

SOME FEATURES OF AVALANCHE BREAKDOWN PHENOMENA

Part 1: TRANSISTORS AND DIODES

R.S. SHARMA* AND M.A. PEER*

The temperature variations of the breakdown voltages of some commonly-used transistors and zener diodes, the negative-resistance characteristics of a transistor in the avalanche mode and their dependence on the base-circuit conditions, the temperature dependence of the Miller's index n and its role in the disappearance of the negative-differential resistance in the input characteristics of the transistor have been studied experimentally and explained theoretically. It is concluded that the nature of the reverse volt-ampere characteristics of a p - n junction depends upon the impurity concentrations on the two sides of the depletion layer. When the impurity concentrations are low, there is a negative differential resistance in the output characteristics of the transistor operating in the avalanche mode.

Indexing Terms : Avalanche Breakdown, Negative Resistance

A TRANSISTOR biased in the avalanche multiplication region shows a negative-differential resistance between collector and emitter. This makes it possible to operate the transistor for special high-speed switching purpose in the "avalanche mode" corresponding to operation beyond the sustaining voltage. A lot of work has been done to study the behaviour of the transistor in the avalanche multiplication region (Huang 1967, McKay 1954, Maheshwari & Nigam 1974, Miller 1955, Tokuyama 1962), yet it is felt that the negative-resistance characteristics of the transistor and their dependence on the breakdown mechanism, the base-circuit conditions and the ambient temperatures offer a phenomena which is not fully-understood. An experimental study of the transistor in the avalanche mode has been conducted under various base-circuit conditions so as to enable one to understand the mechanism of negative-resistance phenomena. In this work, the results of the experimental study of the various aspects of the avalanche breakdown phenomena in transistors are presented and a theoretical explanation of these observations has been provided.

EFFECT OF THE BASE-CIRCUIT CONDITIONS

Figure 1 shows the circuit diagram used to study the common-emitter output avalanche characteristics of a transistor. A study of the collector-to-emitter breakdown voltage BV_{CEX} indicates that this voltage depends on the supply voltage V_{BB} and on the resistance R_B connected across the base and emitter terminals. Huang (1967), has given a relation to explain the temperature behaviour of the breakdown voltage BV_{CEX} . The breakdown voltage when the emitter-base junction is reverse biased with a voltage V_{BB} through a resistance R_B is given by

$$BV_{CEX} = BV_{CBO} \left[1 - \frac{(r_b + R_B)I_{CBO}}{V_{BB} + V_D} \right]^{1/n} \quad (1)$$

Here BV_{CBO} is the collector-to-base breakdown voltage when emitter is open, r_b is the base-spreading resistance, V_D is

the threshold voltage of the emitter-base diode, I_{CBO} is the reverse leakage current under open-emitter conditions and n is the Miller's index. The Miller's index n is believed to be independent of temperature (Huang 1967). BV_{CBO} is believed to increase more or less linearly with increasing temperature (Huang 1967, McKay 1954, Tokuyama 1962). The temperature dependence of BV_{CBO} is given by the relation (Huang 1967, Maheshwari & Nigam 1974)

$$BV_{CBO}(T) = BV_{CBO}(T_0) \{1 + \beta'(T - T_0)\}, \quad (2)$$

where, β' is the temperature co-efficient and T_0 is the room temperature. BV_{CEX} can have a positive or negative temperature co-efficient depending upon whether $(V_{BB} + V_D)/(R_B + r_b)$ is greater than I_{CBO} or is less than I_{CBO} at the temperature under consideration. The relation (1) has been used by Maheshwari and Nigam (1974) to explain the negative-temperature co-efficient of BV_{CEX} of a germanium pnp transistor 2 SA12 and the positive-temperature co-efficient of BV_{CEX} in the case of silicon nnp transistor CIL 471 when the emitter-base junction is reverse biased with $V_{BB} = 10$ V through a resistance $R_B = 10k\Omega$. We studied the breakdown phenomena of large number of transistors of different reverse leakage currents under various bias conditions but failed to notice the phenomena of the change of the temperature co-efficient of BV_{CEX} from negative to positive as mentioned by Maheshwari & Nigam (1974) in any of the transistors we studied including CIL 471. It is not felt necessary to give the complete details here. The observations regarding the dependence of the breakdown voltages BV_{CEX} and BV_{CB} on the emitter-base voltage V_{EB} and the resistance R_B are given here, as these results are referred to in the latter part of this paper. The circuit of Fig. 1 is used to study the dependence of the collector-emitter breakdown voltage BV_{CEX} of a transistor on the emitter-base voltage V_{EB} applied in the forward as well as reverse directions. Here R_B is kept zero. The results are shown in Fig. 2. The breakdown voltage BV_{CEX} decreases as the emitter-base junction is more forward biased for most of the transistors with the exception of the silicon planar epitaxial transistors BF 195 D (BEL) and 201 CEERI. The collector-base

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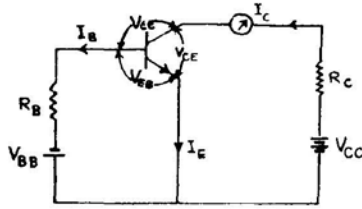


Fig. 1. Circuit used to obtain the common emitter output avalanche characteristics.

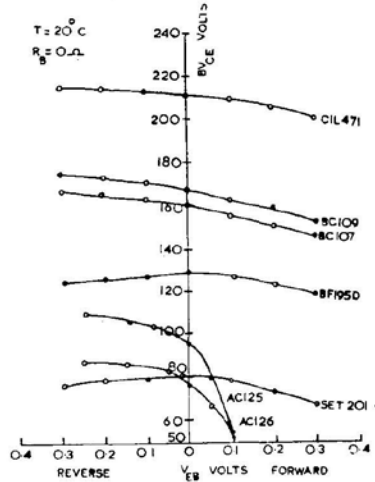


Fig. 2. Breakdown voltage BV_{CEX} as a function of emitter-base voltage V_{EB} applied in the forward and reverse directions. Here $R_B=0$.

breakdown voltage BV_{CB} of these transistors also shows a similar dependence of the emitter-base voltage V_{EB} and the results of this study are depicted in Fig. 3 for some commonly-used germanium and silicon transistors. Variations of the breakdown voltage BV_{CEX} and BV_{CB} with the base-circuit resistance R_B are given in figures 4 and 5

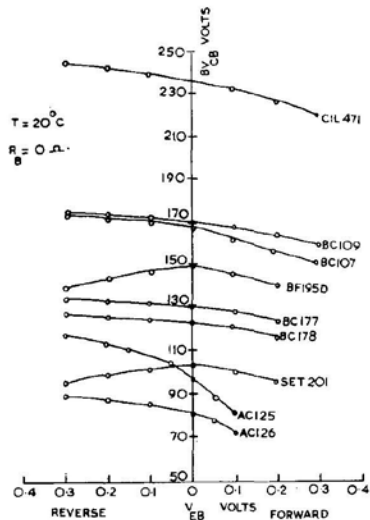


Fig. 3. Breakdown voltage BV_{CB} as a function of emitter-base voltage V_{EB} applied in the forward and reverse directions; $R_B=0$.

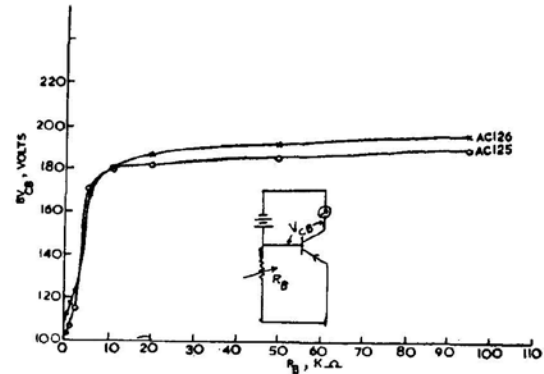


Fig. 4. Dependence of BV_{CB} on R_B . Here $V_{BB}=0$. $BV_{CB}|_{R_B=\infty} = BV_{CBO}$.

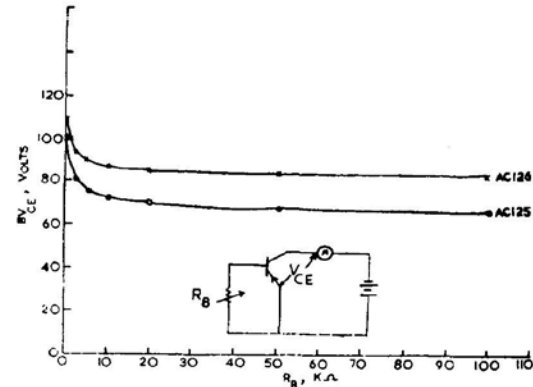


Fig. 5. Dependence of BV_{CEX} on R_B . Here $V_{BB}=0$ $BV_{CEX}|_{R_B=\infty} = V_S$ sustaining voltage.

respectively. For $R_B = \infty$, $BV_{CEX} = V_S$ the sustaining voltage and $BV_{CB} = BV_{CBO}$. For $R_B=0$, $BV_{CEX} = BV_{CB}$.

Let us consider theoretically the effect of the resistance variations of the base-circuit resistance R_B and the supply voltage V_{BB} on the temperature co-efficient of the breakdown voltage BV_{CEX} as given by relation (1). When $R_B=0$ and $V_{BB}=\infty$, BV_{CEX} will be equal to BV_{CBO} and it should have the same temperature co-efficient as that of BV_{CBO} . Now consider the case when R_B is infinite and V_{BB} is zero. In this limiting case BV_{CEX} is equal to the sustaining voltage V_S . The sustaining voltage V_S is related to BV_{CBO} through the expression (Huang 1967, Cassigonal 1966)

$$V_S = BV_{CBO} (1 - \alpha_0)^{1/\alpha_0} \quad (3)$$

where, α_0 is the current amplification factor under normal operating conditions and is less than one.

Comparing equations (1) and (3), one concludes

$$\frac{(r_b + R_B) I_{CBO}}{V_{BB} + V_D} \bigg|_{R_B = \infty} = \alpha_0 \quad (4)$$

From eqn. (4), it is clear that $\frac{(r_b + R_B) I_{CBO}}{V_{BB} + V_D}$ can not be made greater than one simply by increasing the

value of R_B or by reducing the value of V_{BB} , unless either of relations (1) and (3) is wrong. In other words, the temperature co-efficient of BV_{CEX} can not be altered by changing the base circuit conditions. Both the voltage BV_{CEX} and BV_{CBO} should have the same temperature co-efficient. A negative-temperature co-efficient of BV_{CEX} is not possible, if BV_{CBO} has a positive-temperature co-efficient.

TEMPERATURE CO-EFFICIENT OF BV_{CBO}

In order to understand the behaviour of the temperature co-efficient of the breakdown-voltage BV_{CEX} , it is necessary to study experimentally the effect of temperature on the breakdown voltage BV_{CBO} . The variations of BV_{CBO} for some commonly-used zener diodes (avalanche diodes), germanium and silicon transistors with temperature changes are given in Fig. 6. It is observed in the case of zener diodes CAZ-33 and CAZ-47 that the temperature co-efficient of the breakdown voltage is positive at low temperatures and it reverses its sign at elevated temperatures. The breakdown voltages of the above-mentioned zener diodes decrease with the rise of temperature above about 110°C. BV_{CBO} of the germanium alloy junction transistors AC126, AC127, AC128, AC187, AC188 and 2SA12, decreases with the increase of temperature. Similar observations have been made on the behaviour of the temperature co-efficient of the breakdown voltages of small-signal audio-frequency silicon transistors BC177 and CIL471. Unlike the above-mentioned transistors, the collector-to-base reverse-breakdown voltage of the RF silicon planar epitaxial transistors BF195D and 201 CEERI increases with the rise of temperature in the range of room temperatures and shows a negative-temperature co-efficient at higher temperatures.

There is no doubt that the breakdown voltages of zener diodes have positive-temperature co-efficient but it is wrong

to conclude that the temperature co-efficient of the breakdown voltages of all semiconductor devices, suffering from breakdown due to avalanche multiplication, is positive. Even in the case of zener diodes operating at high temperatures, temperature co-efficient of BV_{CBO} is negative. Relation (2) is not even valid for zener diodes over a wide range of operating temperatures.

In zener diodes with breakdown voltages in excess of 6 V, the mechanism of breakdown is due to avalanche multiplication. The impurity concentrations on either side of the junction of the device are about $5 \times 10^{16}/\text{cm}^3$ or more. The carrier mobility decides the temperature co-efficient of the breakdown voltage at low temperatures. The carrier mobility decreases with the increase of temperature and a given breakdown current is attained at a relatively large value of reverse voltage at a higher temperature. Thus the breakdown voltage shows a positive-temperature co-efficient.

Unlike zener diodes, the doping concentration of the original material of a typical transistor is about $10^{15}/\text{cm}^3$ or even less. Due to low original impurity concentrations, thermally-generated carriers, resulting from the heating of the transistor play an important role in deciding the temperature co-efficient of the breakdown voltage of transistors. The current rises with the increase of temperature, overcoming the decrease in current due to the decrease of the mobility with the rise of temperature. A given breakdown current is reached at a lower voltage, resulting in a negative-temperature co-efficient of BV_{CBO} . The same argument applies for zener diodes operating at high temperatures (above about 110°C). The thermally-generated carriers become comparable in number to the original doping concentration at high temperatures and decide the nature of the temperature co-efficient of the breakdown voltage. Thus BV_{CBO} of a device can have a negative

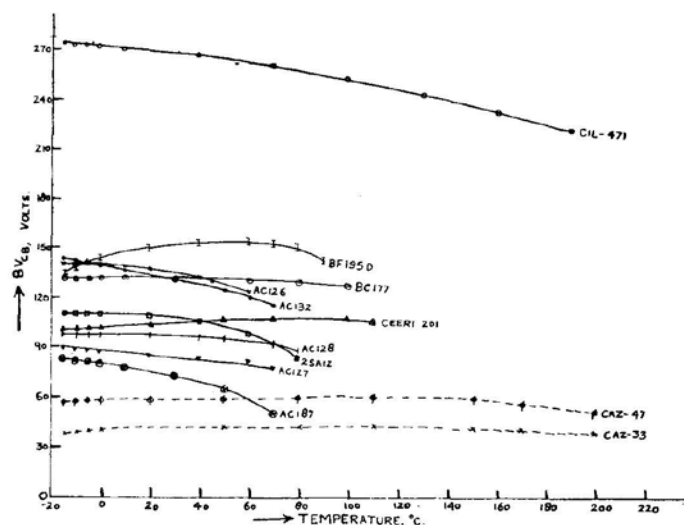


Fig. 6. Temperature variations of the breakdown voltages for some commonly used zener diodes and transistors.

temperature co-efficient when the impurity concentration of the original material is low or when the device is operated at elevated temperatures. The nature of the temperature co-efficient of BV_{CEX} needs no more explanation.

Some transistors, like the planar epitaxial transistor BF195D show a positive temperature co-efficient of the breakdown voltage at low operating temperature and a negative temperature co-efficient at high temperature. A study of the transfer characteristics of the transistor BF195D at low temperatures has shown that the breakdown phenomena in this case is due to punch-through. The transfer characteristics of the transistor BF195D at 20°C and 40°C are given in Fig. 7, along with the circuit

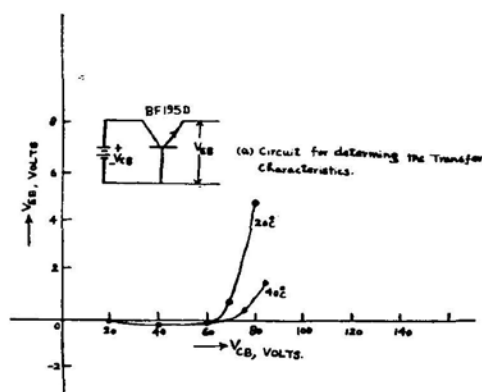


Fig. 7. Transfer characteristics of transistor BF 195 D.

used for studying the punch-through phenomena. It is evident from this figure that for V_{CB} smaller than punch-through voltage, V_{EB} of this transistor is nearly zero. For V_{CB} above the punch-through voltage, V_{EB} increases with increasing V_{CB} . When punch-through of the transistor has occurred, the transistor behaves as though the emitter and collector regions are tied together by a fixed voltage source and the base is connected to both through a reverse-biased junction. This statement is further supplemented by the study of the nature of the variations of BV_{CEX} and BV_{CB} of BF195D with the emitter-base voltage as shown in figures 2 and 3 respectively. It is evident from figures 2 and 3 that the breakdown voltage of the transistor BF195D decreases with the increase of the reverse bias. The emitter-base depletion layer expands into the base region when this junction is slightly reverse biased, resulting in a decrease of the base width and consequently reducing the voltage at which the punch-through of the transistor takes place. The variations of BV_{CEX} or BV_{CB} with emitter-base voltage applied in the reverse direction thus provides a new method of testing the punch-through phenomena in transistors. The thickness of the depletion layer decreases with the rise of temperature. Consequently the punch-through voltage increases with temperature. In other words, punch-through voltage has a positive-temperature co-efficient. For the transistor

BF195D, the punch-through voltage is slightly less than the avalanche breakdown voltage in the range of room temperatures. Therefore, the temperature co-efficient of the breakdown voltage of this transistor is positive at low temperatures. As the temperature of the transistor rises, the punch-through voltage increases and its avalanche breakdown decreases. At a higher temperature, the avalanche breakdown voltage is less than the punch-through voltage. The temperature co-efficient of the breakdown voltage reverses its sign at that temperature. Similar observations have also been made on the silicon transistors 201 CEERI. Negative resistance I_C-V_{CB} characteristics have been observed in these cases at high temperatures. The reverse volt-ampere characteristics of silicon transistor BF195D are given in Fig. 8 at different temperatures.

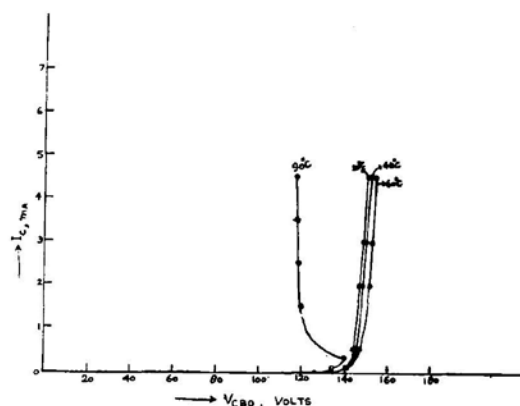


Fig. 8. Reverse volt-ampere characteristics of BF 195 D at different temperatures. At low temperature, the breakdown phenomena is due to punch-through, while at high temperature, it is avalanche breakdown.

NEGATIVE-RESISTANCE CHARACTERISTICS

Transistors biased in the avalanche multiplication region (both the emitter-base and the collector-base junctions are reverse biased) may show a negative-differential resistance between the collector and the emitter terminals. The present explanation (Huang 1967, Gray *et al.* 1964, Fitchen 1971) of this phenomenon is based on the fact that the collector-to-emitter breakdown voltage BV_{CEX} decreases if the emitter-base junction is made more forward biased, as is evident from Fig. 2. An increase in the collector-base voltage results in an increase in the base current, which subsequently increases the voltage drop across the base-spreading resistance and makes the already reverse-biased emitter-base junction less reverse biased or even forward biased. This increases the base current and makes the emitter-base junction more strongly forward biased. The process is regenerative and the negative-resistance characteristics results as an outcome of the breakdown phenomena taking place at a lower voltage.

The above model fails to explain some of the observed facts mentioned below about the negative resistance phenomena of the transistor operating in the avalanche mode. The common-emitter output avalanche characteristics of a transistor are usually drawn with constant base current as the parameter and they show negative differential resistance. If the base current of the transistor is kept constant while obtaining the output avalanche characteristics of the transistor, the question of the emitter-base junction becoming more forward biased relative to its original condition does not arise at all. Further, there may be a negative-differential resistance between the collector and base when the emitter is open. The $V_{CB}-I_C$ characteristics of an alloy-junction germanium transistor AC125 with emitter open is represented here in figure 9 as an example. The increase in temperature of the transistor results in the disappearance of the negative-differential resistance. Finally, the transistor working in the normal operating region (the emitter-base junction forward biased and the collector-base junction reverse biased) may not show any negative-resistance characteristics).

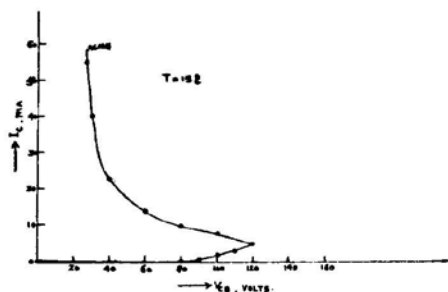


Fig. 9. Reverse volt-ampere characteristics of germanium-alloy transistor AC125 with open-emitter circuit.

A better explanation for these observations is based on the changes in the properties of the collector-depletion layer, viz; the barrier height, barrier width and its resistance, with the electric field applied across the junction. The barrier height V_D , at a temperature T is given by

$$V_D = (kT/q) \ln p_p n_n / n_i^2 \quad (5)$$

where, p_p and n_n are the majority carrier densities of the p and n type semiconductors respectively, n_i is the intrinsic concentration, k the Boltzmann's constant and q the electronic charge. The width of the barrier increases with the increase of the voltage and the resistance of the barrier layer is very high. With the increase of the applied voltage above the avalanche breakdown voltage, the intrinsic concentration n_i increases very rapidly. The barrier width and potential height V_D reduces abruptly and the resistance of the barrier layer becomes very small. The depletion layer is not in a position to retain the high voltage applied across it to bring about the avalanche breakdown. The device current increases with the fall of the voltage across the depletion layer. The internal resistance of the voltage supply takes care of the fall of the voltage across

the junction. Thus the sudden change in the properties of the depletion layer results in a negative-differential resistance property of the junction.

The basic requirement for the appearance of the negative-differential resistance in the output characteristics of the transistor operating in the avalanche mode is that sharp changes in the properties of the depletion layer should take place at application of breakdown voltage. The multiplication factor for voltages below the breakdown voltage should be as small as possible. This condition demands that the impurity concentrations on either side of the junction should be low. In other words, the product $p_p n_n$ should be small. The lower the impurity concentration of the original material of the device, the better will be the negative-resistance characteristics when operated in the avalanche mode. The difference between the breakdown voltage at the peak and valley points will be large. In other words, the junction will be able to hold a large voltage before the breakdown and a small voltage after the breakdown. When n_i^2 becomes equal to $p_p n_n$, the material loses its rectifying property and behaves like an ordinary semiconductor. In that case, the voltage will rise again along with the increase of current. The basic requirement of low value of the product $p_p n_n$ is usually met in most of the commonly-used germanium and silicon transistors. Unlike transistors, avalanche diodes are manufactured from semiconductor materials of high impurity concentrations. Evidently, they do not show negative-resistance characteristics.

When both the emitter-base and collector-base junctions of a transistor are reverse biased, maximum depletion of charged mobile carriers occur at the collector-base junction of the transistor due to recombination of the electrons and holes at the low depletion layers. The collector current will be small and a given breakdown current will be reached for a large voltage. There is a negative differential resistance in the output characteristics of the transistor. The effect of biasing the emitter-base junction in the forward direction is just opposite. Carriers injected from the emitter into the base neutralize immobile charges of the collector-depletion layer and change the properties of the barrier layer drastically. As a result of the carriers injected into the base, the conductivity of the base material increases. The barrier resistance is small even before the onset of breakdown. A large current can flow across the depletion layer and the multiplication factor is high. The breakdown takes place at a lower voltage and the change in the properties of the barrier layer is gradual. Thus the negative-differential resistance may not appear in the output characteristics of the transistor.

MILLER'S INDEX 'n'

Before considering the role of changes in the value of the Miller's index n on the negative-resistance characteristics and the breakdown voltage of a device, it is important to know the parameters which influence the value of n .

It is well known (Yepifanov 1974) that n depends on the resistivity of the semiconductor and the type of the substrate. It is also known (Yepifanov *loc. cit.*) that p -base material has a somewhat higher value of n than the n -base semiconductor, but the nature of its dependence on the resistivity of the material is not clear. It is stated in this work without direct experimental proof that n increases with the increase of the resistivity of the semiconductor. Accordingly, p -base material should have a high value of n due to its high value of resistivity (hole mobility is smaller than electron mobility). A logical justification to this statement has been provided in the following, based on the knowledge of the dependence of the avalanche breakdown voltage on the resistivity of the semiconductor. The Miller's index is related to the avalanche multiplication factor M through the empirical relation (Millman & Halkias 1972)

$$M = \{1 - (V_C/BV_{CB})^n\}^{-1}, \quad (6)$$

where, V_C/BV_{CB} represents the ratio of the applied reverse voltage to the breakdown voltage of the junction under consideration. The dependence of M on n , according to relation (6) is depicted in Fig. 10 for various values of V_C/BV_{CB} . If the Miller's index is large, the multiplication factor is small. It is known that the materials of high resistivity have large values of breakdown voltages. A high value of the breakdown voltage is possible only in a material bearing a small value of the multiplication factor M . Thus n is large for materials of high resistivity.

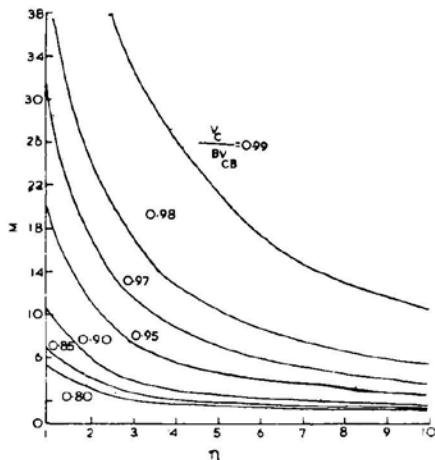


Fig. 10. Theoretical dependence of multiplication factor, M on the Miller's index n for different values of V_C/BV_{CB} .

The Miller's index n is believed to be independent of temperature (Huang 1967, McKay 1954). But no direct experimental proof has been given in literature to justify this statement. The temperature dependence of n has been determined experimentally in the case of zener diodes using the relation for the diode current I_C at a voltage V_C

$$I_C = MI_{CO} = I_{CO} \{1 - (V_C/BV_{CB})^n\}, \quad (7)$$

where, I_{CO} is the reverse-leakage current of the diode at low voltages at which no multiplication occurs. From the experimentally-determined values of the breakdown voltage BV_{CB} at different temperatures, the temperature dependence of the Miller's index has been computed. The results of this study for silicon zener diodes CAZ-11, CAZ-22, CAZ-33 and CAZ-47 are depicted in Fig. 11. In the case of transistors, relation (3) is used to study the temperature variations of n . From the experimentally-determined temperature variations of V_S , BV_{CBO} and α_0 , the various values of n at different temperatures have been found for germanium alloy-junction transistors AC126, AC127, AC128 and AC132. The variations of n with temperature for these transistors are also given in Fig. 11. It is concluded from this study that n decreases with the rise of temperature.

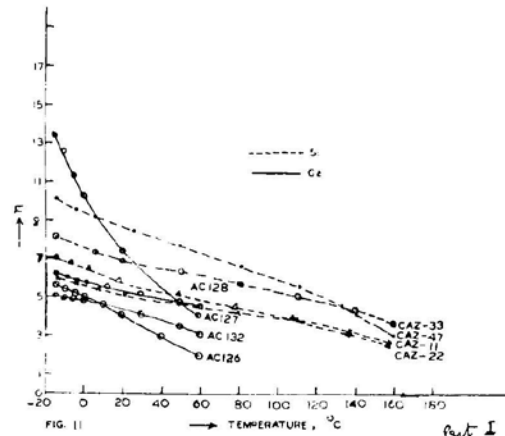


Fig. 11. Variations of the Miller's index n with temperature.

As the temperature of the device rises, the resistivity of the material decreases and so n decreases.

EFFECT OF TEMPERATURE ON THE NEGATIVE RESISTANCE CHARACTERISTICS

It is well known (Huang 1967, Maheshwari & Nigam 1974) that the increase of temperature results in the disappearance of the negative-differential resistance in the output characteristics of the common-emitter transistor operating in the avalanche mode at higher temperatures. There is a large generation of electrons and holes in the transistors operating at elevated temperatures even in the absence of the applied voltage. Changes in the properties of the depletion layer take place gradually on the application of the voltage across the junction. The resistance of the depletion layer is already low for voltages below the breakdown voltage. The presence of a large number of thermally-generated carriers makes the onset of the breakdown gradual. Thus the negative-resistance phenomenon does not appear in the output characteristics of the transistor.

The temperature dependence of n plays an important role so far as the effect of temperature on the negative-resistance characteristics is concerned. The Miller's index n controls the sharpness of the onset of the breakdown. When it is small, the multiplication factor is large. A large multiplication of the carriers before the onset of breakdown is undesirable for negative-resistance characteristics, as it reduces the breakdown voltage and allows the breakdown to occur gradually. Value of n is small for transistors operating at high temperatures or for transistors operating under normal bias conditions (i.e. emitter-base junction forward biased and collector-base junction reverse biased). For transistors operating in the avalanche mode, n is large. Very small multiplication takes place at low voltages below the breakdown voltage resulting in a high value of the breakdown voltage (see figures 2 and 3) and a negative-differential resistance in the output characteristics.

CONCLUSION

The nature of the reverse volt-ampere characteristics of a p - n junction depends upon the impurity concentrations of the two sides of the junction. When the doping is low, there is a negative-differential resistance in the output characteristics of the transistor operating in the avalanche multiplication region. Lower the impurity concentration on either side of the depletion layer, better will be negative resistance characteristics of the device.

The difference between the peak and valley voltages will be large and the onset of the breakdown will be sharp.

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SOME FEATURES OF AVALANCHE BREAKDOWN PHENOMENA Part 2 : GATE-CONTROLLED DIODES

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The breakdown characteristics of the gate-controlled diodes have been studied at various gate voltages and different temperatures. The purpose of this study has been to find out the effect of surface conditions on the nature of the differential-resistance properties of the reverse characteristics of the gate-controlled diodes and the temperature co-efficient of the breakdown voltage. It is found that although the surface conditions affect the breakdown voltage appreciably, they do not alter the differential-resistance characteristics or the temperature co-efficient of the breakdown voltage. The turn-on voltage is found to depend on the magnitude of the reverse bias and the gate voltage. The turn-on voltage decreases with the increase of reverse voltage.

Indexing Terms: Avalanche Breakdown, Gate-Controlled Diodes, Negative Resistance

TRANSISTORS biased in the avalanche-multiplication region may show a negative-differential resistance between the collector and the emitter terminals. There may be a negative-differential resistance even between the collector

and the base when the emitter is open. In the case of zener diodes, the temperature co-efficient of the avalanche-breakdown voltage is negative at room temperatures, while that of commonly-used transistors is negative. The phenomena have been discussed by the authors in Part 1. Surface conditions may play an important role in deciding the nature of differential-resistance

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