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Observations of Electron-Hole Current Pinching in Indium Antimonide

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The temporal variation at high electric fields of the current and voltage in n-type InSb is examined. The observations show the behavior characteristic of self-pinching of the electron-hole plasma current. There is good agreement with theory for the observed times for the pinching process as a function of current. The calculated sum of the average energies of the electrons and holes in the plasma is 0.037 ev. Oscillations in the electric field of apparently different character are observed during the pinch, and when a longitudinal magnetic field is applied.

IN an earlier communication[1] it was suggested that some observations of the current-voltage characteristics in n-type indium antimonide could be explained in terms of a "self-pinching" of the electron-hole plasma at high currents. In this article we report observations of the current and voltage as a function of time which provide substantial corroboration for the occurrence of pinching. In addition, there is evidence for the occurrence of oscillations and instabilities of a character like that found in gaseous plasma pinches.

The material used was n-type indium antimonide in single crystalline form, cut in a bridge shape (see Fig. 1), typically of width 0.042 cm, thickness 0.040 cm, and length between arms 0.25 cm. All measurements were made at 77°K. Two different sets of crystals were used: one set (A) had electron concentrations of 2×10^{14} cm^{-3}, while the other set (B) had electron concentrations in the range 1–4×10^{13} cm^{-3}. At low electric fields the electrons had mobilities in the range 3.5 to 6.5×10^5 cm^2/v-sec.

Current pulses were produced by discharging a coaxial line through the crystal and its associated circuit, shown in Fig. 1. The pulses had rise times of the order of 0.02 μsec, and had durations in the range 0.25 to 1.4 μsec. Observations of the voltage differences between points A and B and between points C and D allowed a display of the current and voltage along the crystal. The resistance R_1 and R_2 maintained constant current conditions in the crystal.

The essential features of the behavior of n-type InSb at high electric fields have been detailed by several authors.[2–5] At electric fields of several volts/cm, the current-voltage relationship becomes nonlinear, because of a heating up of the electrons to energies in excess of thermal equilibrium. At fields of the order of 200 v/cm, the electrons produce electron-hole pairs in high density, and this pair density increases rapidly with increasing electric fields. The effects investigated in the present work occur only after the field is sufficiently high to produce an electron-hole plasma of a density such that the conductivity is affected. The variation of the sample's conductivity with time thus affords a means of studying the variation of the plasma contribution to the conductivity with time.

Typical photographs obtained with the crystals A are shown in Fig. 2. The current and voltage at fields too low to cause impact ionization are displayed in Fig. 2(a). The pulses are smooth functions of time, and both current and voltage behave in a similar manner. The rise time of about 0.04 μsec is due to the observing oscilloscope. In this figure the applied voltage is too small to produce an observable increase in carrier density, as detected from the current pulse and from other measurements of the Hall coefficient. However, Fig. 2(b) shows the behavior of the current and voltage at fields high enough to show an appreciable increase in the carrier density. The breakdown at 1 is due to the production of electron-hole pairs in densities comparable to the initial electron concentration, and this causes the large decrease in voltage observed. As can be seen from the voltage pulse, the breakdown occurs in a time not much smaller than 0.01–0.02 μsec. The amplifier is too slow to follow the initial rise of the voltage pulse to its peak, especially at the higher currents. At the lower currents, a plot of peak voltage as a function of current falls on an extrapolation of the intermediate field curve

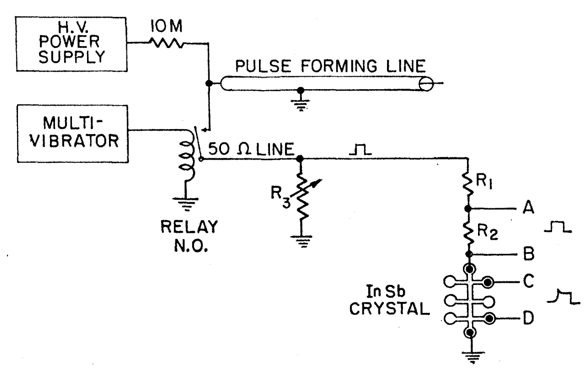

FIG. 1. Schematic diagram of measuring circuit. All lines are coaxial cable, and R_1 and R_2 are chosen to give approximately constant current conditions through crystal. R_3 is varied to match the line impedance. Pulses A-B and C-D are observed simultaneously with two high-speed differential amplifiers and a Tektronix dual-beam oscilloscope.

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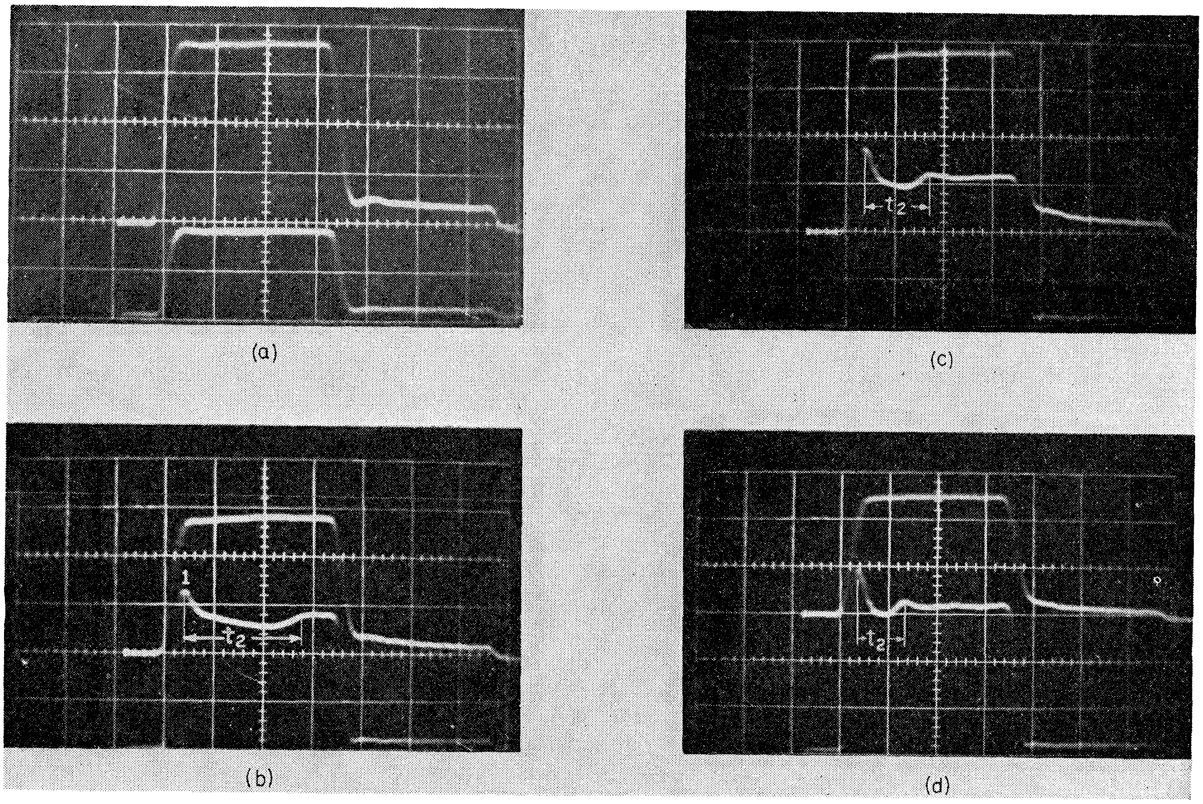

FIG. 2. Current and voltage pulses. Upper trace is proportional to the current through the crystal; the lower trace is proportional to the voltage along the crystal. Time scale is 0.1 μsec/division. Currents are (a) 1.4 amp, (b) 5.5 amp, (c) 7.3 amp, and (d) 9.7 amp. Sensitivities for the voltage pulse are 39 v/cm div for (a) and 79 v/cm div for (b), (c), and (d).

which holds when no breakdown occurs. The field which sustains the breakdown is about 200 v/cm, in agreement with previous measurements. However, it is noted that after the time t_2 the voltage rises again by an amount which is seen to be a weak function of the current. It is also seen that the time t_2 decreases as the current is increased, as shown in Figs. 2(c) and 2(d). A similar series of photographs has been obtained for crystals B, with only quantitative differences in the time t_2 (which will be discussed below) and the height of the voltage increase.

The electron-hole pairs produced by the breakdown in the crystal are able to move about in the crystal in a way very similar to the motion of electrons and ions in a plasma of ionized gas. At sufficiently strong currents, it is thus expected that the self-magnetic field of this electron-hole plasma will be able to pinch it down to a volume smaller than the dimensions of the crystal. On being pinched down, the resistance of the plasma will be increased because of the increased electron-hole scattering and because of the increased magnetoresistance in the larger azimuthal magnetic field. The increase in resistance which takes the time t_2 to occur is of just the character that would be expected for pinching. Two points of comparison with theory may be used to verify this conclusion. One is the functional dependence of the time t_2 on the current, and the other is the magnitude of the resistance increase.

In our case the dominant terms in the equations of motion of the plasma are the magnetic pressure and the collisional contribution to the momentum. The solution of the equations, ignoring the smaller terms, yields the qualitative result that the time for pinching should be about 0.1 μsec.[1] The smaller terms are of importance mainly at the initiation and halt of the pinch. An analysis including all of the terms[6] yields equations from which the time t_2 may be calculated as a function of the plasma current I_p. From the complete analysis, it can be seen that the radially inward velocity of the pinch rises from 0 to values of 10^5–10^6 cm/sec in about 10^{-12} sec. If the pinch is assumed to be adiabatic, the velocity increases little for weak pinches, and only by factors of 2 or 3 for the strongest pinches, during the pinch process.

The measured values of the time t_2 as a function of I_p are shown in Fig. 3. The current due to the electrons originally present has been subtracted out, using the values for current measured at fields below breakdown and a small extrapolation to the fields after breakdown. The subtracted currents are in the range 2.8 to 4.0 amp for crystals A, and 0.72 to 0.83 amp for crystals B.

[6] M. Glicksman (unpublished).

It is seen that both crystals A and B yield curves which give the $t_2=\infty$ value of I_p of 1.0 amp. I_p at $t=\infty$ is equal to $I_c'=3ck(T_e+T_h)/2ev$, where v is the electron drift velocity, and T_e and T_h are the electron and hole temperatures, respectively. There is excellent agreement of this value for crystals with such a large difference in initial electron concentration. Thus, these measurements yield a more precise value for $k(T_e+T_h)$ than that quoted earlier.[1] The new value is 0.037 ev and indicates a transverse random energy of the electrons comparable to the optical phonon energy[7] of 0.025 ev. The partition of energy between the electrons and holes will depend on the importance and effectiveness of the electron-hole scattering.

Also shown in Fig. 3 are two curves calculated from a numerical solution of the equations of motion for the pinch.[6] The adjustable parameter, the value of I_c', was chosen as 1.0 amp, as forced by the data. There is an excellent fit with experiments on crystals B with a value of hole mobility $\mu_h=10\,000$ cm²/v-sec; to fit the results for crystals A requires a hole mobility of about 7000 cm²/v-sec. It is expected that the crystals A (with larger impurity concentration) will have a lower hole mobility than crystals B, and these values are in fair agreement with measured hole mobilities[8] in p-type InSb.

The check on the magnitude of resistance change is less quantitative. The pinch equations yield a value for the minimum radius of the pinch. This radius can be used to calculate the expected change in resistance due to the magnetoresistance effect alone, and the result is in reasonable agreement with observation at the higher currents, but gives too small a value of the resistance increase at the lowest currents. The relative changes observed are much larger in crystals B than A, since the plasma contribution to the conductivity is much larger in crystal B.

As can be seen in Figs. 2(c) and 2(d) oscillations are present in the "pinched" condition, of a frequency which increases with increasing current. These oscillations are coherent in phase from pulse to pulse, and are believed to be caused by the expansion and contraction of the pinch about its equilibrium radius. They are damped out after several periods at most currents, but persist for many periods at the higher currents.

The application of a longitudinal magnetic field B_1 causes significant changes in the pinch. In the absence of the field, the pinch is apparently stable for periods at least as long as 1.4 μsec. With a B_1 as small as 10 gauss at low currents, this stability disappears after the first pinching down and the voltage shows oscillations phased randomly with respect to the pulse. As

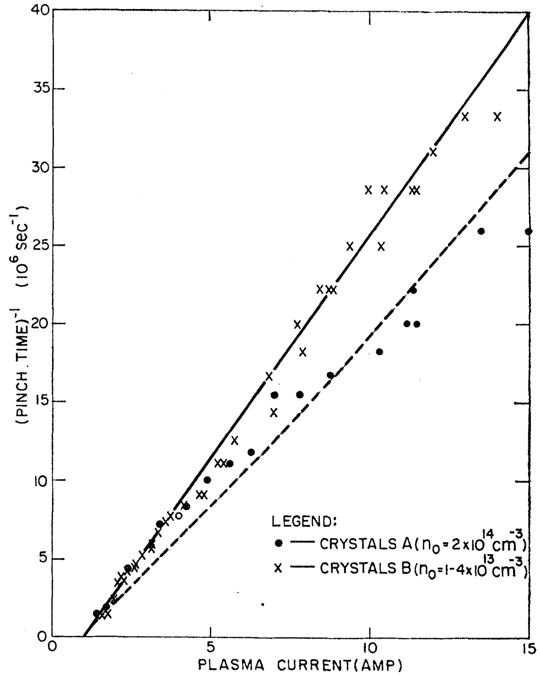

FIG. 3. Reciprocal of the pinch time as a function of plasma current. Curves are calculated for different values of the hole mobilities: solid line, $\mu_h=10\,000$ cm²/v-sec; broken line, $\mu_h=7000$ cm²/v-sec.

B_1 is increased, the magnitude of the resistance change during the pinch is decreased and all signs of pinching disappear for a value of B_1 which depends on the current; in this case the random-phased oscillations occur immediately after breakdown. It is believed that these oscillations are of the same character as those described by Larrabee and Steele[9]; they may also be related to instabilities observed to occur above certain critical magnetic fields in gas discharges.[10]

The general behavior of the pinching in a longitudinal magnetic field is only partially analogous to that of a gaseous plasma, in that pinching is inhibited at strong fields. The oscillations (which may be related to effects at the surface[9]) play a vital role. It is observed, for example, that a small transverse magnetic field causes oscillations and apparently inhibits formation (or observation) of pinching. Further studies of these effects are continuing.

ACKNOWLEDGMENTS

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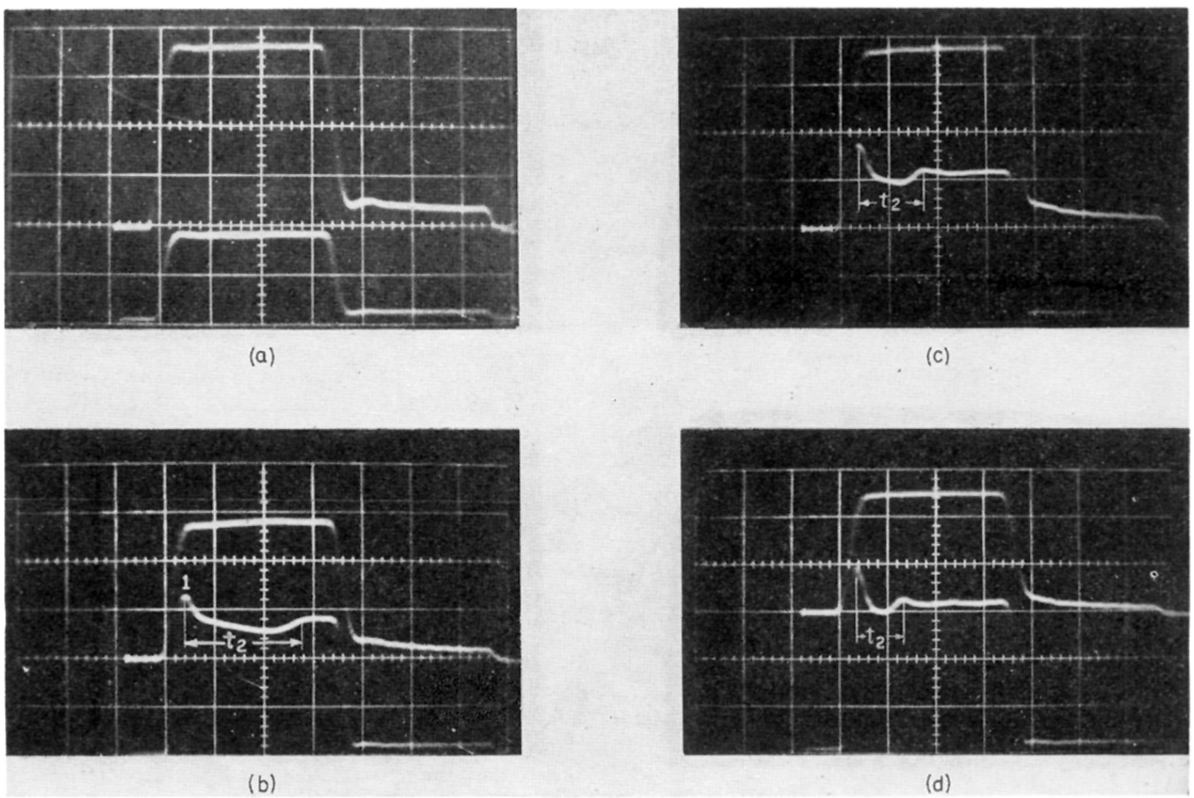

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