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Alloyed Junction Avalanche Transistors

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A new device, the avalanche transistor, is described. Its properties derive from the utilization of the multiplication inherent in the breakdown process of reverse-biased semiconductor junctions. These junction transistors have regions of designable alpha greater than unity and are similar in many respects to point-contact and hook-collector transistors. They should, however, have advantages in speed and designability. Large regions of negative resistance of moderate magnitude can also be obtained in appropriate circuits. The device should find wide application in both switching and transmission. Design information for avalanche transistors is given.

1. INTRODUCTION

It has been shown recently that reverse biased silicon and germanium junctions break down as a result of a multiplicative process which is analogous to multiplicative breakdown in a gas.[1, 2, 3] Minority carriers which are thermally or otherwise generated diffuse to the high field region of the reverse biased junction, where they are accelerated, producing hole-electron pairs by collision with the atoms of the crystal lattice. As in the case of ionization of a gas, the rate of pair production is dependent upon the electric field distribution; however, it has been found that in the case of semiconductors holes and electrons are comparably effective in producing additional current carriers. The holes and electrons which are produced by collision may themselves produce additional pairs, and so on, resulting in an avalanche. As the junction reverse bias is increased, the space charge layer widens, the maximum electric field increases, and the total rate of pair production increases. At a particular value of reverse voltage, called the breakdown voltage, the multiplication of the minority current carriers becomes essentially infinite. The current then increases very rapidly, being limited only by the external circuit resistance.

In semiconductors the number of minority carriers which are multiplied may be augmented and controlled by means of an emitter junction which is placed in close proximity to the reverse-biased, multiplying collector junction. The result, of course, is a simple n-p-n or p-n-p junction transistor which with proper design may exhibit considerable multiplication of the emitter current at voltages well below the breakdown voltage. The existence of this multiplication mechanism, which has been called avalanche multiplication, in reverse biased transistor collector junctions is of very great interest both from a transmission as well as from a switching point of view. So far as switching is concerned, it means that a simple junction device may have a current gain, or alpha, greater than unity and in appropriate circuits, be capable of exhibiting a negative resistance just as point-contact or hook-collector transistors do. Such a device may be used as the active element in pulse generator, regenerative pulse amplifier, or counter circuits. The effect of this multiplicative process on transmission applications is also important. Large regions of designable negative resistance of moderate magnitude may be attained in two terminal circuits and used to reduce losses in transmission systems. In general, the alteration in collector characteristics due to avalanche multiplication means that single stage amplifiers may be unstable and/or may exhibit a high degree of distortion depending on the operating conditions.

Further discussion of the negative resistance characteristic will be presented in a later section. Additional objectives of this paper are to indicate how an avalanche transistor can be characterized relative to its terminal behavior and to present design information which will enable the design of avalanche transistors for specific applications. The discussion will be in terms of alloyed transistors; however, the ideas presented are applicable to other structures.

It should be pointed out here that many junctions break down at or near the surface at a voltage considerably below that expected from the bulk properties of the junction. In these cases the multiplication of the bulk junction never rises very much above unity before "surface breakdown" occurs. Even though the surface breakdown also is frequently multiplying, only a small percentage of the emitter current is multiplied. The discussion in this paper is primarily applicable to transistors which exhibit "body breakdown."

2. THEORY

The multiplication of reverse biased step junctions, such as those of transistors made by the alloy-diffusion method, closely follows the empirical expression[3]

$$M = \frac{1}{1 - (V/V_B)^n} \tag{1}$$

where V_B is the junction body breakdown voltage and n is a parameter which varies with the resistivity and resistivity type of the material on the high resistivity side of the junction. In alloyed junction transistors this side is the base. Presumably the value of the parameter n varies also from semiconductor to semiconductor. For alloyed step junctions on p-type germanium, measured n values for different resistivities have ranged from 4.5 to 6.5. On n-type germanium n is approximately 3 throughout the investigated range. The breakdown voltage, V_B, rises monotonically with the resistivity of the base layer.

Equation (1) says that the alpha of a transistor has the form (neglecting space charge layer widening effects)

$$\alpha(V) = \alpha_0 M(V) = \frac{\alpha_0}{1 - (V/V_B)^n} \tag{2}$$

where α_0 is the value of the current gain at very low voltage, or, more accurately, the fraction of the emitter current which is collected, neglecting multiplication. This equation implies a designable alpha greater than unity for junction transistors. From equation (2) the voltage, V_S, at which alpha becomes unity is given by

$$V_S = V_B \sqrt[n]{1 - \alpha_0} \tag{3}$$

Thus V_S is completely determined by the body breakdown voltage of the collector junction, the low-voltage alpha and the value of n for the particular junction. With proper design V_S can be made only a small fraction of V_B. Obviously a device designed to take advantage of the multiplication effect should have as high an α_0 as possible and as low a value of the parameter n as is available. The advantage clearly lies with the p-n-p as opposed to the n-p-n transistor in germanium. Another requirement is that the transistor technology be sufficiently advanced that the body breakdown of the collector junction can be observed. At present this means roughly that the breakdown voltage must be kept low, that is, below about 50 volts.

In linear applications which impose that α must remain below unity or that distortion be minimized, different requirements are necessary. For such applications high V_S is desired, which in turn calls for high base resistivity. Fulfilling this requirement, however, may necessitate a compromise, since high base resistivity results in limited frequency cutoff at low voltages because of space-charge layer punch-through.[4] Base resistance considerations may likewise put an upper limit on permissable base resistivity. In such a case the use of n-p-n transistors seems advisable,[5] and the operating voltage should remain always comfortably below V_S.

In the circuit configuration of Fig. 1 the avalanche transistor behaves like a gas discharge device in several respects. Its characteristic includes

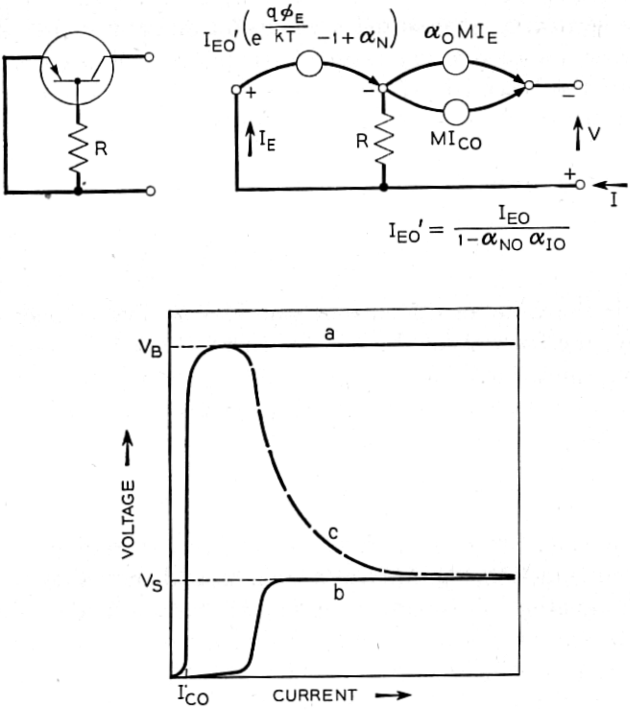


Fig. 1 — Avalanche transistor negative resistance circuit.

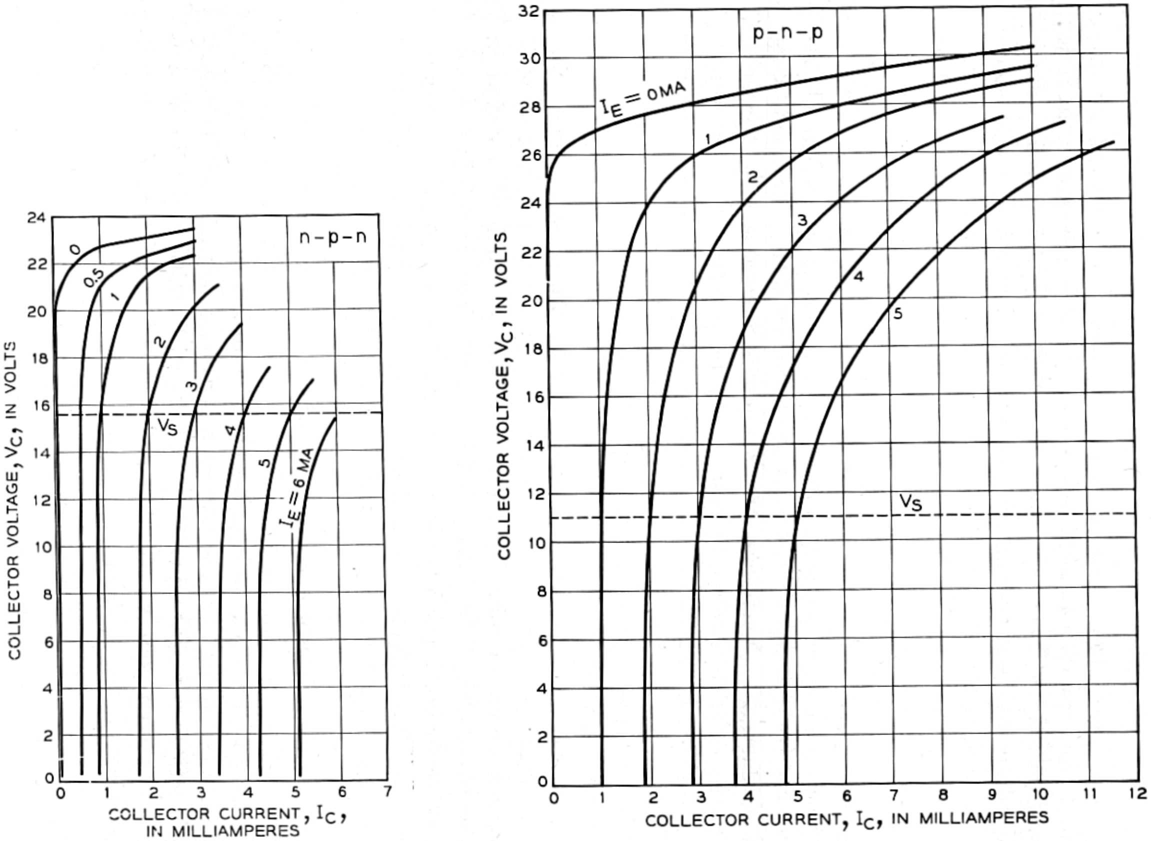
a high resistance region and a low resistance region separated by a region of negative resistance. The origins of the negative resistance in the two cases, however, exhibit distinctions which should be pointed out. In the gas discharge, negative resistance results after breakdown primarily from the increased cathode efficiency due to changes in the field configuration because of the space charge effects of the carriers. In the solid state analogue, the charges already resident in the discharge region in the form of the ionized chemical impurities in the lattice outnumber the carriers traversing the high field region by many orders of magnitude at reasonable current densities. Hence the field configuration is not significantly current-dependent. Furthermore, there is no cathodic regenerative mechanism in the solid discharge (gamma process), and photoregeneration in germanium is only $\sim 10^{-4}$ efficient. Townsends' β mechanism has been demonstrated to be the dominant agency in maintaining the discharge.[2, 3] Therefore, the avalanche breakdown in the solid generally does not inherently lead to negative resistances. There would, however, be the possibility of negative resistance at very high current densities.

The negative resistances observable are the result of the fact that with avalanche transistors it is possible to look across the discharge in two different ways. One is directly across the avalanche multiplication region alone (from the base to the collector of a transistor) and the other is across a source of minority carriers and the multiplication region in series (from emitter to collector with base floating). In the former case base-to-collector breakdown leading to near zero incremental resistance occurs at that voltage at which the avalanche multiplication becomes infinite. In the latter case, because of continuity of current requirements, emitter-to-collector breakdown occurs at V_S, that voltage at which the multiplication times the α_0 of the transistor becomes unity. Any circuit configuration which in effect goes from the former to the latter condition with increasing current will exhibit negative resistance.

Curve (a) in Fig. 1 is the normal reverse characteristic of the collector junction, as measured collector to base with emitter open, indicating the breakdown voltage, V_B. For a theoretical transistor this curve is determined by the equation

$$I = MI_{CO} = \frac{I_{CO}}{1 - (V/V_B)^n} \tag{4}$$

Since the emitter is open circuited it does not contribute any minority carriers to the discharge. Curve (b) in Fig. 1 is the reverse characteristic of the collector junction (as measured collector to emitter with base



(*a*) (*b*)

Fig. 2 — Collector characteristics of alloyed junction transistors exhibiting avalanche multiplication. (a) n-p-n and (b) p-n-p.

open). According to the equivalent circuit of the transistor the current is given by the equation

$$I_c = \frac{MI_{co}}{1 - \alpha_0 M} \tag{5}$$

and it is seen that current increases, subject only to limitation by circuit resistance, when the collector voltage reaches V_S, the voltage corresponding to unity total alpha or $\alpha_0 M = 1$. Since the emitter current of alloyed junction transistors is primarily made up of minority carriers emitted into the base region, the emitter efficiency in this case can be said to be high. It is apparent that if the emitter efficiency could be made to vary with current, then it would be possible to obtain a negative emitter-to-collector resistance. This is the purpose of the base resistor shown in Fig. 1. For low currents the impedance of the emitter junction is high, since the voltage-current characteristic is exponential in character, and most of the current flows through the base resistor. As the voltage is increased essentially curve (a) is traced out. Near the breakdown voltage the current increases, the emitter-to-base voltage increases in the forward direction, and the impedance of the emitter junction becomes smaller in comparison with the base resistance. This process results in increased emitter current. Thus the characteristic, curve (c), begins to depart from curve (a), and as a larger and larger fraction of the total current is transferred from the base circuit to the emitter circuit, curve (c) approaches curve (b) asymptotically.

3. CHARACTERIZATION

In view of the above description of the multiplication properties of transistor junctions, it is clear that the collector characteristics of all transistors, in which a surface breakdown does not intervene, will look like those shown in Figs. 2(a) and 2(b). In Fig. 2(a), the measured collector characteristics for a representative n-p-n transistor are shown. Fig. 2(b) gives the same information for a representative p-n-p unit. The horizontal dashed line in each case indicates the voltage V_S at which α becomes unity. This voltage is of course a function of the particular value of α_0 for each transistor. Either of these transistor types would have somewhat more distortion as a common base amplifier than has hitherto been expected from transistor theory neglecting avalanche effects.

As has already been emphasized, the p-n-p has a decided advantage for monostable, astable, or bistable switching applications. A suitable characterization for an avalanche transistor designed for switching use

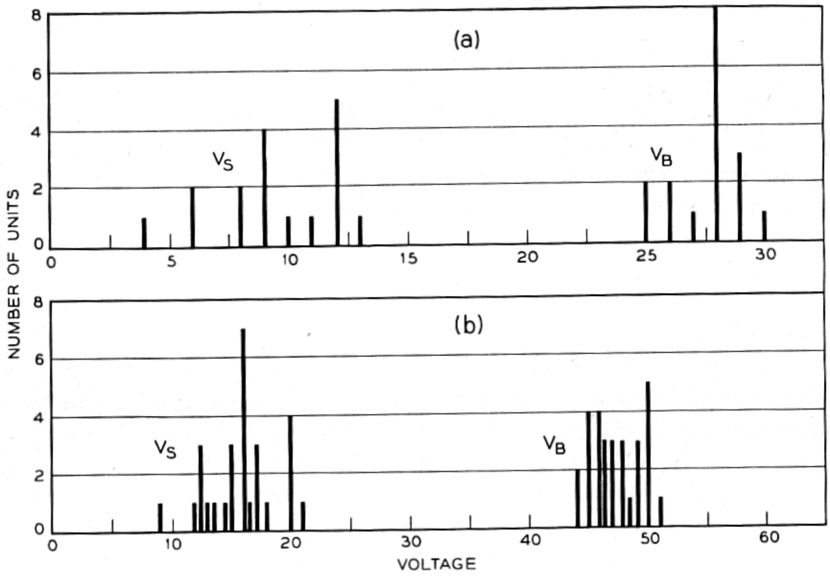


Fig. 3 — Distributions of V_B and V_S for avalanche transistors. (a) Base resistivity = 0.2 Ω-cm; (b) Base resistivity = 0.5 Ω-cm.

would certainly involve the body breakdown voltage of the collector, V_B, and the voltage at which the total α of the transistor is unity, V_S, which can be thought of as a sustain voltage. The breakdown voltage is a function of the base layer resistivity, while the ratio of the sustain voltage to the breakdown voltage is a function of the low-voltage alpha of the transistor. Therefore, the ability to control these parameters involves only the ability to control base layer resistivity and α_0. These are problems which have already claimed considerable attention with good results in other transistor designs.

Groups of such avalanche transistors have been made at Bell Telephone Laboratories. Figs. 3(a) and 3(b) give distributions of V_B and V_S for groups of about 25 transistors made on 0.2 Ω-cm and 0.5 Ω-cm n-type material. In Figs. 4(a) and 4(b) are given the relations between V_S and α_0 for the two groups.

The spreads in V_B for both groups of transistors largely reflect slight deviations from the nominal resistivity. Although the germanium in both cases was zone levelled, it is estimated that there is a ±5 per cent variation in resistivity for individual wafers. Undoubtedly some variation is due to surface breakdowns very close to but below the body breakdown. The spread in V_S is, of course, partially the result of the spread in V_B insofar as the variation in V_B is the result of variation in the bulk material. The remainder stems from the distribution of α_0 values. No vigorous attempt was made to control α_0 carefully or to hold rigid limits on base resistivity for these sample groups.

From (3) it can be seen that log V_S/V_B when plotted versus log $(1 - \alpha_0)$ for transistors of different α_0 should yield a straight line of slope $1/n$. Solid lines of slope $\frac{1}{3}$ have been drawn in Fig. 4 along with dashed lines of slope $\frac{1}{6}$. The adherence to the $n = 3$ law is confirmed.

Equation (2) gives the total α of a transistor when multiplication is taken into account. Values calculated from this equation are plotted in Fig. 5 in comparison with values determined by ac α measurements and with α values obtained from the measured static collector characteristics for a representative unit from the group having base layer resistivity

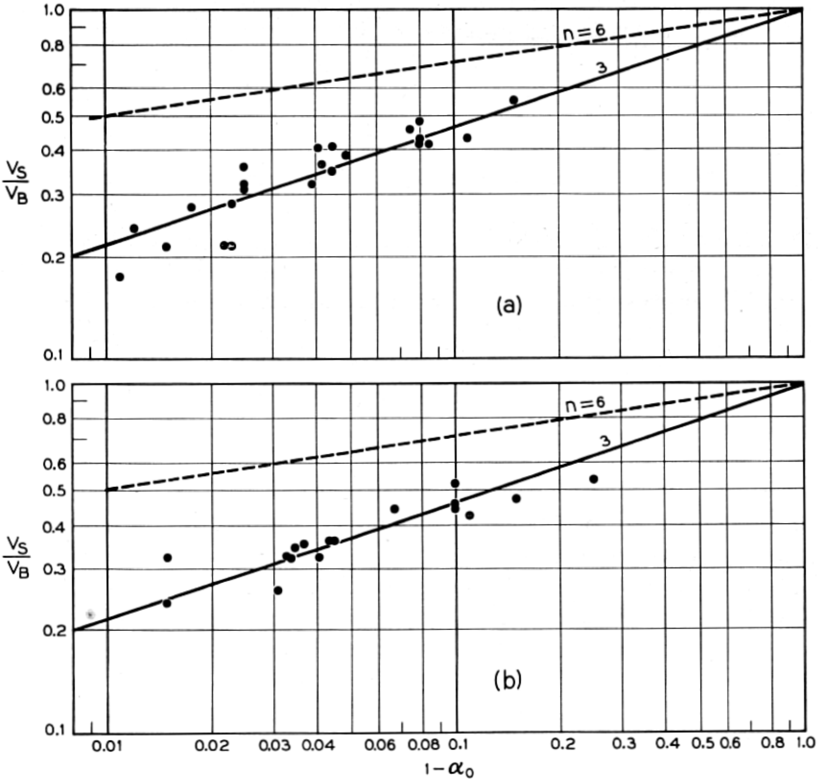


Fig. 4 — Plot of V_S/V_B vs $1 - \alpha_0$. (a) Base resistivity = 0.2 Ω-cm. (b) Base resistivity = 0.5 Ω-cm.

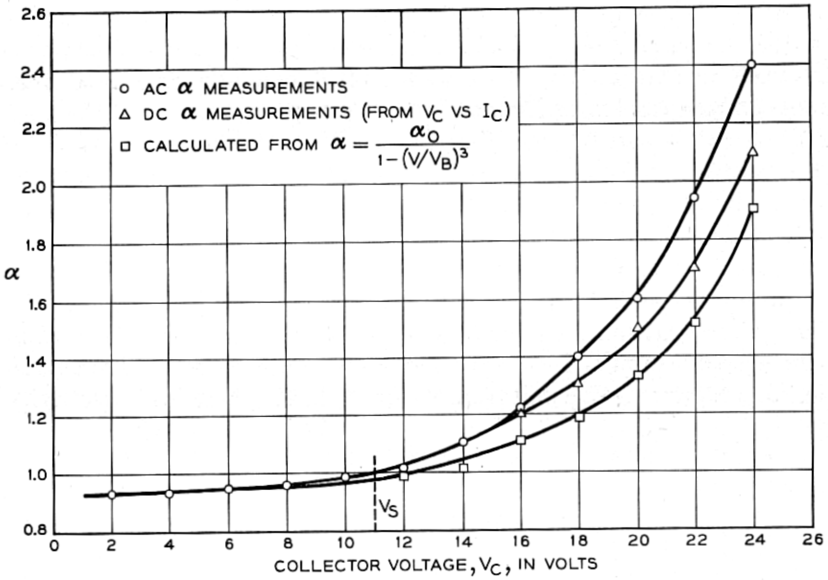


Fig. 5 — Alpha versus collector voltage for an avalanche transistor.

of 0.2 Ω-cm. The agreement is good. It is quite general for the formula to give a slightly lower value of α than is observed in this type of experiment. The functional form of the multiplication and especially the value of the exponent were determined from an experiment which minimized effects on α_0 of changes in the base current flow pattern.[3] The experimental α as determined above would be expected to be higher than theoretical because when α goes above unity, the majority carrier flow from the collector to the base biases the emitter so that α_0 increases with increasing total α. This effect is the opposite of the effect in which α_0 decreases with increasing large emitter current in ordinary junction transistor operation with α less than unity.

The frequency characteristic of the multiplicative increase in α is of great interest. Theoretically the multiplication process should be extremely fast. The response time of the multiplication should be comparable with the transit time for carriers across the high field region in the reverse biased junction. This time would be a small fraction of a millimicrosecond in all practical junctions. Therefore, the frequency cutoff of the total alpha should not be measurably smaller than the frequency cutoff of the α_0. Actually the effect discussed above, which increases α_0 with increasing total α (when above unity), and therefore, with increasing collector voltage, could have an even greater effect on the frequency cutoff of α_0. Again it would be expected that the change would be in the direction of increasing f_N. Fig. 6 gives measured frequency cutoffs of total α vs. the collector voltage for the same representative unit which was used for Fig. 5. The theoretical curve was calculated[5] from

$$f_N = \frac{f_{NO}}{\left[1 - \left(\dfrac{V_C f_{NO}}{3.65 \times 10^{-13} N_I A}\right)^{1/2}\right]^2} \tag{6}$$

This equation merely takes into account the variation of base width due to widening of the collector space-charge layer with increasing voltage.[4, 6] There is a sharp departure upwards from the theoretical curve for the points corresponding to total α greater than one. This behavior is in line with the above explanation. Again, the reverse effect is observed with increasing large emitter currents in junction transistors operated in the ordinary manner. Thus the frequency characteristics of the multiplied alpha are as good as, and can be better than, the frequency char-

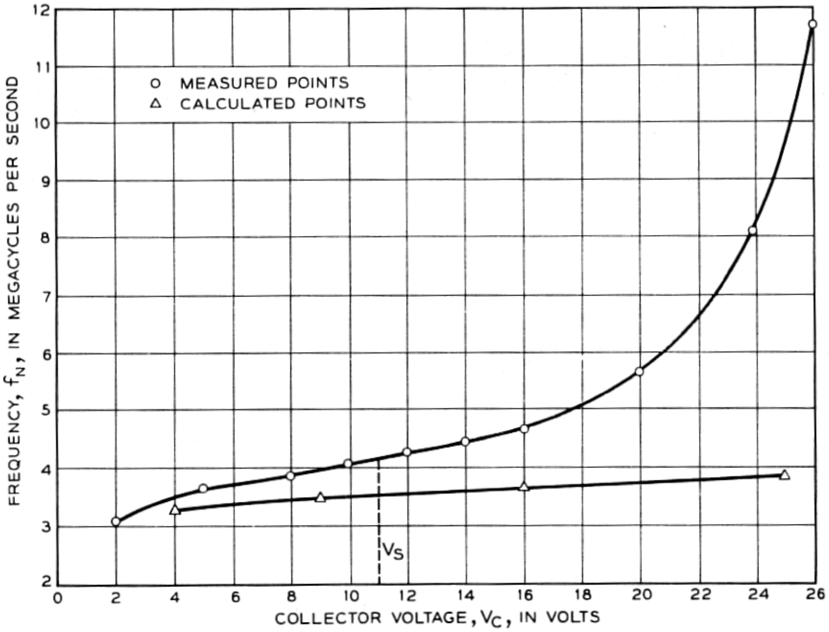


Fig. 6 — Frequency cut-off of alpha versus collector voltage for an avalanche transistor.

acteristics of α_0. This means that any device which utilizes the negative resistance inherent in the α greater than unity will be limited in frequency only by the dispersion in transit time across the base.

The temperature variation of both V_B and V_S is comparatively small. The breakdown voltage of np junctions increases slowly with increasing temperature at the rate of about 0.1 per cent per degree centigrade.[7] Aside from the change in V_B, V_S will be affected also by changes in $1 - \alpha_0$ with temperature. In the case of p-n-p germanium transistors a drastic change of $1 - \alpha_0$ by a factor of two with temperature would give only a 25 per cent change in V_S. Data given by Ebers and Miller[5] show that such changes would require very large temperature changes. However, it should not be supposed that devices based on the avalanche principle would always be very temperature insensitive. For example, in the circuit shown in Fig. 1, the mechanism which switches from the high breakdown voltage to the low breakdown voltage path may be highly temperature sensitive, unless remedial steps are taken, because the saturation current is intimately involved.

4. DESIGN DATA

The principal designable features of an avalanche transistor are the V_B and V_S values. From the discussion in the next section, it will be

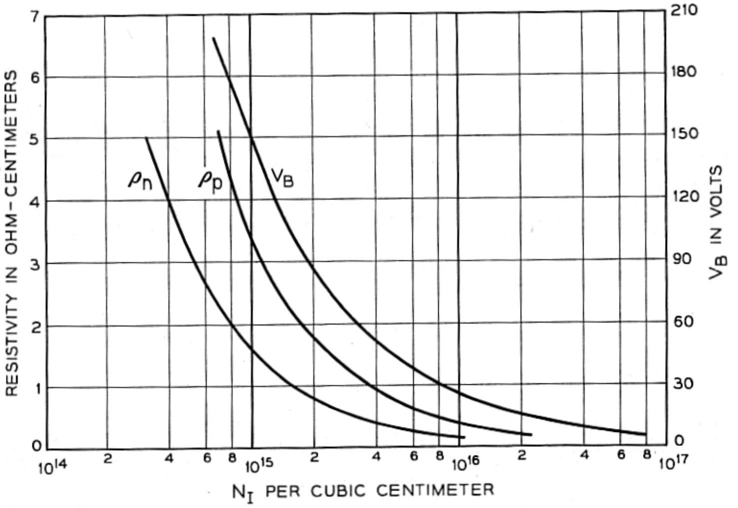


Fig. 7 — Resistivity and breakdown voltage versus net density of impurity centers.

TABLE I

n	High Resistivity Side of Step Junction
4.7	0.15 Ω-cm, p type
5.5	0.25 Ω-cm, p type
6.6	0.5 Ω-cm, p type
~6	2.0 Ω-cm, p type
3	0.1 Ω-cm, n type
3.4	0.6 Ω-cm, n type
3	2.0 Ω-cm, n type

seen that some of the considerations in ordinary transistor design, like keeping the base resistance low, sometimes are no longer important. The control of V_B, as pointed out above, is simply a matter of controlling the base layer resistivity. Miller[3] has given the breakdown voltage as a function of the net density of impurity centers on the high resistivity side of a germanium step junction like those made by the alloy process. These data are given in Fig. 7. This illustration also contains plots of the resistivity of the high resistivity side vs. the net density of impurity centers for n and p germanium material. These latter curves were redrawn from data given by M. B. Prince.[8] They represent the best available information on this subject at this time.

V_S is a function of V_B, $1 - \alpha_0$, and the pertinent parameter n. n is not completely independent of V_B since for a given type of transistor, n-p-n or p-n-p, both n and V_B are functions of the base layer resistivity. The experimental values of n for various base layer resistivities and resistivity types in germanium have been determined by Miller[3] and are given in Table I.

It is important that the space charge region of the collector not punch through the base layer below the breakdown voltage if the full interval between V_B and V_S is to be utilized. This requirement effectively puts an upper limit on the frequency cutoff for each base resistivity value, since the base width must be at least as wide as the space-charge region at the breakdown voltage. Fig. 8 gives the maximum frequency cutoff vs. the resistivity of the base region for p-n-p germanium avalanche transistors.

It is conceivable that if base layer width could be controlled very accurately, this punch-through phenomenon could be used to determine the peak of the negative in the resistance curve shown in Fig. 1 instead of relying on uniformly well etched junctions to show exactly the same breakdown voltage.

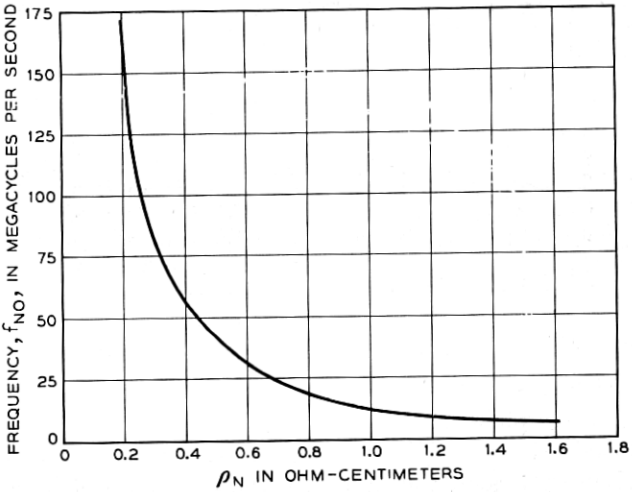


Fig. 8 — Maximum low-voltage frequency cut-off of alpha versus resistivity of base region for alloyed junction pnp transistors.

5. APPLICATIONS

In the region of collector voltage for which the alpha of an avalanche transistor is greater than unity, its terminal characteristics are quite similar to those of a point-contact transistor or a hook-collector transistor.[9, 10, 11] Hence most of the switching circuits designed for point-contact transistors could also use avalanche transistors. To provide a large voltage swing in such circuits the breakdown voltage of the collector junction should correspond to body breakdown and α_0 should be as large as possible in order to give a low value of the sustaining voltage, V_S. This latter requirement also leads to a low power dissipation when the transistor switch is in the ON (closed) condition.

One of the most serious limitations on the usefulness of hook-collector transistors is switching speed. Since the multiplication phenomenon involves the emission of minority carriers by the hook junction and the transport of these carriers across the hook region, a dispersion in transit time exists which results in a low alpha cutoff frequency for the device. In fact, the effective cutoff frequency may be an order of magnitude less than the cutoff frequency which would be calculated on the basis of the transport of the minority carriers across the base layer. As has already been pointed out, avalanche transistors exhibit alpha cutoff frequencies indistinguishable from those of non-multiplying devices. Frequency cutoffs of alpha in the range of 5 to 10 mc/sec are easily obtainable, even in pnp avalanche transistors, since the resistivity of the base layer can be quite low and hence punch through is inhibited for the necessarily thin base layers. Since the initial rate of change of current or voltage in pulse circuits is proportional to both alpha and alpha cutoff frequency, the rise times obtainable with avalanche transistors easily fall in the tenth microsecond range.

Another limitation on the switching speed of point-contact or hook-collector transistors results from the storage of minority carriers. This phenomenon manifests itself when one attempts to open the transistor switch after it has been driven into the current saturation region. In bistable type circuits using avalanche transistors the minimum collector voltage is automatically limited to the sustaining voltage, V_S, and the transistor never goes into the current saturation region. The collector junction never becomes forward biased, and there is none of the usual storage of minority carriers.[12]

One of the most interesting applications of avalanche transistors is as a two terminal, negative impedance element. Such a circuit has many applications in both switching and transmission. The circuit analysis of this application will be presented since it exemplifies the usefulness of the large-signal junction transistor theory and since the negative resistance characteristic that is obtained is typical of that for avalanche transistors.

The circuit to be discussed is shown in Fig. 1. An equivalent circuit, based on the work of Ebers and Moll,[13] is also shown in Fig. 1. The quantities α_{NO} and α_{IO} are the low voltage normal and inverse alphas. The voltage Φ_E is the voltage across the emitter junction. It is assumed that the base resistance is included in R. It is apparent that

$$I = \alpha_{NO} M I_E + M I_{CO} \tag{7}$$

If (1) and (7) are combined the following equation can be obtained

$$V = V_B \sqrt[n]{1 - \frac{I_{CO} + \alpha_{NO} I_E}{I}} \tag{8}$$

if it is assumed that the applied voltage, V, is large compared to Φ_E. In order to plot a voltage-current characteristic it is necessary to have a relation between I_E and I. From the equivalent circuit

$$I = \frac{\Phi_E}{R} + I_E \tag{9}$$

Since

$$\Phi_E = \frac{kT}{q} \ln \frac{I_E + (1 - \alpha_{NO}) I'_{EO}}{I'_{EO}} \tag{10}$$

where the quantity I'_{EO} is the reverse current of the emitter junction with the collector shorted to the base, it follows that

$$I = I_E + \frac{kT}{qR} \ln \frac{I_E + (1 - \alpha_{NO})I'_{EO}}{I'_{EO}} \tag{11}$$

(8) and (11) completely determine the negative resistance characteristic of the circuit of Fig. 1. A measured curve for a particular transistor in this circuit is shown in Fig. 9.

In some applications the slope of the negative resistance characteristic is of primary importance. It can be shown that

$$\frac{dV}{dI} = -\frac{V}{nI} \frac{1 - \alpha_{NO}M \dfrac{dI_E}{dI}}{1 - M} \tag{12}$$

or

$$\frac{dV}{dI} = -\frac{V}{nI}\left[1 - \left(1 - \alpha_{NO}\frac{dI_E}{dI}\right)\left(\frac{V_B}{V}\right)^n\right] \tag{13}$$

For values of R in the vicinity of 5,000 ohms and I_E greater than a milliampere,

$$\frac{dI_E}{dI} = \frac{1}{1 + \dfrac{kT}{qR}\dfrac{1}{I_E}} \simeq 1 \tag{14}$$

and

$$\frac{dV}{dI} = -\frac{V}{nI}\left[1 - (1 - \alpha_{NO})\left(\frac{V_B}{V}\right)^n\right] = -\frac{V}{nI}\left[1 - \left(\frac{V_S}{V}\right)^n\right] \tag{15}$$

This relation, in itself, is of very little utility since V and I are related in a complicated manner as can be seen by examining (8) and (11). However, if a plot of the negative resistance characteristic is available, this equation provides a theoretical check on the negative resistance at a given operating point. For example, consider the negative resistance characteristic shown in Fig. 9. The transistor used in obtaining these data had the following characteristics: $V_B = 36$ and $(1 - \alpha_0) = 0.047$. From the curve, for an operating point of 16 volts and 6 milliamperes, the measured negative resistance is 450 ohms. Substitution of appropriate values in equation (15) yields a negative resistance of 400 ohms. In every case that has been investigated a similar discrepancy has been found to exist. The higher value of negative resistance is attributed to an increase in α_0 due to the focusing effect of the voltage drop in the base layer. Actually what happens is that the center of the emitter, under these conditions of operation, becomes more forward biased than the outer edge, thus improving the transport efficiency since there is proportionately less surface recombination.

In some applications it would be very convenient if the type of negative resistance characteristic described above could be obtained without resorting to external circuit elements; in other words, if a true two terminal negative resistance could be obtained. As was explained above, the purpose of the external resistance in Fig. 1 is effectively to switch the current from the base collector loop to the emitter collector loop. Another way of interpreting the effect of the resistor is that it changes the effective alpha of the transistor by causing a higher percentage of the total current to be injected minority carrier current. A p-n-p (or n-p-n) structure designed in such a way that the alpha increases with emitter current would yield the same result. Such a device is shown in Fig. 10 along with the negative resistance characteristic obtained between emitter and collector. It is observed that the structure is not significantly different from a nonsymmetrical alloyed junction transistor in which the roles of the emitter and collector have been interchanged. For low values of current the alpha of the transistor is low and the peak voltage attained may be as much as 95 per cent of the breakdown voltage. As the current increases, a voltage drop occurs in the base layer. This drop biases

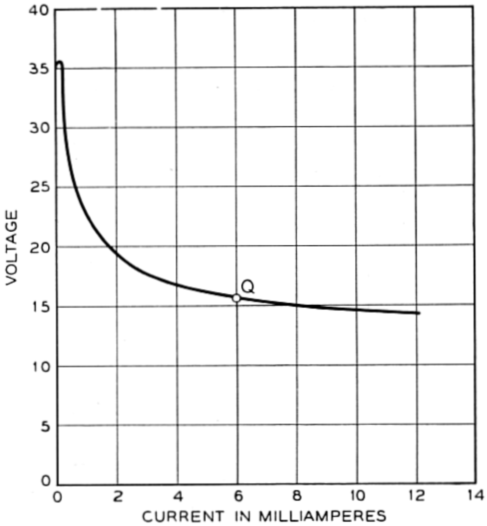


Fig. 9 — Measured avalanche transistor negative resistance characteristic.

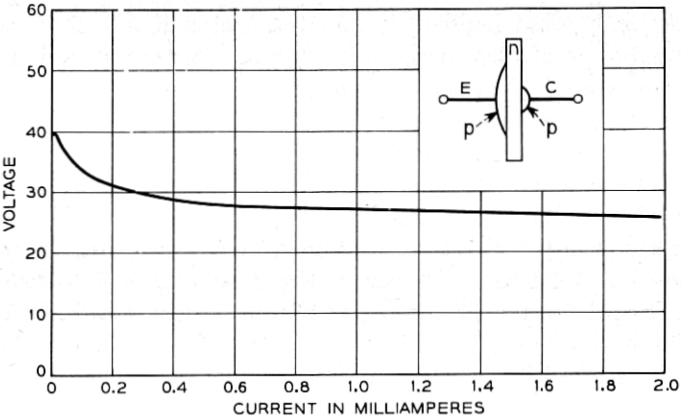


Fig. 10. — Two terminal avalanche device characteristic.

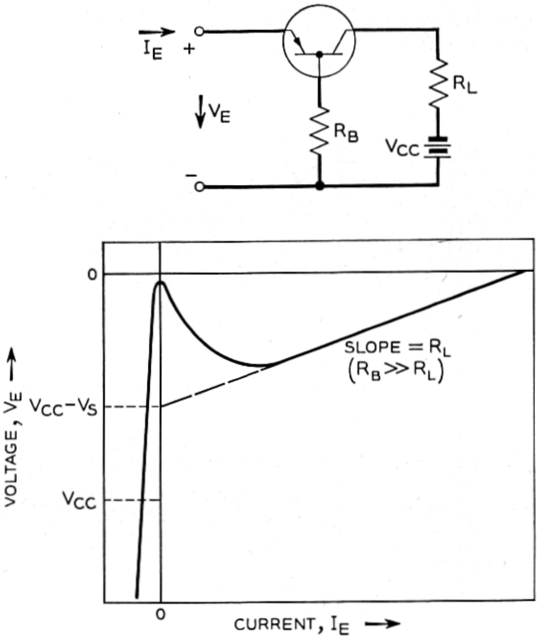


Fig. 11 — Emitter negative resistance characteristic of the avalanche transistor.

the outside of the emitter less forward than the center, and the alpha increases, resulting in a negative resistance.

It is worthwhile, in passing, to make a few statements concerning the type of negative resistance obtained in the circuit of Fig. 11. Such circuits, using point-contact transistors, have been amply discussed by Anderson.[9] Therefore this circuit will be discussed with the objective of pointing out the differences in the behavior when avalanche transistors are used. The general features of the negative resistance characteristic are also shown in Fig. 11. First of all the peak point is depressed below the origin an amount equal to the emitter floating potential plus the $MI_{CO}R_B$ drop in the external base resistance (neglecting internal base resistance). The initial slope of the negative resistance characteristic is governed by the collector supply voltage and how nearly it approaches the breakdown voltage, V_B. Since the magnitude of the negative resistance characteristic is given approximately by $(1 - \alpha)R_B$, it is apparent that the negative resistance approaches zero as the collector voltage approaches the sustaining voltage, V_S.

6. CONCLUSIONS

A new device has been described which is similar in some respects to point-contact transistors and hook-collector transistors. Avalanche transistors should prove to be very useful in both switching and transmission applications.

As has been shown, the behavior of avalanche transistors is quite well understood. In addition the terminal characteristics are sufficiently well related to the structure of the device to enable the design of devices to meet the needs of specific applications. It is believed that the presence of avalanche multiplication in transistor junctions may open up a whole new class of devices which can perform circuit functions not previously feasible with any single device.

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The authors would like to acknowledge the benefit of many discussions with J. L. Moll. J. J. Kleimack fabricated the first devices on which body breakdown could consistently be observed. Many of the data were gathered by W. C. Meyer.

Note: Approximately coincident with the submission of this article a paper covering related material appeared in the March, 1955, R. C. A. Review. It is entitled "Delayed Collector Conduction, A New Effect in Junction Transistors" by M. C. Kidd, W. Hasenberg, and W. M. Webster. As the divergence in titles indicates, the subject is treated from a somewhat different viewpoint in the two papers.

REFERENCES

1. McKay, K. G. and McAfee, K. B., Electron Multiplication in Silicon and Germanium, Phys. Rev., **91,** pp. 1079–1084, Sept. 1, 1953.
2. McKay, K. G., Avalanche Breakdown in Silicon, Phys. Rev., **94,** pp. 877–884, May 15, 1954.
3. Miller, S. L., Avalanche Breakdown in Germanium, Phys. Rev. (in publication).
4. Shockley, W., Transistor Electronics: Imperfections, Unipolar and Analogue Transistors, Proc. I.R.E., **40,** pp. 1289–1313, Nov., 1952.
5. Ebers, J. J. and Miller, S. L., Design of Alloyed Junction Germanium Transistors for High Speed Switching, B.S.T.J. **34,** pp. 761–782, July, 1955.
6. Early, J. M., Effects of Space-Charge Layer Widening in Junction Transistors, Proc. I.R.E., **40,** pp. 1401–1406, Nov., 1952.
7. Pearson, G. L. and Sawyer, B., Silicon p-n Junction Alloy Diodes, Proc. I.R.E., **40,** pp. 1348–1351, Nov., 1952.
8. Prince, M. B., Drift Mobilities in Semiconductors, I. Germanium, Phys. Rev., **92,** pp. 681–687, Nov. 1, 1953.
9. Anderson, A. E., Transistors in Switching Circuits, Proc. I.R.E., **40,** pp. 1541–1558, Nov., 1952.
10. Shockley, W., Sparks, M., and Teal, G. K., p-n Junction Transistors, Phys. Rev., **83,** pp. 151–162, July 1, 1951.
11. Ebers, J. J., Four-Terminal p-n-p-n Transistors, Proc. I.R.E., **40,** pp. 1361–1364, Nov., 1952.
12. Moll, J. L., Large-Signal Transient Response of Junction Transistors, Proc. I.R.E., **42,** pp. 1773–1784, Dec., 1954.
13. Ebers, J. J. and Moll, J. L., Large-Signal Behavior of Junction Transistors, Proc. I.R.E., **42,** pp. 1761–1772; Dec., 1954.