PLASMA PINCH EFFECTS IN INDIUM ANTIMONIDE

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In pulsed studies of the properties of n-type indium antimonide at 77°K in high electric fields, some interesting effects were observed in the presence of an external longitudinal magnetic field.[1] It is now suggested that these observations indicate the presence of pinching effects for the electron-hole pair current in indium antimonide. It is believed that this represents the first published indication of the existence of pinch effects in a solid. Of course the pinch effect in gaseous plasmas[2] is well known.

Measurements were made on two samples with an electron density of 2×10^{14} cm^{-3} at low electric fields. The single crystal used for the observations shown in Fig. 1 was rectangular in cross section, 0.39 mm × 0.60 mm, and about 8 mm long. The voltage was measured between two cross arms which were part of the crystal, spaced 2.5 mm apart. The pulse length of 1 μsec and repetition rate of 1 cps were chosen to minimize heating effects. Data obtained from the two samples agreed well within the precision of measurement, which was about 3 %.

The pertinent results are shown in detail in Fig. 1, in which the measured current is plotted as a function of voltage for three cases: (1) with no external magnetic field, (2) with an applied longitudinal magnetic field of 350 gauss, and (3) with an applied longitudinal magnetic field of 3500 gauss. In the first case, it is seen that at low voltages the current is ohmic, dropping off to lower than ohmic slope for voltages greater than several volts. At voltages above about 20 volts there is a change in behavior, with the current rising more steeply than before, and the slope continually increasing to the highest voltages observed. This general increase is due to electron-hole pair creation in the crystal.[1,3] Curve (2) follows the same values until a current of 5 amperes, at which point it abruptly begins to rise sharply with a slope greater than that of curve (1). However, for currents of 13 to 20 amperes, curve (2) approaches curve (1) and for currents larger than 20 amperes the curves are again coincident.

Curve (3) is somewhat displaced from the other two at low voltages, indicating a higher resistance. Since it is expected that there is no longitudinal magnetoresistance at low voltages, this is ascribed to the geometry used (samples with arms) which involves some disturbance of the current lines at the side contacts so that the magnetic field is not parallel to the current in this region. The effect observed is only about 5 % of that observed in the same transverse magnetic field.[3] It is noted for curve (3) that the current rises very steeply at voltages of the order of 60 volts and continues in this rise to the highest currents obtained.

It is clear that the curves in a longitudinal magnetic field rise more steeply than does the curve with no external magnetic field. These sharper-rising curves are believed proportional to the current density j as a function of electric field. Curve (1) rises less steeply, however, because for currents larger than 5 amperes the current

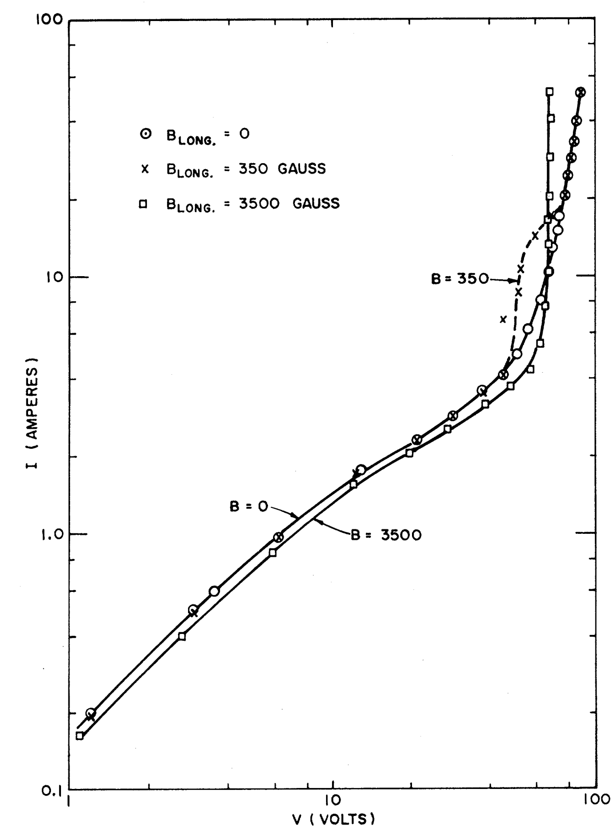

FIG. 1. Current as a function of voltage for n-type indium antimonide at 77°K. The current and the magnetic field were in the [100] direction.

due to the electron-hole pairs is pinched down by the self-magnetic field: this electron-hole current occupies a geometrical space effectively much smaller than the cross section of the sample. This curve is not then proportional to the current density, but should be stretched in the direction of increasing ordinate to yield such a proportionality, i.e., the I-V curve is less steep than the j-V curve. Where the pinch becomes very small, the density will become large enough to give appreciable electron-hole scattering. In addition, there will be an appreciable magnetoresistance effect due to the large azimuthal magnetic field. Both of these effects will increase the electric field necessary to produce a given current density, adding to the slowness of rise of curve (1).

With the application of a longitudinal magnetic field, the pinched plasma should be affected in two ways. In the first place it will be enlarged. The equilibrium diameter of a pinched plasma in a gas is larger in an external longitudinal magnetic field,[4] and when the field is about equal to the azimuthal current-produced magnetic field[4,5] the pinch is effectively destroyed. In addition, there is an improvement in the stability of the pinch of gaseous plasmas in an external longitudinal magnetic field.[4,6,7]

The effect of the magnetic field can be seen from the behavior of the curves in Fig. 1. At 5 amperes pinching sets in, in the absence of a longitudinal magnetic field. For both curves (2) and (3) there is no pinching at this current, however. For curve (2), when the current becomes so large that the azimuthal self-magnetic field approaches the strength of the external magnetic field, the current does pinch down, reaching an equilibrium similar to that without the external field for currents of 20 amperes and higher. For curve (3), with an external longitudinal field of 3500 gauss, the azimuthal self-field is too small over the range investigated to give pinching.

The pinched plasma current in the solid can be treated in a way similar to the situation in the gas.[2,8,9] Such a treatment yields the following condition for a "steady state" pinched plasma with no applied magnetic field:

$$I \approx I_{\mathrm{cr}} = 2ck(T_e + T_h)/ev,$$

where k is Boltzmann's constant, T_e and T_h are the mean kinetic temperature of the electrons and holes in the plasma current, v is the electron drift velocity, and I is the current in electromagnetic units. When I approaches I_{cr}, appreciable pinching will occur. The drift velocity is known from previous work.[1,3] The sum of the electron and hole mean energies, at a current of about 5 amperes, is then found to be 0.13 ev. This value is reasonable, indicating that the average energy is larger than the optical phonon energy[10] of 0.025 ev, but less than the band gap of about 0.2 ev. In the 350-gauss longitudinal magnetic field, currents of 10 to 15 amperes correspond to self-magnetic fields at the sample surface of 110 to 165 gauss. This is apparently sufficient to initiate pinching, in qualitative agreement with the gaseous plasma results observed by Bezbatchenko and co-workers.[4]

It is expected that the size of the pinch, in the absence of the longitudinal magnetic field, will be limited by a balance between the supply of electron-hole pairs and the loss through diffusion and recombination outside the pinch. For small external longitudinal fields, this may still be the dominant effect, since curves (1) and (2) are coincident at currents of 20 amperes and higher.

The current in the presence of external transverse magnetic fields will also be affected by the pinching, with the expectation that the plasma current will be forced to one side of the crystal by the external field. Calculations of the plasma current in the presence of external magnetic fields are in progress.

The question of the stability of such a pinched discharge is worth further exploration. The experiments involved pulses of 1 μsec duration, with a rise time of the order of 0.1-0.2 μsec. Estimates of the time of contraction, using the theoretical results of Leontovich and Osovets[11] for a gaseous plasma, yield about 0.01 μsec. This treatment ignores collisions, and thus gives a lower limit for this time. A simple estimate which includes the effects of scattering yields about 0.1 μsec for the crystal used. This time is much longer in InAs, and somewhat longer (because of the lower hole mobility) in the p-type InSb used in previous work.[12] It may be for this reason that similar effects were not observed at currents of 100 amperes in InAs,[13] or the p-type InSb. In both of these materials the I-V curve was much steeper than that observed in n-type InSb in the absence of a longitudinal magnetic field, in agreement with the expectation that no pinching occurred during those observations.

The period of quasi-stability of the pinch must have been at least of the order of 1 μsec, since there was no sign of changing currents during the pulse. It should be noted that the observing oscilloscope would not have noted any oscillations in the current or voltage at frequencies above several megacycles per second.

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MULTIPLET STRUCTURE OF EXCITONS IN CdS*

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A band model has been proposed recently by a number of authors[1,2] to explain the optical reflection and luminescence excitation spectra of CdS,[3,4] wurtzite structure. The model assumes a p-like valence band and an s-like conduction band with the extrema at $\vec{k}=(0,0,0)$, in the reduced zone. The p-like valence band is split by the crystal-field and spin-orbit effects into three bands. Using these assumptions, optical selection rules may be derived from the symmetry properties associated with the bands. The individual bands may be tentatively assigned by interpreting the polarization effects observed in the experiments with use of the selection rules. The assignment of the extrema to be at $\vec{k}=(0,0,0)$ is not unique since other symmetry points of the zone have group properties, as far as the selection rules are concerned, isomorphic with those at $\vec{k}=(0,0,0)$. In terms of the model, the extrema at $\vec{k}=(0,0,0)$, Fig. 1, indicate the energy splittings and the symmetry assignments as deduced from experiments in this laboratory[5] as well as elsewhere.[3,4] The upper valence band symmetry assignment of Γ_9 is indicated by the fact that at 4.2°K the edge luminescence is completely polarized perpendicular to the c axis.

This note is to report on the line absorption spectra near the absorption edge of CdS single crystals at 4.2°K and on the possible interpretation using this model. The absorption spectra were taken of single crystal platelets grown by the vapor phase sublimation method. The samples used were free of visible streaking often observed in platelets of this material. Further, the samples were not subject to any kind of surface preparation, such as polishing, etching, or cleavage. Since the c axis of the crystal lay in the plane of the platelet, orientation was easily

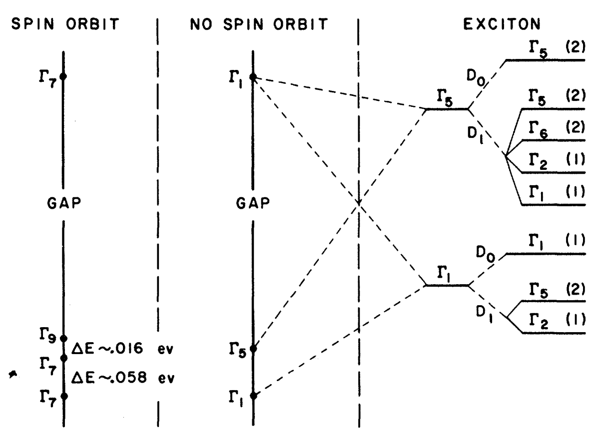

FIG. 1. Band structure at $\vec{k}=(0,0,0)$ of wurtzite CdS, and the possible exciton levels when spin-spin interactions are included.