Pinch Effect in Indium Antimonide

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The critical current at which pinching occurs in indium antimonide has been measured by three independent methods: (a) by noting the current at which the pinched current-voltage characteristic deviates from the unpinched characteristic that is obtained in the presence of a longitudinal magnetic field H, using crystals of sufficiently high resistance for the avalanche breakdown current to be considerable, before pinching sets in, as the electric field is increased; (b) by noting the current at which the magnetoresistance, as a function of H, shows a change in its behavior; and (c) from a study of the critical current as a function of H. The three methods lead to a value for the critical pinching current of 4–5 amp. This current is the same for both single-crystal and polycrystalline samples, and is insensitive to small changes in the donor concentration or cross-sectional area of the crystal. The value of the critical current leads to a mean carrier temperature of 0.04 ev in avalanche breakdown. An irregular form of noise is observed when the crystal is operated in the transition region between the pinched and unpinched conditions, and it is thought that this noise is caused by pinching-unpinching instabilities.

INTRODUCTION

At the International Semiconductor Conference held at Rochester, in 1958, Glicksman and Steele[1] presented some data on the effects of an external, longitudinal, magnetic field on the current-voltage characteristic of single crystals of indium antimonide at high electric fields. At the time, these effects were unexplained, but, subsequently, the same authors ascribed them to self-pinching of the current in the crystal.[2] The work described in this paper corroborates and extends the experimental results of Glicksman and Steele. Furthermore, it is found that the self-pinching hypothesis appears adequate to explain the effects observed when a variety of experimental parameters (crystal perfection, impurity concentration, cross-sectional area, magnetic field strength) are varied. In addition, instabilities have been observed in the current-voltage characteristics when the crystal is being operated in the transition region between the pinched and unpinched conditions. From these various studies it has proved possible to derive an unambiguous value for the critical current for pinching in indium antimonide. In the next section, the conditions necessary for self-pinching will be discussed. This will be followed by detailed descriptions of the experiments which established that self-pinching was occurring at currents greater than about 4 amp.

NECESSARY CONDITIONS FOR PINCHING TO OCCUR

The customary criterion for the occurrence of self-pinching is that the energy density of the circumferential magnetic field caused by the current flow through the crystal should be equal to that of the carrier energy density. That is,

$$B_\theta^2/8\pi = k(nT_n + pT_p), \quad (1)$$

where B_θ is the circumferential magnetic field, k is Boltzmann's constant, n and p are the electron and hole densities, respectively, while T_n and T_p are the average electron and hole temperatures, respectively. It is clear that, for pinching to occur, carriers of both sign are necessary; if the crystal were strongly n-type, for example, the tendency of the electron flow to pinch to a narrow cross section would be counteracted by the effect of the space charge field set up by the ionized donors left behind. If the crystal is in avalanche breakdown, however, the electron and hole densities become equal and significantly greater than the donor or acceptor concentrations. Quenching of the pinch effect by space charge fields will not occur then, since both carriers are mobile. Thus, putting $n=p$, expression (1) becomes

$$B_\theta^2/8\pi = nkT, \quad (2)$$

where $T = T_n + T_p$.

Consider a current column of circular cross section, radius r. Let the current be i. Then

$$i/\pi r^2 = ne(v_n + v_p) = nev, \quad (3)$$

where v_n, v_p are the drift velocities of the electrons and holes, respectively. Now

$$B_\theta = 2i/r. \quad (4)$$

Hence, from Eqs. (2)–(4), there will be a critical current for pinching (i_{c0}), given by

$$i_{c0} = 2kT/ev. \quad (5)$$

Thus, the two prime conditions that must both be met for pinching to occur in an extrinsic semiconductor are: (i) The magnitude of the current must exceed the critical value given by Eq. (5); and (ii) the electric field E in the crystal must be at least equal to the field necessary for avalanche breakdown (E_B).

In these present experiments, as well as in those of Glicksman and Steele, a longitudinal magnetic field (B_z) was used for diagnostic purposes. It is then necessary to consider the external magnetic field flux contained by the pinch. Suppose the current column is

[1] M. C. Steele and M. Glicksman, J. Phys. Chem. Solids **8**, 242 (1959).
[2] M. Glicksman and M. C. Steele, Phys. Rev. Letters **2**, 461 (1959).

circular, with a radius R at the outset of the pinching, and that the radius of the pinched column is r, as before. As the column pinches, the magnetic flux contained within it is compressed from an area πR^2 to an area πr^2, provided there is no flux leakage. The condition at the critical current for pinching then becomes

$$B_\theta^2 = 8\pi nkT + B_z^2[1 + L\pi(R^2 - r^2)], \tag{6}$$

where the factor L is included to allow for the possibility of the diffusion of magnetic flux out of the pinch column. The diffusion constant D is given by

$$D = c^2/4\pi\sigma,$$

where c is the velocity of light, and σ is the plasma conductivity. As we shall see, the lowest current at which pinching occurred was 5 amp. The applied field strength was about 200 v cm^{-1}, and, at this field, the drift velocity[1,3] is about 3×10^7 cm sec^{-1}. The cross-sectional dimensions of the crystal were 0.06 cm by 0.04 cm. Thus, at 5 amp, the carrier concentration was about 4×10^{14} cm^{-3}, and, hence, D was of the order of 10^7 cm^2 sec^{-1}. Thus, even in as short a period as 0.1 μsec, the magnetic field could diffuse about a cm, so that we are justified in putting $L=0$ in Eq. (6). We thus obtain, for the initiation of pinching,

$$i_c = (2kT/ev) + (B_z^2/i_c)(R/2)^2. \tag{7}$$

From Eqs. (6) and (7) it can be seen that: (i) With $B_z=0$, the critical current i_{c0} is independent of the cross-sectional area of the crystal; (ii) when $B_z\neq0$, the increased pressure inside the pinch results in the final pinch radius r being greater than when $B_z=0$; (iii) when $B_z\neq0$, $(di_c/dB_z)=R/2$ when B_z is sufficiently large.

EXPERIMENTS

A. Experimental Techniques

The experimental techniques used in these studies were standard. The samples used in this work consisted of bars of square or rectangular cross section, provided with side-arms for the attachment of voltage leads. Because it was found that the experimental results did not differ significantly if the samples were polycrystalline rather than single crystal, most of them were cut from two lots of n-type polycrystalline material with excess donor concentrations of 2×10^{14} cm^{-3}. Heavy current leads were attached at the ends of the bar, and lighter voltage leads on the side-arms, by means of a suitable solder. The samples were immersed in liquid nitrogen for all of the experiments.

Constant current pulses were applied to the samples by discharging a charged 50-ohm coaxial line, using a mercury relay as the switch. The pulse length was 1.6 μsec, and the repetition rate generally about 20 cps. Care was taken to establish good matching of the sample circuit to the coaxial line, under *all* operating conditions. The current delivered to the crystal was deduced from an oscilloscope display of the voltage drop, across a small resistor in series with the crystal. Under all operating conditions, it was established that this current remained constant for the duration of the pulse. The voltage drop across the sample, or the part thereof appropriate to the pair of side-arms, was also displayed on the oscilloscope.

(B) Current-Voltage Characteristics

The first experiments paralleled those of Glicksman and Steele in that the donor concentrations and dimensions of the specimens were very similar, and the current-voltage characteristics were obtained both with and without an external magnetic field H applied in a direction parallel to the current flow. The only significant difference was that the data shown in Fig. 1 were obtained on a polycrystalline sample, whereas those of Glicksman and Steele were obtained on single crystal samples. Even so, the results, and particularly those produced by B_z, are essentially identical, thus demonstrating that crystal orientation and perfection are not of prime importance. This seems reasonable if the observed effects result from pinching.

Glicksman and Steele deduce that self-pinching occurs from the effect that the external, longitudinal, magnetic field has on the current-voltage characteristics. Their argument, in summary, is as follows: When pinching occurs, the electron-hole concentration is considerably increased over that of the unpinched condition. The resulting enhancement of electron-hole scattering will cause the crystal to have a greater resistance than it would have when unpinched. The apparent resistance is still further increased by the transverse magnetoresistance, caused by the circumferential magnetic field, which will be much greater for the pinched than the unpinched state.

As described in the previous section, when a longitudinal magnetic field is applied to the crystal, it will tend to "unpinch" the current flow until the latter becomes large enough for its self-magnetic field to overcome the effect of the applied field. Thus, while unpinched by a magnetic field, the crystal will have a lower resistance, but when the current is sufficiently large, the resistance will revert to that appropriate to the pinched characteristics.

This is the interpretation of the data in Fig. 1. With $H=0$, pinching begins at a current of about 6 amp, in good agreement with Glicksman and Steele who observed this to occur at about 5 amp. With $H=325$ gauss, the data follow the unpinched characteristic of lower resistance at currents greater than 6 amp, until the current is high enough for pinching to take place.

A more comprehensive set of data in the current-voltage domain of interest is shown in Fig. 2. There are two basic characteristics, the one at $H=0$, labeled the

[3] Y. Kanai, J. Phys. Soc. Japan 13, 967 (1958).

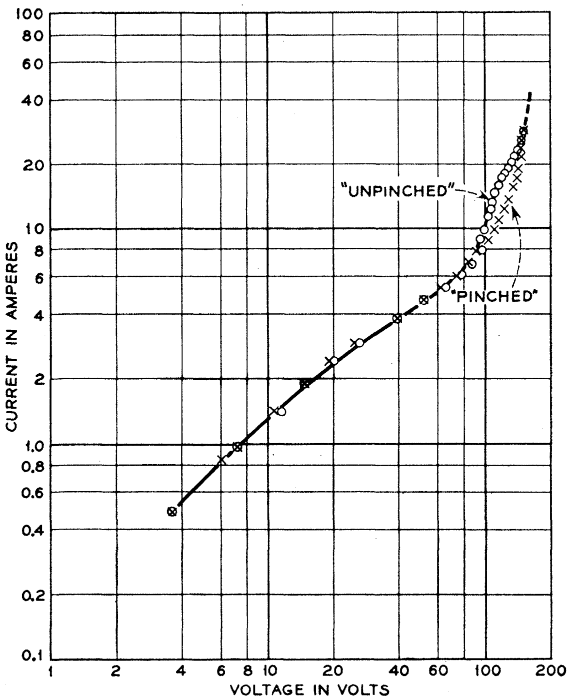

FIG. 1. Current-voltage characteristics of InSb crystal, with and without an applied longitudinal magnetic field, showing the deviation between the pinched and the unpinched characteristics.

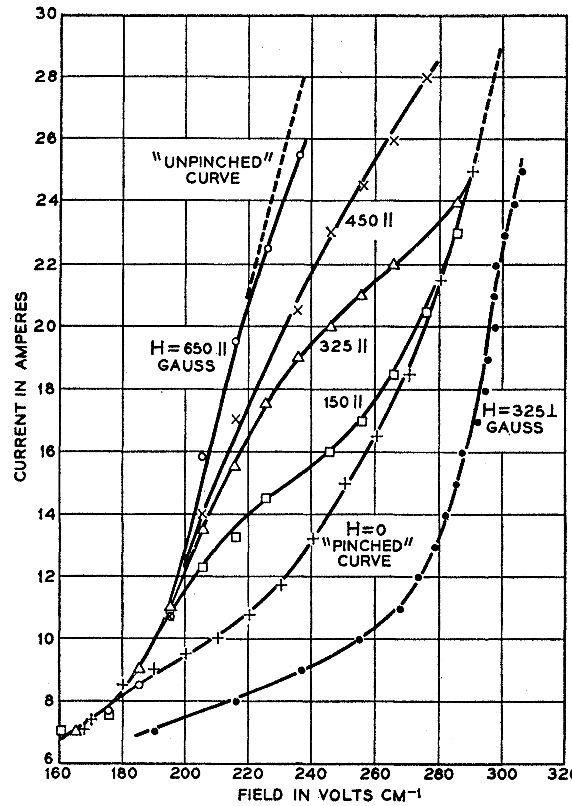

FIG. 2. Current-voltage characteristics for various applied magnetic fields, showing the pinched and unpinched characteristics and the transitions between them as a function of H.

"pinched" curve, and the curve at the left-hand side, labeled the "unpinched" curve. In the presence of a longitudinal magnetic field, the current as a function of field follows the unpinched curve until the current becomes high enough for pinching to occur, whereupon the current-voltage curve shows a transition over to the pinched curve. It is clear from Fig. 2 that, as H is increased, the current has to reach higher values before pinching can occur, as is to be expected from Eq. (7).

Also shown in Fig. 2 is the effect of a magnetic field applied in a direction perpendicular to the current flow. The effect is quite different from that of a longitudinal field, it being simply an increase in the resistance of the sample at all currents, due to transverse magnetoresistance.

To establish further that the effects in the current-voltage characteristics did not have spurious origins, the following tests were made: (a) It was established that samples prepared without side-arms behaved in the same way as those with side-arms, thus showing that the side-arms had no noticeable effect on the current flow. (In the samples without side-arms, the voltage leads were soldered to the ends of the bar, close to the current leads.) It was also found that the load impedances in the side-arm circuits were not critical. (b) Using samples of somewhat lower resistivity (by a factor of two) caused no noticeable change in the critical current, as measured from the current-voltage characteristics with, and without, a magnetic field. However, these characteristics were of inferior quality compared with those of the higher resistivity material, probably because of the difficulty of reaching E_B before a current of magnitude equal to i_{c0} occurred. (c) In another experiment, a high-resistivity sample with a well-defined pinch threshold was etched so as to reduce its cross-sectional area by a factor of two. The critical current remained unchanged, in keeping with Eq. (5).

(C) Observation of Instabilities

As emphasized earlier, it was established that the current remained constant for the duration of the pulse under *all* operating conditions. This was not true of the voltage pulse, which, under certain operating conditions, exhibited instabilities. It was found that the voltage between the side-arms was constant for the length of the pulse when the crystal was operated below the critical pinching current, or on the pinched or unpinched characteristics. However, when the crystal was operated in the transition region between the pinched and unpinched curves, the voltage pulses became "noisy", as shown by the typical example in Fig. 3. No two oscilloscope traces appeared identical, and the noise was definitely not oscillatory in character. Rather, the appearance of the voltage pulse suggests more or

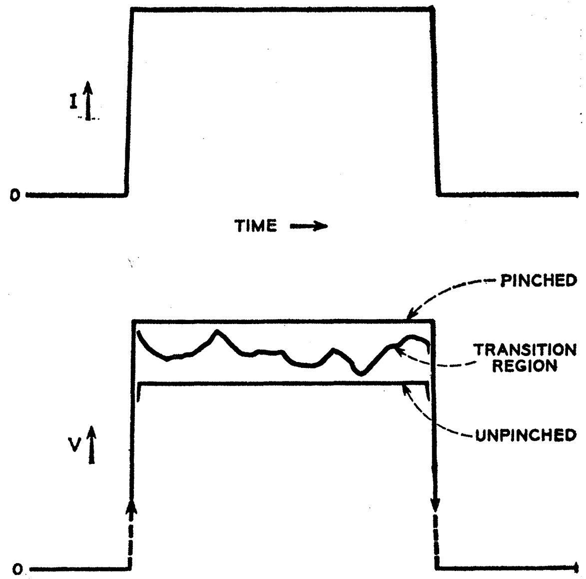

FIG. 3. Schematic representations of the current and voltage pulse shapes, illustrating the voltage instabilities observed in the pinching-unpinching region.

less violent changes occurring in the current flow, the most likely interpretation being that, in the transition region between the pinched and unpinched characteristics, the current column is relatively unstable as it is continually pinching and unpinching. This interpretation receives support from measurements of the amplitude of the voltage surges. The lower curve in Fig. 4 illustrates the lowering (ΔV) of the voltage across the sample, as the increasing magnetic field drives the current from the pinched to the unpinched condition. At higher fields, ΔV tends to increase again as the effect of the magnetoresistance increases. The upper curve represents the peak-to-peak amplitude of the voltage surges in the transition region, as estimated visually from the oscilloscope displays. It is clear that the noise amplitude is, at most, about 30% of ΔV, showing that the instantaneous operating point is careering about somewhere between the pinched and unpinched characteristics. The noise amplitude reaches a maximum for an operating point somewhere between the pinched and unpinched characteristics, a feature that aided in the determination of the critical current for pinching as described below. It should be noted that there is no indication (or expectation) of a negative resistance in the current-voltage characteristics, which could cause the noise.

As the noise occurred only in the transition region, it was ascribed above to pinching-unpinching instabilities. By analogy with pinches in gases, further instabilities, for example, kink instabilities, of a linear pinch might be expected, which would lead to wriggling of the pinched column within the crystal. An additional cause of wriggling is to be expected, namely, local heating. Such wriggling of the current column need not necessarily give rise to voltage instabilities between the side-arms, and, indeed, in the present work, no instabilities were observed when the current was in the fully pinched condition.[4]

(D) Determination of the Critical Pinching Current

The quantity of most interest in these investigations is the critical current for self-pinching i_{c0}, in the absence of an external magnetic field. Most of the 14 samples used in this work showed a divergence of the pinched and unpinched characteristics at a current lying between 7 and 8 amp. However, this divergence current could not be located accurately from the current-voltage characteristics, in general, because of the complications arising from the magnetoresistance effects. The most satisfactory method of locating this divergence current was to plot the change in voltage across the side-arms as a function of H, for various currents through the sample. When magnetoresistance alone was present, the voltage increased steadily with H. When the magnetic field also served to unpinch the current, however, the voltage at first decreased, as H increased from zero, as in Fig. 4. In this way the divergence current could be quite accurately determined, and it usually lay between 4 and 6 amp. However, in general, this divergence current will only be i_{c0}, if, at this current, the crystal is sufficiently far into avalanche breakdown. That this was the case was not always clear, thus raising the question whether pinching would be observed at lower currents, if the avalanche breakdown could be established at still lower currents.

According to various authors,[1,3,5] avalanche breakdown occurs in InSb at a field of about 160 v cm^{-1}.

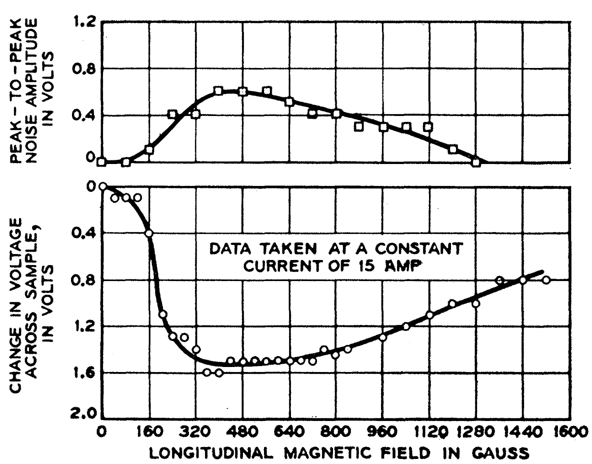

FIG. 4. Curves illustrating the amplitude of the noise and the effect of longitudinal magnetoresistance as a function of H.

[4] Since this paper was submitted for publication, M. Glicksman and R. A. Powlus [Phys. Rev. **121**, 1659 (1961)] have reported some generally similar observations of noise on the voltage pulses, though, apparently, these observations were not confined solely to the transition region.

[5] A. C. Prior, J. Electronics and Control **4**, 165 (1958).

This was confirmed in the present experiments; for the 14 samples studied, as determined by inspection of the current-voltage characteristics, avalanche breakdown occurred at 180±25 v cm^{-1}. Accordingly, a sample was prepared (by reducing its cross-sectional area) so that E_B was obtained at a lower total current. The current-voltage characteristics for this sample were then obtained in the usual way, with, and without, a longitudinal magnetic field. The results are shown in Fig. 5. Here it was found that the two curves could be fitted to each other very well, at low currents, by applying a scaling factor of 0.86 on the abscissa for the data taken with a magnetic field present. The excellence of the fit implies that the longitudinal magnetoresistance is, to sufficient approximation, a constant proportional effect, even in the avalanche breakdown region. From the curves in Fig. 5, it is clear that avalanche breakdown does occur at currents appreciably below i_{c0} as the pinched and unpinched characteristics do not separate immediately after the current-voltage curve has completed its upward swing. By inspection, the critical current, unambiguously arrived at, is about 5 amp.

Equation (7) indicated an alternative method for deriving i_{c0}, namely, to plot i_c against H. The current i_c can be taken to be roughly the current at which the noise amplitude reaches a maximum, and this is easily determined as a function of H. Thus, a plot of i_c against

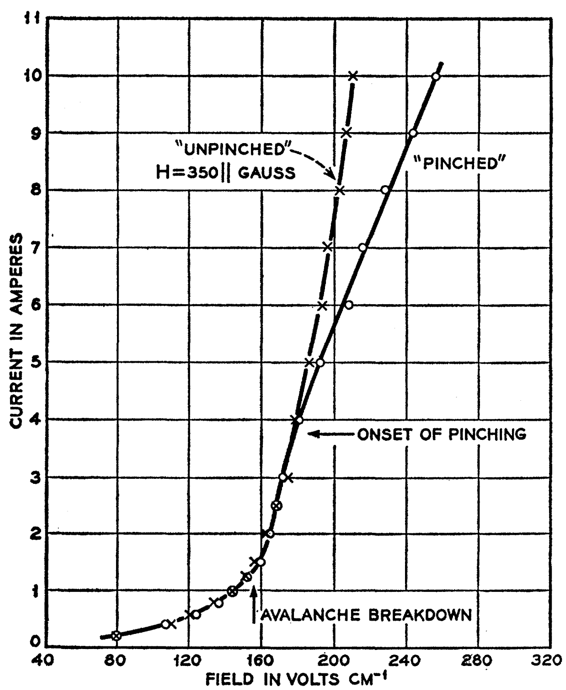

FIG. 5. Current-voltage characteristics for a sample where the critical pinching current was appreciably higher than the current at the onset of avalanche breakdown. A scaling factor of 0.86 has been applied to the field axis of the data taken in the presence of a longitudinal magnetic field, so as to fit the two curves to each other in the prebreakdown region, thereby adjusting for the magnetoresistance effect.

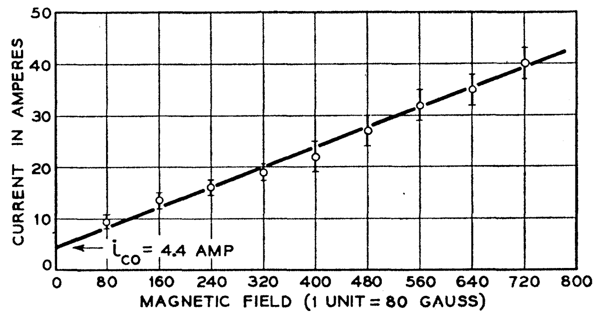

FIG. 6. Critical current as a function of H, as derived from observations of the occurrence of noise in the voltage pulses.

H, when extrapolated to $H=0$, would yield a value for i_{c0}. The advantage of this method is that it does not require the crystal to be well into avalanche breakdown at i_{c0}. A typical plot of i_c versus H is given in Fig. 6, where it will be seen that the relation between i_c and H can be satisfactorily represented as linear, even to very low values of H. It appears sufficiently accurate to make a linear extrapolation to $H=0$, which yields a value for i_{c0} of 4.4 amp, in excellent agreement with the value derived from the curves of Fig. 5.

DISCUSSION

It is clear that the experimental results bear out, at least qualitatively, the expectations of the self-pinching hypothesis. Consequently, it is worth considering some of the implications of these experiments in some detail.

(A) Observation and Size of Critical Current

It has been shown that a sufficiently advanced state of avalanche breakdown can be reached before pinching sets in, if the crystal *resistance* is sufficiently high, by using either high resistivity material or small cross-sectional areas. If these conditions were not met, no pinching effects were observed. Further, in accordance with the pinching model, the value of the critical current, in the absence of an external magnetic field, was found to be independent of the crystal cross-sectional area and resistivity, over the rather restricted ranges in which these parameters were varied, and the same for both single-crystal and polycrystalline samples.

From the critical current of about 5 amp, we can estimate the mean carrier energy, kT, using Eq. (5). In InSb, the drift velocity[1,3] at 200 v cm^{-1} carriers is about 3×10^7 cm sec^{-1}. If we suppose that $T_n=T_p$, we thus obtain a value for kT_n of 0.04 ev. This value is regarded as reasonable (to within a factor of 2), it being about 15% of the ionization energy when the latter is taken to be roughly equal to the energy gap.[6]

[6] W. Shockley, Czech. J. Phys. 11, 81 (1961).

(B) Dependence of Critical Current on H

From Fig. 6 it is apparent that i_c varies approximately linearly with H. This is consistent with Eq. (7) at large values of H where the second term on the right-hand side becomes more important than the first. The linear extrapolation of the experimental data to $H=0$ thus yields a value for i_c which is slightly low, and, in fact, there is a slight suggestion in the data that the curve is concave upwards at low magnetic fields. However, this error cannot be very great in view of the agreement in the values of i_c derived from independent experimental techniques.

From Eq. (7), the slope of the line in Fig. 6 should be $R/2$, and the value for the average crystal diameter so obtained is 0.05 cm, in excellent agreement with the actual dimensions, 0.04 cm$\times$0.06 cm.

(C) Radial Electric Field and Carrier Concentration

If all the carriers pinched inwards, they would leave a fixed positive space charge due to the donors. With a donor concentration of 2×10^{14} cm^{-3} and, for complete pinching to the center of the crystal, the relation $\text{div}D=4\pi\rho$ leads to a potential difference of about 3000 volts between the center of the crystal and the surface. In view of this preposterous result, it must be concluded that the donors remain essentially compensated by an electron cloud. Thus, if any pinching is to occur, it will be done only by the extra carriers created by the avalanche conditions. That there are sufficient excess carriers can be checked using Eq. (3). We have noted earlier that at a current of 5 amp, Eq. (3) yields $n=4\times 10^{14}$ cm^{-3}, which is appreciably in excess of the donor concentration, as required.

(D) Increased Resistance of Pinch

In the arguments presented earlier it was conjectured that the resistance of the pinched current would be greater than that of the unpinched state at a given current because of the combined effects of the increased transverse magnetoresistance and electron-hole scattering.[2] However, from data such as that in Fig. 5, the increase in resistance is by a factor of 2 or more, which seems much larger than can be reasonably expected of a transverse magnetoresistance effect alone.[7] On the other hand, the increased resistance is hard to account for on the basis of conventional electron-hole scattering mechanisms. For these to be responsible for the effect would require an electron mobility of the order of 10^7 cm^2 v^{-1}, which is two orders of magnitude higher than the accepted value. It must be concluded, therefore, that the increase of the resistance is not quantitatively understood at present, though this may be because of our lack of knowledge of scattering processes for hot carriers in a plasma.

CONCLUSIONS

It is apparent that the various phenomena investigated in these experiments are in good agreement with the self-pinching hypothesis, confirming the conclusion of Glicksman and Steele. Furthermore, it is very unlikely that the experimental results could have any other explanation. In particular, the pinching hypothesis accounts for the magnitude of the critical current and the shapes of the current-voltage characteristics, with and without applied magnetic fields, for crystals of various dimensions and impurity contents. The noise observations in the transition region between the pinched and unpinched conditions suggest pinching-unpinching instabilities, though further work would be needed to establish the exact origin of this noise.

ACKNOWLEDGMENTS

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[7] R. F. Broom, Proc. Phys. Soc. (London) **71**, 471 (1958).