Anomalous conductivity of semiconducting BiSb alloys in strong electric and longitudinal quantizing magnetic fields

N. B. Brandt, N. A. Sidorenko, and G. D. Yakovlev

Moscow State University

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It was observed that the conductivity of semiconducting BiSb alloys with narrow forbidden bands increases sharply in a strong electric field, in the case of interband breakdown, under the influence of a longitudinal quantizing magnetic field. The concentration of the nonequilibrium electron-hole plasma in a field ~50 kOe reaches a possible value 10^{17}–10^{18} cm^{-3}.

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The influence of a quantizing magnetic field on the electric conductivity of narrow-band semiconductors in the case of interband breakdown in a strong electric field has hardly been investigated. Yet such investigations are of great interest, particularly in connection with the possibility of obtaining, in the course of the interband breakdown, of large concentrations of electron-hole plasma (EHP). We report here the results of the measurements of the conductivity σ of n-type semiconducting $Bi_{1-x}Sb_x$ alloys ($x=0.07$, 0.1, 0.15) in strong electric fields **E** up to ~100 V/cm with the current oriented along the trigonal crystallographic axis C_3, in the presence of a longitudinal magnetic field **B** up to ~50 kOe and at $T\approx 4.2$ K. The samples had typical dimensions $1\times 1\times 5$ cm. The current contacts were ohmic, and the potential contacts pointlike. The features of the sample mounting are given in[1]. We used for the measurements rectangular current pulses up to ~150 A, of duration ~2 μsec and repetition frequency ~1 Hz, thus avoiding substantial heating of the samples by the measuring current. The results of the measurements in strong electric fields, in the case of interband breakdown, are qualitatively the same for all the investigated alloys, and will be described below by citing the data for the alloy $Bi_{0.90}Sb_{0.10}$. In this alloy the width of the forbidden band, determined by the distance between practically mirror-symmetrical electron and hole extrema at L points of the Brillouin zone, is $\epsilon_g\approx 15$ meV. The electron equal-energy surfaces are three triaxial ellipsoids (with centers at L points), inclined at an angle ~6° to the basal plane and rotated relative to one another through $\pm 120°$, At the chosen orientation $\mathbf{E}\|\mathbf{B}\|C_3$, the ellipsoids are equivalently disposed relative to the external fields. The effective masses of the electrons in the principal axes of the ellipsoid are $m_1\approx m_3\approx 4\times 10^{-3}m_0$; $m_2\approx 0.3m_0$, where m_0 is the mass of the free electron.[2] The electron density in the alloy is $n\approx 7\times 10^{14}$ cm^{-3}, and the mobility is $\mu\approx 8\times 10^5$ cm^2/V sec. The contribution made to the conductivity by thermally excited intrinsic carriers at $T\approx 4.2$ K can be neglected. Owing to the large dielectric constant ($\sim 10^2$)[3] and the low effective masses, the semiconducting $Bi_{1-x}Sb_x$ alloys are strongly doped already at $n<10^{14}$ cm^{-3}. The electron Fermi energy in the investigated samples was $\epsilon_F\approx 2$ meV.

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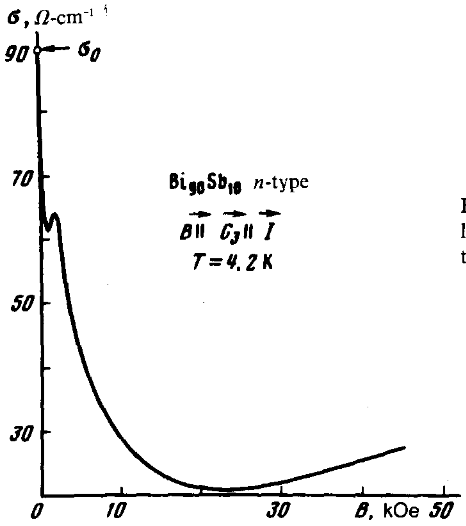

FIG. 1. Dependence of the conductivity σ on the longitudinal magnetic field intensity **B** in the electric-field region where Ohm's law is valid.

Figure 1 shows the dependence of the conductivity σ on the intensity of the longitudinal magnetic field **B**, measured at 4.2 K in weak electric fields in which Ohm's law is valid. The ultraquantum limit of the magnetic field is reached in the investigated alloy already in fields ~ 1 kOe and the observed oscillation of the conductivity near ~ 1 kOe is apparently due to emergence of the zeroth Landau level. With increasing **B**, the conductivity decreases and reaches in a field $\mathbf{B}=\mathbf{B}_m \approx 20$ kOe a minimum ($\sigma_0/\sigma_m \approx 4$), after which it increases monotonically. Similar dependences of σ on **B** were observed in the superconducting alloys $\mathrm{Bi}_{1-x}\mathrm{Sb}_x$ at $\mathbf{B} \| \mathrm{C}_3 \| \mathbf{E}$ in a number of studies,[4] but have not been fully interpreted to this day. We note that at $\mathbf{B} \| \mathrm{C}_3$ and in the investigated field interval $\mathbf{B} \lesssim 50$ kOe there is not observed magnetic freezing of the electrons from the conduction band on the impurity levels in the semiconducting n-type $\mathrm{Bi}_{1-x}\mathrm{Sb}_x$ alloys.[5] The ratio of the spin and orbital masses in the investigated alloy at $\mathbf{B} \| \mathrm{C}_3$ is such that in fields $B \lesssim 50$ kOe one can neglect the change in the width of the forbidden band.[4] Thus, the observed dependence of σ on **B** is due to the dependence of the electron mobility μ on the field **B**. This dependence can be due to a change in the character of the electron scattering as a result of the change in statistics (from Fermi to Boltzmann) which takes place in the ultraquantum magnetic-field limit.[6]

We measured directly the current-voltage characteristics (CVC) of the samples. Both with and without an external magnetic field, the differential conductivity dJ/dE was positive. The dependences of the conductivity $\sigma = J/E$ on the electric field **E**, plotted from the results of the CVC measurements, are shown in Fig. 2. At $B=0$ the dependence of σ on **E** is similar to that observed earlier[1]: Ohm's law is valid up to fields $E \approx E_0 \approx 0.5$ V/cm. In the interval $E_0 \lesssim E \lesssim E_1 \approx 4$ V/cm the conductivity decreases with increasing E approximately like $\sigma \sim E^{-0.45-0.5}$, and this is possibly due to scattering by acoustic phonons. In fields $E \gtrsim E_1$, the value of σ increases rapidly with increasing E as a result of impact ionization of the valence band ("interband breakdown")—an electron-hole plasma (EHP) is produced in the sample. Some slowing down in the growth of σ in fields $E \gtrsim E_p \approx 20$ eV is due to the onset of the pinch effect in the EHP. An external magnetic field $B \gtrsim 1$ kOe alters noticeably the character of the $\sigma(E)$ dependence. With increasing **B** the field E_0 decreases: at $B \approx 45$ kOe we have $E_0 \approx 5 \times 10^{-2}$ V/cm, i.e., it is smaller by a factor of about 10 than at $B=0$. In addition, starting with fields $B \gtrsim 5$ kOe a deviation from Ohm's law tending to increase σ appears in the region $E \gtrsim E_0$, while in fields $B \gtrsim 20$ kOe the decreasing section on the $\sigma(E)$ plot vanishes and the conductivity at $E \gtrsim E_0$ increases everywhere with increasing E. The changes of σ in the interval E_0—E_1 do not exceed σ_0 in order of magnitude. The most interesting at $B \neq 0$, in our opinion, are the results in fields $E > E_1$. It is clearly seen from Fig. 2 that the $\sigma(E)$ dependence at $E > E_1$ becomes ever stronger with increasing **B**: whereas at $B=0$ the conductivity in interband breakdown increased by ~10 times in the investigated electric-field interval, at $B \approx 45$ kOe the conductivity of the sample in the same electric field increased ~10^3 times! The character of the evolution of the $\sigma(E)$ dependences under the influence of the external magnetic field allows us to assume that (just as at $B=0$) an interband breakdown accompanied by EHP production takes place at $B \neq 0$ in a field $E > E_1$. In the course of the breakdown, the

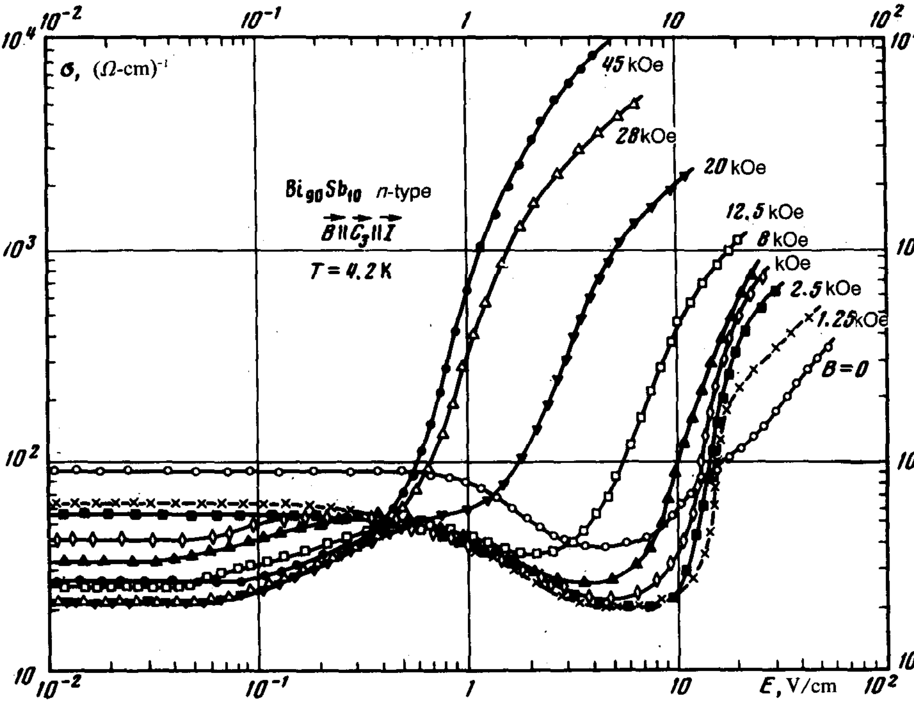

FIG. 2. Plots of the conductivity σ against the electric field intensity E at various values of the external longitudinal field **B**.

increase of the EHP conductivity is usually due to the increase of the electron and hole concentrations. If this assumption is correct, then in a field ~ 50 kOe the nonequilibrium EHP reaches a concentration $(5-7)\times 10^{17}$ cm^{-3}! That is to say, a sufficiently strong longitudinal magnetic field makes it possible to increase effectively the EHP concentration in the breakdown. To our knowledge, no such effect was observed heretofore.

In the interband breakdown, the increase of the EHP concentration under the influence of the magnetic field can occur in the ultraquantum limit[1)] because the density of states at the zero Landau levels of the conduction and valence band increases with increasing **B** (while at the same time ϵ_g is practically independent of B, see above). It is estimated that the EHP concentration in a field $B \approx 50$ kOe can exceed by more than 100 times the EHP concentration at $B=0$. In addition, the EHP pinching which is observed at $B \approx 0$[1] and causes, as is well known,[7] the mobility and the average concentration of the EHP to decreases, should not take place in fields $B \gtrsim 1$ kOe. Estimates show that the conductivity can increase several fold as a result of this effect, compared with $\sigma(B=0)$.

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[1)] In interband breakdown the average electron energy is of the order of ϵ_g, but in this case it is estimated that the ultraquantum limit is reached in fields $B \gtrsim 10$–20 kOe.

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