Transverse breakdown in n-InSb ($T=77$ K)

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Impact ionization under the action of a Hall electric field (transverse breakdown) under conditions of the magnetoconcentration effect has been studied experimentally and theoretically. A nonmonotonic dependence of current on magnetic field was observed. The appearance of a minimum in $I(H_0)$ and of a section with negative magnetoresistance indicates unambiguously the onset of transverse breakdown. Features of the effect are noted which arise when the electron-hole plasma is pressed towards faces with greatly differing recombination rates.

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1. Interband impact ionization in polar semiconductors takes place as a result of the runaway of a small group of electrons (scattered through small angles) in an electric field, when the electrons acquire more energy between scattering events than they give up in exciting optic phonons. This phenomenon in the absence of a magnetic field has been studied fairly thoroughly. The transverse breakdown effect (TB) which arises in sufficiently strong crossed electric and magnetic fields (Fig. 1) under the action of the Hall field E_x set up by the main (non-runaway) bulk of the current carriers, has been much less studied. Glicksman *et al.*[1] were the first to indicate the possibility of this effect. A clearer theoretical analysis of the TB effect was carried out by Andronov *et al.*[2] It turns out that in a strong magnetic field perpendicular to the electric field, electrons can, in the process of emitting optic phonons, go into trajectories with larger cyclotron energy. Many repetitions of this process lead to runaway of the electrons, producing the TB effect. There are relatively few[1-4] experimental demonstrations of the TB effect in semiconductors and they all reduce to the observation of the current-voltage characteristics and Hall effect in sufficiently strong magnetic fields.

We present here qualitatively new experimental and theoretical results that demonstrate unambiguously the onset of TB under conditions for the magnetoconcentration effect (MCE) which leads to appreciable nonuniformity in the distribution of the electron-hole plasma over the crystal cross section (the x axis in Fig. 1).

The magnetic-field dependences of the current (I) and the current-voltage characteristics are obtained for the plasma directed towards faces with greatly differing surface recombination rates (s). The effective electric field profiles (E_{eff}) produced by TB are calculated. It is shown that the nonmonotonic form of $I(H_0)$, and the appearance of a minimum in $I(H_0)$ and of a section with negative magnetoresistance unambiguously indicate the onset of TB under MCE conditions.

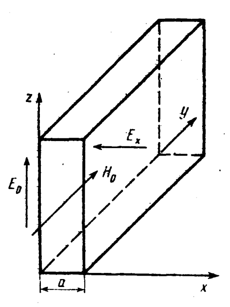

FIG. 1.

2. The continuity equation describing the stationary distribution of a plasma pressed towards the face $x=0$ (Fig. 1) as a result of ambipolar drift in crossed fields, has the form

$$-D_h\frac{d}{dx}\left\{\frac{(2N+1)\,dN/dx}{1+N(1+h^2)}\right\}-V_0\frac{d}{dx}\left\{\frac{N(N+1)}{(1+\alpha N)[1+N(1+h^2)]}\right\}=g(N+1)-rN(N+1), \qquad (1)$$

$$V_0=b_{e0}b_hH_0E_0/c,\quad h=(b_eb_h)^{1/2}H_0/c,\quad b_e=b_{e0}/(1+\alpha N).$$

Here $N=n/n_0$; n and n_0 are the concentrations of plasma and of impurity electrons; b_h and D_h are the hole mobility and diffusion coefficient; b_e is the electron mobility under conditions of electron-hole scattering[5]; α is a parameter of this scattering; $r=r_0n_0$; r_0 is the quadratic bulk recombination coefficient; g is the impact ionization coefficient.

Calculations of the $I(H_0)$ dependence and of E_{eff} were carried out for electric and magnetic fields $E_0=250$, 300 V cm^{-1}, $H_0>100$ Oe. Under these conditions the plasma is strongly concentrated at the $x=0$ face, and the current in the specimen is relatively small as a result of the small lifetime of the current carriers in this region, due to surface and bulk recombination currents, so that the self-magnetic field of the current is not taken into account.

The $g(E)$ dependence was chosen to be of the form[6]

$$g=g_0\exp(-\bar{E}_0/E),$$

$\bar{E}_0=1700$ V cm^{-1}, $g_0=3.6\times10^9$ s^{-1}. In the crossed electric and magnetic field geometry we can write

$$E=E_{eff}=(E_0^2+E_x^2)^{1/2}/(1+\beta H_0),$$

where

$$E_x=-\frac{D_h}{b_h}\frac{(1-h^2)\,dN/dx}{1+N(1+h^2)}-\frac{b_e}{c}H_0E_0\frac{N+1}{1+N(1+h^2)}. \qquad (2)$$

The above choice of E is such that the decisive value for interband TB is the total field[2,6]

$$E_s=(E_0^2+E_x^2)^{1/2}$$

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It was also taken into account that the threshold field E_s increases linearly with field H_0 (Refs. 2, 7). To allow for this fact, a factor $(1+\beta H_0)^{-1}$ is introduced into the expression for the impact ionization coefficient (into E_{eff}). The value of β is determined by comparing the experimental values of breakdown fields E_s for different H_0 according to data of Andronov *et al.*[2]:

$$\frac{E_{1s}}{1+\beta H_1}=\frac{E_{2s}}{1+\beta H_2},$$

which gives $\beta = 4\times 10^{-4}$ Oe^{-1}. If $H_0=0$ then $E_s \approx E_0$ and the expression for g agrees with values measured[6] in the absence of a magnetic field. The impact ionization coefficient chosen by us decreases in weak magnetic field: $b_e H_0/c < 1$, which agrees with experimental and calculated results.[7-9] On increasing H_0 further, $g(H_0)$ increases, since the Hall field increases, and in very strong fields ($h>1$) it decreases again, due to a reduction in E_x (Eq. 2).

The boundary conditions correspond to equality of the ambipolar carrier currents[1)] at the faces $x=0$ and $x=a$ to the corresponding surface recombination currents: $-s_0N(x=0)$ and $s_1N(x=a)$. The current is

$$I=\int_0^a j_z\,dx,\quad j_z=en_0b_eE_0\left[\frac{(N+1)^2}{1+N(1+h^2)}-\frac{D_hH_0}{cE_0}\frac{2N+1}{1+N(1+h^2)}\frac{dN}{dx}\right]. \quad (3)$$

In deriving Eqs. (1) to (3) it was assumed that $b_h \ll b_e$. Numerical solution of the equations was carried out for the following values of the parameters:

$$b_{e0}=10^8 \text{ cgs esu},\quad b_h=2\cdot 10^6 \text{ cgs esu},\quad D_h=200 \text{ cm}^2/\text{s},$$
$$r_0=10^{-8}\text{ cm}^{-3}/\text{s}^{-1},\quad n_0=10^{14}\text{ cm}^{-3},\quad \alpha=5\cdot 10^{-3},\quad a=10^{-2}\text{ cm}.$$

For the two values $E_0=250$ and 300 V cm^{-1} the $I(H_0)$ relations were plotted for plasma onto pressed towards a "dirty" surface ($s_0=10^6$ cm·s^{-1}, $s_1=10^3$ cm·s^{-1}) and a "clean" surface ($s_0=10^3$ cm·s^{-1}, $s_1=10^6$ cm·s^{-1}), (Fig. 2). The value of E_{eff} was calculated at different points in the specimen (Fig. 3).

3. The narrowness of the forbidden gap and the small electron effective mass enable impact ionization to arise in relatively weak electric fields ($E_0\approx 200$–250 V·cm^{-1}); the condition $b_eH_0/c>1$, essential for a strong Hall field to appear, is then already satisfied for $H \gtrsim 300$ Oe. Specimens ($n_0\approx 1.2\times 10^{14}$ cm^{-3}, $b_{e0} \approx 1.8\times 10^8$ cgs esu) were prepared in the form of plane dumbbells with asymmetrically finished faces and with

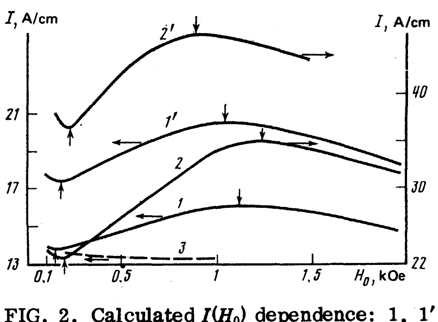

FIG. 2. Calculated $I(H_0)$ dependence: 1, 1') $s_0=10^6$ cm·s^{-1}, $s_1=10^3$ cm·s^{-1}; 2, 2') $s_0=10^3$ cm·s^{-1}, $s_1=10^6$ cm·s^{-1}; 1, 2, 3) $E_0=250$ V·cm^{-1}; 1', 2') $E_0=300$ V·cm^{-1}; 3) $E_x=0$. The arrows here and in Figs. 4 and 5 indicate the positions of the extrema.

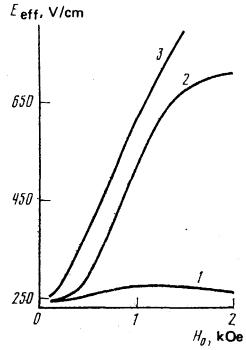

FIG. 3. Calculated $E_{eff}(H_0)$ dependence: $s_0=10^3$ cm·s^{-1}; $s_1=10^6$ cm·s^{-1}; 1) $x=0$, 2) $x=a/20$, 3) $x=a$.

rounded corners to prevent possible breakdown in high-field corners. Otherwise the magnetic field would lead to the formation of regions of strong electric field near the corners of the specimen, since the Hall field is shorted by the contacts there.[10] The working region had dimensions $0.5\times 0.01\times 0.15$ cm. One of the faces was treated with M5 abrasive powder to produce a surface recombination rate $\approx 10^6$ cm·s^{-1}, the other was cleaned with SR-4 polishing fluid ($s\approx 2\times 10^3$ cm·s^{-1}). The electric field was in the form of rectangular pulses of 1 μs duration and repetition frequency 50 Hz to avoid Joule heating. The characteristics obtained were printed on a chart recorder.

Figures 4 and 5 show the mean experimental $I(H_0)$ dependences for different boundary conditions (Fig. 4) and values of the external electric field E_0 (Fig. 5). It can be seen from these that the $I(H_0)$ variation is nonmonotonic. This $I(H_0)$ behavior is due to the action of two competing mechanisms: the suppression of impact ionization as a result of electron magnetization and the development of TB in the Hall field. The initial current falloff is due to the decrease of $g(H_0)$ and the increased recombination (both surface and bulk) near the $x=0$ face. Transverse breakdown then starts up [$g(H_0)$ grows] and the full current increases with increasing magnetic field (negative magneto-resistance). The experimental dependences agree well quantitatively with the theory (see Fig. 2). If transverse breakdown is not taken into account in the calculations (Fig. 2, curve 3, $E_x=0$), $I(H_0)$ falls monotonically.

The nonmonotonic form of the theoretical and experimental $I(H_0)$ plots is thus due entirely to the TB effect. The appearance of maxima of $I(H_0)$ in fields $H_0>10^3$

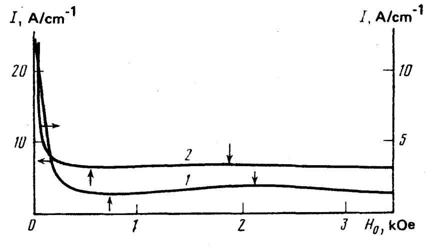

FIG. 4. Measured $I(H_0)$ dependence: $E_0=250$ V·cm^{-1}; 1) $s_0=2\times 10^3$ cm·s^{-1}, $s_1=10^6$ cm·s^{-1}; 2) $s_0=10^6$ cm·s^{-1}, $s_1=2\times 10^3$ cm·s^{-1}.

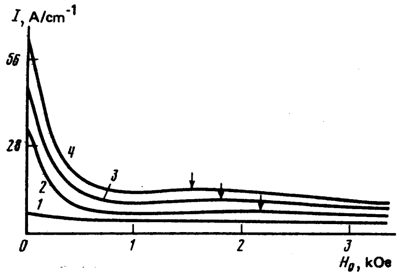

FIG. 5. Measured $I(H_0)$ dependence: $s_0=2\times10^3$ cm·s^{-1}, $s_1=10^6$ cm·s^{-1}; 1 to 4) $E_0=100$, 260, 280, 310 V·cm^{-1}.

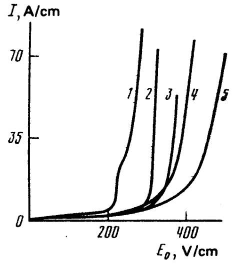

FIG. 6. Measured current-voltage characteristics: $s_0=2\times10^3$ cm·s^{-1}, $s_1=10^6$ cm·s^{-1}; 1 to 5) $H_0=0$, 0.5, 1, 2, 3.3 kOe.

Oe is caused by the magnetization of the current carriers (although the calculated bulk plasma concentration continues to grow up to fields ≈ 2 kOe).

For the further discussion we note some characteristic properties of the spatial plasma distribution under conditions of impact ionization and MCE. As a result of intensive removal of electron-hole pairs from the volume at one of the faces ($x=0$), a narrow layer is formed where bulk and surface recombination are dominant. Outside this layer the plasma concentration depends weakly on the state of the surface, while the concentration at the face $x=a$ remains at the impurity level. The layer itself affects in different manners the overall conductivity of the crystal. For $s_0=10^6$ cm·s^{-1} and weak magnetic fields ($H_0\approx 100$ to 250 Oe) the current is determined by the main volume of the crystal. In this volume

$$n\approx n_0 \exp[g\tau(1-x/a)],$$

where $\tau=a/V_0$, and the position of the $I(H_0)$ minimum is fairly accurately determined by the obvious condition

$$d(g\tau)/dH_0=0,$$

since E_{eff} is practically uniform over the cross section in weak magnetic fields. It is only at $H_0>1$ kOe, when the transverse drift velocity (V_0) exceeds s_0 appreciably, that the layer plays a dominant part in determining the specimen conductivity. If $s_0=10^3$ cm·s^{-1}, the layer makes the main contribution to the conductivity even in weak magnetic fields. In that case E_{eff} (see Fig. 3) is extremely nonuniform over the specimen cross section: it is large near $x=a$ and small in the layer region (because of diffusion and electron-hole scattering).

We now consider the results shown in Figs. 2, 4, and 5 in more detail.

As the plasma becomes pressed towards the clean surface we notice a shift in the minimum of the $I(H_0)$ curves in the direction of larger magnetic fields (Figs. 2 and 4). As H_0 increases, the degree of concentration of the plasma into the layer increases and the nonlinear volume recombination and electron-hole scattering are intensified, which requires larger E_x for the current to start rising in the specimen compared with concentration at a dirty surface.

The shift of the minimum with increasing electric field E_0 into the region of larger magnetic fields is due to the fact that the relative change in rate of impact ionization decreases with increasing H_0 [saturation of $g(E_{eff})$].

The decrease of the current in fields $H_0\gtrsim 10^3$ Oe is due to magnetization of the carriers. Curve 1′ has a maximum in a weaker magnetic field than curve 1 (Figs. 2 and 4) because of the indicated saturation of $g(E_{eff})$. The formation of the layer upon compression towards a clean surface (curves 2 and 2′ in Fig. 2) has a different effect on the shift in the maximum of $I(H_0)$ than in the case $s_0=10^6$ cm·s^{-1}.

Electron-hole scattering in the layer has a two-fold effect. On the one hand it lowers the electron mobility and hinders current growth in the layer, while on the other hand this same lowering of the mobility delays the onset of magnetization of the current carriers. For $E=300$ V·cm^{-1} the plasma concentration near the surface ($x=0$) is so large that intense electron-hole scattering and quadratic recombination noticeably weaken the growth of the layer conductivity on increasing magnetic field, and the effect of the magnetization on the layer conductivity appears earlier (the maximum of curve 2′ lies more to the left than that of 1′ in Fig. 2). At $E=250$ V·cm^{-1} (Fig. 2, curves 1 and 2) electron-hole scattering and recombination weaken, allowing effective accumulation of particles in the layer with increase of H_0. The effect of magnetization on the layer conductivity is therefore reduced, leading to a change in the alternation of the maxima.

Current-voltage characteristics measured for different values of magnetic field are shown in Fig. 6. As can be seen, the value of threshold breakdown field (E_0) depends nonmonotonically on magnetic field (E_0 is less at $H_0=2$ kOe than at $H_0=1$ kOe), which is certainly evidence of the initiation of TB. However, such a method of fixing TB is less accurate. As can be seen from Figs. 4 and 5, transverse breakdown appears at $H<1$ kOe [according to the minimum in the $I(H_0)$ dependence].

[1)]It was assumed that the inherent plasma concentration is appreciably less than the impurity electron concentration.

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