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# **TEST CODE for TRANSISTORS**

## **SEMICONDUCTOR DEFINITIONS and LETTER SYMBOLS**



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J. S. Schaffner

S. K. Ghandi

B. J. Rothlein

K. Uhler

### Task Group on Definitions of Semiconductors

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J. M. Early, 52-54

B. J. Rothlein, 52-54

J. J. Ebers, 52-54

J. S. Schaffner, 52-54

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## TEST CODE for TRANSISTORS

### DEFINITIONS

- Acceptor** (in a Semiconductor)—See Impurity, Acceptor.
- Barrier** (in a Semiconductor) (Obsolete)—See Depletion Layer.
- Base Electrode** (of a Transistor)—An ohmic or majority carrier contact to the base region.
- Base Region**—The interelectrode region of a transistor into which minority carriers are injected.
- Boundary, P-N**—A surface in the transition region between P-type and N-type material at which the donor and acceptor concentrations are equal.
- Carrier**—In a semiconductor, a mobile conduction electron or hole.
- Collector** (of a Transistor)—An electrode through which a primary flow of carriers leaves the interelectrode region.
- Conduction Band**—A range of states in the energy spectrum of a solid in which electrons can move freely.
- Conductivity Modulation** (of a Semiconductor)—The variation of the conductivity of a semiconductor by variation of the charge carrier density.
- Conductivity, N-type**—The conductivity associated with conduction electrons in a semiconductor.
- Conductivity, P-type**—The conductivity associated with holes in a semiconductor.
- Contact, High Recombination Rate**—A semiconductor-semiconductor or metal-semiconductor contact at which thermal equilibrium carrier densities are maintained substantially independent of current density.
- Contact, Majority Carrier** (to a Semiconductor)—An electrical contact across which the ratio of majority carrier current to applied voltage is substantially independent of the polarity of the voltage while the ratio of minority carrier current to applied voltage is not independent of the polarity of the voltage.
- Crystal Pulling**—A method of crystal growing in which the developing crystal is gradually withdrawn from a melt.
- Depletion Layer** (in a Semiconductor)—A region in which the mobile carrier charge density is insufficient to neutralize the net fixed charge density of donors and acceptors.
- Diffusion Constant** (in a Homogeneous Semiconductor)—The quotient of diffusion current density by the charge carrier concentration gradient. It is equal to the product of the drift mobility and the average thermal energy per unit charge of carriers.
- Diffusion Length**—In a homogeneous semiconductor, the average distance to which minority carriers diffuse between generation and recombination.
- Diode, Semiconductor**—A two-electrode semiconductor device having an asymmetrical voltage-current characteristic.
- Donor** (in a Semiconductor)—See Impurity, Donor.
- Doping**—Addition of impurities to a semiconductor or production of a deviation from stoichiometric composition, to achieve a desired characteristic.
- Doping Compensation**—Addition of donor impurities to a P-type semiconductor or of acceptor impurities to an N-type semiconductor.
- Drift Mobility** (in a Homogeneous Semiconductor)—The average drift velocity of carriers per unit electric field.
- Note:** In general, the mobilities of electrons and holes are different.
- Electrode** (of a Semiconductor Device)—An element that performs one or more of the functions of emitting or collecting electrons or holes, or of controlling their movements by an electric field.
- Electrons, Conduction**—The electrons in the conduction band of a solid, which are free to move under the influence of an electric field.
- Element** (of a Semiconductor Device)—Any integral part of the semiconductor device that contributes to its operation.
- Emitter**—See Emitter, Majority and Emitter, Minority.
- Emitter, Majority** (of a Transistor)—An electrode from which a flow of majority carriers enters the interelectrode region.
- Emitter, Minority** (of a Transistor)—An electrode from which a flow of minority carriers enters the interelectrode region.
- Energy Gap** (of a Semiconductor)—The energy range between the bottom of the conduction band and the top of the valence band.
- Extrinsic Properties** (of a Semiconductor)—The properties of a semiconductor as modified by impurities or imperfections within the crystal.
- Fermi Level**—The value of the electron energy at which the Fermi distribution function has the value one-half.
- Forming, Electrical** (Applied to Semiconductor Devices)—Process of applying electrical energy to a semiconductor device in order to modify permanently the electrical characteristics.
- Generation Rate** (in a Semiconductor)—The time rate of creation of electron-hole pairs.
- Hall Constant** (of an Electrical Conductor)—The constant of proportionality  $R$  in the relation
- $$E_h = R \mathbf{J} \times \mathbf{H}, \text{ where}$$
- $E_h$  = Transverse electric field (Hall field)  
 $\mathbf{J}$  = Current density  
 $\mathbf{H}$  = Magnetic field.

**Note:** The sign of the majority carrier can be inferred from the sign of the Hall constant.

**Hole**—A mobile vacancy in the electronic valence structure of a semiconductor which acts like a positive electronic charge with a positive mass.

**Imperfection (of a Crystalline Solid)**—Any deviation in structure from that of an ideal crystal.

**Note:** An ideal crystal is perfectly periodic in structure and contains no foreign atoms.

**Impurity, Acceptor (in a Semiconductor)**—An impurity which may induce hole conduction.

**Impurity (Chemical)**—An atom within a crystal which is foreign to the crystal.

**Impurity, Donor (in a Semiconductor)**—An impurity which may induce electronic conduction.

**Impurity, Stoichiometric**—A crystalline imperfection arising from a deviation from stoichiometric composition.

**Intrinsic Properties (of a Semiconductor)**—The properties of a semiconductor which are characteristic of the pure, ideal crystal.

**Intrinsic Temperature Range (in a Semiconductor)**—The temperature range in which the electrical properties of a semiconductor are essentially not modified by impurities or imperfections within the crystal.

**Junction (in a Semiconductor Device)**—A region of transition between semiconducting regions of different electrical properties.

**Junction, Alloy (in a Semiconductor)**—A junction formed by alloying one or more impurities to a semiconductor crystal.

**Junction, Collector (of a Semiconductor Device)**—A junction normally biased in the high-resistance direction, the current through which can be controlled by the introduction of minority carriers.

**Junction, Emitter (of a Semiconductor Device)**—A junction normally biased in the low-resistance direction to inject minority carriers into an inter-electrode region.

**Junction, Fused (in a Semiconductor)**—A junction formed by recrystallization on a base crystal from a liquid phase of one or more components and the semiconductor.

**Junction, N-N (in a Semiconductor)**—A region of transition between two regions having different properties in N-type semiconducting material.

**Junction, P-N (in a Semiconductor)**—A region of transition between P- and N-type semiconducting material.

**Junction, P-P (in a Semiconductor)**—A region of transition between two regions having different properties in P-type semiconducting material.

**Junction (Semiconductor), Diffused**—A junction which has been formed by the diffusion of an impurity within a semiconductor crystal.

**Junction (Semiconductor), Doped**—A junction produced by the addition of an impurity to the melt during crystal growth.

**Junction (Semiconductor), Grown**—A junction produced during growth of a crystal from a melt.

**Junction (Semiconductor), Rate-grown**—A grown junction produced by varying the rate of crystal growth.

**Lifetime, Volume**—The average time interval between the generation and recombination of minority carriers in a homogeneous semiconductor.

**Majority Carrier (in a Semiconductor)**—The type of carrier constituting more than half of the total number of carriers.

**Minority Carrier (in a Semiconductor)**—The type of carrier constituting less than half of the total number of carriers.

**Mobility**—See Drift Mobility.

**Mobility, Hall (of an Electrical Conductor)**—The quantity  $\mu_H$  in the relation  $\mu_H = R\sigma$ , where  $R$  = Hall constant and  $\sigma$  = conductivity.

**Ohmic Contact**—A contact between two materials, possessing the property that the potential difference across it is proportional to the current passing through.

**Photovaristor**—A varistor in which the current-voltage relation may be modified by illumination, e.g., cadmium sulphide or lead telluride.

**Point Contact**—Pressure contact between a semiconductor body and a metallic point.

**Primary Flow (of Carriers)**—A current flow which is responsible for the major properties of the device.

**Recombination Rate, Surface**—The time rate at which free electrons and holes recombine at the surface of a semiconductor.

**Recombination Rate, Volume**—The time rate at which free electrons and holes recombine within the volume of a semiconductor.

**Recombination Velocity (on a Semiconductor Surface)**—The quotient of the normal component of the electron (hole) current density at the surface by the excess electron (hole) charge density at the surface.

**Semiconductor**—An electronic conductor, with resistivity in the range between metals and insulators, in which the electrical charge carrier concentration increases with increasing temperature over some temperature range. Certain semiconductors possess two types of carriers, namely, negative electrons and positive holes.

**Semiconductor, Compensated**—A semiconductor in which one type of impurity or imperfection (e.g., donor) partially cancels the electrical effects of the other type of impurity or imperfection (e.g., acceptor).

**Semiconductor Device**—An electron device in which the characteristic distinguishing electronic conduction takes place within a semiconductor.

**Semiconductor Device, Multiple Unit**—A semiconductor device having two or more sets of electrodes associated with independent carrier streams.

Note: It is implied that the device has two or more output functions which are independently derived from separate inputs, e.g., a duo-triode transistor.

**Semiconductor Device, Single Unit**—A semiconductor device having one set of electrodes associated with a single carrier stream.

Note: It is implied that the device has a single output function related to a single input.

**Semiconductor, Extrinsic**—A semiconductor with electrical properties dependent upon impurities.

**Semiconductor, Intrinsic**—A semiconductor whose electrical properties are essentially characteristic of the pure, ideal crystal.

**Semiconductor, N-type**—An extrinsic semiconductor in which the conduction electron density exceeds the hole density.

Note: It is implied that the net ionized impurity concentration is donor type.

**Semiconductor, P-type**—An extrinsic semiconductor in which the hole density exceeds the conduction electron density.

Note: It is implied that the net ionized impurity concentration is acceptor type.

**Space Charge Region** (Pertaining to Semiconductor)—A region in which the net charge density is significantly different from zero. See also Depletion Layer.

**Thermistor**—An electron device which makes use of the change of resistivity of a semiconductor with change in temperature.

**Transistor**—An active semiconductor device with three or more electrodes.

**Transistor, Conductivity Modulation**—A transistor in which the active properties are derived from minority carrier modulation of the bulk resistivity of a semiconductor.

**Transistor, Filamentary**—A conductivity modulation transistor with a length much greater than its transverse dimensions.

**Transistor, Junction**—A transistor having a base electrode and two or more junction electrodes.

**Transistor, Point-contact**—A transistor having a base electrode and two or more point-contact electrodes.

**Transistor, Point-junction**—A transistor having a base electrode and both point-contact and junction electrodes.

**Transistor, Unipolar**—A transistor which utilizes charge carriers of only one polarity.

**Transition Region**—The region, between two homogeneous semiconductor regions, in which the impurity concentration changes.

**Valence Band**—The range of energy states in the spectrum of a solid crystal in which lie the energies of the valence electrons which bind the crystal together.

**Varistor**—A two-electrode semiconductor device having a voltage-dependent nonlinear resistance.

**Zone Leveling** (Pertaining to Semiconductor Processing)—The passage of one or more molten zones along a semiconductor body for the purpose of uniformly distributing impurities throughout the material.

**Zone Purification** (Pertaining to Semiconductor Processing)—The passage of one or more molten zones along a semiconductor for the purpose of reducing the impurity concentration of part of the ingot.

## LETTER SYMBOLS

The Standard has been divided into three Sections:

- 1) Electrical quantities, dealing primarily with voltage, current, and time quantities.
- 2) Electrical parameters, dealing with the relationship between specific electrical quantities.
- 3) List of letter symbols in alphabetical order.

Electrical quantities at the device terminals are defined in Section 1. The electrical parameters of Section 2 are ratios of the terminal electrical quantities; i.e., they are two terminal-pair open- and short-circuit ratios. Letter subscripts are used for these ratios throughout this Standard; numeric subscripts following the matrix convention may be used when convenient, especially in the analysis of electric circuits.

### 1. Electrical Quantities

#### 1.1 Quantity Symbols

1.1.1 Instantaneous values of current, voltage, and power, which vary with time, are represented by the lower case letter of the proper symbol.

Examples:  $i$ ,  $v$ ,  $i_e$ ,  $v_{EB}$

1.1.2 Maximum, average (direct-current), and root-mean-square values are represented by the upper case letter of the proper symbol.

Examples:  $I$ ,  $V$ ,  $I_e$ ,  $V_{EB}$

#### 1.2 Subscripts for Quantity Symbols

1.2.1 Direct-current and instantaneous total values are indicated by upper case subscripts.

Examples:  $I_C$ ,  $I_C$ ,  $v_{EB}$ ,  $V_{EB}$ ,  $P_C$ ,  $P_C$

1.2.2 Varying component values are indicated by lower case subscripts.

Examples:  $i_c$ ,  $I_c$ ,  $v_{eb}$ ,  $V_{eb}$ ,  $p_c$ ,  $P_c$

1.2.3 If necessary to distinguish between maximum, average, or root-mean-square values; maximum or average values may be represented by the addition of a subscript *m* or *av*.

Examples:  $i_{cm}$ ,  $I_{cm}$ ,  $I_{CM}$ ,  $I_{cav}$ ,  $i_{CAV}$

1.2.4 Abbreviations to be used as subscripts. (For example, see Figure 1 and Basic Symbols Chart 1.2.5.)

*E, e* = emitter electrode

*B, b* = base electrode

*C, c* = collector electrode

*J, j* = electrode, general

*X, x* = circuit node

*M, m* = maximum value

*AV, av* = average value

*Q* = average (direct-current) value with signal applied.

1.2.5 Basic Symbols Chart (Table I)

TABLE I

| SYMBOLS                                                                                                    |                                       |                                          |
|------------------------------------------------------------------------------------------------------------|---------------------------------------|------------------------------------------|
|                                                                                                            | <i>i, v, p</i>                        | <i>I, V, P</i>                           |
| Subscripts<br><i>e</i><br><i>b</i><br><i>c</i><br><i>j</i><br><i>E</i><br><i>B</i><br><i>C</i><br><i>J</i> | Instantaneous Varying Component Value | RMS or Effective Varying Component Value |
|                                                                                                            | Instantaneous Total Value             | Average (dc) Value                       |

1.3 The Subscript Sequence Conforms to the Mathematical Convention for Writing Determinants from a Set of Fundamental Kirchhoff's Equations

1.3.1 The first subscript designates the electrode at which the current is measured, or where the electrode potential is measured with respect to the reference electrode, or circuit node, designated by the second subscript. (Conventional current flow into the electrode from the external circuit is positive.) When the reference electrode or circuit node is understood, the second subscript may be omitted, where its use is not required to preserve the meaning of the symbol.

1.3.2 Supply voltage may be indicated by repeating the electrode subscript. The reference electrode may then be designated by the third subscript. Examples:  $V_{EB}$ ,  $V_{CC}$ ,  $V_{BB}$ ,  $V_{EEB}$ ,  $V_{CCB}$ ,  $V_{BBC}$

1.3.3 In devices having more than one electrode of the same type, the electrode subscripts are modified by adding a number following the subscript and on the same line.

Example:  $B_2$

In multiple unit devices the electrode subscripts

are modified by a number preceding the electrode subscript.

Example:  $2B$

Wherever ambiguity might arise the complete electrode designations are separated by hyphens or commas.

Example:  $V_{1C_1-2C_1}$

1.3.4 When necessary to distinguish between components of current or voltage the symbols may be used as shown in Figure 2.1. The illustration shows a case where a small varying component is developed in the collector circuit of a transistor.

## 2. Electrical Parameters

### 2.1 Parameter Symbols

2.1.1 Values of four-pole matrix parameters, or other resistances, impedances, admittances, etc., inherent in the device, may be represented by the lower case symbol with the proper subscripts.

Examples:  $h_{ib}$ ,  $z_{fb}$ ,  $y_{oe}$ ,  $\alpha_{fb}$ ,  $h_{IB}$ ,  $\alpha_{FB}$

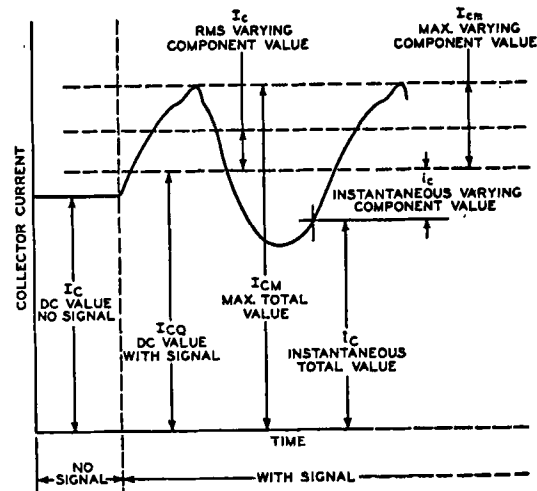


Figure 2.1—Illustration of proper symbol usage.

2.1.2 Values of four pole matrix parameters or other resistances, impedances, admittances, etc., in the external circuits, may be represented by the upper case symbols with the appropriate subscripts.

### 2.2 Subscript for Parameter Symbols

2.2.1 Static<sup>1</sup> values of parameters are indicated by the upper case subscript.

Examples:  $r_B$ ,  $h_{IB}$ ,  $\alpha_{FB}$

2.2.2 Small-signal values of parameters are indicated by the lower case subscript.

Examples:  $r_b$ ,  $y_o$ ,  $h_{ib}$ ,  $z_{ob}$ ,  $\alpha_{fb}$

2.2.3 The first subscript or subscript pair in matrix

notation, identifies the element of the four-pole matrix.

- $i$  or  $11$  = input
- $o$  or  $22$  = output
- $f$  or  $21$  = forward transfer
- $r$  or  $12$  = reverse transfer

Examples:  $V_i = h_i I_i + h_r V_o$   $V_1 = h_{11} I_1 + h_{12} V_2$   
 $I_o = h_f I_i + h_o V_o$   $I_2 = h_{21} I_1 + h_{22} V_2$

Note: Voltage and current symbols in matrix notation are designated with a single digit subscript. The subscript 1 = input. The subscript 2 = output.

**2.2.4** The second subscript or the subscript following the numeric pair identifies the circuit configuration. When the common electrode is understood, the second subscript may be omitted.

- $e$  = common emitter
- $b$  = common base
- $c$  = common collector
- $j$  = common electrode, general.

Examples: (common base)

$I_i = y_{ib} V_{ib} + y_{rb} V_{ob}$   $I_1 = y_{11b} V_{1b} + y_{12b} V_{2b}$   
 $I_o = y_{fb} V_{ib} + y_{ob} V_{ob}$   $I_2 = y_{21b} V_{1b} + y_{22b} V_{2b}$

<sup>1</sup> The static value is the slope of the line from the origin to the operating point on the appropriate characteristic curve.

**2.2.5** Electrical parameters characterizing the behavior of a device with associated circuitry are designated by upper case symbols with an appropriate subscript; e.g.,  $Z_i$ ,  $Z_o$ . The termination may be indicated by an additional subscript such as:  $o$  = alternating-current open-circuit termination;  $s$  = alternating-current short-circuit termination;  $a$  or other appropriate subscript for other terminations. This additional subscript may be omitted.

Examples:  $Z_{io}$ ,  $Z_{is}$ ,  $Z_{ia}$ ,  $Z_{i \text{ match}}$

### 3. Letter Symbols in Alphabetical Order

The following list has been compiled according to the conventions set forth in Sections 1 and 2 of this Standard.

In general, the first symbol given for each electrical quantity or parameter illustrates the basic symbol with the subscript which designates the reference electrode or common electrode. (See Sections 1.3.1 and 2.2.5.) The transfer ratio of the current generator shunting the collector branch low-frequency equivalent circuit is shown in Figure 2.

$\alpha_F$ ,  $\alpha_{FB}$ ,  $\alpha_{FC}$ ,  $\alpha_{FE}$ —The static value of the short-circuit forward current transfer ratio.<sup>2</sup>

$\alpha_f$ ,  $\alpha_{fb}$ ,  $\alpha_{fc}$ ,  $\alpha_{fe}$ —The small-signal short-circuit forward current transfer ratio.<sup>2</sup>

$\alpha_R$ ,  $\alpha_{RB}$ ,  $\alpha_{RC}$ ,  $\alpha_{RE}$ —The static value of the short-circuit reverse current transfer ratio.<sup>2</sup>

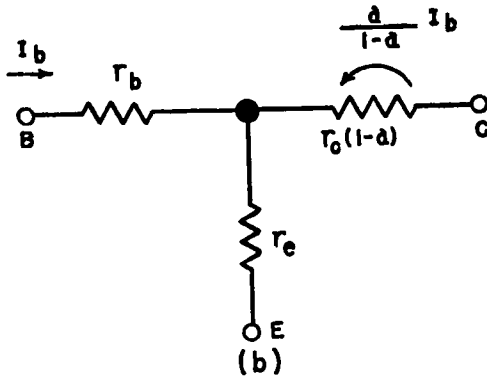
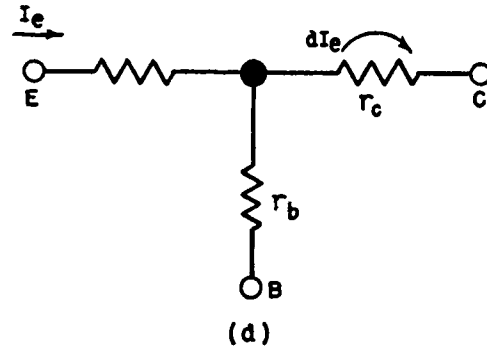


Figure 2.2—Low frequency  $T$  equivalent circuit. (a) base common; (b) emitter common.

$\alpha_r$ ,  $\alpha_{rb}$ ,  $\alpha_{rc}$ ,  $\alpha_{re}$ —The small-signal short-circuit reverse current transfer ratio.<sup>2</sup>

<sup>2</sup> The algebraic sign of  $\alpha$  for the common base configuration is taken as positive in accordance with established usage, therefore  $\alpha_{fb} = -h_{fb} = -h_{21b}$ .

$C_o$ ,  $C_{ob}$ ,  $C_{oc}$ ,  $C_{oe}$ —The capacitance measured across the output terminals with the input open-circuited to alternating-current.

$f_a$ ,  $f_{ab}$ ,  $f_{ac}$ ,  $f_{ae}$ —The frequency at which the magnitude of the small-signal short-circuit forward current transfer ratio is 0.707 of the low-frequency value.

$h_F$ ,  $h_{FB}$ ,  $h_{FC}$ ,  $h_{FE}$ —The static value of the short-circuit forward current transfer ratio.

$h_f$ ,  $h_{fb}$ ,  $h_{fc}$ ,  $h_{fe}$ ,  $h_{21}$ ,  $h_{21b}$ ,  $h_{21c}$ ,  $h_{21e}$ —The small-signal short-circuit forward current transfer ratio.

$h_i$ ,  $h_{ib}$ ,  $h_{ic}$ ,  $h_{ie}$ —The static value of the short-circuit input resistance.

$h_o$ ,  $h_{ob}$ ,  $h_{oc}$ ,  $h_{oe}$ ,  $h_{11}$ ,  $h_{11b}$ ,  $h_{11c}$ ,  $h_{11e}$ —The small-signal value of the short-circuit input impedance.

$h_o$ ,  $h_{ob}$ ,  $h_{oc}$ ,  $h_{oe}$ —The static value of the open-circuit output conductance.

$h_o$ ,  $h_{ob}$ ,  $h_{oc}$ ,  $h_{oe}$ ,  $h_{22}$ ,  $h_{22b}$ ,  $h_{22c}$ ,  $h_{22e}$ —The small-signal value of the open-circuit output admittance.

$h_R$ ,  $h_{RB}$ ,  $h_{RC}$ ,  $h_{RE}$ —The static value of the open-circuit reverse voltage transfer ratio.

$h_r$ ,  $h_{rb}$ ,  $h_{rc}$ ,  $h_{re}$ ,  $h_{12}$ ,  $h_{12b}$ ,  $h_{12c}$ ,  $h_{12e}$ —The small-signal value of the open-circuit reverse voltage transfer ratio.

$I_{BO}$ ,  $I_{BEO}$ ,  $I_{BCO}$ —The base current when the base is biased in the reverse (high resistance) direction with respect to the reference electrode and the other electrode(s) is direct-current open-circuited (to the reference electrode).

$I_{BS}$ ,  $I_{BES}$ ,  $I_{BCS}$ —The base current when the base is biased in the reverse (high resistance) direction with respect to the reference electrode and the other electrode(s) is direct-current short-circuited (to the reference electrode).

$I_{CO}$ ,  $I_{CEO}$ ,  $I_{CBO}$ —The collector current when the collector is biased in the reverse (high resistance) direction with respect to the reference electrode and the other electrode(s) is direct-current open-circuited (to the reference electrode).

$I_{CS}$ ,  $I_{CES}$ ,  $I_{CBS}$ —The collector current when the collector is biased in the reverse (high resistance) direction with respect to the reference electrode and the other electrode(s) is direct-current short-circuited (to the reference electrode).

$I_{EO}$ ,  $I_{EBO}$ ,  $I_{ECO}$ —The emitter current when the emitter is biased in the reverse (high resistance) direction with respect to the reference electrode and the other electrode(s) is direct-current open-circuited (to the reference electrode).

$I_{ES}$ ,  $I_{EBS}$ ,  $I_{ECS}$ —The emitter current when the emitter is biased in the reverse (high resistance) direction with respect to the reference electrode and the other electrode(s) is direct-current short-circuited (to the reference electrode).

$r_b$ —Resistance of the base branch of the low-frequency equivalent circuit shown in Figure 2.2.

$r_c$ —Resistance of the collector branch of the low-frequency equivalent circuit shown in Figure 2.2.

$r_e$ —Resistance of the emitter branch of the low-frequency equivalent circuit shown in Figure 2.2.

$r_m$ —The product of  $a$  and  $r_e$  of the low-frequency equivalent circuit shown in Figure 2.2.

$t_d$ —The ohmic delay time is the time interval between the rise of a pulse applied at the input terminals and the rise of the minority-carrier-generated pulse appearing at the output terminals.

$t_s$ —The storage time is the time interval between the fall of a pulse applied to the input terminals and the fall of the carrier-generated pulse at the output terminals.

$V_{CF}$ ,  $V_{CBF}$ ,  $V_{EF}$ ,  $V_{EBF}$ ,  $V_{CEF}$ ,  $V_{ECF}$ ,  $V_{BF}$ ,  $V_{BEF}$ ,  $V_{BCF}$ —The direct-current open-circuit voltage (floating potential) between the electrode indicated by the first subscript and the reference electrode when the other electrode is biased in the reverse (high resistance) direction with respect to the reference electrode.

$BV_{CO}$ ,  $BV_{CBO}$ ,  $BV_{CEO}$ ,  $BV_{EO}$ ,  $BV_{EBO}$ ,  $BV_{ECO}$ ,  $BV_{BO}$ ,  $BV_{BEO}$ ,  $BV_{BCO}$ —The breakdown voltage between the electrode indicated by the first subscript when it is biased in the reverse (high resistance) direction with respect to the reference electrode and the other electrode is open-circuited.

$\mu_f$ ,  $\mu_{fb}$ ,  $\mu_{fc}$ ,  $\mu_{fe}$ —The small-signal open-circuit forward voltage-transfer ratio.

$\mu_r$ ,  $\mu_{rb}$ ,  $\mu_{rc}$ ,  $\mu_{re}$ —The small-signal open-circuit reverse voltage-transfer ratio.

$\mu_F$ ,  $\mu_{FB}$ ,  $\mu_{FC}$ ,  $\mu_{FE}$ —The static value of the open-circuit forward voltage-transfer ratio.

$\mu_R$ ,  $\mu_{RB}$ ,  $\mu_{RC}$ ,  $\mu_{RE}$ —The static value of the open-circuit reverse voltage-transfer ratio.

$y_f$ ,  $y_{fb}$ ,  $y_{fc}$ ,  $y_{fe}$ ,  $y_{21}$ ,  $y_{21b}$ ,  $y_{21c}$ ,  $y_{21e}$ —The small-signal short-circuit forward transfer admittance.

$y_i$ ,  $y_{ib}$ ,  $y_{ic}$ ,  $y_{ie}$ ,  $y_{11}$ ,  $y_{11b}$ ,  $y_{11c}$ ,  $y_{11e}$ —The small-signal short-circuit input admittance.

$y_o$ ,  $y_{ob}$ ,  $y_{oc}$ ,  $y_{oe}$ ,  $y_{22}$ ,  $y_{22b}$ ,  $y_{22c}$ ,  $y_{22e}$ —The small-signal short-circuit output admittance.

$y_r$ ,  $y_{rb}$ ,  $y_{rc}$ ,  $y_{re}$ ,  $y_{12}$ ,  $y_{12b}$ ,  $y_{12c}$ ,  $y_{12e}$ —The small-signal short-circuit reverse transfer admittance.

$z_f$ ,  $z_{fb}$ ,  $z_{fc}$ ,  $z_{fe}$ ,  $z_{21}$ ,  $z_{21b}$ ,  $z_{21c}$ ,  $z_{21e}$ —The small-signal open-circuit forward transfer impedance.

$z_i$ ,  $z_{ib}$ ,  $z_{ic}$ ,  $z_{ie}$ ,  $z_{11}$ ,  $z_{11b}$ ,  $z_{11c}$ ,  $z_{11e}$ —The small-signal open-circuit input impedance.

$z_o$ ,  $z_{ob}$ ,  $z_{oc}$ ,  $z_{oe}$ ,  $z_{22}$ ,  $z_{22b}$ ,  $z_{22c}$ ,  $z_{22e}$ —The small-signal open-circuit output impedance.

$z_r$ ,  $z_{rb}$ ,  $z_{rc}$ ,  $z_{re}$ ,  $z_{12}$ ,  $z_{12b}$ ,  $z_{12c}$ ,  $z_{12e}$ —The small-signal open-circuit reverse transfer impedance.

$z_{f\beta}$ ,  $z_{fb\beta}$ ,  $z_{fc\beta}$ ,  $z_{fe\beta}$ —(The reciprocal of  $y_f$ ) The small-signal short-circuit forward transfer impedance.

$z_{i\beta}$ ,  $z_{ib\beta}$ ,  $z_{ic\beta}$ ,  $z_{ie\beta}$ —The small-signal short-circuit input impedance.

$z_{o\beta}$ ,  $z_{ob\beta}$ ,  $z_{oc\beta}$ ,  $z_{oe\beta}$ —The small-signal short-circuit output impedance.

$z_{r\beta}$ ,  $z_{rb\beta}$ ,  $z_{rc\beta}$ ,  $z_{re\beta}$ —The small-signal short-circuit reverse transfer impedance (the reciprocal of  $y_r$ ).

## METHODS OF TEST—SMALL SIGNAL

### 4.0 General

#### 4.1 Scope

This standard deals with the methods of measurement of important characteristics of transistors. In general, these characteristics are referred to as parameters of the devices.

Because of the youthfulness of the transistor art, methods of testing transistors will continue to change considerably before the art can be considered to have "stabilized" sufficiently for complete standardization. This standard corresponds to the current state of transistor testing methods, and its publication is considered preferable to waiting for a future stabilization of the many rapid changes now characteristic of this field.

#### 4.2 General Precautions

Attention is called to the necessity, especially in tests of apparatus of low power, of eliminating, or correcting for, errors due to the presence of the measuring instruments in the test circuit. This applies particularly to the currents taken by voltmeters.

Attention is also called to the desirability of keeping the test conditions, such as collector voltage and collector current, within the safe limits specified

by the manufacturers. If the specified limits are exceeded, the characteristics of the transistors may be permanently altered and subsequent tests vitiated. When particular tests are required to extend somewhat beyond a specified safe limit, such portions of the test should be made as rapidly as possible and preferably after the conclusion of the tests within the specified safe limit.

**4.2.1 Repeatability:** Care must be taken that the measured parameter values are repeatable within precision of measurement after performance of any one or all tests performed on the device.

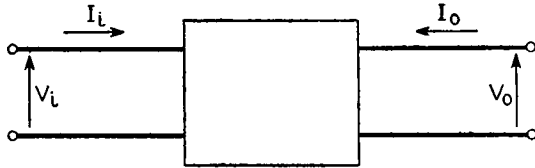


Figure 4.1—General four-terminal network.

#### 4.3 Four-Terminal Representation

Figure 4.1 shows a four-terminal network sometimes known as a two-terminal pair. The behavior of this network may be defined in terms of the quantities  $V_i$ ,  $V_o$ ,  $I_i$ , and  $I_o$ . The alternating input current and voltage are  $I_i$  and  $V_i$  and the output current and voltage are  $I_o$  and  $V_o$ . Similarly, the direct-current characteristics may be represented in terms of the input and output voltage,  $V_i$  and  $V_o$ , and the input and output current,  $I_i$  and  $I_o$ .

Since the transistor may be employed in three circuit configurations usually referred to as common base, common emitter, and common collector, there is a possible ambiguity in the definition of any one parameter unless the circuit configuration is stated definitely. Six possible sets of parameters exist for defining the four-terminal network and the choice of the appropriate set therefore depends on the nature of the device to be characterized.

The  $h$  parameters are used throughout the standard since they are peculiarly adaptable to the physical characteristics of transistors. In previous literature these have been referred to as the series-parallel parameters, but a recent paper<sup>1</sup> coined the name "hybrid" which has become a significant method of identification and will, in the interests of clarity, be used throughout this standard.

A specific method of notation involving the letter subscript is used throughout this standard, but no preference over number subscripts is implied thereby. See IRE Standards on Letter Symbols for Semiconductor Devices, 1956 (56 IRE 28. S1).<sup>2</sup>

The three most commonly used sets of parametric equations are:

Open-circuit impedance parameters

$$V_i = z_i I_i + z_r I_o \quad (4.1)$$

$$V_o = z_f I_i + z_o I_o \quad (4.2)$$

Short-circuit admittance parameters

$$I_i = y_i V_i + y_r V_o \quad (4.3)$$

$$I_o = y_f V_i + y_o V_o \quad (4.4)$$

Hybrid parameter

$$V_i = h_i I_i + h_r V_o \quad (4.5)$$

$$I_o = h_f I_i + h_o V_o \quad (4.6)$$

The input impedance  $h_i$  is the impedance between the input terminals when the output terminals are alternating-current short-circuited.

$$h_i = V_i / I_i \text{ when } V_o = 0.$$

The voltage feedback ratio  $h_r$  is the ratio of the voltage appearing at the input terminals, when they are alternating-current open-circuited, to the voltage applied to the output terminals

$$h_r = V_i / V_o \text{ when } I_i = 0.$$

The forward current multiplication factor  $h_f$  is the ratio of the current flowing into the output terminals, when they are alternating-current short-circuited, to the current flowing into the input terminals

$$h_f = I_o / I_i \text{ when } V_o = 0.$$

The output admittance  $h_o$  is the admittance between the output terminals when the input terminals are alternating-current open-circuited.

$$h_o = I_o / V_o \text{ when } I_i = 0.$$

#### LIST OF TERMS

$V_i$  = alternating input voltage.

$V_o$  = alternating output voltage.

$I_i$  = alternating input current.

$I_o$  = alternating output current.

$V_i$  = direct input voltage.

$V_o$  = direct output voltage.

$I_i$  = direct input current.

$I_o$  = direct output current.

$z_i$  = input impedance, small signal, output open-circuited.

$z_o$  = output impedance, small signal, input open-circuited.

$z_f$  = forward transfer impedance, small signal, output open-circuited.

$z_r$  = reverse transfer impedance, small signal, input open-circuited.

$y_i$  = input admittance, small signal, output short-circuited.

$y_o$  = output admittance, small signal, input short-circuited.

$y_f$  = forward transfer admittance, small signal, output short-circuited.

$y_r$  = reverse transfer admittance, small signal, input short-circuited.

$h_i$  = input impedance, small signal, output short-circuited.

$h_f$  = input resistance, static value, output short-circuited.

$h_o$  = output admittance, small signal, input open-circuited.

$h_o$  = output conductance, static value, input open-circuited.

$h_f$  = forward current transfer ratio, small signal, output short-circuited ( $= -\alpha_f$ ).  
 $h_F$  = forward current transfer ratio, static value, output short-circuited ( $= -\alpha_F$ ).  
 $h_r$  = reverse voltage transfer ratio, small signal, input open-circuited.  
 $h_R$  = reverse voltage transfer ratio, static value, input open-circuited.  
 $z_{in}$  = input impedance, small signal, output termination  $Z_o$ .  
 $z_{out}$  = output admittance, small signal, input termination  $Z_i$ .  
 $V_e$  = alternating emitter voltage.  
 $I_e$  = alternating emitter current.  
 $V_c$  = alternating collector voltage.  
 $I_c$  = alternating collector current.  
 $r_e$  = alternating-current emitter resistance derived from  $T$ -equivalent circuit.  
 $r_b$  = alternating-current base resistance derived from  $T$ -equivalent circuit.  
 $r_c$  = alternating-current collector resistance derived from  $T$ -equivalent circuit.  
 $r_m$  = alternating-current transfer resistance derived from  $T$ -equivalent circuit.  
 $C_o$  = collector capacitance measured at collector electrode.

Note: See also IRE Standards on Letter Symbols for Semiconductor Devices, 1956 (56 IRE 28. S1).<sup>2</sup>

## 5.0 METHODS OF TEST FOR DIRECT-CURRENT CHARACTERISTICS

The static characteristics of a transistor represent its performance only at zero or low frequency. The static characteristics are the input, output, and transfer. In general, these characteristics may be obtained up to the point where thermal effects become significant, or where critical voltages or currents are exceeded. High frequency or pulse methods such as those described in section 5.1.3 may be used to obtain information beyond this point.

### 5.1 Direct-Current Point-by-Point Method

The point-by-point method of obtaining characteristics requires the introduction of a direct voltage or current at one pair of terminals, and the measurement of the current or voltage at either the same or a different pair of terminals, depending upon the characteristics under examination. A family of characteristics can be obtained by measuring a voltage-current characteristic while another voltage or current is changed

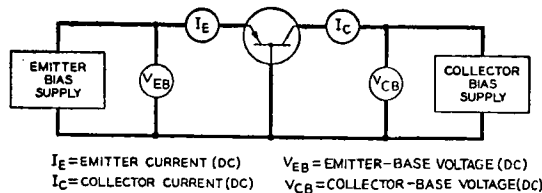


Figure 5.1—General direct-current measurement arrangement.

stepwise over the range of interest in accordance with usual practice. A representative arrangement for the determination of the common base characteristics of transistors is shown in Figure 5.1.

#### 5.1.1 General Precautions in Transistor Measurement:

Test conditions which cause large voltage or current surges, or exceed the safe limit of direct-current power dissipation should be avoided. Large overloads even for a small fraction of a second may cause damage to a transistor or modify its characteristics.

The correct voltage polarity must be observed at all times. Incorrect voltage polarity may seriously damage the transistor and test equipment.

Transistors are inherently temperature sensitive devices. The effect of the ambient temperature must be taken into account, and possibly also the internal temperature rise due to the dissipation in the device occurring during the test.

#### 5.1.2 Visual Displays:

Visual displays of transistor static characteristics are useful for prediction of performance in circuits up to frequencies at which reactance effects become important. Oscilloscopic displays are useful in disclosing small irregularities in the voltage-current characteristics which may escape observation by the point-by-point method. The visual display is particularly useful for determination of trends or orders of magnitude in transistor parameters.

The transistor static characteristics normally displayed visually are: input voltage versus input current; input voltage versus output current; output voltage versus input current; output voltage versus output current; and output current versus input current.

##### 5.1.2.1 General Precautions in Oscilloscopic Display:

As a preliminary step a passive network may be used as a dummy transistor to check the over-all circuit performance before actual application to transistors, and the voltage-current characteristic may be compared with known or published curves.

Cumulative heating effects must be anticipated. If extreme care to prevent overloading is not taken a gradual shift in the observed characteristic is noted.

Instability may result if suitable series resistance is not provided, particularly in the case of point-contact transistors which are in general short-circuit unstable.

In addition, the general procedures noted in section 6.5 must be observed.

#### 5.1.3 Pulse Methods:

It is often of considerable importance to know the static characteristics of transistors beyond the normal operating range where thermal effects would be significant if point-by-point methods were used. In such cases it is necessary to employ pulse methods in which the transistor is allowed to pass currents only for short intervals of such duration and recurrence frequency that the average power dissipation is small.

Pulse methods may be employed for obtaining input, output, and transfer characteristics. The basic circuit elements required for a pulse method are pulse generators and suitable current and voltage indicators. Where one pulse generator is employed, it is usually connected to the appropriate terminals depending upon the characteristic desired, with provision for introducing bias. If more than one pulse generator is used, it is necessary to synchronize the pulses. In general, one pulse generator is adequate and simpler to employ.

A variable amplitude pulse voltage or current is applied to one pair of terminals and simultaneously the corresponding pulse amplitude of current or voltage is measured at the same or a different pair of terminals.

**5.1.3.1 Precautions:** Care must be taken that the original static characteristics are reproducible after the device has been pulsed.

## 5.2 Load (Dynamic) Characteristics

The methods used for the determination of load characteristics from static characteristic curves, and the direct measurement of load characteristics have been published.<sup>3</sup> Load characteristics permit calculation of the performance data for the transistor such as input power, output power, efficiency, dissipations, etc.

### 5.2.1 Direct Measurement of Load Characteristics:

The load characteristics of a transistor can be measured directly, without resorting to calculation from the static characteristics. When reactive effects are significant, they will have considerable effect upon the load characteristic. It is therefore advisable to measure load characteristics at the frequency at which the transistor is to be used.

## 5.3 Maximum Electrode Voltage

When the voltage-current characteristic of a transistor is presented by any appropriate technique, marked changes in slope and/or discontinuities may be noted as a function of electrode voltage and circuit configuration. These may be due to either junction breakdown, thermal gradients, or internal instabilities. In general, a junction breakdown may be correlated with the resistivity of the material in the base layer, while that due to thermal gradients is generally much lower, and is characteristically poorly defined.

**5.3.1 General:** A maximum electrode voltage is measured by the potential which results in a specified change in the parameter being measured. It may also represent a potential above which destructive irreversible changes occur in the transistor. In either event it represents a locus of electrode bias voltages and currents which define maximum usable operating conditions. The maximum electrode voltage will be a function of the common electrode utilized when the characteristics are taken.

When specifying the peak voltage, even though non-destructive, the duration of the peak and the duty

cycle must be specified because of the short thermal time constants of the semiconductor element.

**5.3.2 Definition:** A maximum electrode voltage may be defined on any of the following bases:

- 1) Junction voltage breakdown.
- 2) Maximum power dissipation capability of the transistor.
- 3) Nonlinearity of the electrode voltage-current characteristic.

An example of these limitations is shown for a typical collector voltage-current characteristic in Figure 5.3. In this figure it may be seen that the definitions just given will govern in different regions of the characteristic. The maximum electrode voltage for the characteristic shown will be given by  $V_{C2}$ ,  $V_{C3}$ , and  $V_{C4}$ .

$V_{C2}$  is defined as the voltage corresponding to the point of tangency of the voltage saturation tangent with the  $I_C - V_C$  curve, with input current specified as shown in Figure 5.3.

$V_{C3}$  defines the voltage at which the rated power dissipation is attained.

$V_{C4}$  defines the voltage at which the nonlinearity of the characteristic becomes a substantial limitation to use.

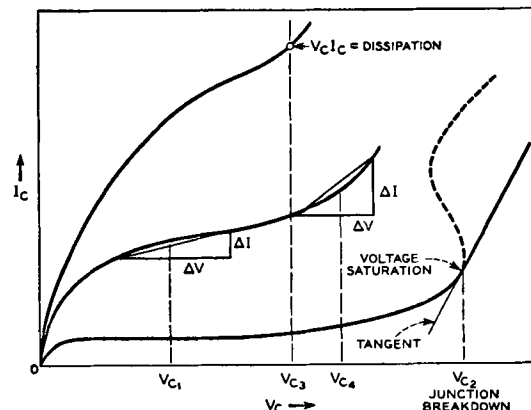


Figure 5.3—Maximum electrode voltages.

**5.3.3 Precautions:** The following specific precautions should be followed in addition to those noted in section 5.1.1. a) High-speed oscilloscopic sweep methods may be preferable to point-by-point and other low-speed methods, because inaccuracies due to thermal gradients and incipient junction breakdown are minimized. b) The electrical characteristics must be reproducible within the margin of error after a determination of maximum collector voltage.

## 6.0 METHODS OF TEST FOR SMALL SIGNAL APPLICATIONS

For purposes of this section small signal operation assumes linearity over the operating range. For linear operation the transistor is completely specified by means of four independent parameters which are in