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PINCH EFFECT IN A SEMICONDUCTOR WITH BIMOLECULAR VOLUME RECOMBINATION

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Numerical solutions of the pinch-effect equations for a degenerate and nondegenerate electron-hole plasma with bimolecular recombination are obtained. The density profiles over the sample cross section, the dependence of pinch radius on electric field strength, and the volt-ampere characteristics (VAC) are found. It is found that in the presence of large currents, pinch formation in the plasma involves saturation of the VAC. The critical currents for appearance of the pinch effect and VAC saturation are calculated.

1. IT is known[1,2] that the pinch effect in an electron-hole plasma in indium antimonide (InSb) is accompanied by an increased resistance of the sample and the volt-ampere characteristics (VAC) show a kink on the saturation side. This effect occurs both in a nondegenerate[1] and in a degenerate[2] electron-hole plasma. If the main recombination channel is determined by linear recombination, then the saturation of the VAC can be attributed to a decrease in the electron mobility,[3,4] since at high densities (strongly developed pinch) in the case of combined scattering[5] (electrons by holes and holes by phonons) the electron mobility decreases in inverse proportion to the carrier density. In the case when the main recombination channel is bimolecular, the saturation of the VAC may be connected with the decrease in the number of carriers in the sample.[6]

Semiquantitative calculations,[4,7] carried out for the case when the diffusion length of the carriers is much larger than the sample dimension, confirm the possibility of such an explanation, but in all the known experiments on the pinch effect in semiconductors the diffusion length is smaller than the dimensions of the sample. It is therefore of interest to explain the main features of the pinch effect on semiconductors as a function of the type of volume recombination.

We have solved numerically the stationary equations of the pinch effect under conditions of bimolecular volume recombination for the case of a pure sample surface (rate of surface recombination s is small). We have constructed three dimensional profiles of the density distribution over the cross section of the sample, as well as the VAC for different values of the ratio of the sample dimension to the carrier diffusion length (the parameter $\sqrt{\gamma}$). We show that at large currents the strong repulsion of the electron-hole plasma from the sample surface (the pinch effect) is accompanied by a kink of the VAC on the saturation side, and the character of these phenomena depend strongly on the parameter γ. With increasing γ, these phenomena occur at larger currents, this being due to the strong hindering influence of the volume recombination at large γ on the initial stage of the pinch. At small values of γ, the VAC may have an N-shaped form. The dependence of the plasma-pinch radius on the current has been plotted. The critical values of the currents at which strong repulsion of the plasma and saturation of the VAC take place are calculated.

2. The investigation is carried out for a cylindrical sample of radius R_0 with identical numbers of electrons and holes (n = p). In the derivation of the equations describing the stationary state of the plasma in the pinch effect, we start from the equations of motion, continuity, and Maxwell's equations, assuming the radial flux to be ambipolar. These equations take the form

$$\mathbf{v}_e = -D_e\frac{\nabla n}{n} - b_e\mathbf{E} - \frac{b_e}{c}[\mathbf{v}_e\mathbf{H}],$$
$$\mathbf{v}_h = -D_h\frac{\nabla n}{n} + b_h\mathbf{E} + \frac{b_h}{c}[\mathbf{v}_h\mathbf{H}], \qquad (1)^*$$
$$\operatorname{div} n\mathbf{v}_e = -\frac{n^2-n_0^2}{2\tau n_0}, \quad \operatorname{div} n\mathbf{v}_h = -\frac{n^2-n_0^2}{2\tau n_0}$$
$$v_{er} = v_{hr} = v_r, \quad \operatorname{rot}\mathbf{H} = \frac{4\pi}{c}\mathbf{j},$$

where $\mathbf{v}_e$ and $\mathbf{v}_h$ are the velocities of the electrons and of the holes; D_i and b_i are the diffusion and mobility coefficients of the electrons and of the holes (i = e, h); in the case of strong degeneracy we have

$$D_i = \frac{2}{3}\frac{\mu_{Fi}}{e}b_i, \quad \mu_{Fi} = \frac{(3\pi^2)^{2/3}}{2m_i^*}\hbar^2 n^{2/3};$$

μ is the Fermi level; m_i^* is the effective carrier mass; H is the magnetic field (in the case considered by us there is only an azimuthal component of the magnetic field, due to the current); τ is the lifetime of the carriers at a small deviation of the density of the equilibrium value n_0. In the case of a clean surface ($s\tau/R_0 \ll 1$), n_0 coincides with the plasma density in the absence of the pinch effect.

We solve Eqs. (1) for the case when the spatial carrier distribution depends only on the radius (the electric field is directed along the z axis). The initial equation describing the distribution of the carriers of the cross section of the sample take the following form:[3,7]

a) for a nondegenerate plasma

$$\frac{dq}{dx} = -\frac{\alpha_{\text{non}}q}{x}\int_0^x q(x')x'\,dx' + \frac{\gamma_{\text{non}}}{2x}\int_0^x [q^2(x')-1]x'\,dx' \qquad (2)$$

*$[\mathbf{v}_e\mathbf{H}] \equiv \mathbf{v}_e \times \mathbf{H}$.

b) for a degenerate plasma:

$$\frac{dq}{dx}=-\frac{\alpha_{\rm deg}q^{1/3}}{x}\int_0^x q(x')x'\,dx'+\frac{\gamma_{\rm deg}}{2x}q^{-2/3}\int_0 [q^2(x')-1]x'\,dx' \qquad (3)$$

where

$$q=\frac{n}{n_0},\quad x=\frac{r}{R_0},\quad \alpha_{\rm non}=\frac{2\pi e^2v_d^2n_0R_0^2}{c^2kT}\quad \alpha_{\rm B}=\frac{6\pi e^2v_d^2n_0R_0^2}{c^2\mu_{Fe}(n_0)}$$

T is the carrier temperature ($T_e = T_h = T$), $v_d = b_eE_z$ is the electron drift velocity, $\gamma_{\rm non,\,deg} = R_0^2 l_D^2$, where

$$l_{D\,\rm non}=(2b_h\tau kT/e)^{1/2}$$

is the diffusion length in the nondegenerate gas, and

$$l_{D\,\rm deg}=[{}^2/_3\mu_{Fe}(n_0)\,b_h\tau/e]^{1/2}$$

in the degenerate gas.

Equations (2) and (3) were derived under the assumption that $b_e/b_h \gg 1$ and $H^2b_eb_h/c^2 \ll 1$. In satisfying the latter relation the magnetoresistance preventing the pinch effect is small in the case of ambipolar diffusion.

The boundary condition for Eqs. (2) and (3) in the case of a clean surface is

$$\int_0^1 q^2(x')x'\,dx'=\frac{1}{2}. \qquad (4)$$

3. Numerical integration of Eqs. (2)–(4) was carried out with the BÉSM-6 computer for different values of $\gamma \neq 0$. At $\gamma_{\rm non} = 0$, Eq. (2) admits of Bennett's analytic solution,[8] which is of the form

$$q=q_0/(1+yx^2)^2. \qquad (5)$$

The constants q_0 and y, according to (2) and (4), are connected by the relations

$$q_0=\frac{8y}{\alpha_{\rm non}},\quad 1-\frac{1}{(1+y)^3}=\frac{3\alpha_{\rm non}^2}{64y}. \qquad (6)$$

Using (5) and (6) we can plot the density profiles for different values of $\alpha_{\rm non}$ ($\gamma_{\rm non} = 0$) and the VAC.

It should be noted that Eqs. (2)–(4), unlike the case of linear recombination,[3] admit of solutions at arbitrarily large values of α, if we disregard the heating of the sample. Figure 1 shows the density profiles for different α and γ. As seen from this figure, at sufficiently strong currents (α), a strong repulsion of the plasma from the surface of the sample takes place (a plasma pinch is produced), and with increasing γ the formation of the pinch occurs at larger currents, since the bimolecular recombination prevents the occurrence of the pinch effect, which is a decrease in the number of currents and consequently of the azimuthal magnetic field H_φ. At small values of γ, the recombination does not influence the initial stage of the pinch effect, and becomes manifest only at the final stage, when the pinch is formed and the density in it is large. Therefore, with increasing γ the plasma pinch and the saturation of the VAC will occur at large currents. Starting with definite currents (α), the plasma pinch is pushed away from the surface and the overwhelming majority of the carriers is concentrated in the region near the axis. Thus, the situation is analogous to the case of linear volume recombination[3] when the plasma pinch, starting with definite values of the current, moves into the interior of the crystal.

Figure 2 shows the dependence of the pinch radius on the parameter α. We have defined the pinch radius as the distance from the sample axis to the point at which the density decreases by a factor e relative to the density on the sample axis. As seen from this figure, with increasing parameter γ the plasma pinch is produced at large currents, and at very large currents, when the pinch is already formed, the main characteristics of the pinch (Figs. 1, 2) do not depend on γ, i.e., a strongly developed pinch is not a side effect.

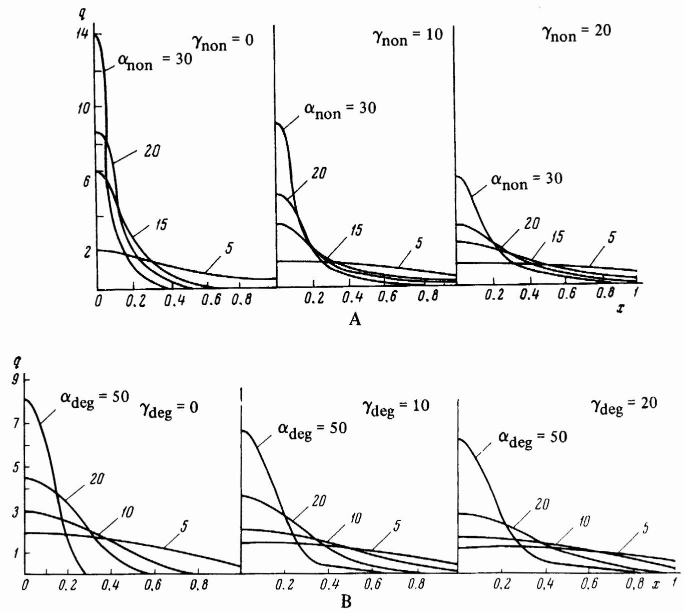

FIG. 1. Spatial distribution of the density in the pinch effect; A—in a nondegenerate plasma, B— in a degenerate plasma.

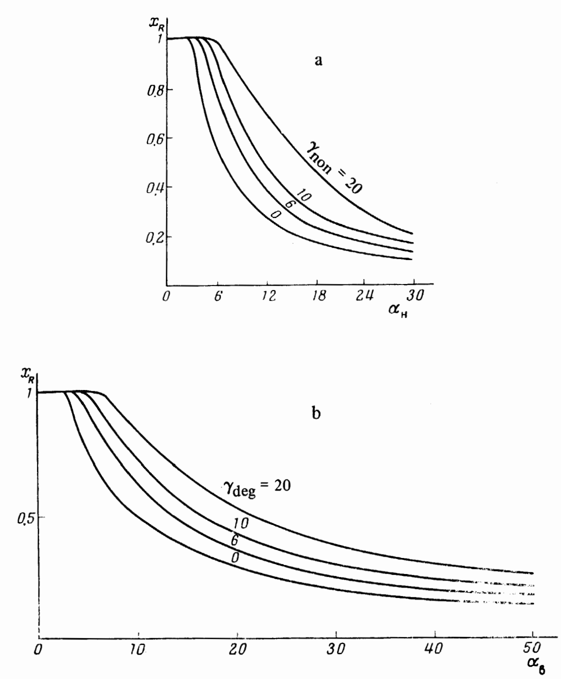

FIG. 2. Dependence of the pinch radius on the parameter $\alpha_{\rm non}$ (current) in a nondegenerate plasma (8) and on the parameter $\alpha_{\rm deg}$(current) in a degenerate plasma (b).

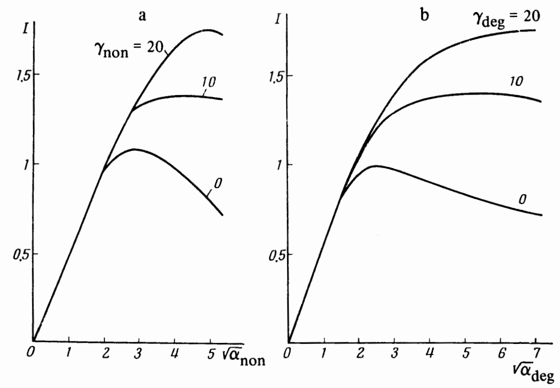

FIG. 3. Volt-ampere characteristics in the pinch effect: a—in a nondegenerate plasma, b—in a degenerate plasma.

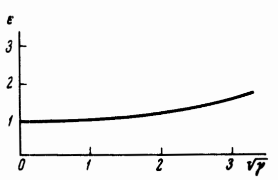

FIG. 4. Dependence of critical electric fields at which the pinch effect occurs on the parameter $\sqrt{\gamma}$.

Figure 3 shows plots of the quantity

$$I = \sqrt{\alpha}\int_0^1 q(x')\,x'\,dx'$$

against $\sqrt{\alpha}$ for different values of γ. Under the conditions when the mobility b_e and the equilibrium density n_0 do not depend on the electric field, the $I(\sqrt{\alpha})$ is the VAC. As seen from Figs. 1–3, the formation of the plasma pinch and the kink in the VAC occur approximately at equal currents. This is connected with the fact that bimolecular recombination becomes manifest most strongly at the instant of pinch formation, when the plasma density is large. At small γ the VAC becomes N-shaped. At $\gamma_{non} = 0$ in the region of the N-shaped section, in the case of nondegenerate plasma we have $I \sim \alpha^{-1/2} \sim E_z^{-1}$.[4,7] In the case of a degenerate plasma, the slope of the VAC is smaller on the N-shaped section.

Using the values of α_{cr} at which the kink of the VAC occurs and the plasma pinch is produced, we can estimate the values of the longitudinal electric field and of the current at which a strong pinch effect arises. We present the estimate for InSb, putting[9] $b_e \approx 6 \times 10^7$ cgs esu (T = 250°K), $b_e = 10^8$ cgs esu (T ≈ 10°K), $n_0 = 10^{16}\ cm^{-3}$ and $R_0 = 2 \times 10^{-2}$ cm.

At such a density, a strong degeneracy of the electron gas is reached at T = 10°K, and at T = 250° (energy of the optical phonons) the plasma is nondegenerate. Recognizing that at $\gamma = 0$ we have $\alpha_{non\ cr} \approx 8$ and $\alpha_{deg\ cr} \approx 6.5$, we get $E_{non\ cr}(\gamma_{non} = 0) \approx 30$ V/cm, $E_{deg\ cr}(\gamma_{deg} = 0) \approx 10$ V/cm, and the critical currents are $I_{non\ cr}(\gamma_{non} = 0) \approx 5$ A and $I_{deg\ cr}(\gamma_{deg} = 0) \approx 3$ A.

Figure 4 shows a plot of $\epsilon = E_{cr}(\gamma \neq 0)/E_{cr}(\gamma = 0)$ against $\sqrt{\gamma}$ for the same parameters (this dependence is the same in both cases). The behavior of the critical current is also analogous.

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