THE PINCH EFFECT IN THE DEGENERATE PLASMA OF INDIUM ANTIMONIDE

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The electrical conductivity and recombination radiation spectra of the electron-hole plasma in indium antimonide, produced in the interior of the crystal by the injection of carriers through contacts, were investigated. At currents of about ~10 A (~5 × 10³ A/cm²) and T = 4.2° K, magnetic compression of the degenerate plasma was observed (the pinch effect). The degree of degeneracy and the compressed plasma filament radius were determined for various currents from the radiation spectra.

THE magnetic compression of a plasma (the pinch effect) by a magnetic field generated by the passage of a current through a semiconductor has been investigated by a number of workers.[1-4] All these investigations were concerned with a nondegenerate plasma.

In our investigation, we used the method of carrier injection into a semiconductor through contacts to obtain very high degrees of degeneracy of the electron–hole plasma at high current densities ($\sim 10^4$ A/cm²) and low (helium) temperatures. The direct proof of the degeneracy of the plasma was provided by the generation of coherent radiation in it and the direct measurements of the recombination radiation spectra, reported by us earlier.[5]

The possibility of generating a degenerate plasma in a semiconductor is due to the strong interaction of the electron–hole gas with the crystal lattice, as a result of which the carrier energy approaches the lattice temperature and at high densities is governed by the Fermi energy.

The condition for the formation of a plasma filament by the magnetic compression of a plasma is the equality of the electron–hole gas pressure and the magnetic field pressure, established by the current. For a cylindrical filament, this is given by the equation[6]

$$-\partial p / \partial r = c^{-1} j_z H_\varphi, \tag{1}$$

where the magnetic field H_φ of the current is found from Maxwell's equation

$$\frac{1}{r}\frac{\partial(rH_\varphi)}{\partial r} = \frac{4\pi}{c} j_z. \tag{2}$$

At the boundary of a filament of radius r_1

$$H_\varphi = 2I / cr_1, \tag{3}$$

where I is the total current.

The pressure of a degenerate electron gas $p = (2/5) n\epsilon_F$ in the case of indium antimonide is governed primarily by the electron gas. Thus, if $n = p$ and $m_n/m_p \ll 1$

$$\varepsilon_F = \varepsilon_F{}^n + \varepsilon_F{}^p \approx \varepsilon_F{}^n, \tag{4}$$

$$\varepsilon_F = \frac{h^2}{2m}\left(\frac{3}{8\pi} n\right)^{2/3}, \tag{5}$$

where n, p, m_n, and m_p are the densities and effective masses of electrons and holes.

By integrating Eqs. (1) and (2) along the plasma filament radius, we obtain

$$I^2 = {}^4/_5 c^2 N \bar{\varepsilon}_F, \tag{6}$$

where $N = \pi r_1^2 \bar{n}$ is the total number of electrons per unit length of the filament, and $\bar{n}$ and $\bar{\epsilon}_F$ are the average values of the density and of the Fermi level across the filament.

Bearing in mind that $I/\pi r_1^2 = e\bar{n}v_z$, we obtain the expression

$$I = \frac{4}{5}\frac{c^2}{e}\frac{\varepsilon_F}{v_z}, \tag{7}$$

which gives the relationship between the current, the Fermi energy (or the carrier density), and the drift velocity v_z in the filament, but which cannot be used to determine the filament radius. Using Eq. (7), we can estimate the order of the currents necessary to produce the pinch effect. Expressing I in amperes, ϵ_F in electron-volts, and v_z in cm/sec, we obtain

$$I = 8 \cdot 10^8 \bar{\varepsilon}_F / v_z. \tag{7'}$$

If we assume the experimentally realizable values $\epsilon_F \sim 10^{-2}$ eV ($n \approx 7 \times 10^{15}$ cm⁻³) and $v_z \approx 10^6$ cm/sec,[7] we obtain the value $I \approx 8$ A, which is in agreement with the experimental values of the currents corresponding to the pinch effect (see below).

To detect and investigate the pinch effect, we used simultaneously two independent methods: the measurement of the electrical conductivity of the plasma (the recording of the current–voltage characteristics) and plasma spectrometry (the measurement of the recombination radiation spectra of electron–hole pairs). A longitudinal magnetic field H_z was used in the plasma diagnostics. The investigation was carried out on relatively pure single crystals of p-type indium antimonide having a carrier density of 4×10^{13} cm^{-3} and a mobility of ~ 7000 cm^2 V^{-1} sec^{-1} at 77°K. A crystal had the following dimensions: cross section $\approx 0.4 \times 0.5$ mm; height 0.5 mm, equal to the distance between the contacts. Carriers were injected by applying short ($\sim 10^{-6}$ sec) current pulses at a repetition frequency of $\sim$ 100 cps, which prevented any perceptible heating of the crystal. Because of the long carrier diffusion (and drift) length, the injection extended over the whole distance between the contacts. At currents of $\sim$ 10 A, the carrier densities $n = p$ in the plasma reached $\sim 10^{16}$ cm^{-3}. The samples were placed in the helium bath of an optical cryostat between the poles of a magnet. The current and voltage pulses were observed on the screen of a high-frequency two-beam oscilloscope. In these measurements, the values of the current and voltage were measured after $t = 0.3\,\mu$sec, which corresponded to the establishment of an equilibrium (steady) state between the electron–hole plasma and the lattice.

Figure 1 shows the dependence of the current on the voltage in the injected plasma for various magnetic fields H_z. When the magnetic field H_z was not applied (curve 1), the conductivity was found to decrease markedly at a current of 5–7 A and particularly at currents of $\sim$10 A. Assuming that the total number of carriers in a sample at a given current remained constant when the magnetic field varied, the reduction in the electrical conductivity of a magnetically compressed plasma was explained mainly by a drop in the mobility due to an increase in the electron–hole scattering because of a rise in the carrier density per unit volume in the pinch effect.

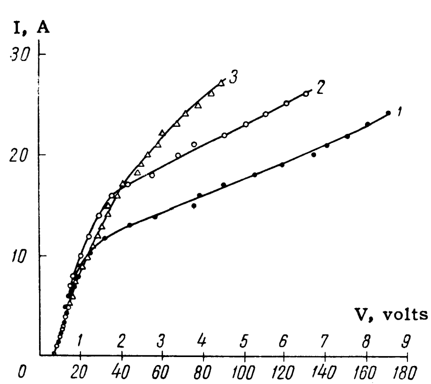

FIG. 1. Dependence of the current on the voltage in an electron–hole plasma in a longitudinal magnetic field: 1) $H_z = 0$; 2) $H_z = 200$ Oe; 3) $H_z = 350$ Oe; $T = 4.2$°K.

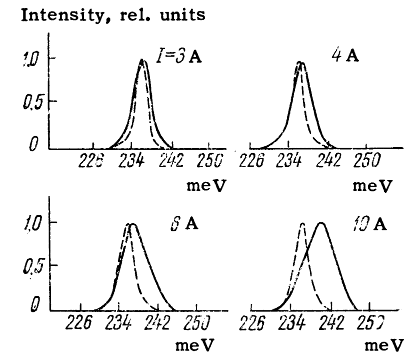

FIG. 2. Radiation spectra of a plasma for various values of the current in $H_z = 0$ (continuous curves) and $H_z = 350$ Oe (dashed curves).

To prove that the observed change in the slope was associated with the pinch effect, the I–V characteristics were recorded in various longitudinal fields $\mathbf{H}_z \parallel \mathbf{I}$, which impeded the formation of a filament.[2] The magnetic field which compressed the plasma at $I \sim 10$ A and $r_1 \sim 10^{-2}$ cm was, according to Eq. (3), $H_\varphi \sim 200$ Oe.

Thus, to disturb the equilibrium in a filament it is sufficient to apply an external longitudinal field H_z of the indicated order of magnitude. As is evident from Fig. 1 (curve 2), to produce the pinch effect in $H_z = 200$ Oe, considerably stronger currents are required than in $H_z = 0$, while in $H_z = 350$ Oe (curve 3) the pinch effect is not observed in the investigated sample in the measured range of currents and voltages.

The spectrometric method is particularly sensitive in the investigation of the pinch effect. Figure 2 shows a series of recombination radiation spectra of electron–hole pairs for various currents. The spectra were recorded at the same time as the current–voltage characteristics in $H_z = 0$ and in $H_z = 350$ Oe. It is clear that in $H_z = 0$ and for currents greater than 4 A, the intensity maxima in the spectra shift toward higher energies and the widths of the spectra become greater. This is because when the current increases, the carrier density in the region of the filament increases as well, and this leads to the filling of the conduction band to higher values of the Fermi energy. In a longitudinal magnetic field H_z, which destroys the plasma filament and distributes the carriers over the whole crystal, the carrier density per unit volume decreases and

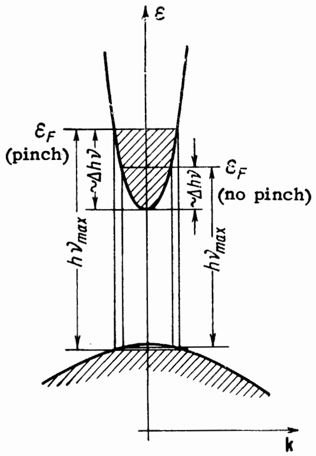

FIG. 3. Population of the energy levels in indium antimonide with and without the pinch effect.

this is revealed clearly by a shift of the maximum in the spectrum toward lower energies and by a reduction in the width of the spectrum (cf. Fig. 2). The onset of the pinch effect can be seen clearly in the spectrum for a current of 4 A, while the effect is still not very obvious in the current–voltage characteristic.

Since, as mentioned earlier, the effective electron mass in indium antimonide is small, the position of the intensity maximum in the radiation spectrum and its width, associated with the direct interband recombination of electrons and holes, is governed only by the population of electron states (Fig. 3). From the recombination radiation spectra, we can deduce that, for I = 10 A and H_z = 350 Oe, the Fermi energy of electrons in the conduction band is ϵ_F = 3.5 meV = 9.7 kT, which corresponds to a density $n_0 = 8 \times 10^{14}$ cm^{-3}. In the same current but in $H_z = 0$ (in the presence of the pinch effect), $\bar{\epsilon}$ = 8.7 meV = 24 kT, which gives $n = 4 \times 10^{15}$ cm^{-3}.

Using the ratio of the densities obtained in this way for the pinch effect ($\bar{n}$) and in the absence of the effect (n_0), we can easily determine the plasma filament radius for various currents:

$$r_1 = \tfrac{1}{2} a (n_0 / \bar{n})^{1/2}, \tag{8}$$

where the dimensions of the crystal are $a/2 = 2 \times 10^{-2}$ cm. The values of the radius obtained in this way are:

I, A:	4	6	8	10
r_1, 10^{-2} cm:	1.4	1.2	1.1	1

It is clear from these results that the radius of the filament amounts to $\approx 10^{-2}$ cm and it decreases when the current increases. It should be mentioned that, because of the absorption of radiation in the crystal, the densities determined from the radiation spectra are too low. This applies particularly to the values of $\bar{n}$. Therefore, the values of r_1 calculated allowing for the absorption may be less by a factor of about 1.5 than the values given here.

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