Theta pinch in germanium

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A 12-fold increase in the number of current carriers moving along the sample axis has been realized in Θ-pinch experiments performed on an electron-hole plasma with a pulsed magnetic field of amplitude equal to 500 kOe. The plasma pinching time under the experimental conditions was 2 μsec, while the thickness δ of the skin layer considerably exceeded the radius a of the semiconductor sample ($\delta/a \gtrsim 100$). The observed effects are in satisfactory agreement with the theoretical predictions.

It is known that the electron-hole plasma in a semiconductor with a bipolar conductivity can undergo strong compression under the action of a magnetic field increasing rapidly in time (Θ pinch).

The first experimental observation of the radial plasma compression effect was reported comparatively recently by Hübner's group[1,2]. This Θ pinching was observed in short cylindrical InSb samples located in longitudinal magnetic fields $B_z(t)$ that increased in time. In the latter run[2] of these experiments a three-fold increase in the electron-hole plasma density was observed in the region near the axis of the Θ pinch. This compression was observed under the condition when the penetration depth of the field $B_z(t)$ into the plasma was only two-three times smaller than the sample radius $a = 0.45$ cm. Unfortunately, the case ($\delta/a \lesssim 1$) investigated in[2] is the most complicated case for the construction of an analytical theory suitable for the quantitative description of the most important characteristics of the dynamics of the processes that occur in a semiconductor Θ pinch. In its turn, the last circumstance makes it quite difficult to extrapolate the results obtained in[1,2] to the case of experiments with other materials, or to the case of work involving a wider range of parameters.

At present the most complete theory of the Θ pinch in semiconductors is the theory developed primarily for the limiting case $\delta/a \gg 1$ in the series of papers[3] (the case $\delta/a \ll 1$ has been studied in detail in investigations with the gas-discharge plasma (see[4])).

Under the conditions when the skin-layer thickness δ is much greater than the sample radius a, and the magnetic-pressure gradient is zero, the contraction of the plasma towards the axis of the sample occurs as a result of the drift of the electrons and holes in the crossed fields $B_z(t)$ and $E_\Theta = r(dB_z/dt)/2$ (the "non-skin" Θ pinch). One of the main conclusions arrived at in[3] consists in the following. The maximum degree of plasma compression, a quantity which is usually characterized by the relation $r_{min}/a \lesssim 0.3$, should be observed if the amplitude $B_z(t) = B_z(\tau_p) = B_{zmax}$ of the magnetic field satisfies the inequality

$$h=(b_e b_h/c^2)B_{z\,max}\gg 1. \tag{1}$$

Here r_{min} is the smallest value of the radius of the compressed plasma at the moment $t = \tau_p$ when $B_z(t)$ has its maximum; $b_{e,h}$ are the electron and hole mobilities. The compression is most noticeable if the duration τ_p of the plasma pinching process is significantly shorter than the volume recombination time τ_r, and the characteristic ambipolar diffusion time $\tau_D \approx a^2/D$, where D is the ambipolar diffusion coefficient. The maximum plasma density is attained on the sample axis, and is roughly given by

$$n_{max}\approx hn_p, \tag{2}$$

where n_p is the density of the homogeneous distribution of the current carriers in the unperturbed plasma. The relation (2) is quite general in nature and is of great practical interest when estimating the limiting characteristics of the pinch effect in experiments with semiconductors.

It is also pointed out in[3] that the most convenient object for the investigation of the characteristics of the behavior of the "non-skin" Θ pinch is germanium with intrinsic conductivity, since in pure germanium samples $\tau_r \approx 10^2 - 10^3$ μsec, while the electron and hole mobilities are fairly high.

Below we give the experimental data obtained in the observation of the Θ pinch in germanium at room temperature ($b_e \approx 10^6$ esu and $b_h = b_e/2$), when during the entire compression process under the conditions of the experiment the inequality $\delta/a \gg 1$ was fulfilled and there was practically no lattice or plasma heating.

Figure 1 shows a block diagram of the experimental setup. The pulsed magnetic field $B_z(t)$ of amplitude 500 kOe and rise (to the maximum value) time $\tau_p \approx 2$ μsec was produced by the discharge of a capacitor bank into a compact single-turn brass solenoid of internal diameter 4.5 mm and length 6 mm. In this case the computed value of the quantity $h \approx 12$, so that the condition $h \gg 1$ is fulfilled. Cylindrical samples of length 4 mm and diameter $2a = 3$ mm were prepared from n-Ge. The conductivity σ of the material of the samples was close to the intrinsic conductivity ($\sigma = 2 \times 10^{10}$ esu, $n_p \approx 2.5$

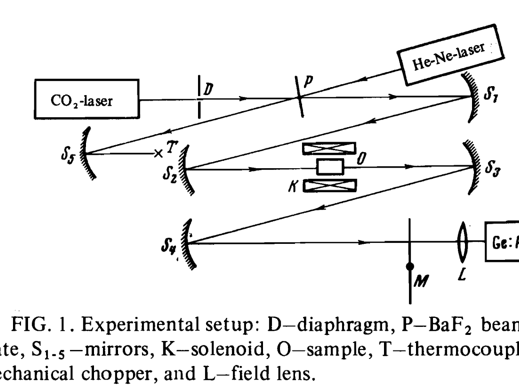

FIG. 1. Experimental setup: D–diaphragm, P–BaF_2 beam-splitting plate, S_{1-5}–mirrors, K–solenoid, O–sample, T–thermocouple, M–mechanical chopper, and L–field lens.

$\times 10^{13}$ cm^{-3}, $\delta \approx (c/2\pi)(\tau_r/\sigma)^{1/2} \approx 100$ cm, and $\delta/a \gtrsim 100$). For the optical observations on the semiconductor samples we had carefully polished plane-parallel ends.

As in the experiments[5], a change in the density of the electron-hole plasma in the course of its pinching was recorded by the well-known method of probing infrared radiation (wavelength $\lambda = 10.6\ \mu$) absorption by the free current carriers in the transmission band of germanium. A CO_2 laser served as a source of monochromatic radiation. The laser radiation was focused by a system of mirrors on the end of a sample at a point with a radial coordinate r. The diameter of the light spot in the region of the sample did not exceed 0.4 mm. The radiation transmitted through the sample was focused on a 2 $\times$ 2 mm germanium collector doped with gold and cooled by liquid nitrogen. In order that the optical system might be adjusted visually, a He-Ne laser ($\lambda = 0.63\ \mu$) was connected coaxially with the CO_2 laser. The output power of the CO_2 laser was controlled with the aid of a chromel-copel—alloy thermocouple. In the experiments, we measured the relative variation—due to the variation in the plasma density along the probe axis—in the intensity of the light transmitted through the sample:

$$\eta=\Delta\Phi/\Phi_0=1-e^{-\Delta nqL}\approx\Delta nqL \quad (\eta\ll 1). \qquad (3)$$

Here Φ_0 is the intensity of the transmitted radiation in the unperturbed plasma; $\Delta\Phi = \Phi_0 - \Phi(t)$; Δn is the change in the plasma density occurring in the course of the compression; q is the cross section for absorption of the radiation by the free current carriers; at room temperature $q = 7 \times 10^{-16}$ cm^2; L is the sample length. The amplitudes Φ_0 of the calibration flux signals were obtained with the aid of a mechanical, probing-radiation chopper (100% modulation).

In the present paper the main attention was given to the plasma compression process; the plasma "decay" phase during the attenuation of the magnetic field $B_z(t)$ after it had attained its maximum value was not studied in our investigations, although the corresponding computations are contained in[3]. There occurred in the experiments surface generation of current carriers, the distinctive features of which process have been analyzed in detail in those same computations.

In Fig. 2, we show the oscillograms of the signals from the infrared radiation receiver (the lower ray) together with those of the signal proportional to the magnetic-field intensity at the center of the solenoid (upper ray). The measurements were made on the axis of the sample and at its periphery at the points r = 0.75a and r = 0.5a.

Analysis of the data contained in the oscillograms shows that the greatest absorption of the infrared radiation and, consequently, the maximum increase in the plasma density occur in the region near the sample axis (Fig. 2a). At the same time the peripheral region $r \approx a$ (Fig. 2b) becomes depleted of carriers (the positive polarity of the signal on the oscillogram corresponds to a decrease in the intensity of the transmitted radiation, or to an increase in the plasma density).

The value $\eta_0 = 0.08$ computed for r = 0 from the oscillograms corresponds to the maximum increase $\Delta n \approx (10 - 12)n_p$ in the plasma density on the sample axis, which is in satisfactory agreement with the predictions of the theory given above for the calculated value h = 12.

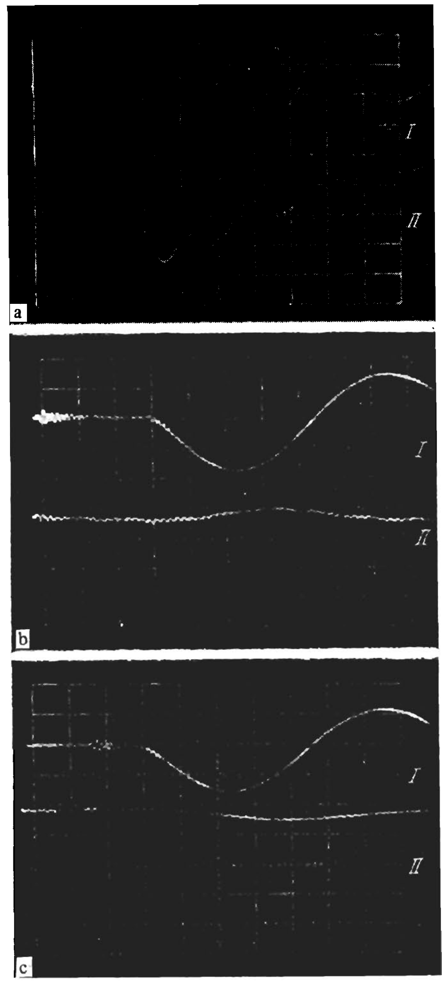

FIG. 2. Oscillograms of I) the magnetic field and II) the infrared radiation absorption signals: a) r = 0, the time scale is 2.5 μsec per division; b) r = 0.75a, the scale is 1 μsec per division, and c) r = 0.5a, the scale is 1 μsec per division; the voltage scale is in all cases 25 mV per division. The amplitudes Φ_0 of the flux calibration signals, obtained with the aid of the mechanical chopper of the probing infrared signal (100% modulation), were, for the cases a, b, and c, equal respectively to 1, 0.8, and 0.7 V.

The depletion of current carriers in the peripheral regions of the semiconductor samples that was observed in the plasma compression process is also in qualitative agreement with the theoretical results[3]. The indicated phenomenon is typical for O-pinch experiments in germanium with an insufficient surface-generation rate for electrons and holes.

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