FOREWORD

This study was initiated by the Biophysics Laboratory, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. The research was conducted by the Electron Device Laboratory, The Ohio State University Research Foundation, Columbus, Ohio, under Contract No. AF 33(616)-8384, (OSU Research Foundation Project No. 1287). The investigators were Mr. K. K. Knaell and Mr. James Hanlon and the research was supervised for the Electron Device Laboratory by Professor M. O. Thurston. Captain G. Potor, Jr., MC, of the Biophysics Laboratory, was the contract monitor for 6570th Aerospace Medical Research Laboratories. The work was performed in support of Project No. 7222, "Biophysics in Flight," Task No. 722203, "Bioinstrumentation." The research sponsored by the contract was started in July 1961 and completed in February 1963.

ABSTRACT

During a routine investigation of transistor behavior certain silicon-grown junction transistors were discovered which manifested unusually high short circuit current gains, h_{fe}. The present investigation was made to determine the basic nature of this h_{fe} and to develop an h_{fe} transistor. Following several unsuccessful attempts at producing devices designed to display h_{fe}, further measurements were made on already existing transistors. These measurements led to several observations unexplainable in the light of the original model; therefore, additional measurements were performed. These measurements gave more insight into the transistor and explained some of the characteristics of its behavior in terms of its high h_{fe}. Attention was then concentrated on the physical structure of the transistor and experiments were performed to alter the structure in an attempt to learn the mechanism causing high h_{fe}. Adsorbed moisture had a tremendously beneficial effect on the dynamic current gain of the device and the high h_{fe} was a surface effect caused by this adsorbed moisture. Finally, a high-gain transistor was produced from a normal unit making use of this information. The amount of high gain of this transistor was variable within limits and the behavior appeared similar to that of the unusual units originally discovered. This transistor will simplify circuitry and will greatly broaden transistor application to the registry of physiological signals.

PUBLICATION REVIEW

This technical documentary report is approved.

J. W. HEIM
Technical Director
Biophysics Laboratory

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I. INTRODUCTION

The high input impedance of a number of special npn silicon-grown junction, diffused-base transistors, in the emitter follower circuit configuration has been investigated by Dandl and May,[1] Potor,[2] McConnell,[3] and Hanlon.[4]

This has been carried to the point that the circuit behavior of a unit is well understood in terms of the h-parameter set for the particular device. In addition, frequency-sensitive kinks in the alternating-current diode characteristics of the emitter and collector junctions have been observed in these units. Units exhibiting these characteristics have been Texas Instrument 2N332 and 2N338 transistors.

Measurements and observations have been made which describe more fully the nature of the high-gain devices. The abnormally high gains are observed only at collector currents less than a microampere. The high-gain units are indistinguishable from normal transistors of the same type under rated operation conditions.

The purpose of this investigation was to develop a high gain, high impedance (10^9 ohm) transistor to simplify circuitry and to broaden transistor application to the registry of physiological signals.

II. INITIAL CONSIDERATIONS

A. RELATION OF CURRENT GAIN TO INPUT IMPEDANCE

The input impedance of an emitter-follower (grounded collector) amplifier is given by:

$$R_{in} = r_b + \frac{\beta + 1 - \dfrac{\beta/r_c}{1/r_c + 1/R_s}}{\dfrac{1}{r_e + R_e} + \dfrac{1}{r_c} - \dfrac{1/r_c^2}{\dfrac{1}{r_c} + \dfrac{1}{R_s}}} \qquad (1)$$

where the quantities are as given in Fig. 1.

Since $r_c \gg r_e + R_e$, this reduces, when $r_c \gg R_s$, to

$$R_{in} \doteq r_b + (\beta + 1)(r_e + R_e). \tag{2}$$

If further: $(B + 1)(r_e + R_e) \gg r_b$ and $\beta \gg 1$

$$R_{in} \doteq \beta(r_e + R_e). \tag{3}$$

Hanlon[4] gives values of $r_e \approx 20K$ to $100K$. If $R_e = 10^6\,\Omega$ and $\beta = 200$,

$$\begin{aligned} R_{in} &\doteq \beta R_e \\ &= 200 \times 10^6\,\Omega\,. \end{aligned} \tag{4}$$

Values for β slightly higher than 200 have been measured for the transistors having high-input impendance for biases in the range $I_c = 1 \times 10^{-6}$ amperes. It is seen from Eq. (4) that the current gain, β, of the transistor is of primary importance in the high-input impendance effect. It may also occur that r_e in Eq. (3) is significant in comparison to R_e in special cases. However, the form of Eq. (4) suggested that attention be concentrated on the explanation of high β.

B. PROPOSED MODEL

The original mechanism proposed to explain the high β at low currents is described below. A grown-diffused transistor has an impurity distribution approximately as shown in Fig. 2. At very low injection levels, the width of the emitter depletion layer is very nearly equal to its zero-bias value and may extend approximately to the region of positive slope (point A in Fig. 2). At higher forward biases the layer becomes narrower and moves to a point such as β in the figure. The region of positive slope is a region where electrons injected into the base are accelerated towards the collector junction by the built-in field. We thus have a situation where, to the left of the minimum, electrons are injected into a region having a retarding field which varies with bias. Although Kroemer,[5] Moll and Ross,[6] and Kennedy and Murley[7] have shown that the base transport factor varies only slightly with built-in field, there is reason to believe that the injection efficiency is more strongly influenced.[8] Qualitatively, the tendency would be for the emitter efficiency to improve as the forward bias is reduced. It was not found possible, however, to predict quantitatively as large as effect as that

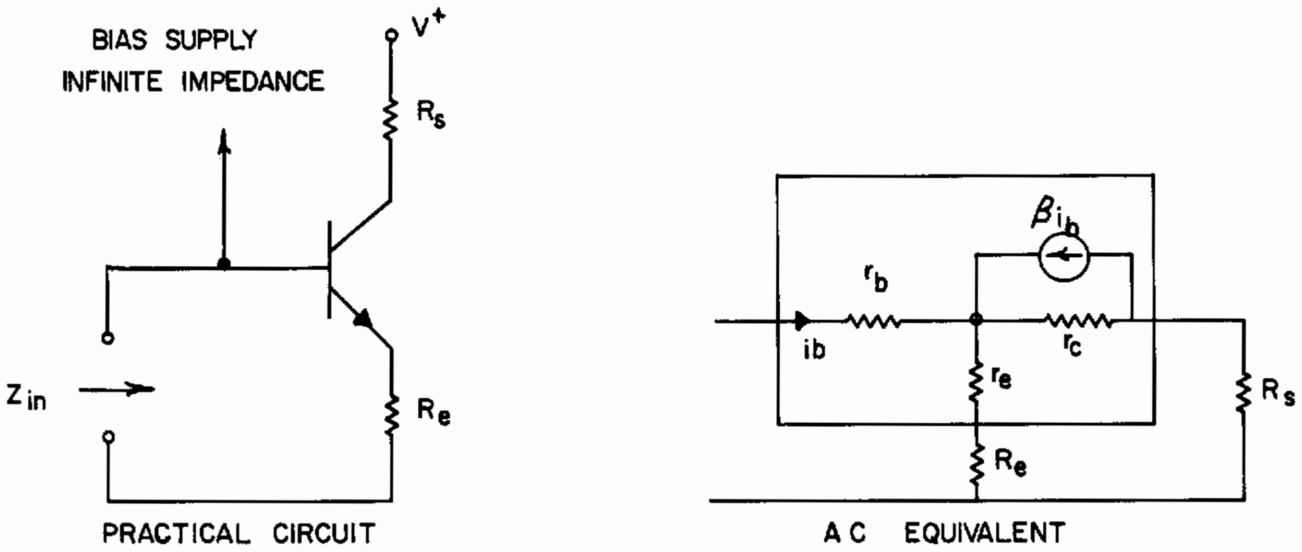

Fig. 1. Input impedance of an emitter follower

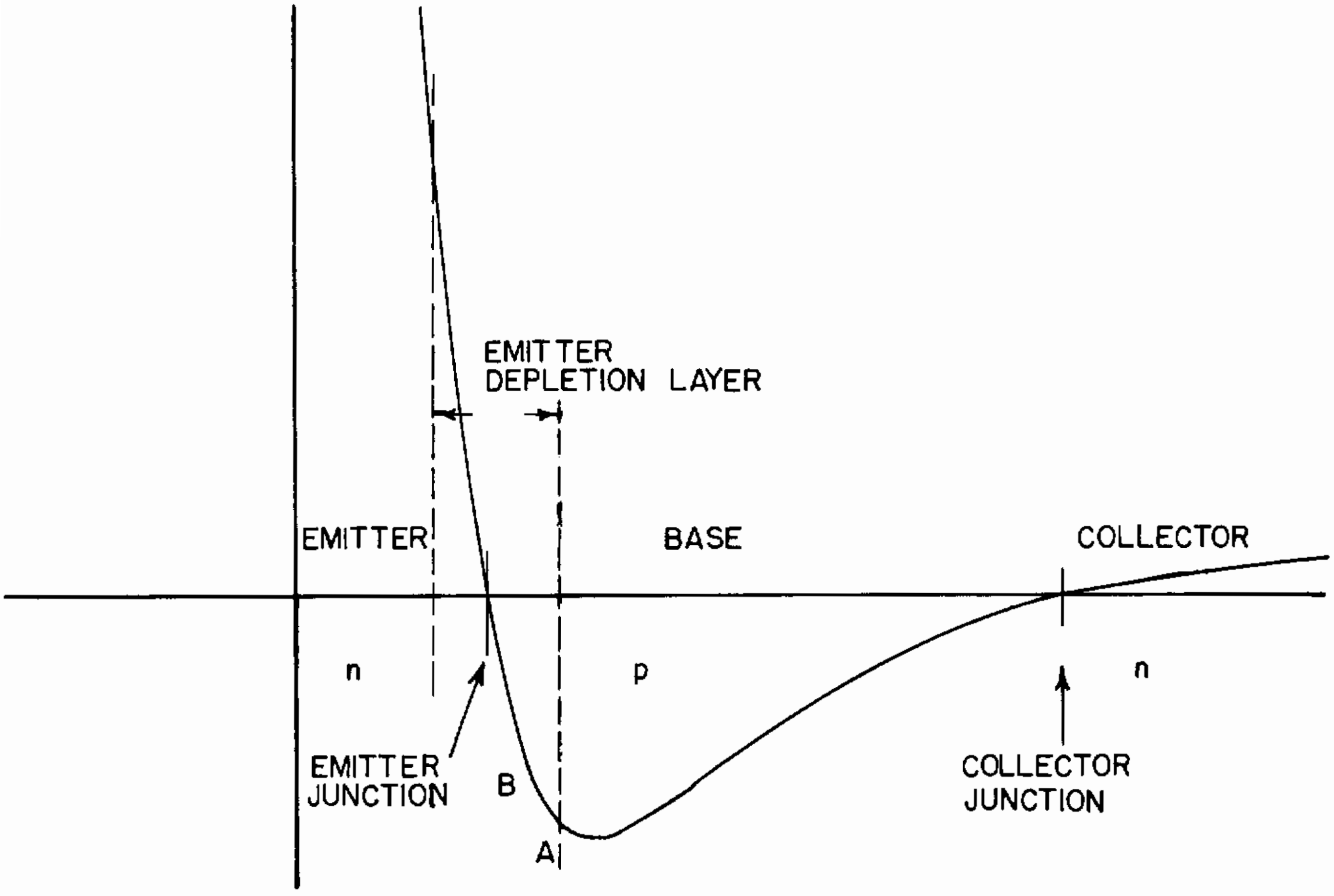

Fig. 2. Ideal impurity distribution in a grown-diffused transistor

observed experimentally. It was decided to attempt to fabricate a few devices with exaggerated impurity distributions in order to see whether substantially increased gains at low bias could be realized.

C. FABRICATION

There appears to be no measurement which could be made easily to determine directly whether this mechanism could account for the high gain. The obvious approach of measuring the base transit time, difficult even at high injection levels, is out of the question at these bias levels.[9,10] This is because of the high impedances present when low bias levels are used, and the necessity of making phase shift determinations at radio frequency where any stray capacitance would not be tolerable.

It was necessary, therefore, to proceed directly to fabricate transistors, varying the emitter junction geometry to obtain the required conditions of the model.

It was decided to produce an alloy-diffused, silicon, planar device. Both npn and pnp units were to be investigated. The geometry proposed was as shown in Fig. 3. A vacuum evaporator and masking arrangement (Fig. 4) was assembled for the emitter junction fabrication process.

The photo resist-oxide masking technique was used in collector junction formation. Figure 4 shows the oxide-masked silicon before diffusion, the evaporation mask, and positioning jig all of which could be heated to 300°C and subjected to electron bombardment for cleaning.[11] In addition, a strip heater was arranged inside the vacuum system so that the emitter alloying could be accomplished under strict ambient control.

The junction parameters to be sought are listed below Ci pnp transistor was first attempted.

Bulk material resistivity:	2 Ω cm. p-type
Depth of junction:	3.47×10^{-4} cm
Surface concentration:	
Thickness of aluminum evaporation: (1% boron doped)	10,000 A
Alloyed depth into silicon:	3000 - 8000 A
Base width:	2.67 - 3.17μ
Avalanche voltage:	$\sim$ 30 volts

The first attempts produced nonrectifying emitters. A method, therefore, had to be obtained to reduce the surface concentration of the diffused layer.

The predeposit method of diffusion was adopted for which the following results were obtained. A 1% source, closed box predeposit was used.

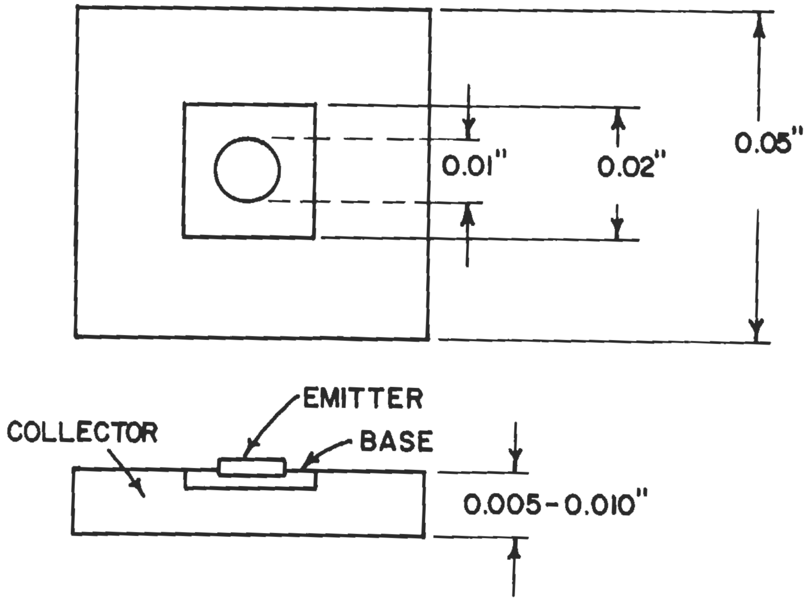

Fig. 3. Alloy-diffused device

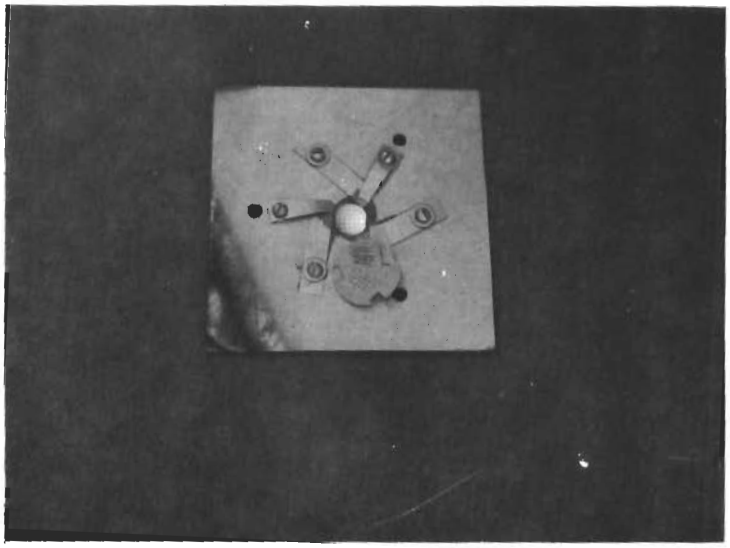

Fig. 4. Evaporation mask, sample holder, and oxide-masked silicon for emitter deposition

Table I. Results of Predeposit Method of Diffusion

	No. 1	No. 2	No. 3	No. 4
Predeposit:				
Time in heat zone	14 min.	5 min.	7 min.	3 min.
Temp. of heat zone before insertion of boat	1250°C	1194°C	1189°C	1176
Surface resistivity	65 Ω/□			
Junction depth	1.01μ			
Surface concentration	4.8 x 10^{19}			
Post diffusion:				
Time in heat zone	90 min.	60 min.	60 min.	60 min.
Temp. before insertion of boat	1250°C	1213°C	1168°C	1187°C
Surface resistivity	125 Ω/□	43.8 Ω/□	26.4 Ω/□	498 Ω/□
Junction depth	8.74μ	4.33μ	3.3μ	2.0μ
Surface concentration	1.5 x 10^{19}(cc-1)	8 x 10^{18}(cc-1)	1.5 x 10^{19}	3 x 10^{17} Ω /

Transistors were fabricated with the No. 4 slice (above). However, these also formed poor emitters. An etching sequence was performed with 10:1 HNO_3-HF while the parameters were periodically checked. No etch treatment was found to improve the emitter diode characteristics. At this point it was decided to divide the work into two efforts: (a) the further development of fabrication techniques and the directed effort to produce an assortment of transistors with a wide range of device parameters; and (b) extension of the previous measurements on the already existing devices, the object of which was (1) to set up equipment and establish a qualifying test for a high gain transistor if obtained, and (2) to learn more about the behavior of the high-gain units if possible.

The measurements which followed were of immediate significance.

III. ADDITIONAL MEASUREMENTS ON ENCAPSULATED UNITS

A. TERMINOLOGY

For the sake of clarity and brevity the following terms, of which subsequent use will be made, will now be explained:

Transistor action - This term specifies the process in which (in the case of an npn transistor) electrons are emitted at one junction and collected at another where the resulting charge causes a change in voltage or a current flow to occur.

Collector action - Known in the literature as extraction, this term applies to the removal of minority carriers from a region by a d pletion layer with suitable boundary conditions. This causes the lowering of minority carrier concentration within a short distance of the depletion layer.

Upsweep of Characteristic - This term will be used when an alterating current is used to sweep through a diode characteristic. It refers to that part of the characteristic in which the voltage is increasing in the forward bias direction thereby causing the forward diode current to increase. Conversely, the downsweep is the return trace during which the forward bias is decreasing.

Kink - This term is used to describe the anomalous curvature in the upsweep of the diode characteristic found in high-gain transistors.

B. TECHNIQUE OF MEASUREMENT

As was mentioned, the impedance levels occurring in the transistor at low biases, and the low level of the signals themselves, make some measurements difficult. The use of shielded cable is somewhat unsatisfactory because of the large loading produced by the shunt capacitance of such cables. It was found advantageous, therefore, to use battery-powered cathode follower tubes contained inside an iron box as impedance transformers to lower the impedance level in the external circuitry. This also had the advantage that the grid produced very slight loading at the point where it was attached. The loading in this case consisted of less than the 5 μμf grid capacitance and the very small positive ion grid current of the tube. This technique made several observations possible over a considerable frequency range with accurate results.*

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* In one case the grid current of the tube produced misleading results. When the grid was connected to a junction otherwise floating, the current was enough in some cases to change the voltage of the junction in the reverse direction. This only occurred with some normal β transistors and at the time was thought to be due to other reasons.

C. DIODE CHARACTERISTICS

The first experiment on commercial units was to display the diode characteristics of the emitter and collector junctions using the cathode follower technique. The circuit used is shown in Fig. 5 where the diode characteristic is shown on the scope with diode voltage horizontal and current vertical. R_b was small enough in most cases to produce a negligible voltage drop. The circuit was calibrated by applying a square wave at the grids. The freedom from phase shift obtained in this circuit was demonstrated by the substitution of a 10-megolum resistor for the test junction at terminals e-b. At 3000 cps the linear resistor characteristic was just beginning to show reactive current component, indicated by the separation of the increasing and decreasing trace into a reactive ellipse. The diode characteristics obtained are similar to those observed by Hanlon. Curves were obtained as shown in Fig. 6. At this time the following significant observations were recorded for which no explanation could immediately be found.

1. The kinks occur in the upsweep of the characteristic only.
2. The kink is frequency dependent, becoming greater and moving up the diode characteristic with increasing frequency.
3. The characteristic between the collector and base leads shows the kink to a greater degree than that between the emitter and base leads.
4. The kink could not be obtained in any case except where the third lead was left floating, i.e., measuring the diode characteristic of the following lead combinations produced no kink:

    a. from base lead to the connected emitter and collector leads,
    b. from collector lead to the connected emitter base leads,
    c. from emitter lead to the connected collector base leads.
    d. from collector lead to base lead with 10^6 ohms between emitter and base lead, and
    e. from emitter to base lead with 10^6 ohms between collector and base lead.

The circuit was next rearranged by placing the grid of tube V_2 at point c so that the potential of the floating junction was displayed along with the diode current. When both these characteristics were displayed simultaneously results were obtained as shown in Fig. 7. The horizontal scale on both curves is voltage across the diode. The vertical scale on the upper curve is diode current, and the vertical scale for the lower curve is the floating junction voltage. The dots on all the curves are the zeros of their respective scales. Curves are shown for the emitter-base diode and collector-base diode. Notes were made of the following facts:

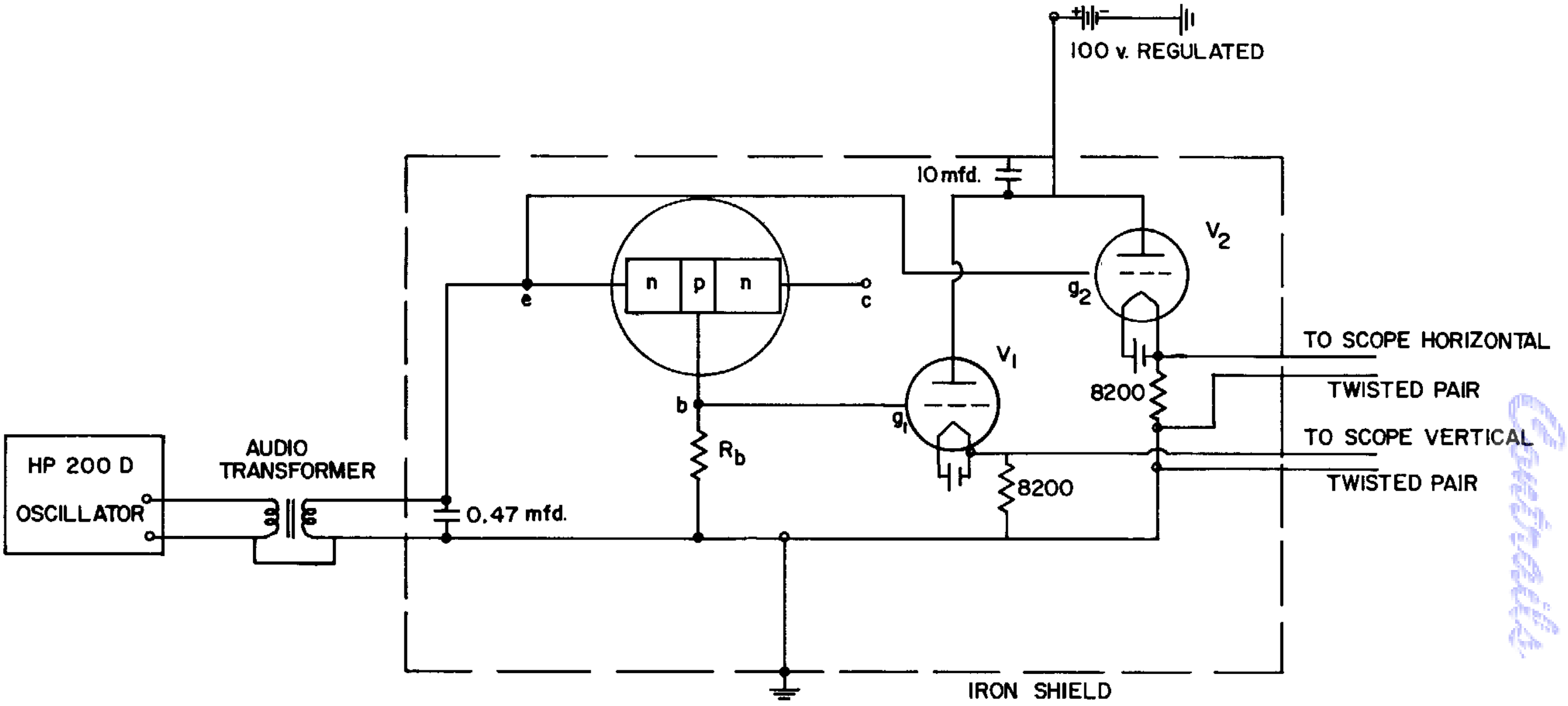
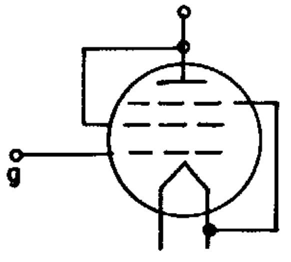
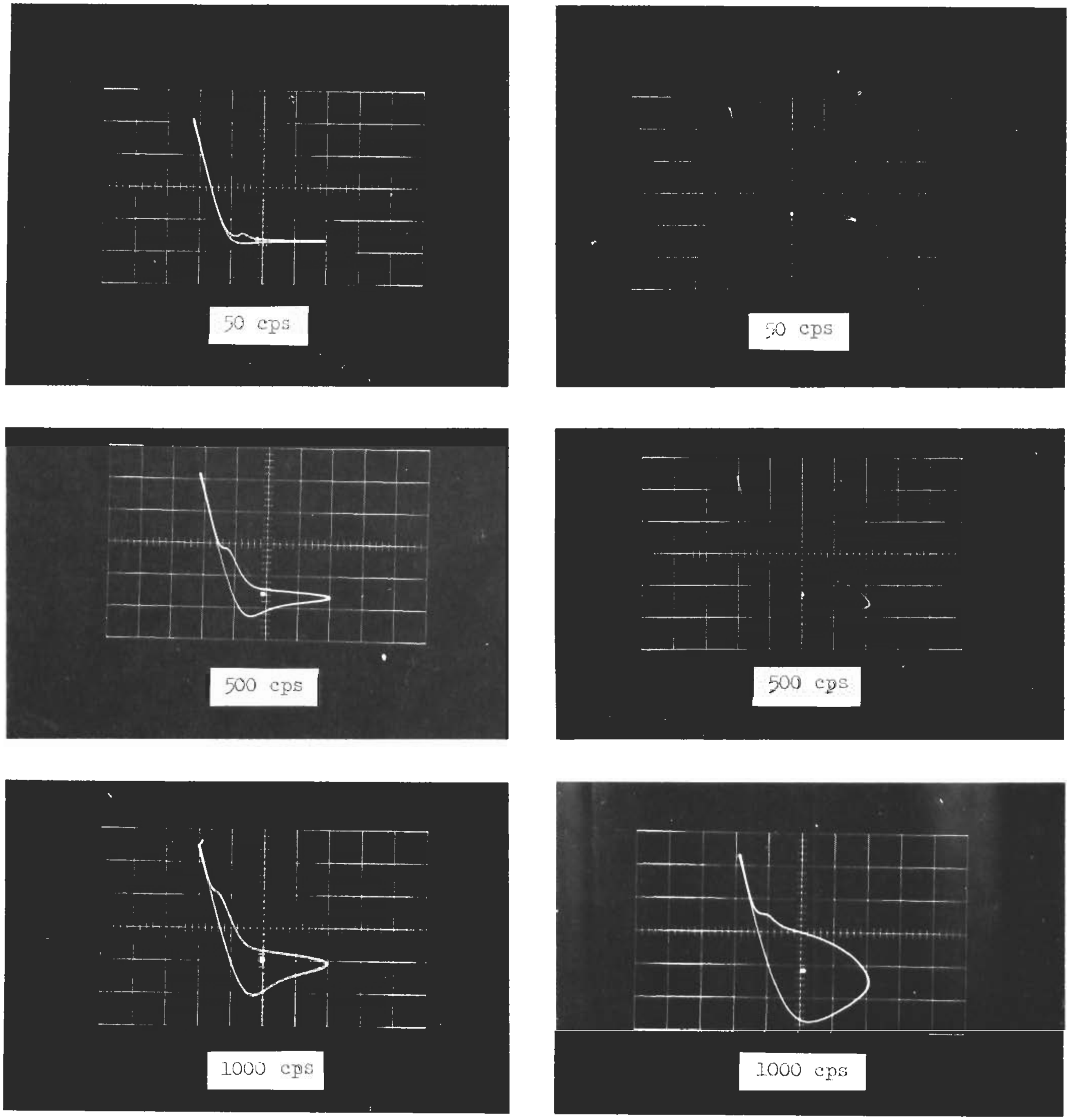


Fig. 5. Diode curve tracer



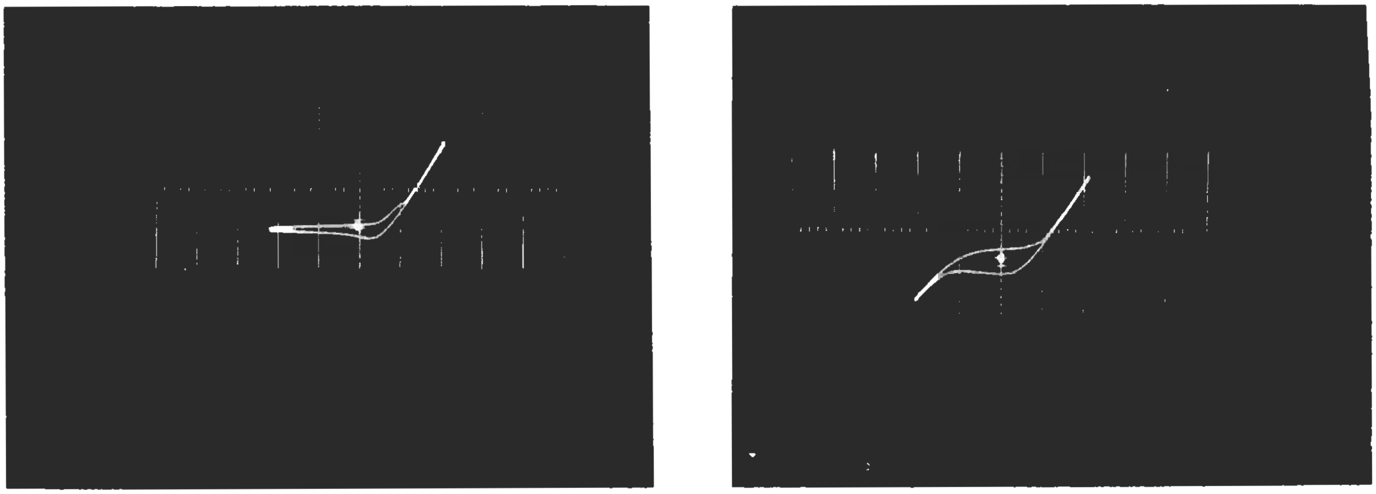
v_1 and v_2 (3S4)
pentode connection



Collector-Base Diode
Emitter Floating

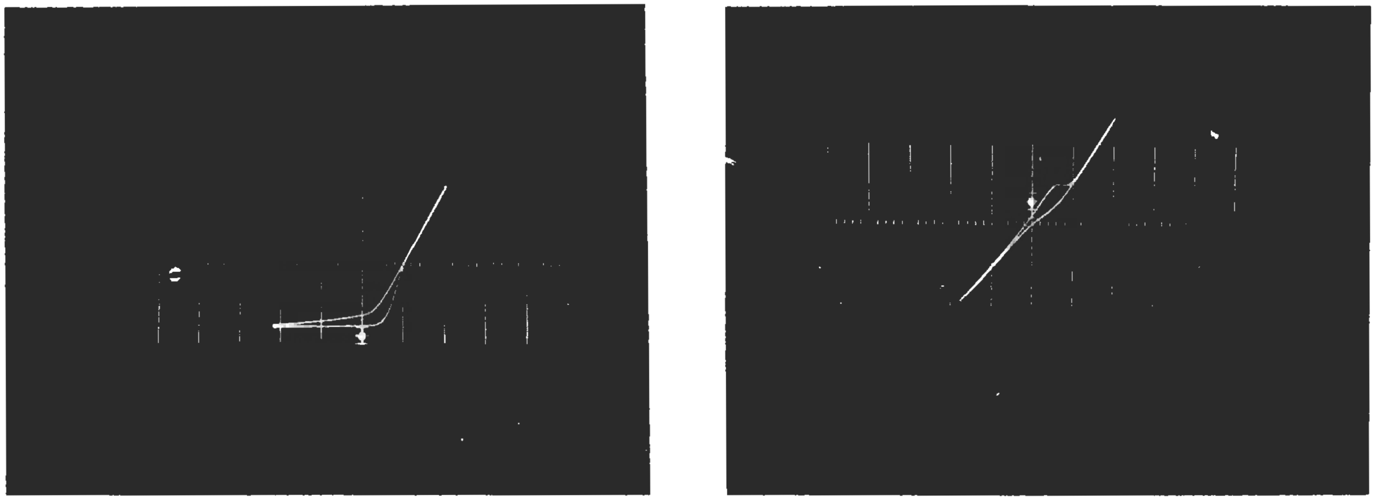
Emitter-Base Diode
Collector Floating

Fig. 6. Diode characteristics of transistor 2N332(80). (Dot denotes zero current, zero voltage.) Scales: vertical - 0.161 μa/cm division; horizontal - 0.294 v/cm division



Collector-Base Characteristic
Horizontal: 0.5v/cm div.
Vertical: 2.17μa/cm div.
Sweep: Clockwise

Emitter-Base Characteristic
Horizontal: 0.5v/cm div.
Vertical: 2.17 μa/cm div.
Sweep: Clockwise



Floating junction (emitter) voltage
Horizontal: 0.5v/cm div.
Vertical: 0.286v/cm div.
Sweep: Counter-clockwise

Floating junction (collector) voltage
Horizontal: 0.5v/cm div.
Vertical: 0.286v/cm div.
Sweep: Clockwise

Fig. 7. Diode characteristics and floating junction voltage of transistor 2N332(20) 500 cps. (Dot denotes zero current, zero voltage.)

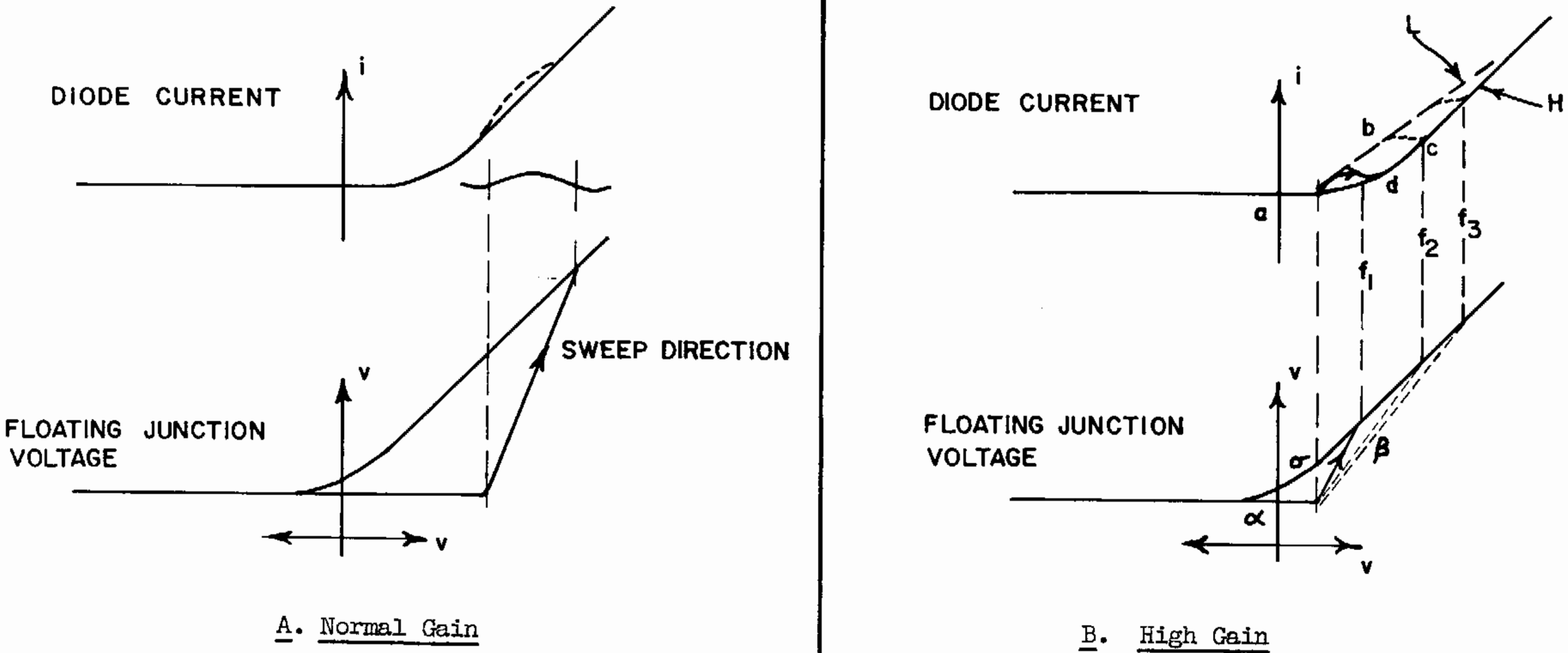
1. The current voltage characteristic of the emitter-base junction shows much more of a general capacitive loop than the collector-base junction. From the resistivities involved it can be concluded that this must be depletion layer capacitance rather than storage capacitance. As is expected the narrower emitter depletion layer does have the higher depletion layer capacity.

2. The region in the vi characteristic where the sweeping voltage is going through the kink is precisely the region in the floating junction characteristic where the floating junction voltage is changing most rapidly (region $\underline{\beta\text{-}b}$ in Fig. 8B). This was verified in many cases and for many frequencies. Figure 13 also shows this effect very clearly. It was also noticed in all cases that normal (lacking high gain) transistors had floating junction characteristics very similar to those of the high-gain transistors, except that region β (Fig. 8) of the voltage characteristic was displaced into the region of high diode conductance. Thus, it could be understood that if a small amount of kink current were present it would now be completely covered up in the large diode current. One transistor was discovered for which this kink was just discernable in the corner of the normal diode characteristic.

Reference to Fig. 8 will be made in discussing a proposed explanation of the kink. The regions denoted by corresponding letters are corresponding times in the sweep of the characteristic. The arrowheads indicate sweep directions.

Starting from zero voltage and increasing the emitter forward bias we proceed from 0 to the region of b, where the diode current may be of the order of $\frac{1}{4}$ microamp, and where the difference between the normal and special units occurs. We consider first a normal unit. At this level the effect of surface recombination, or edge current, according to Iwerson, Bray, and Kleimack[12] is to reduce the emitter efficiency, thus lowering the transistor β. As bias is increased, however, some electrons begin to reach the collector. The boundary conditions at the collector junction are altered; thus the voltage across the junction changes. Another viewpoint is that here transistor action is taking place. As the voltage across the junction changes, a small additional amount of current is required to charge the junction capacity (perhaps 60 $\mu\mu$f). However, this current is not seen in the large amount of diode current. As current is further increased, the collector voltage begins to vary with the emitter voltage, since it is in equilibrum with the electrons injected from the emitter. This explains the upsweep of the diode characteristic. The return trace is that of a normal diode since the charge leaks from the floating junction rather uniformly.

However, in the case of the special high β devices we have significant transistor action occuring at even the low-bias level indicated at β-b. In this case the diode current is very small and the additional amount required to charge the collector capacity is easily seen, and accounts for the kink in the emitter (or collector) diode characteristic.



A. Normal Gain

B. High Gain

f_1, f_2, f_3 represent the effect as frequency is raised.

Fig. 8. Comparison of normal and high gain characteristics

An alternative way of looking at this is that when transistor action is taking place we have an easy path of electron flow to the collector, while after the collector ceases to function the electrons have to flow laterally through the thin region to the base lead. We thus have a mechanism for two different diode characteristics as are shown by the lines H and L in Fig. 8.

This mechanism accounts for the observations listed on kinks. As further verification the following was done:

(1) A small capacitor (300μμf) was connected between the collector and base leads in effect to increase the junction capacity. The result was an increase in the kink current exactly as expected (see Appendix I).

(2) A battery was intermittently connected (reverse bias) from the floating junction to base lead. At low sweep frequency the diode characteristic would change from the high resistance (H) to the low resistance (L) curve (Fig. 8) when the battery was added.

Although the kinks were now explained in terms of the high β, other mechanisms for the exceedingly high β itself at these low currents was not clear.

D. LEAKAGE MEASUREMENTS

To gain further insight into this, more measurements were made on encapsulated units. Leakage currents were measured between various leads and not made of the electrical quality of the junction.

Table II. Emitter-Base Reverse Leakage

Voltage required to produce 10μa leakage (reverse bias)			
Regular Transistors		High β Transistors	
1.9	(2N732)	2N332-80	1.6
3.5	(2N332)	2N332-20	1.15
1.25	(2N332)	2N332-a	1.20
1.75	(2N338)	2N332-b	1.75
		2N338-c	1.20

Table III. Emitter-Collector Leakage

Voltage required to produce 10µa leakage (emitter positive).

Regular Transistors		High β Transistors	
2.2	(2N332)	2N332-80	1.65*
3.7	(2N332)	2N332-20	1.34*
1.65	(2N332)	2N332-a	1.50
1.9	(2N338)	2N332-b	2.0
		2N338-c	1.40

* These characteristics were soft.

The following are reverse collector leakages at 10 volts (reverse bias).

Table IV. Collector Leakage at 10 Volts (collector-to-base)

Regular Transistors		High β Transistors	
38×10^{-9}	amp	2N332(80)	0.9×10^{-9} amp
10	amp	2N332(20)	0.65×10^{-9} amp
7	amp	2N332-a	2.0 (changing) amp
0.6	amp	2N338-c	3.8 - 4.2 (changing) amp
0.8	amp		

The following measurements were also made.

The voltage required to produce a reverse emitter leakage of 0.36µa was determined. This is the column headed "Breakdown Voltage" in Table V. Also the incremental current gain (β) for various base current increments was determined for normal and high-gain transistors. These were arranged in order of diminishing leakage in Table V.

Table V. Emitter Breakdown Versus Current Gain

Transistor No.		Breakdown Voltage	Current Gain (β)			
			ΔI_b .000-.001	ΔI_b .001-.002	ΔI_b .002-.003	ΔI_b .003-.004
Normal Units						
(2N332)	1	0.68	0.2	0.4	0.4	0.4
(2N332)	2	0.80	0.7	1.6	2.4	2.5
(2N332)	3	1.00	1.3	2.3	3.1	3.1
(2N332)	4	1.2	1.8	3.0	3.9	4.0
(2N332)	5	2.2	1.8	3.1	4.1	4.3
(2N332)	6	1.7	3.0	4.4	5.5	

Table V. (Continued)

Transistor No.	Breakdown Voltage	Current Gain (β)			
		ΔI_b .000-.001	ΔI_b .001-.002	ΔI_b .002-.003	ΔI_b .003-.004
Special Units (high β)					
2N332(20)	0.70	12.4	10.4	9.0	
2N332-a	0.73	3.6	3.2	2.9	3.3
2N338-c	0.75	18.5	9.1	5.1	6.1
2N332(80)	1.00	13.4	8.2	7.4	

It is noted from Table V that reverse emitter leakage is a good indicator of current gain among normal units since, arranged in order of decreasing emitter leakage, the transistors are in a sequence of increasing β. However, among the special high-gain units there appears to be no order. The current levels are considerably above the point at which the special units achieve their maximum β.

E. FREQUENCY-GAIN MEASUREMENTS

One of the definite advantages of the cathode follower technique was that the very low capacitive loading of the grids allowed a reliable gain frequency measurement to be made. Noise of all varieties was a problem because an **ac** small signal ($\sim 10^{-9}$ amp **ac**) was superimposed on a base current of $\sim 10^{-8}$ amp (emitter current $\sim 10^{-6}$ amp) in a high impedance circuit with a wide (> 10 Mc) bandwith. The circuit used (Fig. 9) is similar to that of Smith and Hyde[10] in that outputs are taken relative to ground while the demand of low coupling to ground is placed on the transformer used to couple in the **ac** signal. A 455 Kc I.F. transformer was used which had measured values of capacity as follows:

Coil to coil - $\sim 4\mu\mu f$

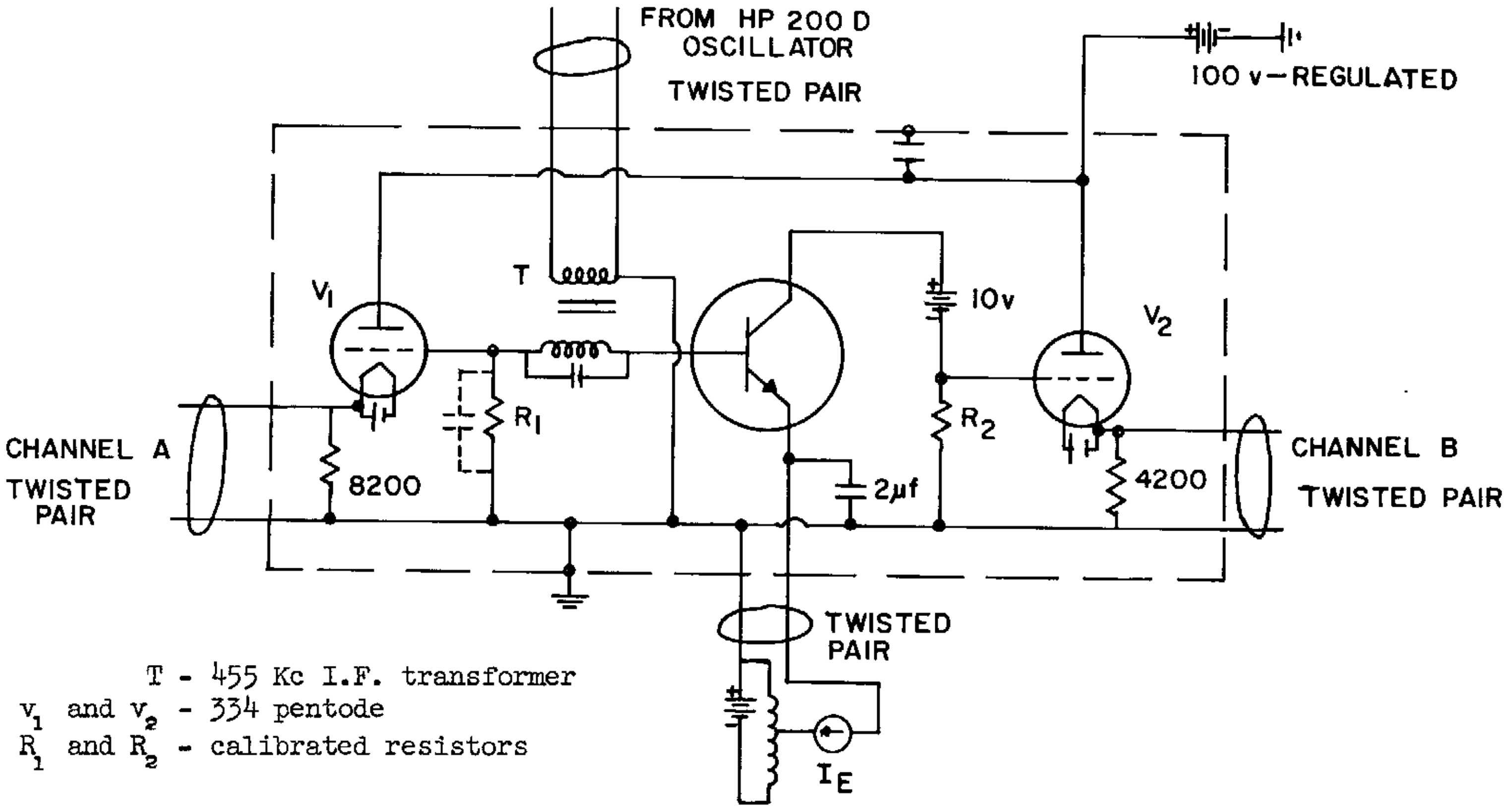
Coil to shield - $\sim 2\mu\mu f$

The quantity which we will define as β is the small signal quantity

$$\beta = \frac{i_c}{i_b}\Bigg/_{v_c \simeq 0} \qquad (5)$$

For the circuit as shown in Fig. 9 this is

$$\beta = \frac{i_c}{i_b} = \frac{v_c R_b}{v_b R_c} = \frac{955 \times 10^3}{10 \times 10^3}\,\frac{v_c}{v_b} = 45.5 \cdot \frac{v_c}{v_b} \qquad (6)$$



T - 455 Kc I.F. transformer

V_1 and V_2 - 334 pentode

R_1 and R_2 - calibrated resistors

Fig. 9. Circuit used in gain frequency and gain bias measurements

In general, β's determined below 60 cps are, as the spread in points show, quite erratic because of the 60-cycle pickup that could not be eliminated; however, the general shape of the curves is correct. Other measurements yielded results which also fell off at low (100 cps) frequencies.

The fall-off in gain was seen to be consistent with the fact that as the frequency was raised, the current into the emitter became largely reactive. A continual check of the current voltage characteristic of the emitter junction, as the gain frequency measurement was made, showed a continual decay of the normal low-frequency diode characteristic into reactive loop at higher frequencies. Increasing the signal level restricted the usual diode characteristic somewhat by making the conductive diode current component increase in relation to the capactive component. This apparently explains the observation made by Hanlon[4] (p. 42) that the measured parameters are somewhat dependent on signal level; however, there is more to this problem than can be explained by the depletion layer capacitance of the emitter junctions. A rough calculation will explain this statement.

From a typical slope of the diode characteristic at these levels we get a diode resistance $R \approx 2 \times 10^5$. The capacitance at these biases is approximately 60×10^{-12}f.

If the frequency is determined at which the reactive current equals the conductive current, (this apparently would indicate where half the current was injected into the base and half was displacement current), we get

$$f_{\frac{1}{2}} = \frac{1}{2\pi RC} \approx \frac{1}{2\pi\ 2 \times 10^5 \times 60 \times 10^{-12}} \approx 30{,}000 \text{ cps.}$$

As Fig. 10 shows, however, the gain is falling off, even at 100 cps. The fact that the emitter current is reactive at these frequencies indicating significant displacement current, even at 100 cps. The apparent limitation of the frequency response of a transistor caused by a capacity associated with its emitter is rather unusual and is apparently due to the high diode resistance at these levels.

F. GAIN-BIAS MEASUREMENTS

These measurements were made at 40 cps. It was found advantageous to add a 300$\mu\mu$f capacitor across the resistor R_1 in Fig. 9. This effectively eliminated high-frequency noise in the circuit but 60 cps pickup remained a problem.

Figure 11 shows these results for several high-gain transistors. I_e is the emitter bias current β as previously defined. These are in agreement with Hanlon's curves (measured by a different method) over

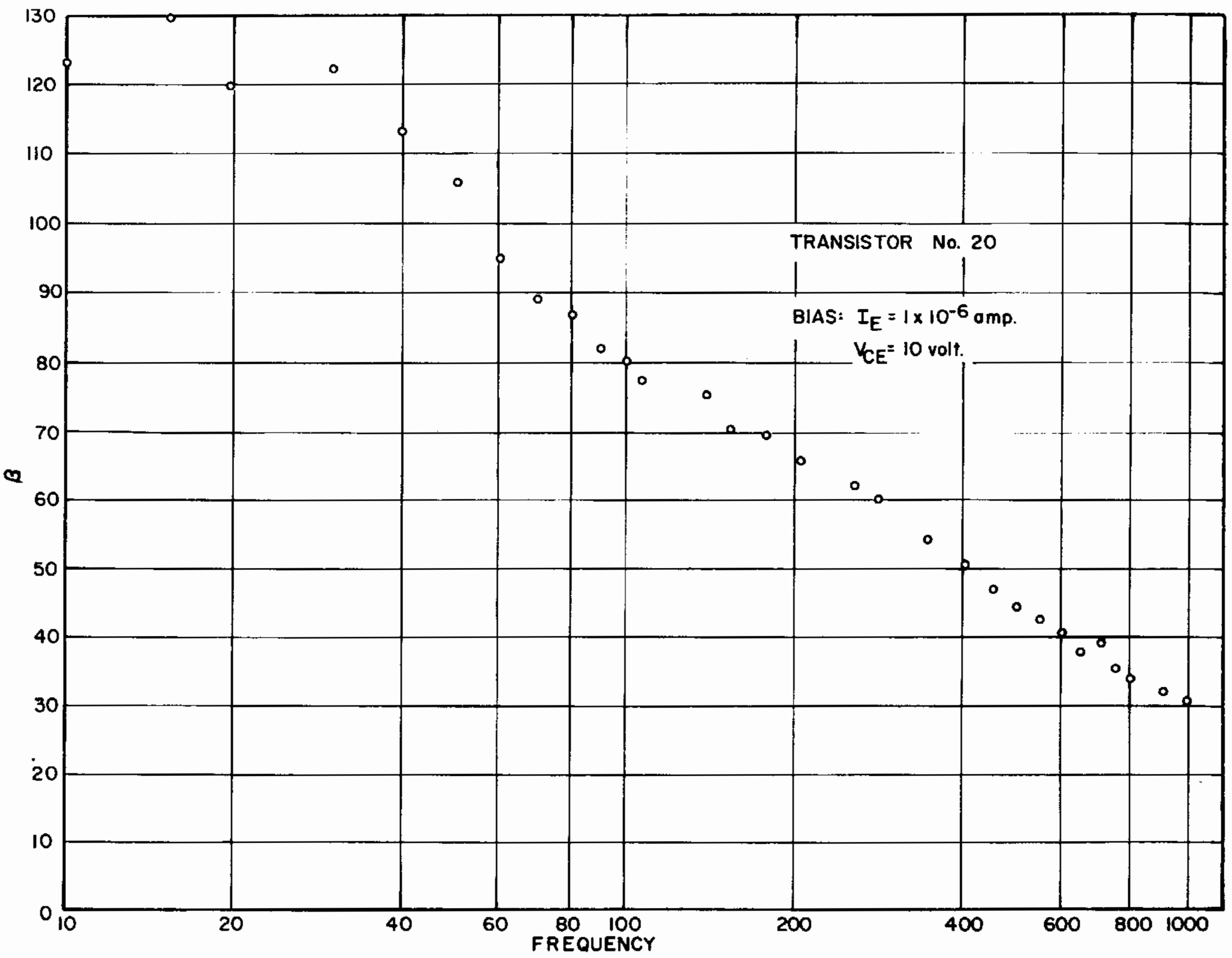


Fig. 10. Gain-frequency of transistor 2N332(20)

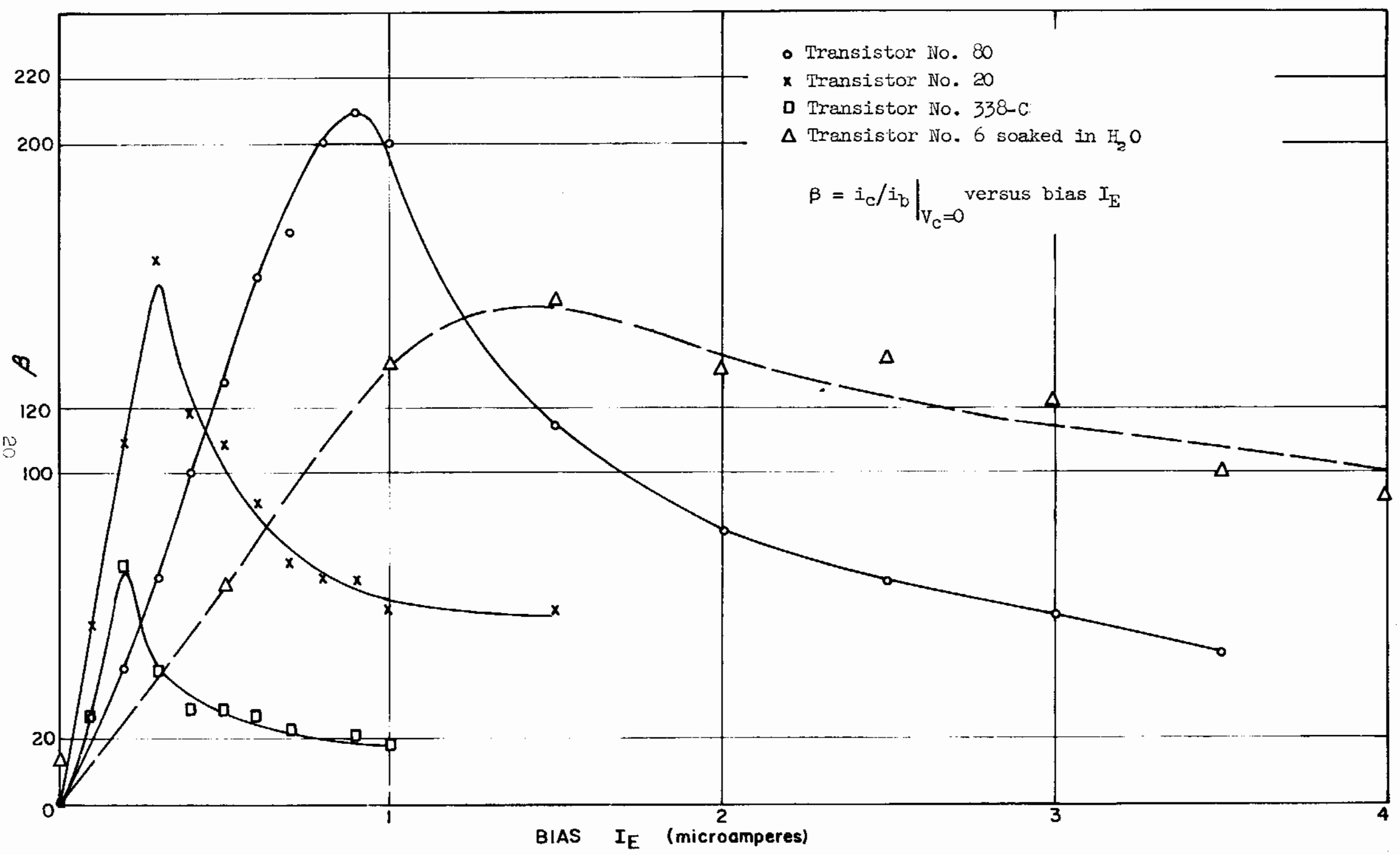


Fig. 11. Results for four transistors

their common range of values; however, these measurements show that a decrease in β occurs at low currents, that the peak β differs among the several units, and that the peak occurs at different bias levels. The collector voltage was maintained at 10 volts in all measurements.

IV. MEASUREMENTS ON EXPOSED UNITS

The kinks observed in the high β transistor were now explained in terms of the high β at low injection; however, the mechanism of high β itself was still not resolved. Several possible explanations for the high β were considered. It was also felt that the base lead overlap onto the emitter or collector might result in an unusual junction structure since lapping and staining of the transistor indicated base widths of approximately 0.4 mil, while the base lead diameter was measured as 2.5 mil and larger at the point of contact on the transistor.*

The importance of base lead position was easily subject to investigation by an etch sequence.

N,N-dimethyl formamide (Matheson, Coleman and Bell, Producer) was found to aid in the removal of the varnish on the transistor structure. Several boilings (B.P. 152-154°C) and coolings in this compound softened the varnish enabling its removal with a pointed instrument.

Figure 12 shows a fixture on a pump station with feed-throughs where a transistor could be pumped to diffusion pump pressure and electrically examined under this vacuum.

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* It was previously established that the high β was not necessarily a result of an abnormally thin base region since a lapping and staining sequence revealed an ordinary basewidth (0.38 mil) uniform across the bar for a high gain unit.

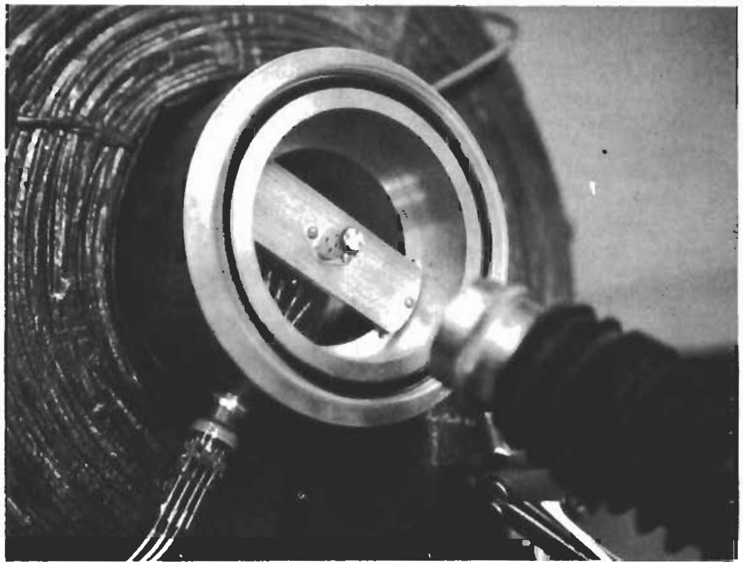


Fig. 12. Fixture covered with quartz plate on pump station for ambient control

Several transistors were run through a cycle of etch and electrical checking using this apparatus. The etching was found to have no major effect on the current gain. Transistor 2N332-80 was also subjected to this treatment. At the final stages in the etching process two transistors showed oscillations when their characteristic were viewed in the Tektronix transistor curve tracer. This interesting side effect is described in Appendix B.

Steps in the etch process consisted of the following:

1. Etch: $\sim$ 2 seconds in 10:1 HNO_3-HF at room temperature with agitation.

2. Etch Stop: Immersion in deionized distilled water ($\sim$ 3 seconds with agitation)

3. Rinse: $\sim$ 10 seconds under running deionized distilled water.

4. Rinse: $\sim$ 3 seconds under a jet of absolute ethanol.

5. Intermediate: ~ 1-2 minute delay while transistor was transported through room atmosphere and inserted in pump fixture.

6. Electrical display of characteristic on curve traces (usually poor).

7. Varied heating under focused illumination from a microcope lamp and alternate display of characteristics on curve tracer until no further drift was observed (usually ~ 15 minutes).

This was carried out under fore-pump vacuum. Exposed unplated base metal of the header was covered with Apiezon wax eliminating contamination of etch.

The most important result observed in the experiment was that admission of air into the vacuum system produced an increase in β on freshly etched units while also increasing the reverse leakage. The admission of air into the system through a silica-gel drying column produced no effect on the characteristics. Breathing on the device increased the high gain even more than when it stood in open air. In this manner the incremental current gain as displayed on a Tektronix 575 Curve Tracer could be varied by a factor of 2 or 3; however, the effect on β for the increment from $i_b = 0$ to 1μa was the greatest. This quantity could be made larger than that of the transistors 2N332(80) or 2N332(20).

A sequence of drying under vacuum and exposure to atmosphere could be repeated several times with similar results. The introduction of the silica gel drying column at any point in the above sequence when admitting air into the system never altered the transistor characteristics.

Allowing the transistor to sit for a day at fore-pump vacuum, however, removed the above described extreme sensitivity of the transistor to the ambient conditions.

It was then established that a normal transistor under its protective varnish film could be given these same high-gain characteristics by allowing it to stand in water for a suitable length of time. Experiments on units thus formed are given in the next section.

V. MEASUREMENTS ON CONVERTED UNITS

The purpose of this section is to demonstrate that the devices produced by exposure to water are much like the ones obtained commercially by illustrating the similarities in their observed behavior.

Figure 13 shows characteristics obtained from transistor No. 5 which was initially a normal low β unit. This transistor, with varnish on and cap off, was soaked in pure water for two hours at room temperature. It was then rinsed in ethanol to remove surplus moisture and immediately inserted in the diode tracer of Fig. 5. It has the characteristic features obtained in the similar displays for the commercial high-gain units. Ordinarily the water treatment increased the junction leakage to such a degree that the floating junction appeared to be short circuited to the emitter. However, repeated checks of this unit during the treatment permitted the process to be stopped at the opportune moment and pictures taken (Fig. 14).

Figure 14 consists of curve tracer photographs of unit 2N332(6). The unit was soaked in water to produce the characteristics shown in Fig. 14A. It was then allowed to dry and Figs. 14B, C, and D were taken at varying lengths of drying times. As moisture was removed the gain given by the lowest increment steadily decreased.

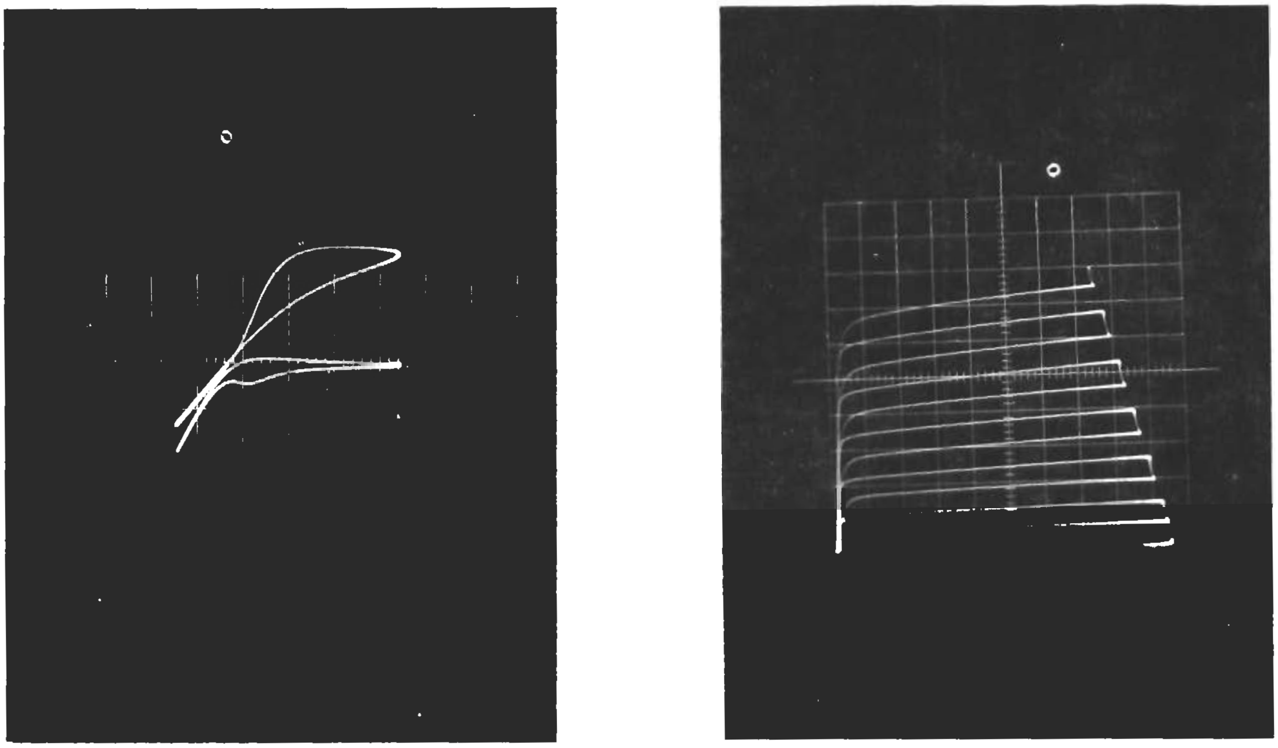
Figure 15 is the small signal β determined in the circuit shown in Fig. 9 and corresponding to the times at which the previous pictures were taken (A, B, C, and D). In this case the behavior of the β's is similar to that of commerically produced units; however, the bias scale is larger than that of the commercial units. Curve A was replotted in Fig. 11 for comparison with commercial units 2N332(80), 2N332(20), and 2N338(C). It is seen that the high β regions of water-treated units hold up at larger bias levels than those of the commercial units. This stability was attributed to a more rugged channel in the model to be described later.

Direct-current plots of forward emitter diode characteristics for cases A, B, C, and D are given in Figs. 16A, 16B, 16C, and 16D for the water-treated unit, 2N332(6). Also similar plots for units 2N338(C) and 2N332(20) are given in Fig. 17 and Fig. 18, respectively. Lines are drawn where these respective units achieve their maximum β. It is interesting to note that the bias current (I_e) where the units reach maximum gain are very close to or below the break in the diode characteristic. This contrasts with the results of Iwerson, Bray, and Keleimack.[6] Apparently the "edge current" of Ref. (6) is not necessarily a degrading factor in these units. This is significant in the model to be described next.

VI. PROPOSED MODELS FOR SURFACE-DEPENDENT TRANSISTOR GAIN

A survey of the literature on surfaces has suggested two mechanisms which may account for the high β exhibited by these devices.

The basic structure is depicted in Fig. 19. Here the typical grown junction configuration has been modified by the growth of an n-type channel into the base region, effectively surrounding the base by the collector junction. Possible effects of this channel will now be considered.



Diode Characteristics
Transistor No. 5
Horizontal: 0.20 v/cm. div.
Upper Curve: Floating junction
potential, scale 1.82 v/cm. div.
Lower Curve: Diode current,
scale 0.695 μa/cm. div.
Sweep frequency 60 cps

Collector Family (Tektronix)
Horizontal: 1 v/cm. div.
Vertical: 10 μa/cm. div.
Base step: 1 μa/step

Fig. 13. Characteristics of a transistor 2N332(5) converted from normal to high gain

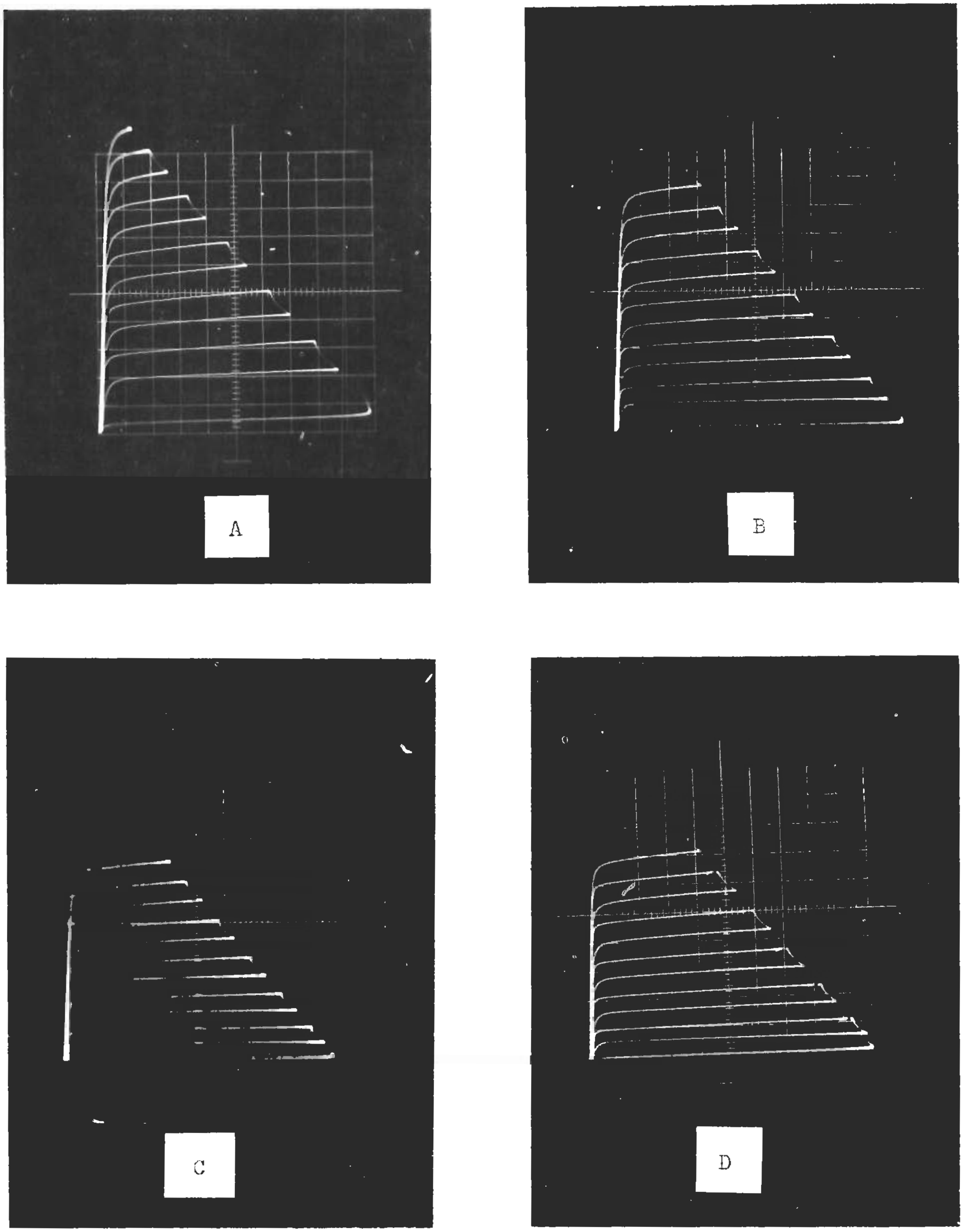


Fig. 14. Curve tracer photographs of transistor treated with water, A, and allowed to dry for increasing lengths of time, B, C, D

Scale: Vertical, 10 μa/cm. div.; horizontal, 1 v/cm. div.; base step, 1 μa/step

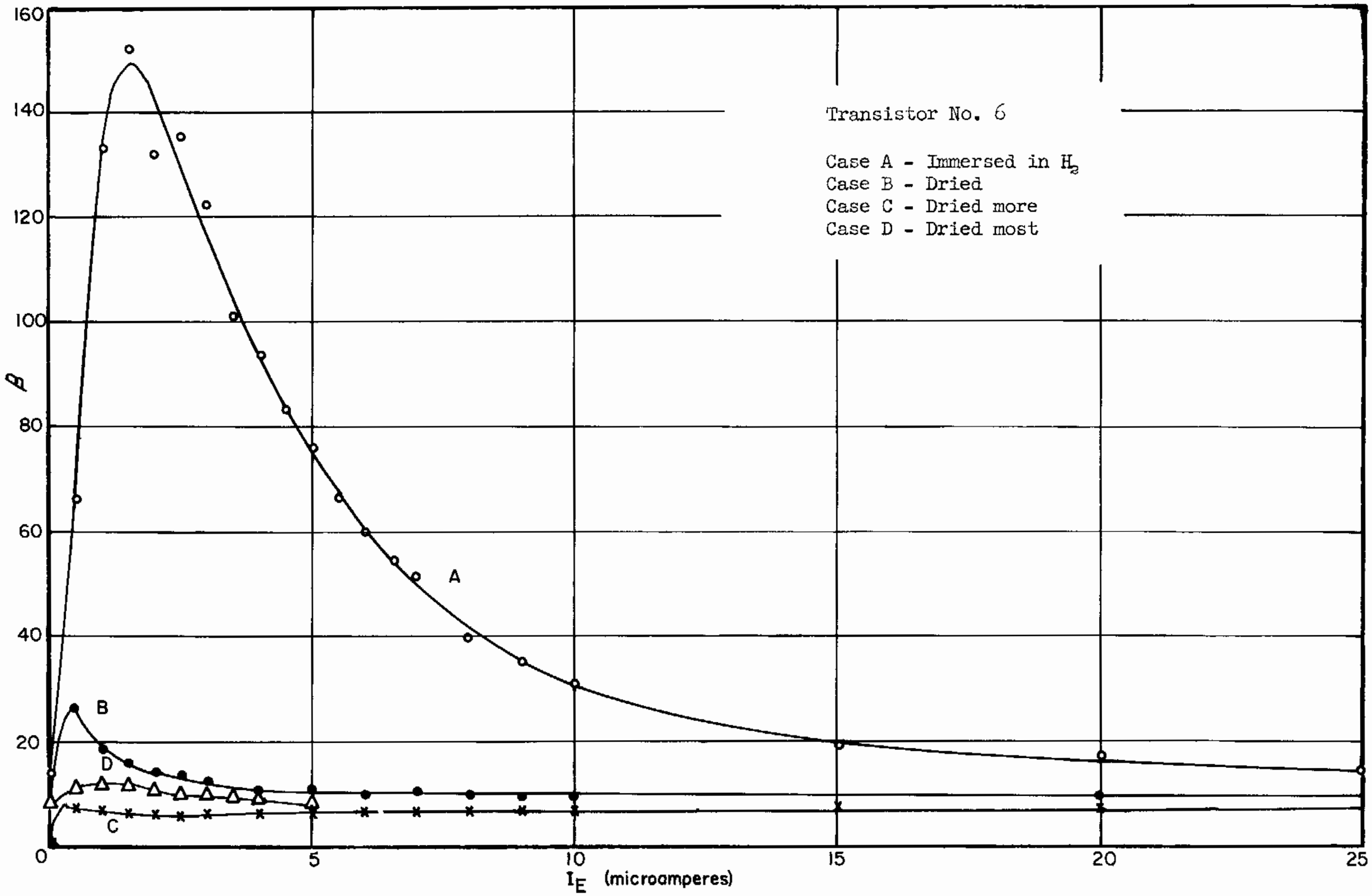


Fig. 15. Transistor β vs. Bias Current

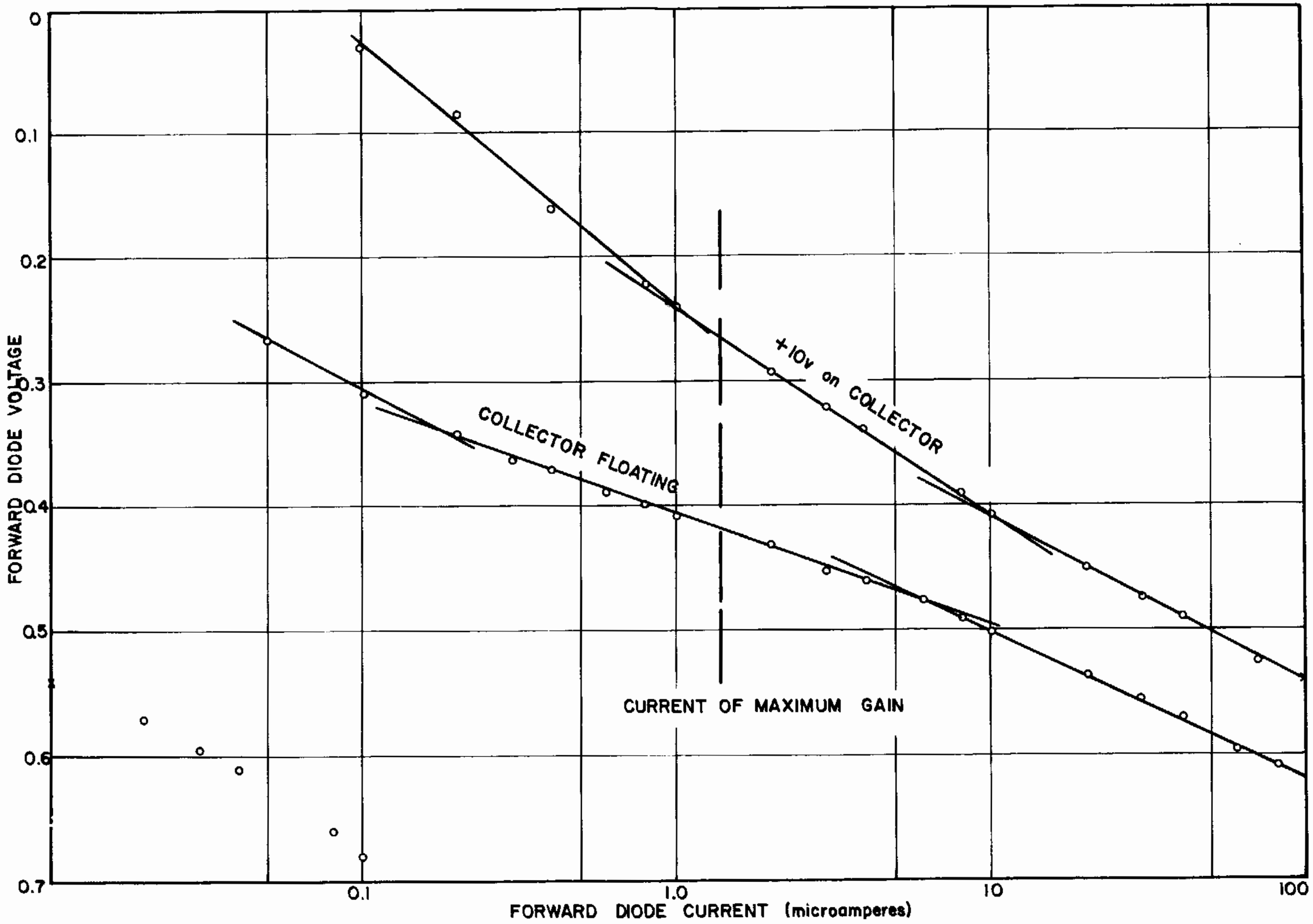


Fig. 16A. Direct current plot of forward emitter diode characteristics

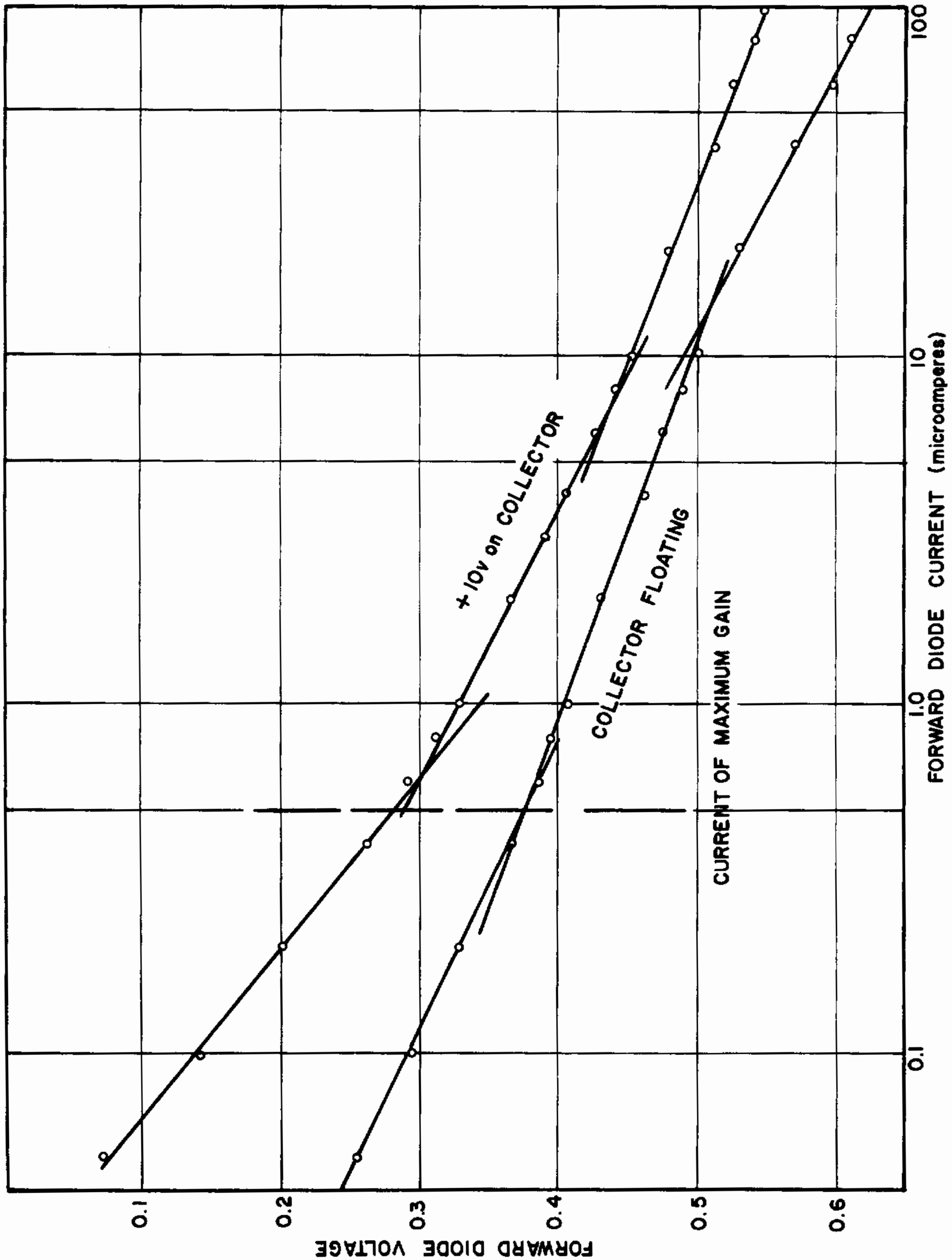


Fig. 16B. Direct current plot of forward emitter diode characteristics

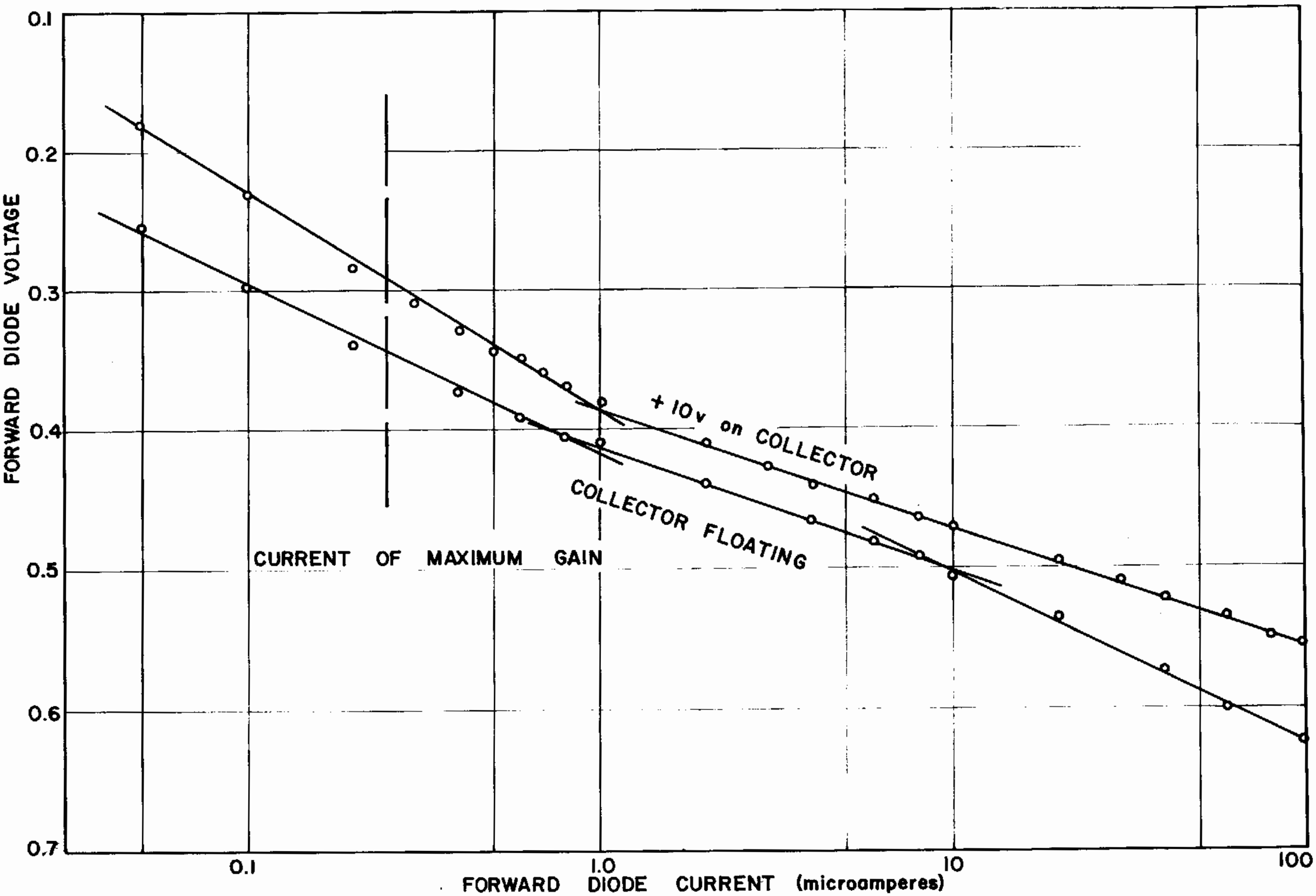


Fig. 16C. Direct current plot of forward emitter diode characteristics

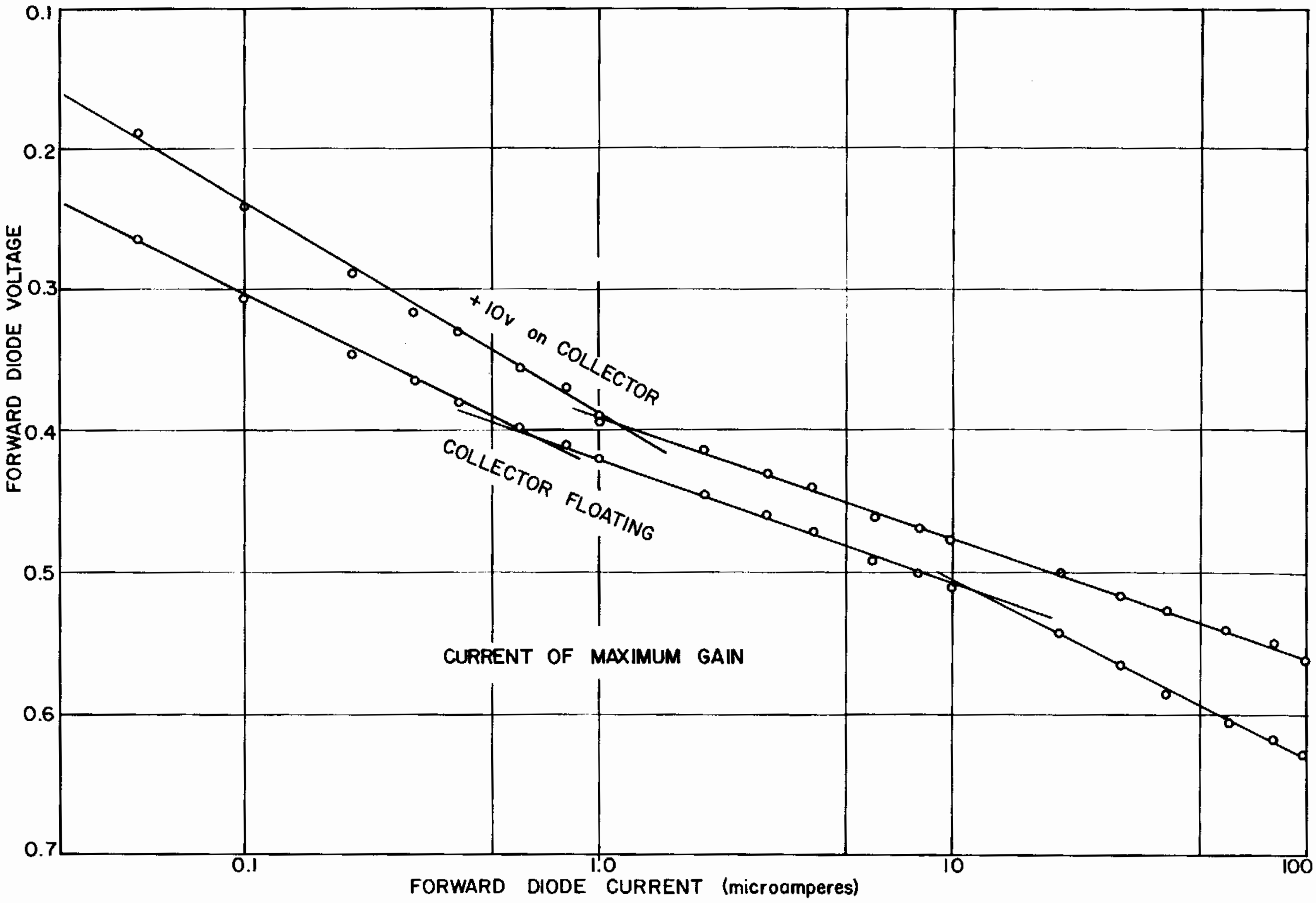


Fig. 16D. Direct current plot of forward emitter diode characteristics

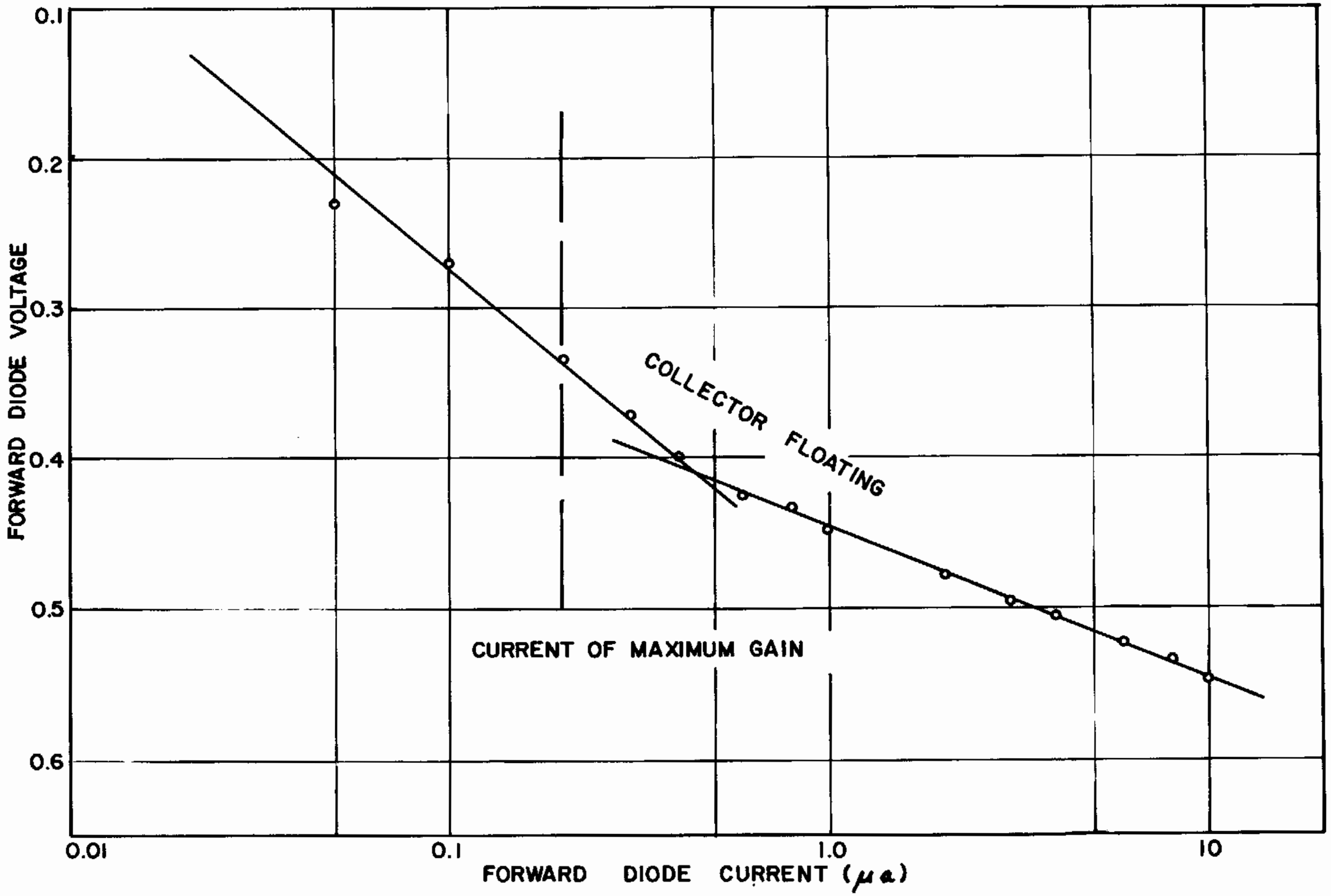


Fig. 17. Forward emitter diode characteristics of transistor 2N338(C)

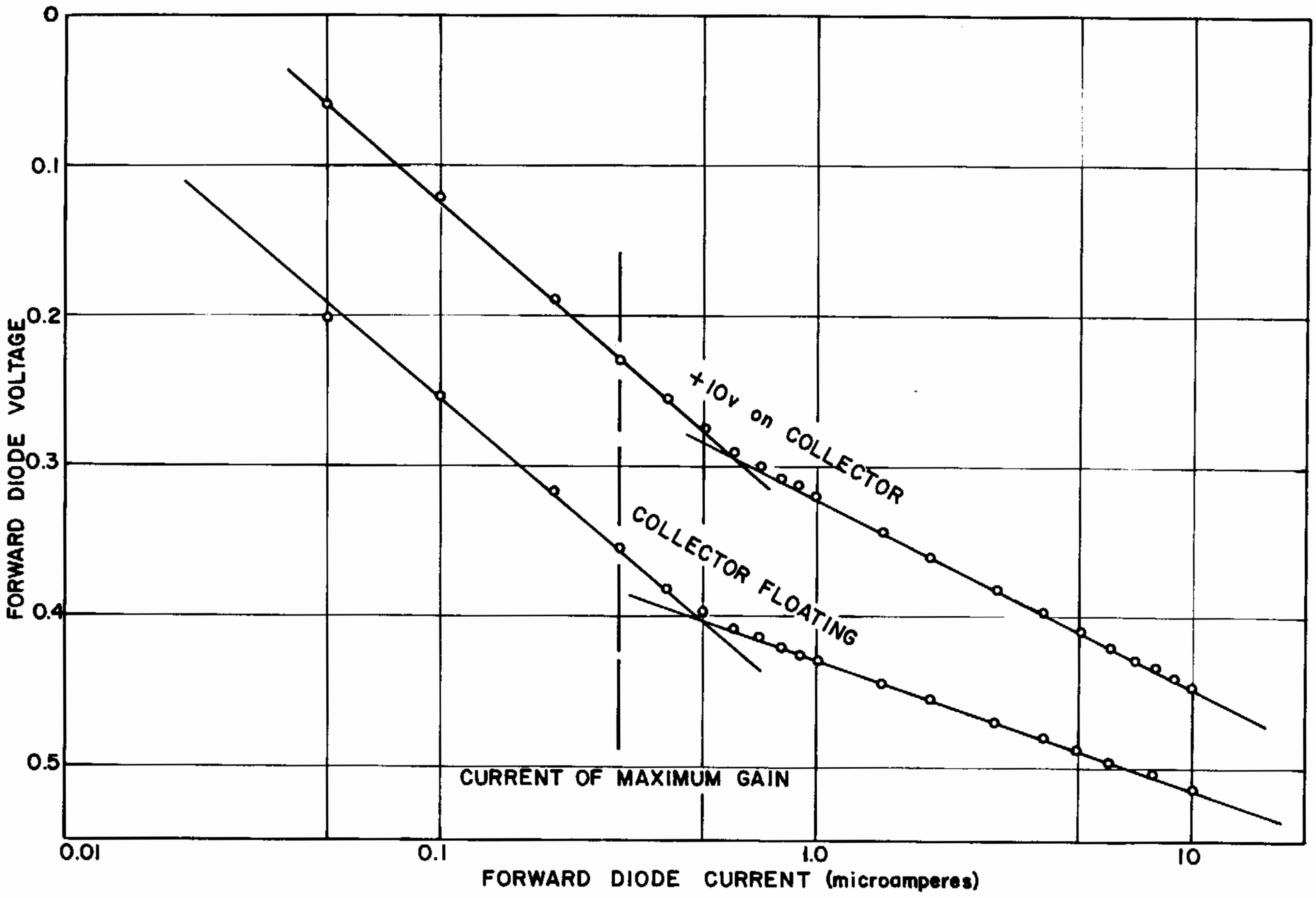
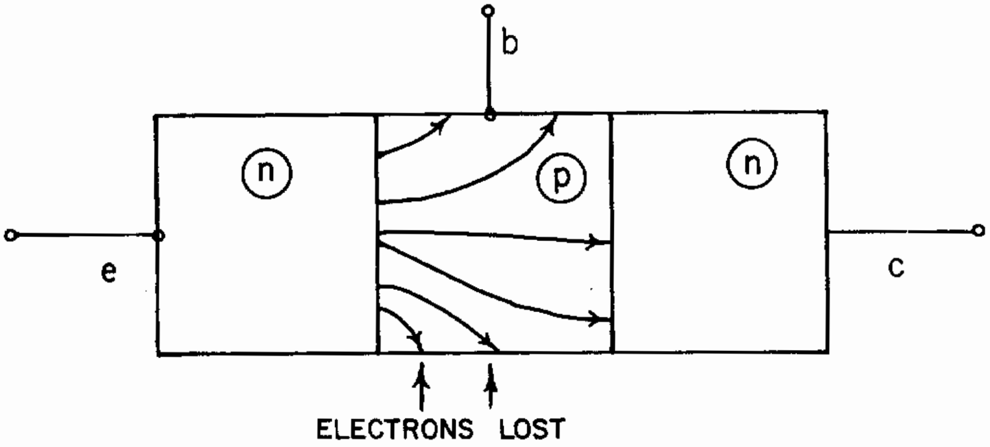
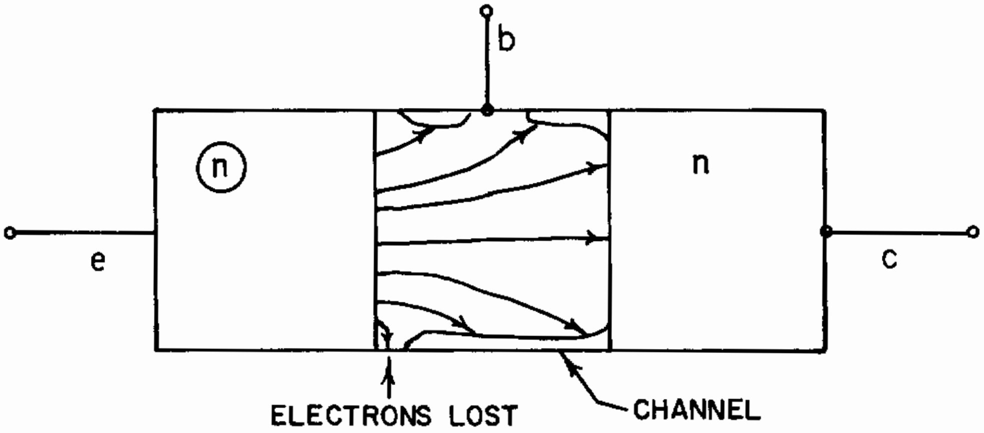


Fig. 18. Forward emitter diode characteristics of transistor 2N332(20)



Normal grown junction structure



Modified grown junction structure

Fig. 19. Proposed model of high β transistor

It has been proposed by several authors[13,14,15,16] that base transport efficiency is the limiting factor on transistor β at medium- and low-bias levels for good transistors. This base transport factor depends almost solely on surface recombination for nearly all transistor configurations. A possibly significant mechanism in the high β units is a reduction of surface recombination as a result of covering part of the base surface with the extended collector junction (Fig. 20).

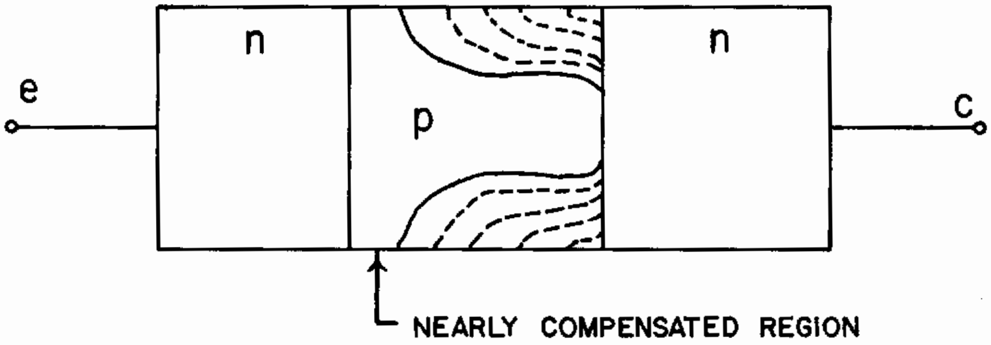


Fig. 20. Reduction of surface recombination

The work of Law and Meigs[17] indicates that the only marked effect of water vapor on silicon is to produce channels. Their results with a traveling light spot on a p-n junction clearly indicate that the effect of water vapor on p-type silicon is to produce an n-type inversion layer. They further show that this channel is capable of collecting a minority carrier charge injected near it (by light) and conducting the charge along the surface to the adjacent n-type material. It is further shown in the above cited work, that the effect of increased injection (by light) is to finally remove the channel completely. Thus we have a basis for postulating that a surface channel does produce collector action, and that this beneficial action is removed at higher injection, thus accounting for the loss of high β at higher levels in the special transistors. The similarity of carrier injection by light and by a forward biased junction makes these arguments reasonable. Appendix III contains an additional observation in support of this surface channel model.

The narrowness of the base makes the direct verification of these channels difficult. The additional capacity produced is nearly insignificant in relation to the normal junction capacity, and a light spot experiment similar to that described in Ref. (11) is not meaningful.

Although there is a possibility that the surface moisture, instead of forming a channel, simply reduces the surface recombination velocity, it is generally accepted that at the moisture levels of this experiment the surface potential is altered sufficiently to produce an inversion layer. Furthermore, it is a familiar result that moisture always causes an n-type inversion layer on p-type material and an accumulation layer on n-type material. It is likely that observed beneficial results of moisture at high injection are the result of lower surface recombination where the channel is removed.[18]

It should be kept in mind that the model as drawn in Fig. 19 somewhat misleadingly suggests that the channel is equivalent to, for example, a diffused layer on the surface. However this is not a completely correct analogy since the channel is an induced effect of bound charge in the surface of the silicon or its oxide.

The surface model described thus far may be objected to from two or three standpoints. Sah[20] and Iwerson et al[12] have shown that in transistors of various geometries the base transport factor is independent of collector current over a range of nine orders of magnitude. This indicates that the low-current fall-off in β (and possibly also its restoration) is an emitter effect. It also appears that the effect of the moisture on β is not just an elimination of surface recombination since the observed values of β are sometimes much greater than the ideal values calculated from bulk properties. An example is the current gain of 10,000 quoted in Ref. 1.

A more correct model probably shows the channel completely across the base, implying a current leakage path from emitter to collector, with the equivalent resistance controlled by the base potential. The behavior is that of a field effect transistor with the emitter and collector as source and drain. This model then gives an explanation for the very efficient transistor action in both directions as in observed from the kinks in the characteristics of both the emitter-base and collector-base diodes. Such a field effect behavior could quite reasonably lead to current gains much larger than those possible in normal transistor action without surface recombination. This explanation of the high-gain phenomenon was suggested by M. Ono[21] and by Loro and Rosenbaum.[22]

VII. RECOMMENDATIONS FOR FURTHER WORK

A field effect device based on the deliberate design and control of a surface channel appears to offer important advantages as a nanowatt amplifier of very high input impedance. The problems involved may, however, be considerable because of the difficulties in maintaining stable channels.

The original approach of attempting to achieve high gain at low currents through the design of conventional transistors with optimized geometry has been given considerable encouragement by the work of Kennedy.[7,8] This approach would probably not yield gains as high as those possible with a surface channel, but would result in devices with greater stability.

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APPENDIX I

CAPACITY ESTIMATE

By connecting a capacitor (C^1) from the floating junction to base and lowering the sweep frequency appropriately (to f^{low}) it was possible to obtain a loop of approximately the same appearance as the characteristic without the capacitor C^1. This indicated that the effect of the two capacitors $C_{jun} + C^1$ and C_{jun} at the two different frequencies were roughly the same. This is stated in equation form as

$$f_{low} \, (C^1 + C_{jun}) = f_{high} \, C_{jun}, \tag{7}$$

or

$$C_{jun} = \frac{f_{low} C^1}{f_{high} - f_{low}} \; . \tag{8}$$

The following values were obtained by the above procedure:

$$f_{low} = 20 \text{ cps}$$

$$f_{high} = 89 \text{ cps}$$

$$C^1 = 300 \mu\mu f,$$

for which Eq. (8) becomes

$$C_{jun} = 87 \mu\mu f \; .$$

Measured values of 60μμf are in sufficient agreement with this value.

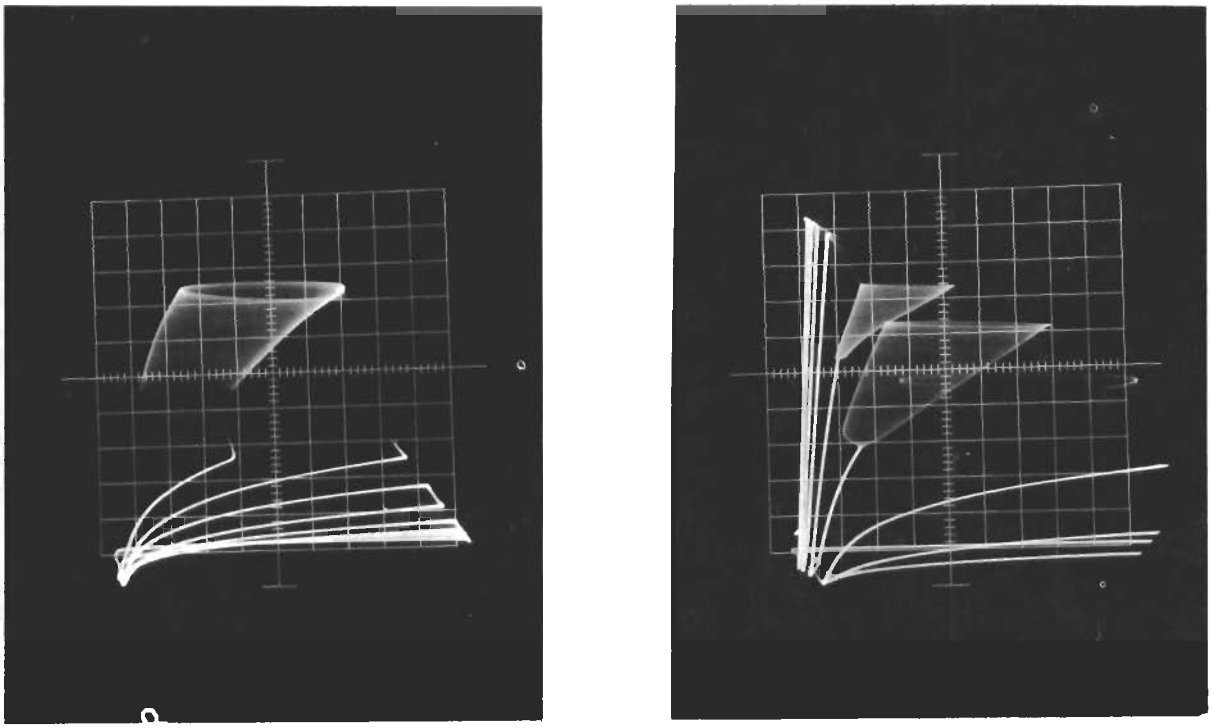
APPENDIX II

RELAXATION OSCILLATIONS

At the last stages in the etch sequence it was observed that oscillations were taking place where the device was displayed on the curve tracer. These oscillations took place through several steps in the etch sequence and also occurred in air as well as in vacuum. The display on the curve traces was as shown in Fig. 21.

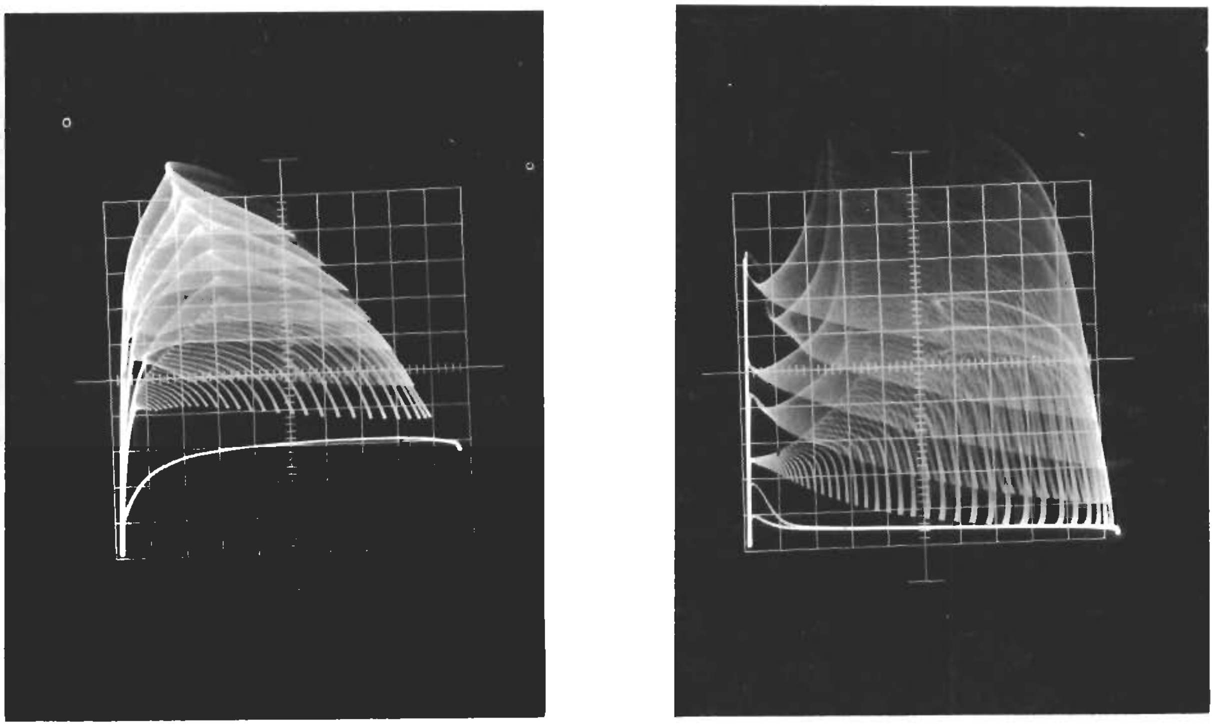
The device was finally made to operate in the circuit shown in Fig. 22, where the capacitor was found necessary as a substitute for the capacity of the shielded line from the pump station fixture to the curve tracer.

Several of the waves are shown in Fig. 23. Some features of the waveform can be accounted for by the assumption of a four-layer device. Figure 24 shows a severe undercut of the base lead typical of the oscillating devices, suggesting that a four-layer diode was formed as in Fig. 22. The deviation of the waveform from that expected of a true four-layer device may be due to the proximity of the base region to the base lead.



Vert: 10 μa/cm. div.
Horiz: 0.1 v/cm. div.
Base Step 50 μa/step

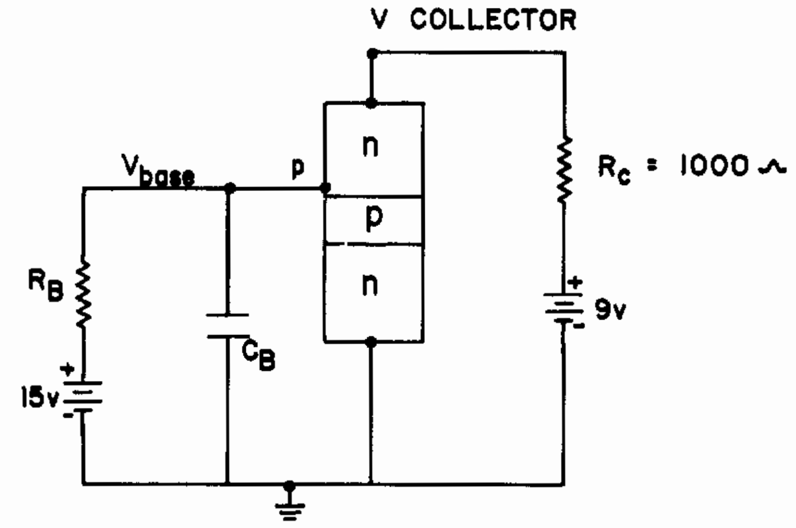
Vert: 20 μa/cm. div.
Horiz: 0.1 v/cm. div.
Base Step 50 μa/step



Vert: 10 μa/cm. div.
Horiz: 1 v/cm. div.
Base Step 10 μa/step

Vert: 10 μa/cm. div.
Horiz: 1 v/cm. div.
Base Step 10 μa/step
(etched more than others)

Fig. 21. Relaxation oscillations



Circuit used to obtain waveforms shown in Fig. 23

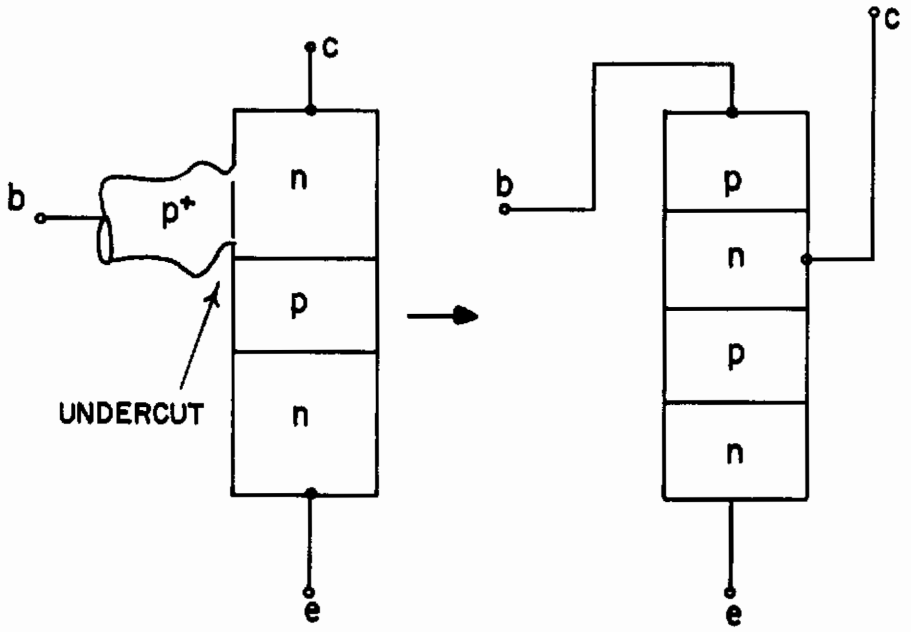
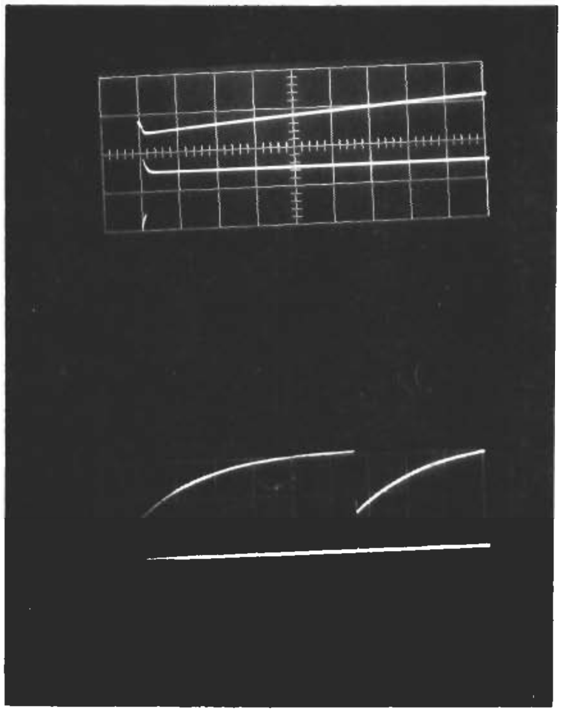
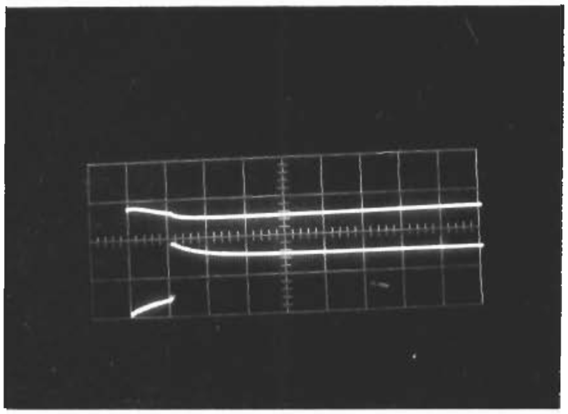


Fig. 22. Pulse generation circuit and possible device

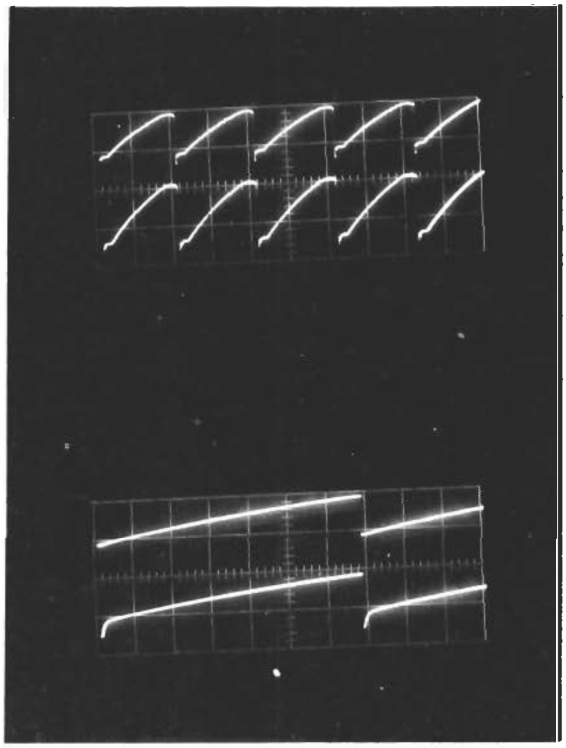


Upper picture - 1 millisec/cm. div.
Lower picture - 10 millisec/cm. div.
Upper trace (base) - 5v/cm. div.
Lower trace (collector) - 5v/cm. div.
R_B = 150 K; C_B = 300 μμf



100 μsec/cm. div.
(chop frequency visible)
Upper trace (base) - 5v/cm. div.
Lower trace (collector) - 5v/cm. div.

Fig. 23. Wave traces



Upper picture: 10 μsec/cm. div. C_B = 300 μμf
Lower picture: 1 millisec/cm. div. C_B = 0.27 μf
Vertical (all traces) 10 v/cm. div.
R_B = 45 K

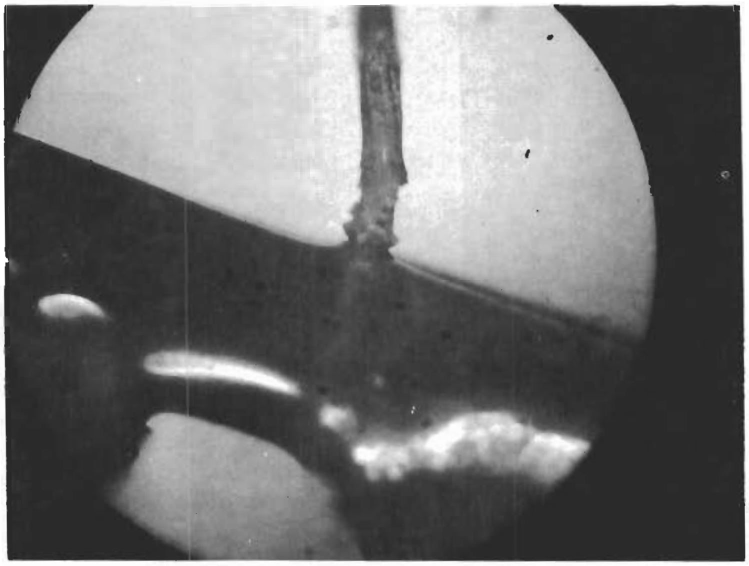


Fig. 24. A 2N332 transistor with base lead undercut by etch. This device produced pulses of form shown in Fig. 23.

APPENDIX III

SENSITIVITY TO LIGHT

It was observed that the high-gain transistors (both commercial and those produced here) were unusually sensitive to light. In particular, the high gain could be completely removed by small amounts of light which hardly affected the gain at higher bias levels. Reference to Fig. 25 shows how the collector display (e.g., Tektronix 575 Curve Tracer) was altered by a slight degree of constant illumination. The solid set of characteristics moved to the dashed set when the light was turned on as indicted by single headed arrows. It can be seen that $\Delta I_c'$ is less than ΔI_c and therefore the high-gain phenomenon was destroyed by the light.

The explanation for this behavior falls naturally from the surface channel model. At high emitter injection levels the channel has been destroyed, and the photocurrent collected is rather small because of the high recombination rate at the exposed surface of the base. However, at low emitter injection levels the channel is present on the surface and is available to collect the photoinjected carriers. This explains why the I_{cO} trace of the set is affected much more than the other.

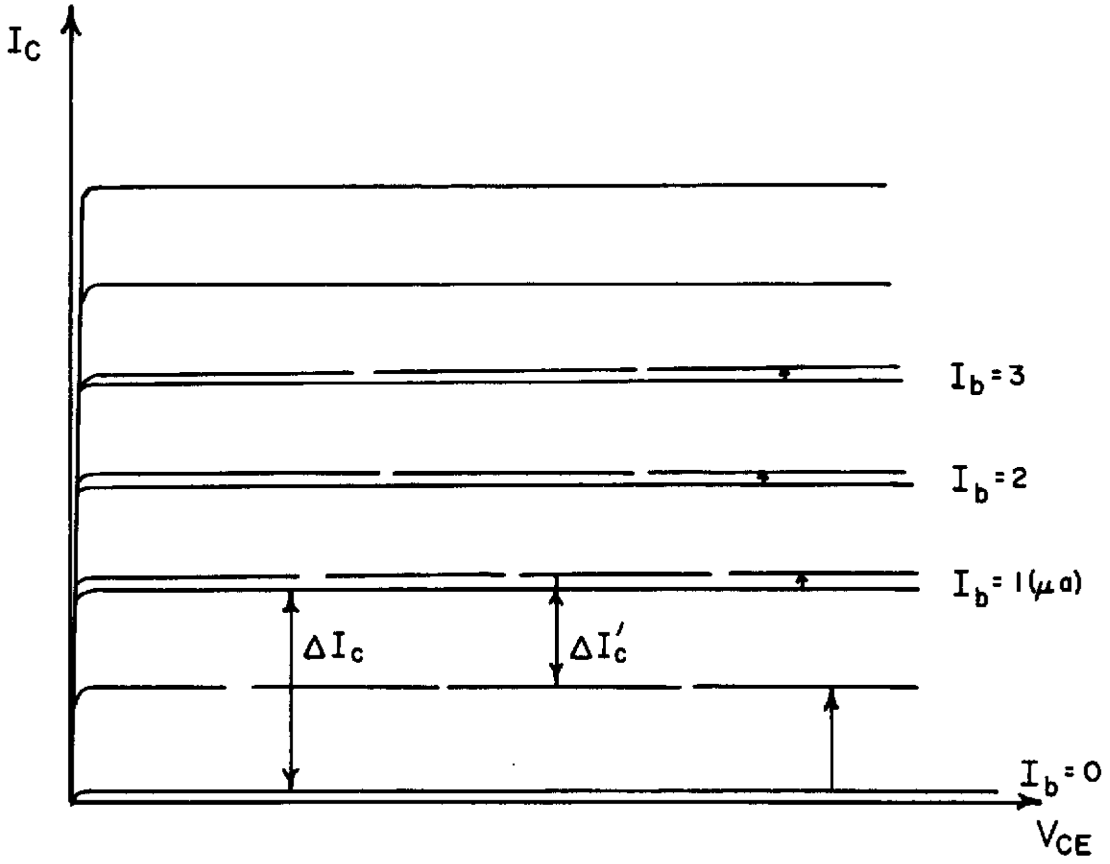


Fig. 25. Alteration of high gain transistor characteristics with light. The solid set represents the collector characteristics with no ambient light. The dashed set represents the characteristics with a small degree of constant illumination.