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AN OPTICAL STUDY OF MAGNETIC CONSTRICTION OF THE ELECTRON-HOLE PLASMA IN InSb

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A study was made of the change in transverse distribution of the intensity of recombination radiation of the electron-hole plasma on avalanche breakdown in single crystals of indium antimonide subjected to a longitudinal magnetic field. A direct proof was obtained for the existence of a magnetic constriction (pinch effect) in avalanche breakdown. The electron-hole plasma temperature was determined from the radiation spectrum. The density of nonequilibrium electron-hole pairs was estimated.

THE generation of high densities of nonequilibrium carriers is of considerable interest in connection with the use of semiconductors as the working substance in quantum oscillators, as suggested by Basov et al.[1] Apart from the so-called pulse method of obtaining population inversion (negative temperatures), discussed by Basov et al,[1] the use of magnetic fields, both intrinsic and externally applied, is a promising method for confining the electron-hole plasma and obtaining a strongly nonequilibrium state. The purpose of the work reported here was a study of the interaction of the electron-hole plasma, produced in indium antimonide crystals in avalanche breakdown, with the magnetic field. The phenomenon of avalanche breakdown is accompanied by infrared radiation, with a spectrum peaked in the region of 5 μ,[2] which makes it possible to use an optical experimental method widely employed in studies of gas discharges.

CONDITIONS FOR THE APPEARANCE OF MAGNETIC CONSTRICTION

An electric field of the order of 200 V/cm intensity applied to indium antimonide crystals can produce a considerable density of nonequilibrium electron-hole pairs by impact ionization ("avalanche breakdown"). Glicksman et al[3,4] investigated the current-voltage characteristics of n-type InSb samples and concluded that in avalanche breakdown one can obtain magnetic constriction of the electron-hole plasma similar to the well-known pinch effect in gas discharges.

The necessary condition for the appearance of magnetic constriction is the equality of the magnetic pressure and the gas pressure (in our case that of the electron-hole "gas"):

$$H^2/8\pi = nkT. \tag{1}$$

The condition (1) can be reduced to a more convenient form:

$$I = 2kTc^2/ev_d, \tag{2}$$

where I is the total current flowing through the sample, T is the sum of the electron and hole temperatures, v_d is the sum of the drift velocities of electrons and holes and n is the density of electrons (holes).

The drift velocity of electrons in InSb in a field of 200 V/cm amounts to 3×10^7 cm/sec.[4] Assuming in Eq. (2) that the sum of the electron and hole temperatures is 500°K, and the sum of the drift velocities to be 3×10^7 cm/sec (the mobility of holes in InSb is considerably smaller than the electron mobility), we obtain the critical current at which magnetic constriction begins; the value of this current is 1 A. Such a relatively low value of the critical current makes it possible to achieve conditions under which the current in the compressed plasma filament is one or two orders of magnitude greater than the critical value; under pulse conditions it is possible to pass currents of up to 100 A through samples of 0.1 mm^2 cross section without noticeable heating of the samples.

An important characteristic of magnetic constriction in a semiconductor is good "thermal" contact of the electron-hole plasma with the crystal lattice. In a strong electric field the average electron energy increases to an energy comparable with that of an optical phonon (optical phonon energies in InSb are 0.025 eV or 300°K[4]); the rise of the electron energy then ceases because of the strong interaction with the lattice: the electron gas begins to cool strongly, emitting optical phonons. Magnetic constriction obviously does not produce any noticeable further increase of the electron energy (electron temperature) and, therefore, the process of magnetic constriction in a semiconductor can, in contrast to gas discharges, be regarded as isothermal.

Since Eq. (2) does not contain the radius, and the temperature during constriction is constant, the relationships (1) and (2) do not determine the equilibrium state and can be used only for estimating the critical current at which constriction begins.

USE OF AN OPTICAL METHOD

Apart from the obvious possibility of proving the existence of magnetic constriction by "visual" observation of the infrared radiation of the electron–hole plasma, a study of the emission spectrum allows us to determine the temperatures of electrons and holes. The dependence of the radiation intensity on time can be used to obtain information on the kinetics of the constriction and the stability of the constricted state. By observing the radiation of a sample placed in an external magnetic field we can investigate the effect of this field on the constricted electron-hole plasma. The emission spectrum of the "hot" electron-hole plasma in InSb lies in the 4—6 μ region where observations with the naked eye are impossible and there are no image converters or other "direct vision" instruments; this, of course, causes the well-known difficulties in optical studies.

EXPERIMENTAL TECHNIQUE

The usual pulse technique was employed to obtain breakdown conditions.[2-4] The duration of the voltage (current) pulse applied to a sample was varied from 0.5 to 4 μsec with a current up to 100 A and a repetition frequency of 25 cps. The samples were in the form of slabs of rectangular cross section, to the ends of which copper or platinum wires were soldered with indium. The sample cross sections varied from 0.05 to 3.0 mm^2 and their lengths ranged from 5 to 15 mm. Measurements were carried out mainly at 78°K, with the samples immersed in liquid nitrogen. The spectra were recorded with a spectrometer IKS-12 and an InSb photoresistor served as the receiver. To increase the sensitivity a special display system was developed for the short pulses from the spectrometer photoresistor, and this system allowed automatic recording of the spectrum. To investigate the distribution of the radiation intensity across the sample, a scanning system with a moving mirror was used with which it was possible to prove conclusively the existence of a constricted plasma filament and to observe the change in the shape of the radiating region under the action of the external magnetic field.

RESULTS OF MEASUREMENTS

The measurements were carried out on a series of n-type InSb samples of various shapes, having impurity concentrations from 5×10^{12} to 5×10^{14} cm^{-3} and mobilities from 5×10^4 to 5×10^5 cm^2-V^{-1} sec^{-1}. Almost all measurements were carried out at liquid nitrogen temperature. All samples, both polycrystalline and single-crystal ones, emitted radiation simultaneously with avalanche breakdown. The forms of the radiation pulse and the corresponding current pulse are shown in Fig. 1, where the current pulse duration is 4 μsec. Figure 1 shows that the radiation pulse has rise and decay times not longer than 1 μsec; such short times are one of the signs that the radiation is not due to heating of the crystal lattice but it is the consequence of the presence of nonequilibrium carriers (recombination of electrons and holes). The observed intensity distribution across the sample thus allows us to find the density distribution of the nonequilbrium electron-hole plasma.

Figure 2 shows the change in the nature of the distribution of the infrared radiation over the sample cross section under the action of an external longitudinal magnetic field. The scanning amplitude was equal to the transverse dimension of the sample (2.6 mm) and the resolving power

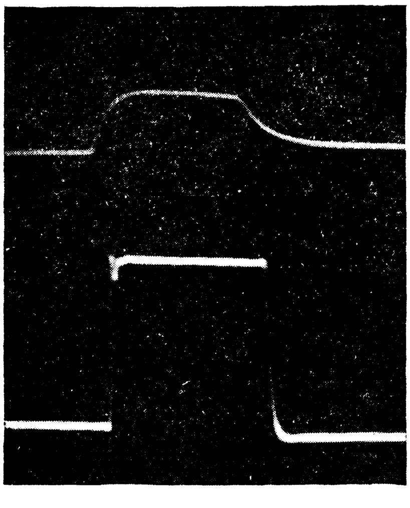

FIG. 1. Shapes of the infrared radiation (top curve) and current (bottom curve) pulses. The current pulse duration is 4 μsec.

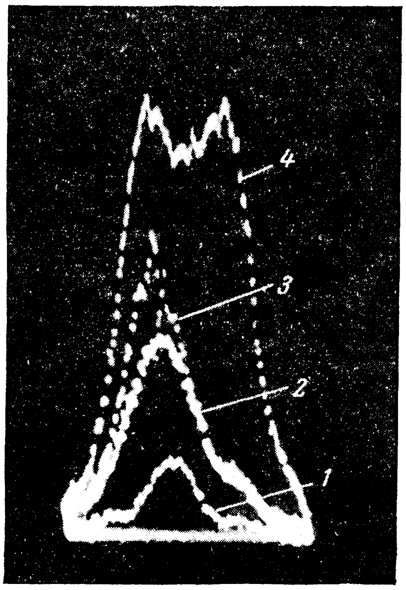

FIG. 2. Curves showing the distribution of radiation intensity along a transverse cross section of a sample: 1) $H_{\parallel} = 0$; 2) $H_{\parallel} = 200$ Oe; 3) $H_{\parallel} = 400$ Oe; 4) $H_{\parallel} = 1000$ Oe. The sample dimensions are 2.6 × 1.4 × 15 mm. The impurity concentration is 10^{14} cm^{-3} (n-type).

of the scanning system amounted to about $\frac{1}{5}$th of this amplitude. The current through the sample was kept constant as the magnetic field was varied.

When there was no external magnetic field the radiating region was localized in the middle of the sample in the form of a thin filament (curve 1 in Fig. 2). An estimate of the dimensions of the radiating region made with an allowance for the resolving power of the scanning system gave a value of about 0.2 mm. On increase of the magnetic field intensity from 0 to 200 Oe the radiating region broadened without any great change in its form (curve 2 in Fig. 2). In magnetic fields of about 400 Oe a considerable instability of the intensity distribution curve was observed (curve 3 in Fig. 2). On further increase of the magnetic field (to 800 Oe) the instability of the radiation was reduced and the intensity distribution curve acquired two peaks (curve 4 in Fig. 2). Further increase of the magnetic field intensity did not produce any further great changes of the intensity distribution curve. We may assume that the density distribution in the electron-hole plasma across the sample cross section becomes "tubular" in shape.

Direct measurement of the transverse dimension of the radiating region allowed us to determine the constricted filament diameter. With a plasma current of 50 A (this is the total current through the sample less the impurity conduction current), the filament diameter was 0.2 mm, corresponding to a current density of $\approx 10^5$ A/cm^2. At this current density and with an electron drift velocity of 3×10^7 cm/sec,[4] the average electron (hole) density in the filament was 5×10^{16} cm^{-3}.

Glicksman and Steele[3] investigated the conductivity of InSb samples in an external longitudinal magnetic field and suggested that the increase of the sample conductivity is due to the destruction of the self-constricted state of the electron-hole plasma by the applied magnetic field. Consequently it is of interest to compare the destruction of the self-constricted state observed visually with the change in the sample conductivity in a longitudinal magnetic field.

Figure 3 shows the dependence of the change in the voltage across the sample (with the current fixed at 70 A) on the external magnetic field: the numbers 1—4 indicate the magnetic field intensities at which the transverse intensity distribution curves (Fig. 2) were recorded. Comparison of Figs. 2 and 3 indicates that the increase in the sample conductivity does not in fact occur at the moment of destruction of the constricted state but somewhat earlier (when the magnetic field increases from 200 to 400 Oe).

To determine the temperatures of electrons and holes the emission spectrum of the electron-hole plasma was recorded. In the absence of an external magnetic field the constricted plasma filament was located in the center of the sample because of the stabilizing action of the magnetic field due to the impurity conduction current. Thus between the sample surface and the radiating region of the "hot" plasma there was a "cold" absorbing region of length l, where $2l$ is the sample thickness; the observed spectrum differed from that of the "hot" plasma by the multiplier $\exp(-kl)$, where k is the absorption coefficient. The true emission spectrum of the electron-hole plasma can be observed by pushing the radiating filament toward the sample surface by means of a transverse magnetic field.

Figure 4 shows the emission spectrum recorded at various values of the external transverse magnetic field. The emission spectrum was recorded only as far as the sensitivity threshold of the InSb photoresistor (5.5 μ). This figure indicates that the magnetic field raises the emission intensity and shifts the spectrum toward short wavelengths.

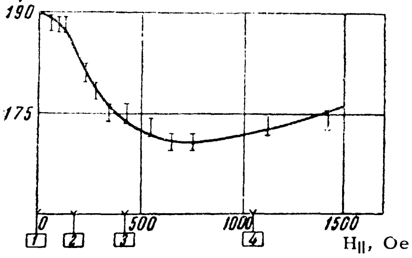

FIG. 3. Curve of the variation of voltage across the sample with applied longitudinal magnetic field at a fixed current of 70 A.

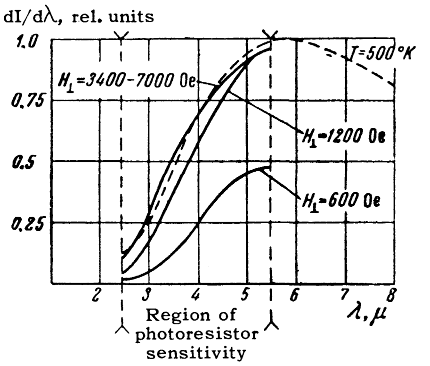

FIG. 4. Spectra recorded at various values of the transverse magnetic field $H_\perp$. The dashed curve is the blackbody spectrum at 500° K.

From 2500 to 7000 Oe the observed spectrum no longer changes and we then have the true spectrum of the "hot" electron-hole plasma. Comparison of the short-wavelength region of this spectrum, within the limits of the photoresistor sensitivity, with the blackbody spectrum shows that the total temperature of electrons and holes can be taken as equal to 500°K.

A periodic instability of the radiation was observed on applying a transverse magnetic field of the order of 100 Oe to some polycrystalline InSb samples having an impurity concentration of 5×10^{12} cm^{-3}. As shown by Fig. 5, stable oscillations of the radiation intensity are generated and their frequency depends both on the intensity of the transverse magnetic field and on the magnitude of the current flowing through the sample. Comparison of the form of the radiation and current pulses shows that the radiation intensity oscillations are directly related to current oscillations. We may assume that these oscillations are due to the instability of the plasma filament.

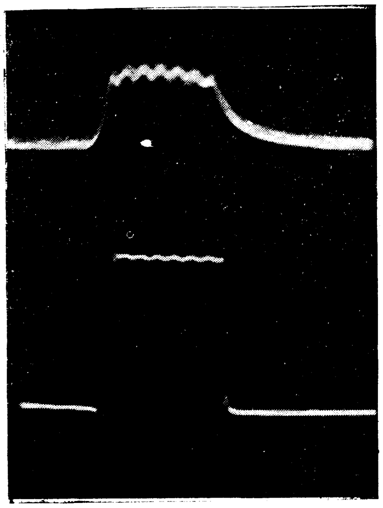

FIG. 5. Shapes of the infrared radiation (top curve) and current (bottom curve) pulses for the case of periodic instability of the radiation intensity. The current pulse duration is 4 μsec.

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