Destruction of pinch channel in a germanium electron-hole plasma by a longitudinal magnetic field

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A pinch effect was observed in an injected electron-hole plasma in germanium at different temperatures and at electric current values close to the Bennett critical power. We investigated the heating of the pinch channel and its destruction by a longitudinal magnetic field. The temperatures and radii of the channel at various instants of time were determined. The experimental results agree with the theoretical premises concerning the pinch effect and confirm the theory of Vladimirov and Shchedrin (Sov. Phys. JETP **36**, 799, 1973) of pinch-channel destruction by a helical instability that arises in a magnetic field.

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1. INTRODUCTION

When the conditions necessary for the development of helical instability in a longitudinal magnetic field are realized in the pinch effect, [1–3] the plasma leaves the pinch channel and the latter is destroyed. This mechanism became qualitatively understood[4] after the pinch effect was observed in a solid-state plasma[5,6] and is extensively used for pinch diagnostics. A theory of the helical instability in the pinch effect has been developed, however, only recently in[7]. According to this theory the pinch channel is destroyed when the longitudinal magnetic field intensity H is equal to or larger than

$$H_d = 2\cdot 2I/cr_{pc}, \tag{1}$$

where I is the current through the channel, c is the speed of light, r_{pc} is the radius of the pinch channel, and $2I/cr_{pc}$ is the intensity of the azimuthal magnetic field of the current I on the channel surface. The physical meaning of the presented result of the theory was explained in[8]. The pinch channel is destroyed when the reciprocal growth rate of the helical instability in the pinch is shorter than the pinching time.

The investigations described here were aimed at experimentally verifying the theory of[7]. We compare the values of r_{pc} determined from formula (1) with those independently determined from the heating of the pinch channel. The results confirm the conclusions of the theory.

2. CONTRACTION OF A PLASMA INTO A PINCH

The experiments were performed on n-Ge samples with resistivity 40 Ω-cm at room temperature and with diffusion displacement length of the carriers ≈0.15 cm. The samples were cylinders of radius R and length l. Their dimensions are listed in Table I. To inject the plasma, indium and antimony-doped tin contacts were fused into the end faces of the samples. The sample surface was etched in boiling Perhydrol.

An injecting rectangular pulse of voltage U was applied to the sample cooled to $T = 77$ K. Typical oscillograms of the current I, observed as U was gradually increased, are shown in Fig. 1. At low U, the current increased monotonically to saturation (curve 1, Fig. 1a). In the case of sufficiently high U, an abrupt increase of the current took place against the background of the slow variation, followed by a nonmonotonic variation of the current (Fig. 1).

The power $W_c = I_c E_c$ (E is the electric field intensity) delivered by the instant t_c to the central part of the sample, where E is maximal, was closed to the Bennett critical power[9,10]

$$W_{cr} = I_{cr} E_{cr} = \frac{4c^2 kT}{q(\mu_n+\mu_p)}. \tag{2}$$

Here k is the Boltzmann constant, q is the electron charge, and μ_n and μ_p are the electron and hole mobilities. This is seen from a comparison of the values of W_c obtained for various temperatures (curve 1, Fig. 2) and W_{cr} (curve 3), calculated from formula at

$$\mu_n = 4.9\cdot 10^7\ T^{-1.66}\ \text{cm}^2/\text{V-sec},\quad \mu_p = 1.05\cdot 10^9\ T^{-2.33}\ \text{cm}^2/\text{V-sec}, \tag{3}$$

and T is in degrees Kelvin. [11]

The values of E were determined by differentiating the potential distributions along the sample, obtained with the aid of a moving probe. The values of W_c increased with increasing U. Figure 2 shows the minimal values of W_c that could be registered.

The nonmonotonic variation of the current at $t > t_c$ is due to the onset of the pinch effect in the sample. This is attested by the noted proximity of W_c and W_{cr}, the results of probing the sample with a longitudinal magnetic field (described in the next section), the characteristic oscillations preceding the pinch (see the review[8]) (curve 2, Fig. 1a), and, finally, the melting of the channel in the sample at sufficiently high applied power and sufficient pulse duration.

The change of the current when the plasma contracts to a pinch is determined by a number of factors. It is a complicated matter to take all these factors into account simultaneously, and it is impossible at present to explain all the singularities of the current variation at $t > t_c$. To check on the theory of the destruction of the pinch channel by a magnetic field, however, this explanation is not necessary, since the required information on the characteristics of the pinch channel can be obtained from general relations that are not very sensitive to the details of the processes that take place in the pinch channel.

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TABLE I.

Sample numbers	2R, cm	l, cm	T, K	T_{pc}, K	$r_{pcst}\cdot 10^2$, cm	$r_{pct}\cdot 10^2$, cm	Oscillogram on Fig. 3
1	0.24	0.58	77				
2	0.24	0.35	77				
3	0.17	0.45	193	400	2.5	2.7	a, 2
4	0.26	0.5	77	230	1.6	1.4	b
5	0.17	0.4	113	336	1.5	1.2	c
5				316	1.3	0.8	d
6	0.24	0.5	77	232	1.3	1.1	e
7	0.24	0.5	77				

Before we describe the experiments on the action of the magnetic field on the pinch, we note the following.

Omitting some details which are immaterial in the first-order approximation, we can assume that under the considered conditions the conductivity of the sample is determined by the total number of the carriers contained in the sample and by their mobility. In the stationary case, the rate at which the nonequilibrium carriers enter the sample through the contacts is equal to the rate of their recombination. When the plasma contracts, the electrons and holes move to the sample axis, their surface recombination decreases, and their effective lifetime increases. This changes the balance between the number of carriers entering the samples and the number of recombining carriers in a way that increases the total number of carriers in the sample and the current flowing through it.

The number of carriers is increased by injection through the contacts and by their drift into the interior of the sample. The characteristic time of this process is $\tau_g \approx l/\bar{v}$, where $\bar{v}$ is a certain mean value of the plasma drift velocity $v=\pi R^2 q\mu_n\mu_p N_d E^2/I$, [12] and N_d is the donor concentration. The time of contraction of the plasma into a pinch is $\tau_c = c^2R^2/2\mu_n\mu_p IE$. [13] When the current flowing through the sample is close to the critical value (2) we have

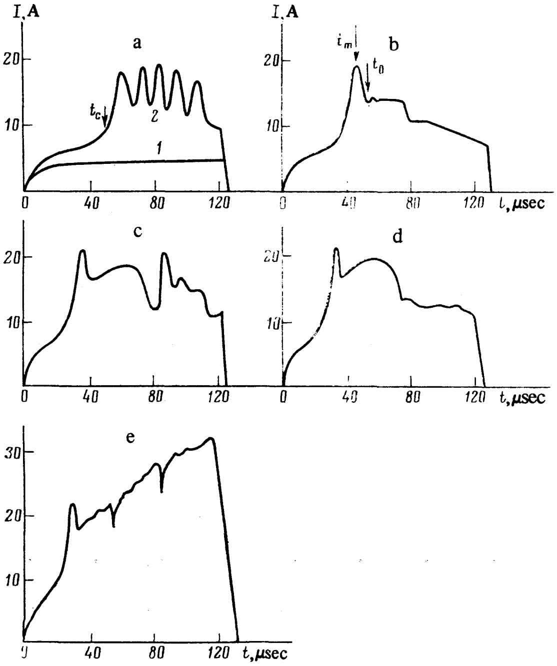

FIG. 1. Current oscillograms (sample No. 1, $T=77$ K); a) curve 1—$U=60$ V, curve 2—90 V, b) 95 V, c) 100 V; d) 103 V; e) 107 V.

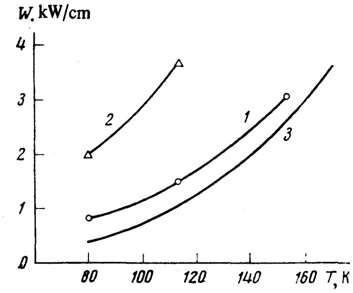

FIG. 2. Temperature dependences of the powers: curve 1—W_c, sample No. 5; curve 2—W_c, sample No. 2; curve 3—W_{cr}.

$$\frac{\tau_g}{\tau_c} \approx \frac{l}{2\pi c^4 k N_d R^4} I_{st}^3 \frac{\mu_n+\mu_p}{T}. \quad (4)$$

It is natural to attribute the increase of the current at $t > t_c$ to the departure of the plasma from the surface. Understandably, the kinetics of the current variation observed in this case (the slowing down of the initial growth, followed by a rapid growth at $t > t_c$) can be realized only if $\tau_g \lesssim \tau_c$. An estimate of the ratio τ_g/τ_c, say for the case of curve 2 of Fig. 1a, when the kinetics in question is distinctly realized, yields $\tau_g/\tau_c \approx 0.5$. When the temperature increased because of the growth of I_{cr}, the ratio τ_g/τ_c increased and the kinetics in question vanished accordingly.

The plasma contraction affects the electron and hole distributions over the sample cross section and their effective lifetime after a time on the order τ_c. This inertia of the contraction process that takes place simultaneously with the current change due to the injection of carriers into the samples (with a characteristic time τ_g) explains the dependence of W_g on R (cf. curves 1 and 2 of Fig. 2) and on U. The growth of W_c with increasing R and U agrees with the accompanying decrease of τ_g/τ_c. The latter follows from formulas (2) and (4) at constant W_c.

The time limit imposed on the current growth upon contraction can be attributed to the onset of quadratic recombination in the case of strong contraction and possibly to electron-hole scattering (see[8]). It must be emphasized in what follows that the value of the current at the maximum and the decrease of the current from the instant t_m to the instant t_0 (Fig. 1b) depend, on top of all other factors, on the rate of contraction of the plasma (on the value of τ_c). The reason is that the smaller τ_c the earlier the stage at which the increase of the number of carriers in the sample is halted as a result of the weakened surface recombination. It is seen from Fig. 1 how the sharpness of the current peak increases and the difference between the currents at the instants t_m and t_0 decreases with increasing U (with decreasing τ_c).

Naturally, the larger τ_c the larger the current and the maximum and the closer it is to the value of the current that might be established if both surface and quadratic recombination are negligible.

3. DESTRUCTION OF PINCH CHANNEL BY A LONGITUDINAL MAGNETIC FIELD

Following the plasma contraction, practically all the power fed to the sample is released in the pinch channel. The maximum power that can be dissipated by a unit length of the plasma pinch is $W_q = 0.9$ kW/cm.[14] In the described experiments, the power delivered to the pinch channel was comparable with or larger than W_q, and the channel was therefore heated.

This heated pinch channel was acted upon by a longitudinal magnetic field H turned on at various instants of time t_M. Up to a certain limiting value, the magnetic field had no effect whatever on the current. At H equal to or larger than this limiting value, the current changed and this change was usually accompanied by oscillations. Figure 3 shows oscillograms of the current at $H=0$, the thick lines showing typical current changes resulting from the application of the magnetic field.

Depending on the applied magnetic field, the character of the current variation differed. A magnetic field equal to or close to the limiting value caused the current to increase with time (Figs. 3a–3e). With increasing H, the maximum value of I reached following this change first increased, then decreased, and finally application of a sufficiently strong field immediately decreased I to a value smaller than or approximately equal to the current at the instant t_c (curve 2, Fig. 3f).

Let us compare the experimental results with the theory. A magnetic field with $H > H_d$ destroys the pinch, causes anomalous diffusion of the electrons and holes[15] towards the sample surface, and decreases the decree of contraction of the plasma. The current through the sample increases, inasmuch as the quadratic recombination and the electron-hole scattering become weaker.

The action of the two indicated mechanisms that increase the current is understandable from the viewpoint of the arguments advanced in the preceding section concerning the reasons why the current decreases when the plasma is contracted. There is also one more reason why the current increases. It is due to the increased mobility of the carriers as they go out of the destroyed heated pinch channel into the surrounding volume with lower temperature. In fact, using the pinch-channel temperatures listed in the table (see the next section) and formula (3), we find that in the case of the oscillograms in Figs. 2b–3e the departure of the carriers from the pinch channel is accompanied by an approximately eightfold increase of μ_p and sixfold increase of μ_n.

In the course of the plasma contraction, there is no such change in the carrier mobilities, and naturally no corresponding current-change mechanism.

In addition to the indicated mechanism that increase the current when the pinch channel is destroyed, the following two mechanism decrease the current: surface recombination and departure of the carriers to the contact; at H close to H_d these mechanisms are turned on at later instants of time than the current-increase mechanism. It is precisely the action of these mechanisms that can explain a current decrease similar to that shown in Fig. 3b, after a sufficiently long time interval.

At large H, the strong anomalous diffusion to the surface causes surface recombination to predominate over all other mechanisms that change the current, and causes the current to decrease immediately after the magnetic field is turned on (Fig. 3e).

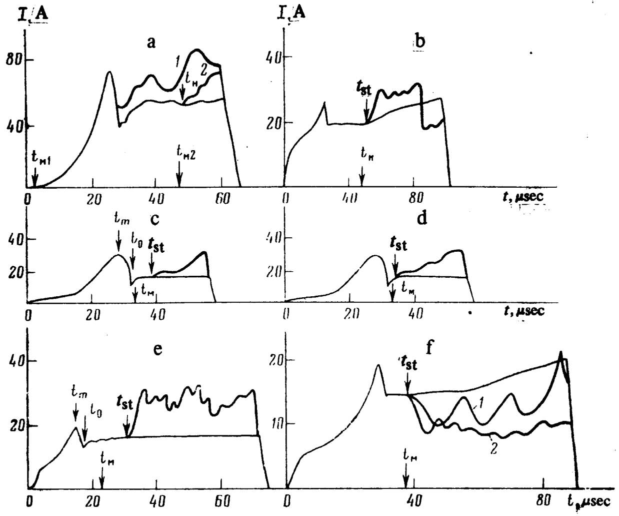

FIG. 3. Oscillograms of current following application of a magnetic field at the instant t_M. The oscillograms at $H=0$ are shown by thin lines, and the current changes due to application of the magnetic field at $t > t_{st}$ are shown by thick lines. a) Sample No. 3, $T = 193$ K, $U = 220$ V, curve 1—$H = 560$ Oe, curve 2—$H = 1030$ Oe; b) No. 4—77 K, 88 V, 490 Oe; c) No. 5, 113 K, 100 V, 250 Oe; d) No. 5, 113 K, 100 V, 350 Oe; e) No. 6, 77 K, 130 V, 450 Oe; f) No. 7, 77 K, 90 V, curve 1—450 Oe, curve 2—700 Oe.

Attention is called to the fact that in a magnetic field there are realized also current values appreciably larger than the maximum current at $H=0$ (Fig. 3e), rather than equal or smaller currents expected under certain assumptions.

This fact can be attributed, first, to the indicated increased mobility of the carriers that leave the heated channel and go into the region with lower temperature. Second, owing to the difference between the kinetics of the plasma contraction into a pinch and the pinch destruction, at some time in the course of the destruction the plasma is in a state in which the quadratic and surface recombinations have a smaller effect on the current than at any instant during the course of contraction, i.e., a state is realized that is closer to the state when both recombination mechanisms are inoperative, in contrast to the case of contraction (see the end of the preceding section). We note in this connection that in a magnetic field the current exceeded significantly the maximum corresponding to $H=0$ only when the current at $H=0$ had a sharp peak and the difference between the currents at t_m and t_0 was small (cf. Figs. 3e and 3d), when, according to the preceding section, the quadratic recombination interrupts rapidly the current growth due to the decrease of the surface recombination.

The value of the limiting magnetic field depended on the instant when the field H was turned on. If H is turned on prior to the formation of the pinch channel, the limiting field is weaker than if H is turned on after the formation of the pinch. This is demonstrated by the current changes shown in Fig. 3a, which are due to magnetic fields that exceed the corresponding limiting values by 5–10% and which are turned on at the instants t_{M1} (curve 1) and t_{M2} (curve 2).

The result can be explained by the dependence of the pinch-destroying field on the radius, as given by formula (1). According to this formula, a thick plasma filament not yet contracted into a pinch channel is destroyed by a weaker magnetic field than a thin one.

Similar results were obtained in[4] for indium antimonide.

Turning on the magnetic field at the instant t_M lead to a change of the current through the sample at the instant t_{st}. One might expect $\Delta t_{st} = t_{st} - t_M$ to be of the order of the reciprocal growth rate of the helical instability in the pinch channel, $1/\mathrm{Im}\,\omega \approx r_{pc}I/2cDH$[7] ($D$ is the diffusion coefficient) or of the order of the characteristic time of the particular mechanism (e.g., recombination—injection of the carriers) that transforms the plasma-distribution change induced in the sample by the helical instability into a current that can be registered. In the former case the dependence of Δt_{st} on H and I should be similar to the dependence of $1/\mathrm{Im}\,\omega$ on these quantities, and in the latter case it is difficult to expect Δt_{st} to have a strong dependence on H and I.

All this notwithstanding, Δt_{st} at sufficiently weak magnetic fields was much larger than $1/\mathrm{Im}\,\omega$. For example, in the case of the oscillogram on Fig. 3e we have $\Delta t_{st} = 7$ µsec, and $1/\mathrm{Im}\,\omega \approx 0.2$ µsec. There was also a strong dependence of Δt_{st} on H (Figs. 3c and 3d) and on $I(U)$.

The observed fact can be explained in the following manner. The pinch channel becomes heated, and its radius increases in the course of time, therefore the field H_d needed to destroy the channel is not constant, but decreases in time. Imagine now that the field H turned on at the instant t_M is $H < H_d(t_M)$. However, at the instant $t_d > t_M$ the inequality $H > H_d(t_d)$ is satisfied as a result of the decrease of $H_d(t)$, and the channel is destroyed. In this case $\Delta t_{st} \approx t_d - t_{st}$ and is determined by the rate of change of r_{pc}. The strong dependence of Δt_{st} on H and I points to a slow variation of r_{st} with time. The data described in the next section confirm the assumed slow growth of r_{pc}. The experimental results are therefore qualitatively accounted for by the theory.[7]

4. RADIUS OF THE PINCH CHANNEL

In the case of a quasistationary pinch, the power W fed to the channel should equal at any instant of time to the Bennet critical value W_{cr} obtained from the equality of the gas kinetic and magnetic pressures. Since W_{cr} depends on the channel temperature T_{pc}, we can determine T_{pc} from W.

We have determined T_{pc} by assuming that W is determined by formula (2) at $T = T_{pc}$, while the mobilities are determined by formulas (3). These assumptions denote neglect of the possible degeneracy of the electrons and holes and neglect of the field induced heating and of the electron-hole scattering. At a sufficiently high channel temperature they will always be valid. In final analysis the assumptions made are substantiated by the subsequently obtained equality of the channel radii obtained by using T_{pc} with the values obtained by another method.

We write down for the pinch channel the heat-balance equation in the form

$$\int_{t_0}^{t} IE\,dt - W_q(t-t_0) = \pi r_{pct}^2 C_q \rho (T_{pc} - T), \quad t > t_0. \tag{5}$$

Here t_0 is the instant of time immediately after the contraction of the plasma into a filament, when it can be assumed that the channel is not yet heated (see Fig. 3c); C_q is the specific heat; ρ is the density; r_{pct} is the average value of the radius in the temperature interval from T to T_{pc}; the instant t corresponds to the temperature T_{pc}.

Using (5), we obtained the radii r_{pct} of the channels corresponding to the current oscillograms shown in Fig. 3. In the calculation it was assumed that $t = t_{st}$, where t_{st} is the instant when the magnetic field begins to influence the current. The obtained values of r_{pct} and T_{pc} are listed in the table.

The calculation of r_{pct} at different $t > t_0$ has shown that at the time of the pulse the radius r_{pct} of the formed channel is increased by approximately 1.5 times. The slow variation of r_{pct} gives grounds for assuming that the values of r_{pct} listed in the table differ little from the real (not average) values of r_{pc} realized at the instants of time t_{st}.

We used formula (1) to determine the pinch channel radius $r_{pc\,st}$ at the instants t_{st}. They are given in the table. A comparison of the obtained values of r_{pct} and $r_{pc\,st}$ indicates that the theory[7] and experiment agree not only qualitatively but also quantitatively, at least in order of magnitude.

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