PUBLICATION

semiconductor products

Minneapolis-Honeywell Regulator Company
MINNEAPOLIS 8, MINNESOTA

FUNDAMENTAL VOLTAGE LIMITATIONS OF A TRANSISTOR

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I. Introduction

One of the most critical limitations of a transistor is the magnitude of voltage to which it can be subjected. The voltage at which a transistor breaks down is a function of both the individual transistor characteristics and its associated circuitry In order to understand the dependency on the circuit, it is necessary to first fully comprehend the basic modes of breakdown—avalanche, alpha multiplication ($\alpha = 1$) and punch through (sometimes called reach through) None of these breakdown phenomena or, for that matter, any mechanism of voltage breakdown is, by itself, damaging. It is the power and heat developed by the usually high current flow under breakdown conditions that results in permanent degradation of the transistor characteristics. This paper presents a summary of the basic breakdown phenomena and the relationships between those phenomena and the actual modes of breakdown observed in typical alloyed junction germanium power transistor applications.

II. Basic Transistor Voltage Breakdown Mechanisms

A. Avalanche Breakdown

Avalanche breakdown is the breakdown of the collector diode, itself, and is in no way dependent on transistor action. This mechanism of breakdown is the same means by which a "zener" diode reaches and maintains a constant potential when a reverse current is passed through it. See Figure 1

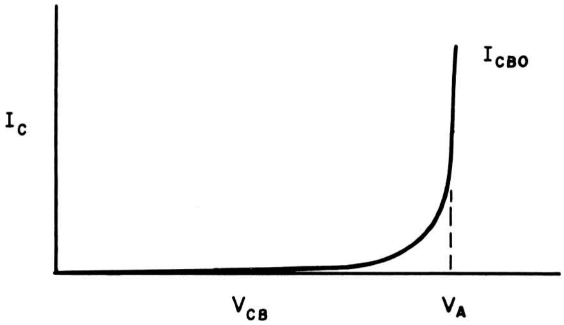

Fig. 1—Avalanche Breakdown.

The additional current carriers that lead to the breakdown are formed by collisions between the rapidly accelerated minority carriers and the valence electrons of the germanium atoms in the crystal network. This carrier increase in similar to that which occurs in a gas tube (Townsend breakdown) In contrast, the true zener type breakdown results from the formation of additional carriers due to the "stripping" of the valence electrons by the high field strength imposed. Zener breakdown does not have a multiplication effect whereas avalanche breakdown does.

The ratio between the actual leakage at any voltage and the current that would flow if there had been no increase in current due to electron collisions is defined as the multiplication factor, m This factor is unity at low voltages and infinity at the avalanche breakdown voltage (see Figure 2)

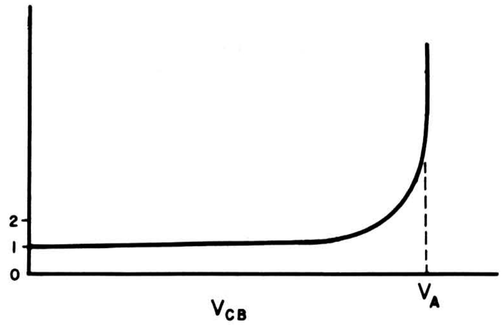

Fig. 2—Multiplication Factor

B. Alpha Equal Unity Breakdown (

The multiplication factor, m, defined in the previous paragraph multiplies the alpha (α_o) of the transistor as well as the leakage current. Therefore, if the alpha of a transistor at low voltages is equal to α_o, then its alpha at any other voltage will be $m\alpha_o$ where m is the multiplication factor at the voltage in question. Because the common emitter current gain, β, is equal to $\alpha/1-\alpha$, it also becomes a function of m. The expression is $\beta = \alpha_o m/(1-\alpha_o m)$

In alloyed junction power transistors the α_o is very close to unity Consequently, as the collector voltage is increased (causing m to increase from unity to infinity), the product $\alpha_o m$ increases from a number slightly less than unity at low voltages to infinity at the avalanche breakdown voltage.

Therefore, at some voltage considerably less than the avalanche breakdown voltage, the factor m will be equal to $1/\alpha_o$ and $m\alpha_o$ will be equal to unity This, in turn, results in an infinite beta or a common emitter breakdown condition as shown in Figure 3.

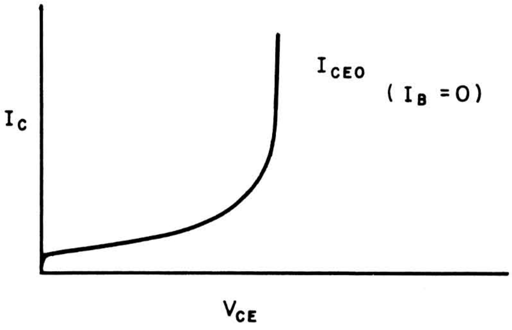

Fig. 3—Alpha Equal Unity Breakdown.

For this reason, this mechanism of breakdown is called $\alpha = 1$ breakdown. However, because it is a function of the multiplication effect of the avalanche breakdown, it is referred to in some literature as the alpha multiplication breakdown.

C. Punch Through Breakdown

The third mechanism of breakdown, punch through, results from the expansion of the space charge region or depletion layer When a negative voltage is applied to the collector of a PNP transistor (positive to the base), the holes in that p-type collector will be attracted to that negative potential. Similarly, the electrons in the n-type base will be attracted to the positive potential applied to the base terminal. This attraction of the carriers away from the junction creates a depletion layer in which there are no free carriers. See Figure 4A. In an alloyed junction transistor the base region has a much higher resistivity than does the collector; therefore, as the voltage is increased the expansion of the depletion layer will occur mainly into the base region. At some particular voltage this depletion layer will expand through the entire base region and actually come into contact with the emitter junction. This is illustrated in Figure 4B. The voltage at which this phenomenon takes place is called the punch through voltage.

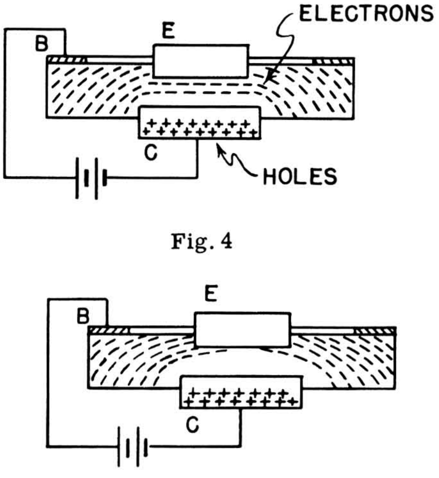

Fig. 4

Fig. 4B

Fig. 4—Punch Through Breakdown.

As the depletion layer expands, the effective base width becomes narrower The narrower base width decreases the chance of recombination in the base region; consequently, the transistor's alpha increases slightly At the punch through voltage, the effective base width has been reduced to zero by the expansion of the depletion layer through tne entire base region. Therefore, there will not be any recombination in the base region (now void of free carriers) and a dynamic short circuit will exist between collector and emitter When punch through occurs, and at higher voltages, the normal transistor action ceases and the base electrode no longer controls the current flow This is in contrast to the $\alpha = 1$ breakdown in which the base is still capable of controlling the transistor at the breakdown voltage and all voltages up to the avalanche breakdown voltage.

When the punch through voltage is exceeded in a common emitter circuit, the resultant dynamic short circuit between collector and emitter permits current to flow that is limited by only the external circuitry and, thus, a breakdown condition exists. Because the $\alpha = 1$ breakdown usually occurs at a lower voltage than punch through, it will in most cases be the observed mode of common emitter breakdown.

III. Breakdown as a Function of the Circuit

Through the understanding of the fundamental modes of voltage breakdown, one can examine and explain the principles involved in the breakdown mechanisms occurring when a transistor is used in a practical circuit. When connections are made to all three electrodes, the breakdown phenomenon is modified and becomes a function of the input circuit source impedance. The breakdown will be discussed first for the two extremes—zero and infinite resistance—and then for a more realistic value of source resistance.

A. Zero Impedance Source

1. Base Terminal Shorted to Emitter

When a reverse voltage is applied between the base and collector terminals, the collector junction leakage will flow If the emitter is then shorted to the base terminal, a small fraction of the collector function leakage will be supplied to the base region through the emitter, resulting in an emitter current equal to $(\beta+1)$ times that fraction of I_{CBO}. This results in a slight increase in the total collector current.

Of greater consequence, however, is the voltage developed across the intrinsic base resistance due to the leakage current flowing into the base terminal. See Figure 5. This voltage is in the direction to forward bias the emitter junction; i. e. to turn the transistor on. As I_{CBO} increases due to increasing collector voltage, this voltage also increases At some particular value of collector voltage the $I_B R_B$ drop will exceed the threshold voltage of the emitter diode. When this occurs the emitter begins to conduct, causing a sharp increase in collector current and a breakdown condition. Figure 6 shows the I_C vs V_{CE} characteristic for the base-shorted-to-emitter condition. The explanation of the negative resistance slope that appears after breakdown occurs is withheld until a later section of this paper

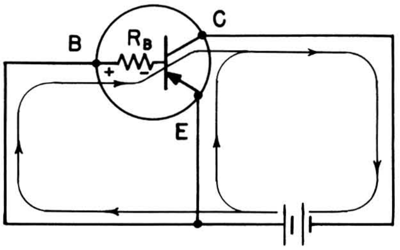

Fig. 5—Base Terminal Shorted to Emitter

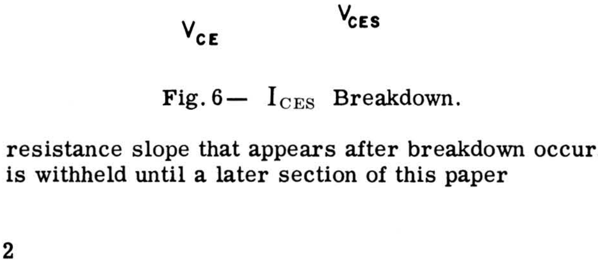

Fig. 6— I_{CES} Breakdown.

If, at the collector voltage just necessary to cause breakdown (V_{CES}), the emitter lead is opened, a "floating" potential will appear between the base and emitter terminals. (The Appendix defines and explains the presence of the emitter floating potential.) As described in the following sections, the value of this voltage (hereafter referred to as V_X) can be used to predict the breakdown voltage for input conditions other than base shorted to emitter

2. Emitter Back Biased

When a reverse voltage is applied between the base and emitter terminals, the collector voltage can be raised above V_{CES} before a breakdown condition occurs. When breakdown does occur, it is for the same physical reason as described for the base-shorted-to-emitter condition. That is, the voltage actually across the emitter junction exceeds the threshold potential, forward biasing the emitter to conduction. Figure 7 shows the circuit for this mode of breakdown and the development of the voltage that causes the emitter to become forward biased. Figure 8 shows the resultant I_C vs V_{CE} curves for various values of back bias voltage.

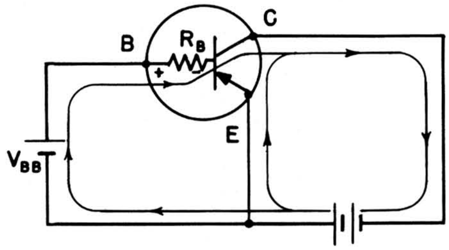

Fig. 7—Voltage Back Bias.

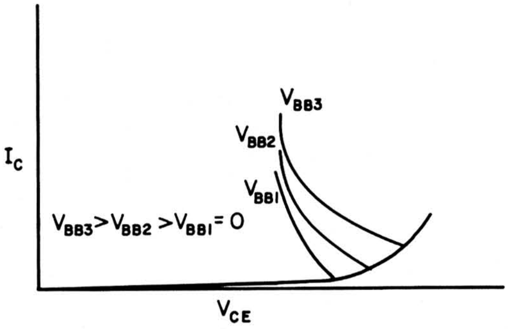

Fig. 8—Breakdown with Voltage Back Bias.

Because the floating potential V_X is an indication of the voltage necessary to forward bias the emitter junction to the conduction, the V_{EBF} must equal $V_X + V_{BB}$ in order to cause conduction when the emitter is back biased by V_{BB} volts. Consequently, the value of V_{CB} resulting in a $V_{EBF} = V_X + V_{BB}$ will be the voltage, collector-to-base, at which the transistor will exhibit a breakdown when it is back biased V_{BB} volts. The collector-to-emitter voltage at breakdown will be $V_{CB} - V_{BB}$. Knowing V_X and V_{EBF} vs V_{CB}, one can predict the V_{CE} to cause breakdown when a back bias voltage is placed between the emitter and base terminals.

B. Infinite Impedance Source

1. Base Open

When a voltage is applied between the collector and emitter (negative to collector for a PNP transistor) with no connection made to the base terminal, all of the collector junction leakage flows into the emitter and is amplified by $(\beta+1)$ Since the emitter junction is forward biased in this configuration (See Figure 9), there will be only a fraction of a volt across it and approximately the full supply voltage across the collector junction. Therefore, the leakage current that is amplified by $(\beta+1)$ can be approximated as the I_{CBO} at $V_{CB} = V_{CE}$.

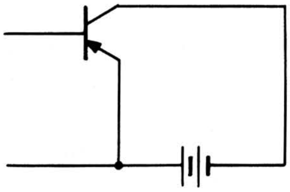

Fig. 9—Open Base Circuit.

As V_{CE} is increased, β approaches infinity as described in the second section of this paper, and at some particular voltage, the open base leakage current increases without bound. The characteristic for this breakdown is shown in Figure 10.

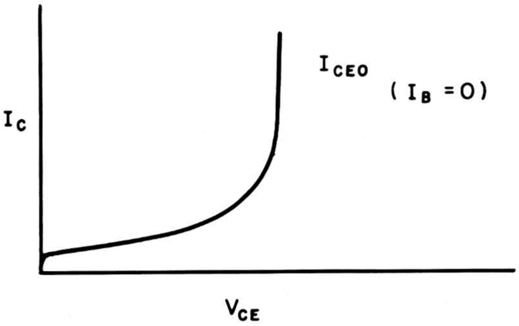

Fig. 10— I_{CEO} Breakdown.

2. Emitter Back Biased

As when the source impedance was zero, the breakdown voltage with an infinite impedance between base and emitter can be raised by back-biasing the emitter junction. However, the back bias now takes the form of a current rather than a voltage.

If a small current is passed through the emitter junction in the reverse direction, a voltage will be developed across the junction. If the collector is open circuited (Figure 11A), the voltage across the emitter diode will be equal to that necessary to cause an emitter junction leakage equal to the back bias. The collector will assume a potential slightly negative to that of the base terminal (collector floating potential), and therefore it will be positive with respect to emitter, almost to the extent that the base is.

If the collector is then shorted to the emitter (Figure 11B), the reverse bias will divide, part into the emitter junction and part into the collector junction. Because the collector and emitter are shorted, they will both assume the same potential with respect to the base. The potential that they assume and the division of the base current depends upon the relative characteristics of the two junctions.

If, as shown in Figure 11C, a voltage is applied between collector and emitter, the collector junction will be subjected to a higher reverse voltage than the emitter Because the base current is constant (fixed current back bias) the increase in collector voltage and, hence, collector diode leakage results in a decrease in emitter diode leakage and emitter voltage. For any particular value of V_{CE}, the V_{EB} and V_{CB} will assume values such that $V_{CB} - V_{EB} = V_{CE}$ and the I_{CBO} and I_{EBO} at these respective voltages will total I_{BB}, the back bias current. As V_{CE} is further increased, V_{CB} will also increase the V_{EB} will decrease. As V_{CE} approaches the value of V_{CB} that results in an I_{CBO} equal to I_{BB}, V_{EB} approaches zero and virtually all of the base current flows out of the collector

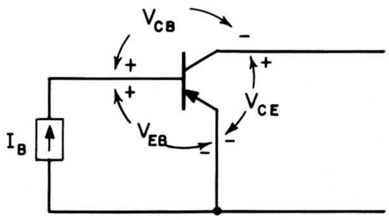

Fig. 11A

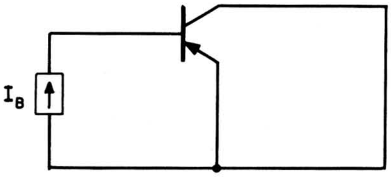

Fig. 11B

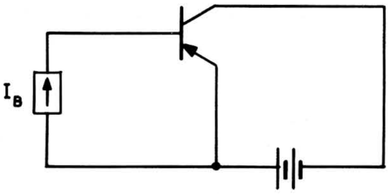

Fig. 11C

Fig. 11—Current Back Bias.

If an attempt is made to increase the collector-to-emitter voltage beyond the value of V_{CB} resulting in an I_{CBO} equal to I_{BB}, all of the base current will flow into the collector, leaving no current to back-bias the emitter Consequently, the emitter becomes capable of forward conduction, resulting in a negative resistance breakdown condition. Figure 12 shows a series of curves for different levels of current back-bias.

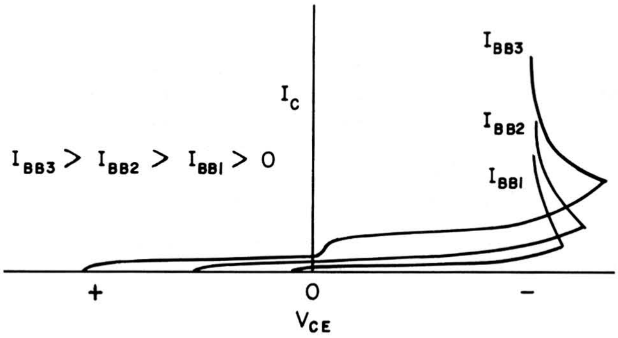

Fig. 12—Breakdown with Current Back Bias.

Therefore, the I_{CBO} vs V_{CB} characteristic can be used to preduct the breakdown voltage when the transistor is back-biased from an infinite impedance source.

C. Resistive Source

When the source impedance is neither zero nor infinite, it is necessary to know both the V_{EBF} vs V_{CB} and I_{CBO} vs V_{CB} characteristics before the breakdown voltage can be predicted. The circuit of Figure 13 shows an example of a transistor being back-biased through a finite resistance.

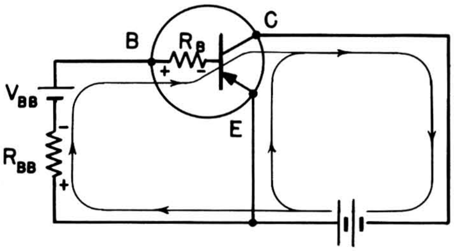

Fig. 13—Resistive Source Circuit.

When V_{CE} is zero, reverse current will flow into both the emitter and collector junctions. The leakage currents of the two junctions result in an IR drop across the external base resistance, R_{BB}, reducing the V_{EB} and V_{CB} voltages. Because the base impedance is finite the base current can and does change with changes in V_{CE}. As V_{CE} is increased the base current also increases, resulting in an increase in the $I_B R_{BB}$ drop which in turn reduces the net voltage between the base and emitter terminals and, hence, the reverse emitter current.

At some particular value of V_{CE}, the emitter floating potential and collector leakage current will be sufficient to cause the voltage actually across the emitter junction to exceed the emitter threshold voltage. As before, when this occurs, the emitter is no longer reversed biased, but rather begins to conduct in the forward direction, resulting in a breakdown condition. At the breakdown voltage, the following expression is satisfied: $V_{EBF} + I_{CBO}R_{BB} = V_X + V_{BB}$ where V_{EBF} is the floating potential and I_{CBO} is the leakage current at the breakdown voltage. This expression predicts a breakdown when the floating potential plus the $I_{CBO}R_{BB}$ ($I_{EBO} = 0$ at breakdown) exceed the back-bias voltage by an amount just equal to V_X.

IV Negative Resistance Characteristic

A. Negative Beta

All of the curves, except for open base condition, show a dynamic negative resistance after the breakdown voltage is reached. The occurrence of this phenomenon can be explained by first referring again to Figure 2. This curve shows the relationship of the alpha multiplication factor to the collector-to-base voltage. Consequently, a curve of α vs V_{CB} could be obtained by simply multiplying the ordinate of Figure 2 by α_o. From a curve of α vs V_{CB}, a plot of $\beta = \alpha/(1-\alpha)$ can be calculated. Such a plot is shown in Figure 14.

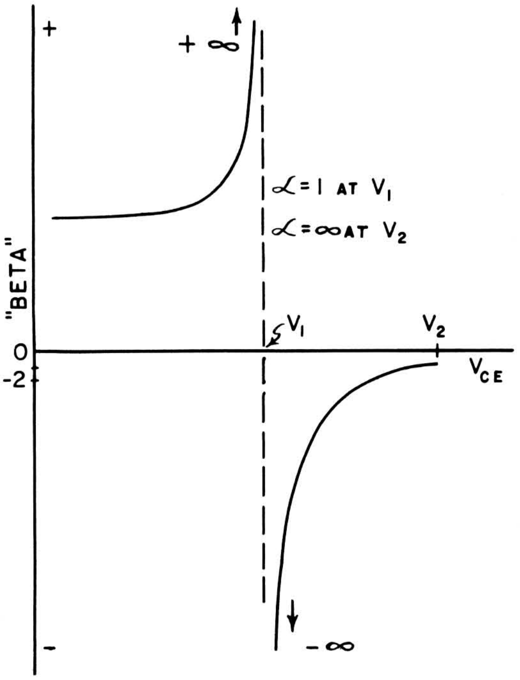

Fig. 14—Common Emitter Current Gain, Beta.

As the $\alpha = 1$ voltage is approached from lower voltages, the current gain becomes increasingly large. Figure 15 shows how the common emitter collector characteristics behave as this $\alpha = 1$ voltage is approached. These curves show that regardless of the input current (true also for input voltage except for the very low values of V_{BE}) as long as it is in the forward direction, the collector current and, thus, the gain tends to infinity as the $\alpha = 1$ voltage is approached. This agrees with the upper portion of Figure 14.

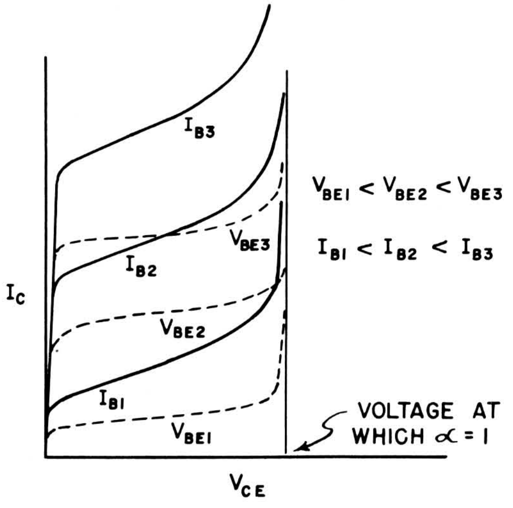

Fig. 15—Common Emitter Collector Characteristics

If these characteristics are examined through the use of a collector current source rather than a voltage source, then with a constant d. c. base bias the collector voltage will rise and assympotically approach the $\alpha = 1$ voltage as the collector current is allowed to increase.

If, however, the polarity of the input is reversed so as to back-bias the emitter junction, the I_C vs V_{CE} characteristic will tend to follow the I_{CBO} curve until the breakdown voltage for the particular back-bias condition is reached. Because this breakdown always occurs at voltages greater than that at which $\alpha = 1$ the common emitter current gain at the breakdown point will be negative. Consequently, increases in reverse base current are multiplied by the transistor's "negative beta" and result in increases in the collector current in the normal direction.

If a collector current source is used, a characteristic curve is obtained that is analogous to that described for the condition of forward bias. That is, for a constant value of back bias, the collector voltage approaches the $\alpha = 1$ voltage as the collector current is increased.

This approachment of the $\alpha = 1$ voltage and an infinite gain with increases in collector current follows from the condition that the reverse base bias is constant, and therefore, the only mechanism by which the collector current can increase is through the increase of magnitude of the transistor's negative current gain.

Because this characteristic starts at a voltage higher than the $\alpha = 1$ breakdown, the voltage must decrease the approach the $\alpha = 1$ voltage as the current increases. Consequently, the resultant characteristic exhibits a dynamic negative resistance and the transistor is dynamically unstable at currents greater than that at which the breakdown occurs. A family of such characteristics for various levels of reverse base bias are shown in Figures 8 and 12. Although the exact nature of these curves is dependent on the impedance of the base-emitter circuit, the same general type of negative resistance characteristic is observed for all impedance levels

B. Emitter Current Concentration

Operation of a transistor in the negative beta region as described above can result in serious deterioration of its characteristics even to the point of a collector-to-emitter short. First, there is the fairly obvious problem that results when a circuit component exhibits negative resistance. Once the breakdown voltage has been exceeded, the current flow will no longer be limited by the back-biased transistor, but rather by only the external circuit. Figure 16 assumes a load resistance of R_L ohms and a transistor back-biased so as to exhibit a breakdown at V_1. As the effective supply voltage exceeds V_2, the point of operation jumps from A to B, resulting in an extremely high power dissipation. In order to remove the transistor from this high dissipation region it is necessary for the voltage to fall to V_3. As the voltage decreases from V_2 to V_3, the point of operation moves from B to C. As the voltage falls below V_3, the operating point jumps from C to D.

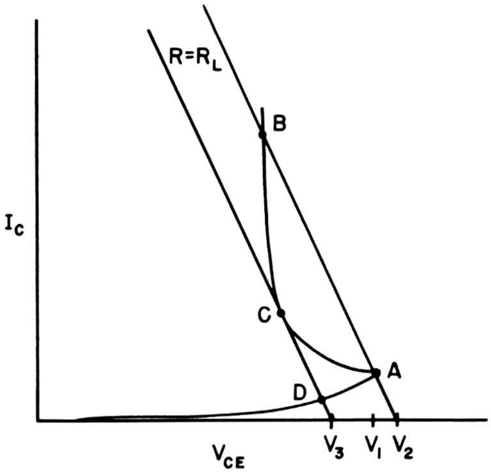

Fig. 16—Load Line Operation.

Second, the high dissipation that occurs as described above is concentrated into a fraction of the total junction area and is, therefore, even more dangerous than might be anticipated.

This concentration or localization of the dissipation is a direct result of the fact that the emitter current flowing when the transistor is operated in the negative beta region is concentrated in the region of the junction that is furthest removed from the base contact (assuming that the junction is uniform) Transistors having a disk emitter will exhibit this current concentration in the geometric center of the junction. In transistors having an annular emitter and an outer base ring the concentration will occur at the inside periphery of the junction. If an annular emitter transistor has outer and inner base contacts and both are back biased, the current will concentrate in a ring intermediate to the two base contacts.

The reverse base current that flows during the negative beta operation creates a voltage gradient within the base region that causes the areas of the junction that are nearest the base contact to be reverse-biased, while interior regions continue to conduct. Figure 17 illustrates the formation of this gradient.

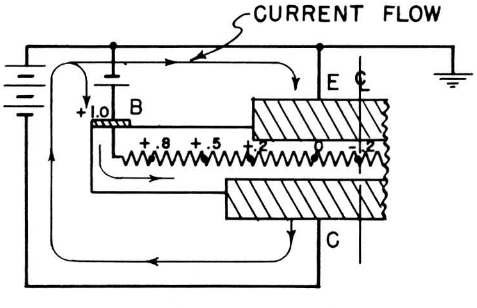

Fig. 17—Base Region Voltage Gradient.

Because only a fraction of the entire junction area is biased in the conducting direction, that fraction must conduct the entire emitter current. Consequently, the heat developed by the VI product is generated in only this small area, resulting in a much greater temperature rise than if the current density were uniform throughout the entire junction. This temperature rise can be sufficient to cause permanent deterioration of the transistor's characteristics or even a thermal runaway condition and a short between collector and emitter

Consequently, in order to refrain from operating in the potentially dangerous negative beta region, it is necessary, whenever the collector voltage is greater than the $\alpha = 1$ voltage, that the reverse base current and voltage exceed the collector junction leakage current and emitter floating potential, respectively The phase or time relationship between the collector voltage and the reverse base signal must be maintained so that the above conditions are satisfied throughout the entire cycle. This precaution will insure that the entire emitter junction will be reverse-biased, thus, preventing the flow of emitter current and the resultant high concentrated dissipation.

V Conclusions

Of the three basic modes of transistor voltage breakdown (avalanche, alpha equal unity and punch through) the avalanche voltage represents the highest voltage at which the transistor can be operated. The punch through breakdown voltage limits the usefulness of the transistor in a common emitter circuit as there is a dynamic short circuit between collector and emitter at all voltages equal to or greater than this voltage. The $\alpha = 1$ voltage is that voltage at which the common emitter current gain goes to infinity and above which the transistor exhibits both a negative beta and a dynamic negative resistance. The transistor can be safely operated at voltages higher than that at which $\alpha = 1$ provided a sufficient back bias is applied to the base terminal.

In a practical application, the transistor to be used must have avalanche and punch through breakdowns in excess of the highest anticipated collector-to-base voltage and an $\alpha = 1$ voltage greater than the collector supply voltage.

In addition, if it is anticipated that the peak collector voltage will exceed the $\alpha = 1$ voltage, provisions must be made to supply reverse voltage and current to the base terminal. This back-bias source must be phased with the collector voltage so that the instantaneous reverse current and voltage exceed, respectively, the instantaneous collector leakage current and emitter floating potential at all collector voltages greater than the $\alpha = 1$ voltage. This prohibits the use of a Class A, transformer-coupled circuit unless the transistor's $\alpha = 1$ voltage is at least twice the peak collector supply voltage.

If, at any time when the collector voltage exceeds the $\alpha = 1$ voltage, the back bias is not sufficient, the transistor will exhibit a breakdown condition. If this occurs as the collector voltage is rising, it becomes virtually impossible, depending upon the load resistance, to remove the operating point from the negative resistance region by merely increasing the back bias. The removal can be effectively accomplished only by the reduction of the collector voltage as was illustrated in Figure 16

One should be precautioned against trying to prevent the occurrence of a breakdown condition through the use of excessive back bias As long as a breakdown does not occur, the magnitude of the back bias is of no consequence. However, if a breakdown should occur, the degree to which the dissipation is concentrated is directly related to the back bias magnitude. Therefore, under conditions of breakdown, the chance of transistor failure will be increased as the reverse bias is increased.

The selection of a transistor and the design of a circuit fulfilling these basic requirements will prevent the occurrence of transistor failures due to voltage breakdown.

Appendix

Emitter Floating Potential

The emitter floating potential (V_{EBF}) is that potential developed between the base and emitter terminals of a transistor when a reverse voltage is applied between the base and collector terminals. Figure I, a pictorial representation of a transistor sectioned at right angles to the semiconductor crystal, shows how this voltage is developed. The collector leakage current flowing into the base terminal produces a voltage drop across not only the intrinsic base resistance but also the resistance of the base material lying between the two junctions. When a high impedance meter is placed between the base and emitter terminals it will indicate a voltage equal to the forward emitter threshold voltage (approximately 0.1 volts for alloyed germanium junctions) plus the collector leakage current times the base resistance. Figure II illustrates this relationship between collector leakage and floating potential.

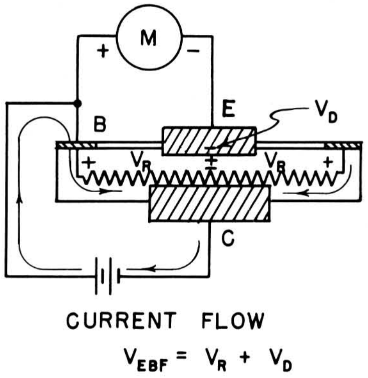

Fig. I—Transistor Cross Section

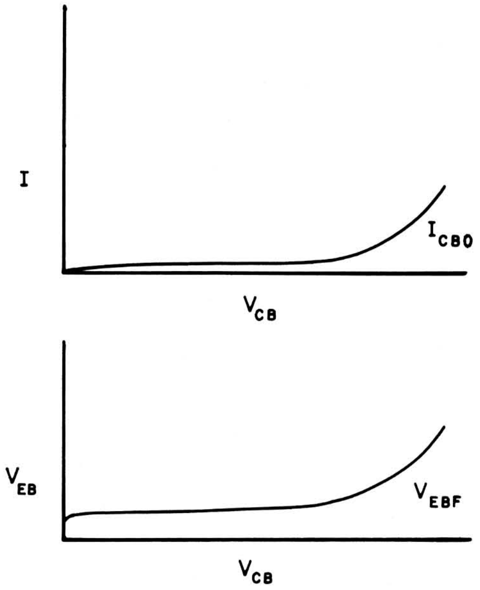

Fig. II— I_{CBO} and V_{EBF}