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SUBJECT: GENERAL CHARACTERISTICS OF GERMANIUM AND SILICON DIODES AND TRANSISTORS

To: Transistor Distribution 2

From: Nolan T. Jones

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Abstract: The construction and electrical characteristics of currently available germanium and silicon diodes and transistors are summarized. The general order of increasing diode forward resistance is alloy junction, grown junction, bonded, and point-contact. The general order of decreaseing back resistance is grown junction, bonded, alloy junction, and point-contact. Transistors included are grown-junction n-p-n, alloy-junction p-n-p, and point-contact.

1.0 Introduction

A brief description of the physical and electrical characteristics of the common semi-conductor diodes and transistors is presented here as a foundation for later discussions of the minority carrier storage characteristics of these devices. This is Chapter II of the author's thesis, "Minority Carrier Storage in Diodes and Transistors." There are four types of construction: point-contact, bonded, grown junction, and alloy or diffused junction, and two materials used in commercial products: silicon and germanium.

1.1 RTMA Type Numbers

The standard type numbers of the Radio-Television Manufacturer's Association are the familiar 1N series for diodes, 2N for the three element transistors, and 3N for tetrode transistors. The diode type numbers such as 1N34, generally denote that the static characteristics will fall within certain specified limits. These are most often taken at three points: the forward current at +1 volt drop, and the currents at two values of back voltage. They are limits in the truest sense; the static characteristics may vary widely between units from the same manufacturer and between manufacturers, although all may fall within the specified limits for the given type number. A letter suffix on the type number may denote different static characteristics,* construction, or manufacturer from that of the original application for the given type number to the RTMA.

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* Higher back resistance in the 1N34A, 1N38A, and 1N56A

The specification of transistors is in a state of flux at present. Several AIEE-IRE committees are studying the problems, and they will probably make specific recommednations for standardization when their work is completed. The electrical description of transistors is included in several articles in the literature* to which the reader is referred.

2.0 Grown-Junction Diodes

The grown-junction diodes are constructed by the introduction of p-type impurities into the n-type melt as the germanium crystal is being grown, converting the remainder of the crystal to p-type with a higher impurity concentration. Then the ingot is cut into small rectangular prisms about 40 mils square and 120 mils long with the p-n junction normal to the length. Non-rectifying or "ohmic" contacts are soldered to each end and the diode has the cross section of Figure 2.1e. The junction is of high quality, i.e. the electrical characteristics are very similar to the ideal theoretical characteristics of a p-n junction.

The current-voltage relationship in an ideal p-n junction diode is the familiar expression:

$$I = I_o \left[\exp(qV/kT) - 1 \right]$$

where V is the junction voltage, k is Boltzman's constant, T is absolute temperature, and q is the electronic charge. This assumes that ohmic drop is negligible. I_o is a function of the temperature and the impurity concentrations of the germanium. The term kT/q is about 0.026 volt at room temperature, so that for positive voltages large with respect to 0.026 the exponential term is much larger than 1, and for negative voltages of the same magnitude the exponential becomes small compared to 1. This means that the expressions for forward and reverse current become:

$$I_f = I_o \left[\exp(V_f/0.026) \right] \qquad |V_f| > 0.026 \text{ volt.}$$

$$I_r = I_o \qquad |V_r| > 0.026 \text{ volt.}$$

At very high reverse voltages, the junction should exhibit a zener breakdown and the dynamic resistance would drop to a very low value. Present day germanium junction devices do not show a true zener, but an ionization or avalanche breakdown[13] due to carriers crossing the junction under extremely high fields.

The static reverse and forward characteristics of all the diode types are illustrated in figures 2.2 and 2.3 respectively. The curvature of the forward characteristic of the grown junction diode, 1784 #7, indicates that ohmic drop is not negligible in this diode. Since the resistivity of the germanium used in these grown junction diodes is relatively high this ohmic drop could be anticipated. The reverse current for the 1786 grown germanium junction diode is quite constant over a wide range of reverse voltage.

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* References 1, 2, 3, 4, 5, and 6 present thorough coverage of the subject.

3.0 Alloy Junction Diodes

The first step in the construction of the alloy or diffused junction diodes is the placing of a pellet of p-type impurity on the surface of an n-type wafer, soft-soldered to a conventional ohmic contact base. Under heating the impurity dot melts and dissolves a small amount of germanium at the surface. The device is allowed to cool, and the solution re-crystallizes producing a highly doped p-region. The cross section is Figure 2.1d. The linear forward characteristic of the 1N92 plotted in Figure 2.3 fits the ideal case quite well. The reverse has noticeable curvature and the magnitude of the saturation (or constant) current is high. This is typical of this particular series of alloy diodes and not the construction method.

An alloy silicon diode, Type A1821 #2, is included in the electrical characteristics. The dynamic forward resistance at currents below 1 ma is the same order as the forward resistance of the germanium devices, but the static resistance, or V_f/I_f, is much larger. The reverse resistance is very high at low voltages; the reverse current is usually measured in millimicroamperes in silicon devices. This particular diode shows what is most likely an avalanche breakdown at 37 volts.

4.0 Point Diodes

The point diodes are made by a large number of manufacturers and in a wide variety of types. Many of these, such as 1N34 and 1N38, have been in general use for years, although much less is known of the physics of point devices even at the present. The construction of point diodes is illustrated in Figure 2.1b. An n-type germanium wafer about 40 mils square and 10 to 20 mils thick is soldered to a metal base to make the usual ohmic contact. Then a catswhisker 1 to 2 mils diameter with a pointed or chisel shaped tip is placed in contact with the wafer's surface. A small amount of mechanical stress is added to the whisker for mechanical stability after contact is made. Then the diode is electrically "formed" for mechanical and electrical stability and the desired electrical characteristics. This forming is basically a heating process and may be done by condenser discharge or by alternating or direct currents of the order of an ampere for a fraction of a second. The effect of this forming is to produce a p-type germanium layer under the point, either by diffusion of impurities from the whisker or by heat production of lattice imperfections.[7] The size and quality of the p-region is apparently a function of the amount and length of time of forming, whisker shape, and least important, whisker material.

The principal physical difference between point and bonded diodes is the whisker material and the electrical prosessing. Point diode whisker materials used are hard, high-melting-point materials such as tungsten and molybdenum. In their commercially available forms, these materials often contain small amounts of p-type impurities.[7] In addition at least one manufacturer actually plates the whisker with an impurity material before construction. During forming the whisker tip retains its shape as the p-region forms, and the whisker apparently does not become physically attached to the germanium. Destruction of common diodes and examination of the surface of the germanium wafers has shown that it is extremely difficult, if not impossible, to determine where the contact had been. The p-n junction is ordinarily of low quality as shown in the electrical characteristics. The current increases directly (though not linearly) as back voltage increases, and the forward characteristic is curved throughout the range.

The electrical characteristics of point diodes are relatively complex functions of resistivity, surface states, and the size and character of the p-n junction. References 1, 2, 8, 9, 10, 11, and 12 furnish information on the subject although none presents a complete point diode theory.

5.0 Bonded Diodes

The whisker material of bonded germanium diodes is a low melting-point material, usually a gold alloy with a p-type impurity material. The electrical processing, or bonding, causes the whisker to melt under the localized heating, and dissolve a small amount of germanium. Cooling allows recrystallization and the result is a small-area, highly-doped p-region. The whisker tip may mushroom, and ordinarily forms a strong mechanical connection to the germanium. Cross section of the bonded diode is shown in Figure 2.1c. The electrical characteristics of the bonded diode illustrated in Figures 2.1 and 2.3, the T5 #29, indicate a high quality junction. Its reverse characteristic has low and fairly constant current. The forward resistance is quite low and the curvature of the forward characteristic is much less than for point devices.

6.0 Grown Junction Transistors

Transistors resemble two diodes on the same germanium wafer constructed so that the forward current in the emitter diode affects the reverse current in the collector diode. The various types of transistors are constructed in the same general way as the diodes of the same type.

Construction of the grown junction transistors is as follows: At a point in the drawing, or growing, of an n-type germanium crystal sufficient p-type impurities are introduced into the melt to cause the germanium to become p-type. The crystal is grown a very short distance and then an excess of n-type impurities is introduced to convert the crystal back to n-type, producing two p-n junctions with a common, thin layer of p-material between. Ohmic contacts are soldered to each end and to the p-region and the n-p-n transistor has the cross section of Figure 2.4d. All commercially available grown junction transistors are n-p-n. Electrical characteristics are illustrated in Figure 2.5a.

Current gain, α, is usually 0.90 to 0.999 and collector resistance, r_c, greater than a megohm.

7.0 Alloy Junction Transistors

Two alloy junction diodes on opposite sides of a very thin wafer produce an alloy or diffused junction transistor. Cross section is shown in Figure 2.4c and electrical characteristics in Figure 2.5b. Both α and r_c are slightly smaller than these parameters for the grown junction transistors; values of 0.85 to 0.99 and 0.3 to 1.0 megohm are typical. Most alloy junction transistors are p-n-p although one alloy n-p-n unit* was marketed for several months.

In normal operation of transistors, the emitter diodes are biased in the forward direction and collectors in the reverse. Forward bias of a p-n junction is p-positive. This means that collector voltage for n-p-n units is positive and for p-n-p negative; hence the inversion of the collector characteristics of these types in Figure 2.5a and 2.5b. The schematic symbol has an arrow in the emitter denoting the direction of forward current flow as in Figure 2.4a.

8.0 Point-Contact Transistors

Construction is illustrated in Figure 2.4b and electrical characteristics in Figure 2.5c. Two contacts are located close together on the surface of an n-type wafer. Only the collector is electrically formed to produce the desired transistor characteristics. The result is that the collector contact area becomes relatively large and its back resistance low. r_c is about 20,000 ohms and α varies from 2 to 3 in most point-contact transistors.

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* RCA 2N35

Signed Nolan T. Jones per DJE
Nolan T. Jones

Approved Donald J. Eckl
Donald J. Eckl

NTJ/jk

Drawings attached:

Figure 2.1 - A-58472
Figure 2.2 - A-58439
Figure 2.3 - C-58442
Figure 2.4 - A-59105
Figure 2.5 - A-58856

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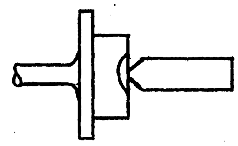
10. Cutler, M., "Point Contact Rectifiers in Germanium: Flow of Electrons and Holes Through the Surface Barrier," Hughes Aircraft Co. Report (May 1, 1953).

11. Cutler, M., "The Flow of Electrons and Holes in Point Contact Rectifiers," Hughes Aircraft Co. Report (April 1, 1953).

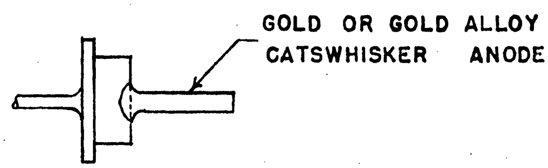
12. Torrey, H. C., and Whitmer, C. A., Crystal Rectifiers, McGraw-Hill Book Co., New York (1948).

13. McKay, K. G., "Avalanche Breakdown in Silicon," Physical Review, Vol. 94, No. 4 (May 15, 1954).

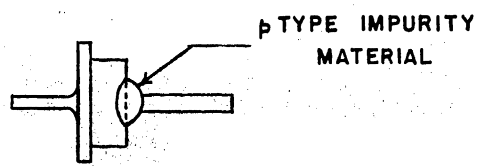
a) SCHEMATIC SYMBOL



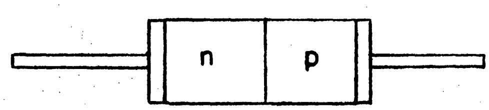
b) POINT CONTACT



c) GOLD BONDED



d) DIFFUSED JUNCTION



e) GROWN JUNCTION

FIG. 2.1

DIODE CONSTRUCTION TYPES

A-58472

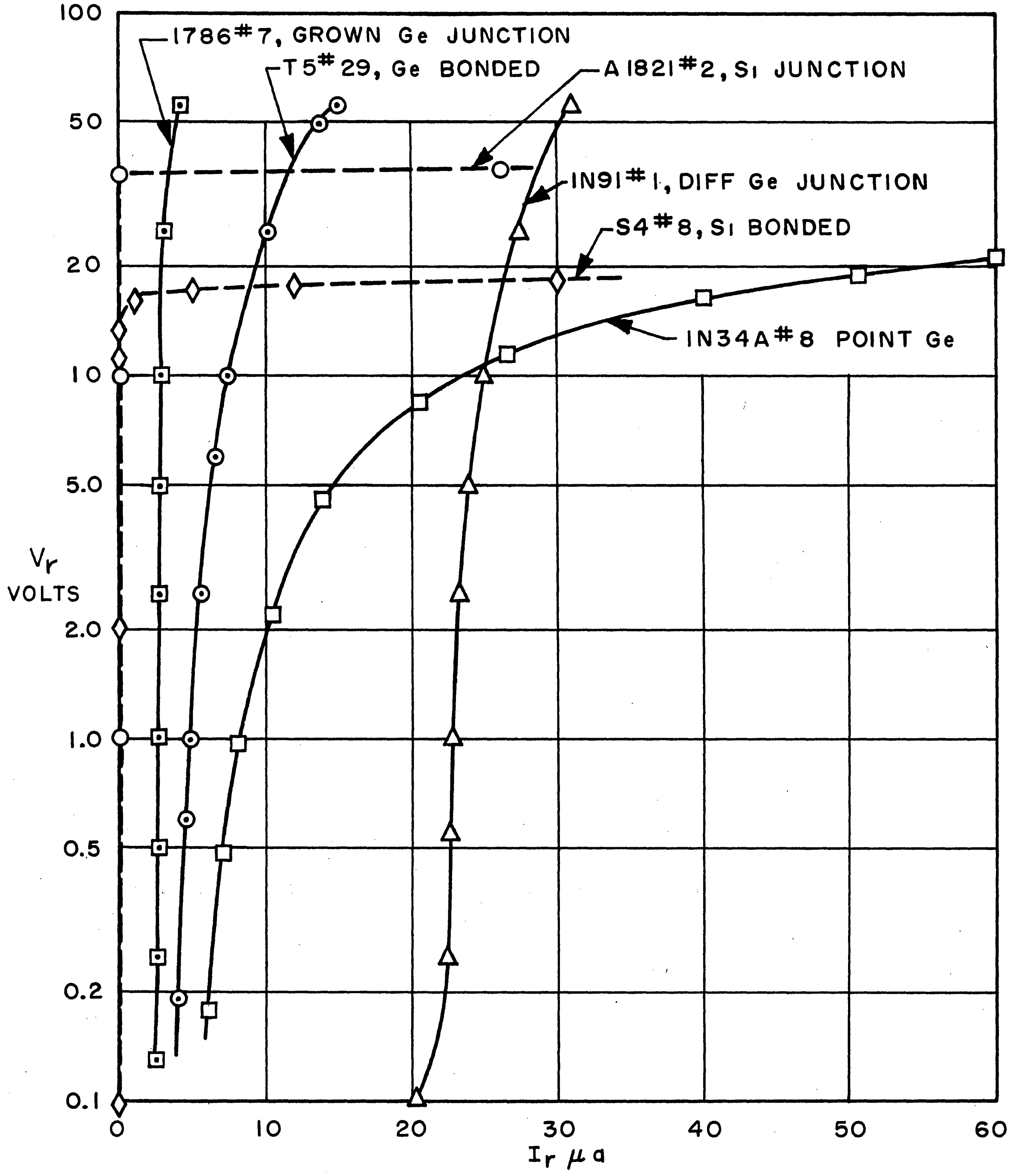


FIG. 2.2

TYPICAL STATIC REVERSE CHARACTERISTICS OF DIODES

A-58439

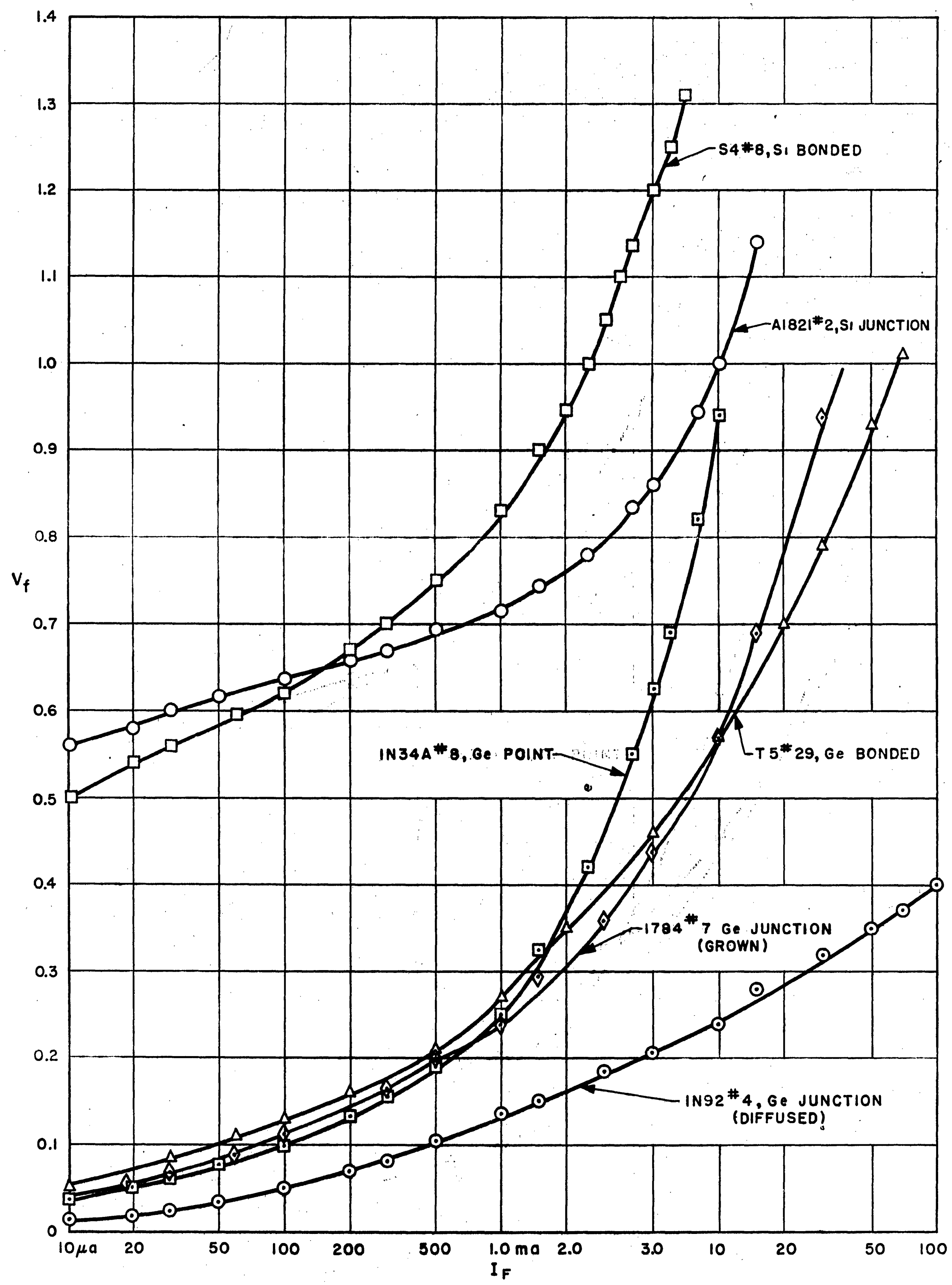
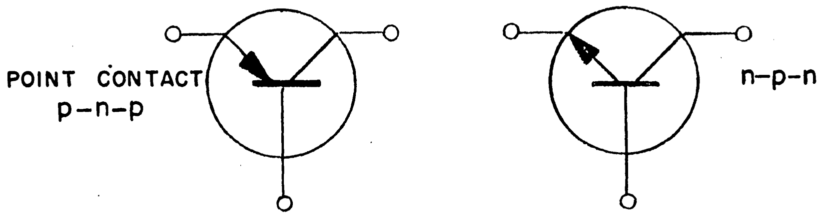


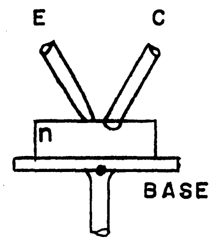
FIG. 2.3

TYPICAL STATIC FORWARD CHARACTERISTICS OF DIODES

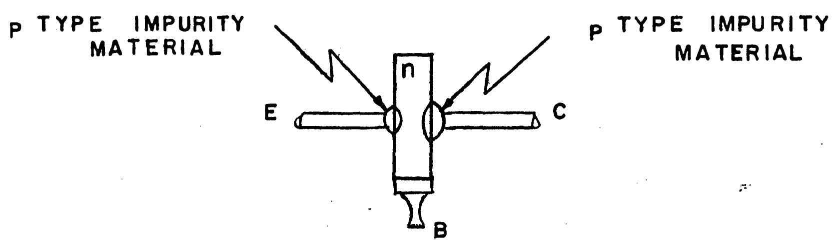
C-58442



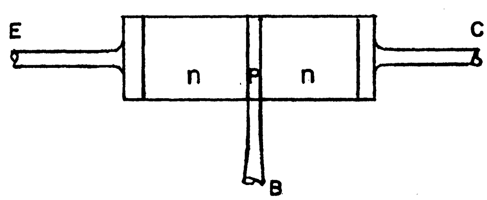
a) SCHEMATIC SYMBOLS



b) POINT CONTACT



c) DIFFUSED JUNCTION

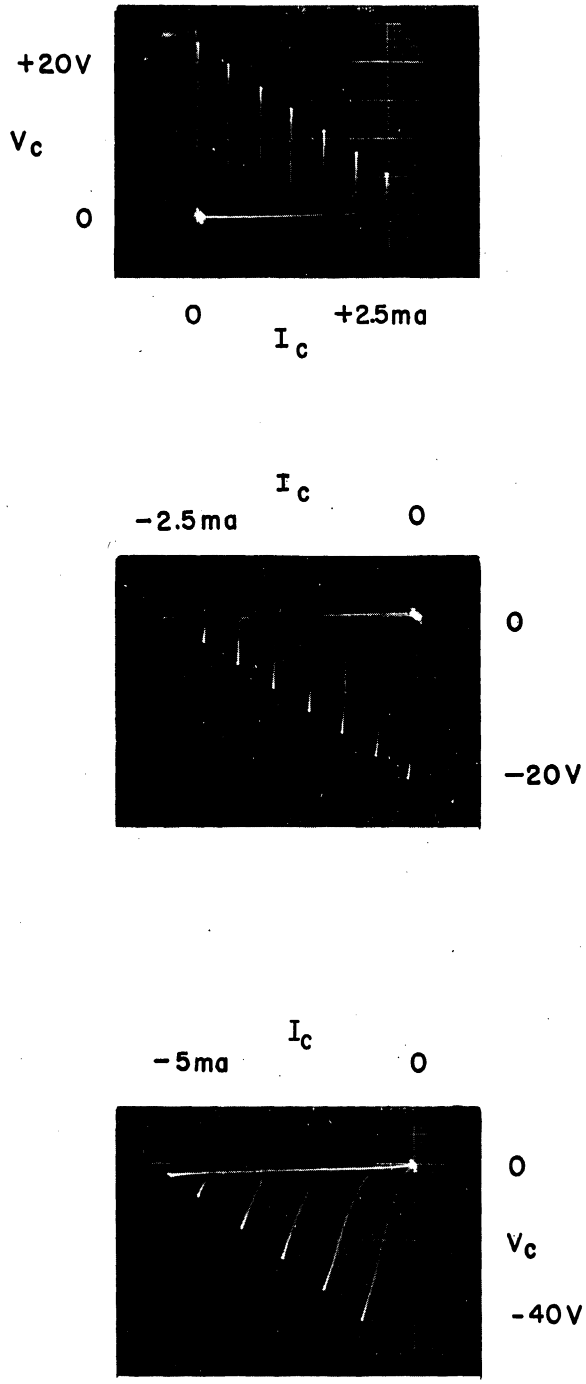


d) GROWN JUNCTION (n-p-n)

FIG. 2.4

TRANSISTOR CONSTRUCTION TYPES

A-59105



(a) GROWN N-P-N JUNCTION RDR TYPE 2517 NO. 10

ΔI_e = 0.5 ma IN ALL CASES

(b) ALLOY OR DIFFUSED P-N-P JUNCTION CBS-HYTRON 2N36 NO. 2

(c) POINT CONTACT RCA TA 165 NO. R 386

FIG. 2.5

COLLECTOR CHARACTERISTICS OF THE THREE COMMON TYPES OF TRANSISTORS

A-58856