material, it should be kept in mind that in order to avoid possible troubles due to reradiation from heated optical elements to the detector, the transmission region of any material from which transmitting components are made should extend beyond the wavelength bandpass of the instrument, at both ends of the spectrum. Thus the selection of a glass which may cut off at around 5 μ is open to question, since the radiation detector used in the system may very well be sensitive out to 6 μ or beyond, although the long wavelength limit of the system may be determined by some other factor.

There are some special silicate glasses which recover transmission at wavelengths beyond the 2.8 μ absorption band and give a reduced transmission out to about 5 μ; this performance is illustrated by the transmission curve in Figure 5-1 for a lead silicate glass, Corning No. 186sJ. Such glasses should be used with caution, however, because of the possibility of reradiation associated with the wide absorption band centered at about 3 μ.

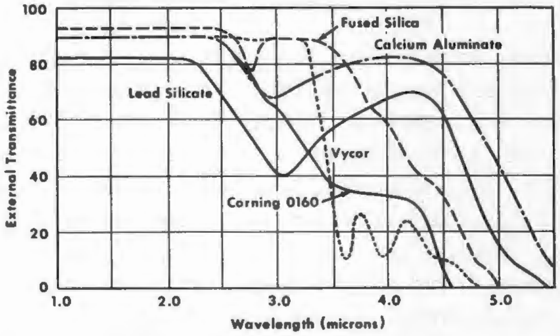


Fig. 5-1. The transmission of several infrared-transmitting glasses; thickness, 2 mm.

In order to achieve transmission beyond 4.5 μ, glass makers have necessarily investigated glasses which do not contain silica. An example is the Eastman Kodak Company glass EK-25, developed 10 years ago, which transmits to 5.5 μ. It should be noted again that certain outstanding examples of nonsilica glasses, such as arsenic trisulfide and both amorphous selenium and arsenic-modified selenium, are treated in Chapter 4 and hence are not discussed here.

No attempt will be made in this short treatment to give an exhaustive account of the many efforts that have been made to produce suitable infrared-transmitting glasses. Rather, reference will be made to major laboratories where this work has been done, and specific comments will be given only on the materials which seem to show the most promise. In this connection, a good reference is "ERDL"—the report of the conference on infrared optical materials, filters, and films held at Fort Belvoir on 10 February 1955.

Work has been under way for a number of years at the National Bureau of Standards to produce glasses transmitting into the infrared. Baria-titania-silica glasses useful to 4.5 μ were developed, perhaps with lanthanum oxide or other oxides added. Calcium aluminate and other unusual glasses were experimented with. At the Ohio State University, Dr. H. H. Blau has also worked along these lines for a number of years. His germanium dioxide and lead tellurate glasses have been the most promising, with cut-offs at about 6 μ. In view of the relatively high cost of germanium, tellurium glasses have been given more attention. A ternary-system glass containing tellurium dioxide, aluminum dioxide, and barium fluoride transmits to 6 μ. It is yellow or orange, has a softening point of around 450°C, polishes well, but is soft enough to be scratched with a knife and thus may be satisfactory for lenses but not for sealing windows. Among possibilities that do not look too promising are vitreous germanium sulfide, which transmits to 9 μ and is insoluble; arsenic triselenide (As_2Se_5), which transmits to 12 μ; and the antimony oxide glass developed at the Battelle Memorial Institute. The last-named is a ternary glass with Sb_2O_3 and Al_2O_3 as the chief components, along with Na_2O, K_2O, and perhaps other oxides. The best samples show partial absorption at 3 μ, followed by a transmittance of around 70% which drops off sharply between 5 and 6 μ to opacity at about 6.2 μ.

Calcium aluminate glass now seems to be the most promising possibility for the intermediate infrared region, if one of the more conventional materials is not chosen. Work has gone on in various laboratories in this country and abroad on the development of this glass. The basic components are calcium oxide and aluminum oxide, but additional components, usually alkali oxides, are added in order to give a more workable and stable glass, to control melting temperature, and to increase resistance to devitrification. It would be out of place to go into details here; the interested reader is referred to a series of reports prepared by the Bausch and Lomb Optical Company under an Air Force research and development contract (see Chapter 6 references). Transmission curves of calcium aluminate glasses prepared at the National Bureau of Standards, Bausch and Lomb, and the Corning Glass Works have been examined. A "typical" curve is given in Figure 5-1, which, however, shows relatively small absorption in the water band at 3 μ. Note that the transmission recovers by about 3.5 μ, but to a lower value than might be hoped. Efforts have been exerted to free the glass from water absorption so as to give it a smooth transmission function from 2.5 μ to beyond 4 μ. A laborious but successful method that has been used is to break up the glass, or even grind it to a powder, and then heat it in an atmosphere of dry gas or in a vacuum furnace so as to drive off as much water vapor as possible. The powder is then melted and recast carefully, and it is found that the water absorption has largely disappeared.

Some samples of calcium aluminate glass are yellowish or even dark brown in color, perhaps because of iron oxide content; others are crystal clear. Durability of the polished surface is not in general as good as for optical glasses — both liquid water and water vapor cause some deterioration. Surfaces can be protected by chemical treatment or by evaporated coatings of magnesium fluoride or silicon monoxide. If the evaporated coatings are of the proper quarter-wavelength thickness, surface reflection is reduced and the external transmittance of the sample is increased. The glasses can not be reheated and reformed as in the molding process, so the desired component shapes must be cast from the melt or ground from blanks.

The physical and chemical properties of calcium aluminate glass are in general as satisfactory as those of most of its competitors; some typical data are shown in Table 5-1. These are averages of data reported by Corning for glass No. 9751 and by Bausch and Lomb for glasses Nos. RIR-10, RIR-11, and RIR-12.

TABLE 5-1. Approximate Values of Some Physical Properties of Typical Calcium Aluminate Glasses

Specific gravity	~3
Refractive index	1.63 at 2 μ
Nu-value (reciprocal dispersion)	46
Dielectric constant	9.6 at 8.6 × 10^9 cps at room temperature
Softening temperature	~900°C
Thermal conductivity	3.2 × 10^{-3} cal/(cm sec C°) at 25°C
Thermal expansion coefficient	8.3 × 10^{-6}/C° in a temperature range from 25°C to 300°C
Specific heat	0.18 at 25°C
Hardness	Knoop number ~600
Young's modulus	15.2 × 10^6 psi at room temperature
Torsion (shear) modulus	5.91 × 10^6 psi at room temperature
Poisson's ratio	0.287 at room temperature

Bausch and Lomb has announced two additional infrared glasses, RIR-2 and RIR-20; it is believed that these are *not* calcium aluminate glasses. The refractive index for these glasses at a wavelength of 2 μ is 1.75 for RIR-2 and 1.82 for RIR-20. Neither glass shows deep absorption at 3 μ; rather, the external transmittance (of a 2-mm sample) drops from about 90% at 2 μ to between 70 and 80% in the region 3 to 4 μ. The transmittance of RIR-2 drops sharply at 4.5 μ to 0 at 5 μ while that of RIR-20 drops more slowly from about 5 μ to 0 at 6 μ. The manufacturer states that these glasses can be treated in the normal manner in casting, reheating, and molding, except that their softening points are higher than those of ordinary optical glasses. Also, they do not exhibit the surface deterioration tendencies shown by calcium aluminate glass.

Plastics

Plastic materials have been used only to a limited extent in infrared instrumentation applications. Perhaps their most attractive feature is that they are available in large-area pieces, which is in contradistinction to the situation for the single-crystal materials. Thus, plastics can be used for protecting radiometers and spectrometers from atmospheric effects, and perhaps as windows for nonevacuated detector cells. Their use as windows or irdomes is limited, however, by the fact that in thicknesses satisfactory for nonsupported optical elements they usually do not exhibit sufficient transparency. To put it another way, very thin films of many plastics show attractive infrared transmission properties, but in thicknesses of a millimeter or more their transmission is much less suitable. Still, one can consider using rather thin plastic sheets and supporting them by a wire mesh or a suitable metal spider so as to retain the desired figure and provide the necessary mechanical strength. The small, partial occlusion of the field of view caused by these metal parts is usually not important, especially since the mesh or spider is located in an out-of-focus position in the optical system. That is, the spider or mesh must be located so that a false signal is not generated by scanning or chopping motions.

Among the common plastics which may well be considered for infrared applications are polyethylene and polymethylmethacrylate (available commercially as Lucite or Plexiglas). Transmission curves of these two materials are shown in Figures 5-2 and 5-3. These curves are in fact representative of the transmission of thin films of many different plastics.

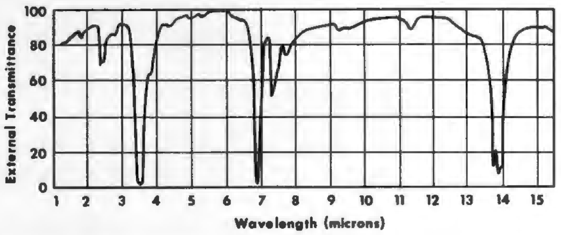


Fig. 5-2. The transmission of polyethylene; thickness, 0.1 mm.

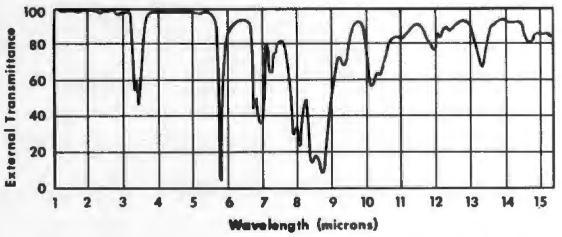


Fig. 5-3. The transmission of Plexiglas or Lucite (polymethylmethacrylate); thickness, 0.02 mm.

Except for narrow bands, where only a small amount of energy is absorbed, and for broader bands in some materials, the transmission is seen to be relatively good. But for thicker samples, the regions of small absorption deepen rapidly and widen considerably, so that the absorption becomes so great that the material may no longer be satisfactory for the intended use.

The very nature of plastics, which can be thought of as consisting of chains of molecules and molecular groups, indicates that these absorption bands will always be present. Indeed, these bands are used to identify organic materials by spectroscopic methods; each absorption band is representative of a particular molecular bond or configuration. An excellent discussion of these identification techniques was given by Harry H. Hausdorff at the Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy in March 1951. His paper, "Analysis of Polymers by Infrared Spectroscopy," has been published by and is available from the Perkin-Elmer Corporation of Norwalk, Conn.; it is identified as IR957-107. Table 5-2, derived from Hausdorff's paper, shows the wavelengths at which various molecular bonds and groups absorb infrared radiation — these are the characteristic absorption bands of the bonds or groups noted.

TABLE 5-2. Wavelengths of Characteristic Absorption Bands

Molecular Bond or Group	Wavelengths of Absorption (μ)
O-H	2.8
N-H	3.03, 6.12, 6.46
C-H	3.4, 6.81
Carbonyl	5.75
Methyl	7.26, 7.71
Ester	8, 9.74
C-O	9 (broad), 13.47 to 14.20
C-Cl	14 to 15

Another plastic which has found some use as a window material in infrared instruments is Kel-F, a polymer of trifluorchloroethylene. It can be produced in large quantities and is easy to shape and mount. Kel-F is preformed and then quenched to eliminate the milky appearance; if it is subsequently annealed it loses transmission and again becomes milky. It is difficult to manufacture with suitably high transmission in thickness greater than about 0.25 in. Kel-F has a low thermal conductivity; when it is quenched to improve transmission it may therefore crack. A further difficulty is that refractive index may vary throughout a sample, sometimes as a gradient. The transmittances of two different thicknesses of Kel-F are shown in Figure 5-4.

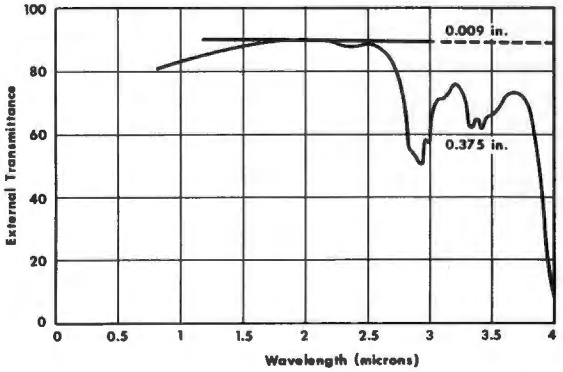


Fig. 5-4. The transmission of Kel-F for two thicknesses.

Kel-F exhibits many of the advantages and disadvantages for optical use that are shown by most plastics. In summary, the advantages are availability in a variety of shapes and sizes, and the convenience and adaptability of processing techniques; the disadvantages are poor transmission in suitable thicknesses, a tendency to cold flow and deform, and low melting temperature.

CHAPTER 6

BIBLIOGRAPHY

During the preparation of this report it was necessary to make extensive searches of the technical and scientific literature. Frequent reference is made, especially in the data sheets of Chapter 4, to scientific journals, handbooks, and other standard reference works. References are also made to the authors' personal notes and to private communications betwen the authors and the several persons who kindly supplied unpublished data and other information.

In addition to the references cited specifically, there is a large body of descriptive matter which bears at least partially on optical materials. References of this sort are included in the present chapter and are suggested for background reading and as sources of more general information in the field. Also, there exists a large and continually growing fund of information in what might be called the borderline scientific literature, that is, the progress, technical, and special reports from contractors to government agencies. These are not in the open scientific literature and are not readily available to all who may wish to see them, even though they may carry no security classification. The major problem for the new investigator is simply to become aware of the existence of this large body of information and of specific items therein which may be of great assistance to him in his work. In order to aid the infrared worker along these lines, appropriate reports in this borderline category are also listed in the bibliography that follows. It should be noted that this bibliography specifically excludes the standard scientific literature; the reader is referred to such bibliographic aids as *Chemical Abstracts* and *Physics Abstracts* for items that are to be found therein. The entries in the bibliography comprise several general reference works, followed by unclassified reports which pertain particularly to optical materials for infrared use.

For further information about any items in the bibliography, or classified reports, the Infrared Information and Analysis Center at The University of Michigan may be contacted.

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