Resonant impact ionization in $Bi_{1-x}Sb_x$ semiconducting alloys

E. V. Bogdanov, N. B. Brandt, V. M. Manankov, and L. S. Fleĭshman
M. V. Lomonosov Moscow State University

(Submitted 9 December 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **35**, No. 2, 75–77 (20 January 1982)

Resonant maxima have been observed in the impact-ionization rate g, and associated oscillations have been observed in the conductivity σ, in $Bi_{1-x}Sb_x$ semiconducting alloys in quantizing magnetic fields. The effects seem to result from the vertical Auger transitions predicted theoretically by Takeshima [J. Appl. Phys. **44**, 4717 (1973)].

PACS numbers: 79.20.Fv, 72.20.My

Resonances have recently been observed experimentally in the probabilities for phonon, plasma, and Auger recombination of nonequilibrium carriers in narrow-gap semiconductors in quantizing magnetic fields.[2] These resonances are observed in magnetic fields for which the distances between the Landau levels are equal to the characteristic recombination energy. Since many of the processes which determine recombination–in particular, Auger transitions–can also go in the opposite direction, we would expect to find resonances in the rate of carrier generation in quantizing magnetic fields. To the best of our knowledge, this effect has not been observed previously.

In this paper we are reporting measurements of the conductivity and the rate of impact ionization of the valence band in n-type $Bi_{1-x}Sb_x$ semiconducting alloys ($x = 0.09, 0.10, 0.11, 0.12, 0.14, 0.15$) in a longitudinal magnetic field H up to 40 kOe at the temperature $T = 4.2$ K. The current flowed along the bisector (C_1) and twofold (C_2) crystallographic axes. According to galvanomagnetic measurements in weak electric fields E, these alloys have an electron concentration $n \simeq 10^{14}$-10^{15} cm^{-3} and a mobility $\mu \simeq 6 \times 10^5$-6×10^6 cm^2/(V • s) at $T = 4.2$ K. At such concentrations, $Bi_{1-x}Sb_x$ semiconducting alloys are in the heavy-doping region. The width of the energy gap ϵ_g of the alloys is determined by the distance between the three hole extrema at the L points of the Brillouin zone and the three essentially mirror-image electron extrema[3,4]; this width varies from 12 to 21 MeV (Ref. 4). The present measurements were carried out under given-voltage conditions by the method of Ref. 5. Square voltage pulses with a rise time less than 1 ns were produced by a mercury-relay pulse generator.

Figure 1a shows the dependence of the rate of impact ionization on the strength of the magnetic field for two fixed values of the electric field in a sample of composition $Bi_{0.86}Sb_{0.14}$ in the orientation $\mathbf{H} \parallel \mathbf{I} \parallel C_1$. On both of these curves there are maxima of the resonance type, at positions (10 and 21 kOe), which do not depend on the strength of the electric field. At the same values of the magnetic field, the curve of the current I (the conductivity) against the magnetic field has maxima (curves 1, 2, and 3 in Fig. 1b). At electric fields below the threshold, no oscillations

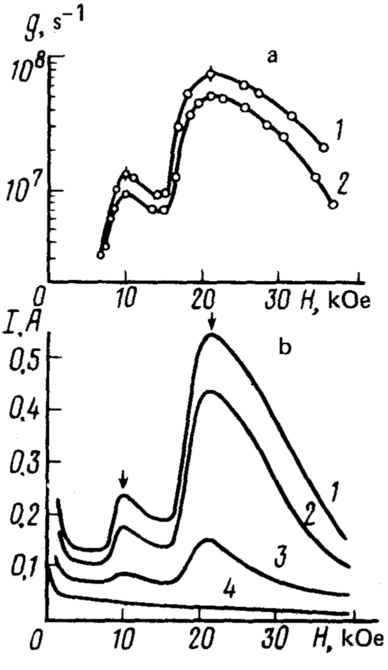

FIG. 1. Dependence of the rate of impact ionization, g (part a), and of the current I (part b) on the strength of the longitudinal magnetic field H in $Bi_{0.86}Sb_{0.14}$ in the orientation $\mathbf{H} \parallel \mathbf{I} \parallel C_1$ at the following values of the electric field E: 1–50; 2–45; 3–35; 4–20 V/cm.

are observed in the conductivity (curve 4 in Fig. 1b).

Similar results were obtained for all the samples studied; the magnetic fields H_N at which the maxima are observed in the rate of impact ionization and in the conductivity increase with increasing antimony concentration and thus with increasing gap width ϵ_g (Fig. 2).

The resonant maxima in the rate of impact ionization may occur in a magnetic field because of vertical Auger transitions[1] (see the inset in Fig. 2). Under the condition

$$\epsilon_{N,s} - \epsilon_0^- = \epsilon_g , \qquad (1)$$

where $\epsilon_{N,s}$ and ϵ_0 are the energies of the N, s level and of the lower Landau level, these Auger transitions have a minimum threshold energy; this circumstance combines with the particular features of the state density at the bottom of the Landau bands to cause a resonant increase in the rate of impact ionization. The positions of the resonances are determined exclusively by the parameters of the energy spectrum; they are independent of the strength of the electric field. Using the semiempirical spectral model developed by Smith *et al.*[6] which describes light carriers in a quantizing magnetic field in $Bi_{1-x}Sb_x$ (Ref. 3), we can easily determine the magnetic fields H_N from condition (1):

$$H_N = M \frac{cm_0}{e\hbar} \frac{\epsilon_g^2}{N} , \qquad (2)$$

where m_0 is the mass of a free electron, M is a product of matrix elements, and $N = 1, 2, 3, \ldots.$ The arrows in Fig. 1 show the values calculated for H_N for $Bi_{0.86}Sb_{0.14}$ ($\mathbf{H} \parallel \mathbf{I} \parallel C_1$) with allowance for the change in ϵ_g in a magnetic field[7] from the known parameters of the spectrum of electrons from two equivalent valleys[3,4] for $N = 1, 2$. We see that these fields agree well with experiment. The electrons from the third

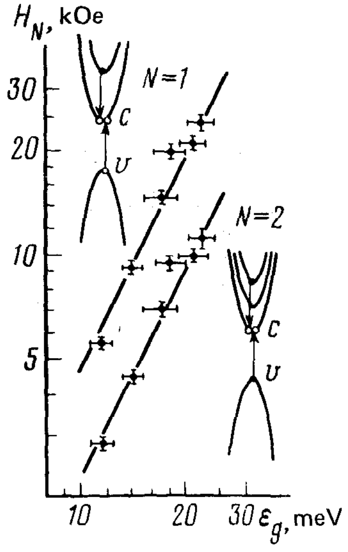

FIG. 2. Dependence of the magnetic fields H_N at which resonances are observed on the size of the energy gap, $\epsilon_g(H = 0)$, for the orientation $\mathbf{H} \parallel \mathbf{I} \parallel C_1$. The curves were calculated from Eq. (2) with allowance for the change in the gap in a magnetic field[7] for $N = 1$ and $N = 2$. The insets show the schemes for the corresponding vertical Auger transitions between Landau levels in the conduction band (c) and in the valence band (v).

valley have a mass essentially half as large,[3] so that they make additional contributions to only the resonances with even indices.

When the change in the gap in a magnetic field[7] is taken into account, expression (2) gives a satisfactory description of the gap dependence of the position of the resonance (Fig. 2); this agreement constitutes evidence in favor of the possibility that the observed effects stem from vertical Auger transitions.

Measurements show that the carrier lifetime remains constant over the magnetic field range 3–40 kOe. The observed maxima in the conductivity can accordingly be attributed to an increase in the steady-state carrier concentration at resonances of the impact-ionization rate.

When the magnetic field is instead oriented along the twofold axis, we again observe maxima in the rate of impact ionization and the conductivity; the values of H_N in this case are smaller than the corresponding values for the orientation $\mathbf{H} \parallel \mathbf{I} \parallel C_1$ by a factor of about 1.7, in accordance with the anisotropy of the small cyclotron masses of electrons in the $Bi_{1-x}Sb_x$ alloys.[3]

It is difficult to directly measure the rate of impact ionization for samples with magnetic field oriented along the trigonal axis because of the large negative magnetoresistance, but again in this case we can see oscillations in the magnetoresistance.

1. M. Takeshima, J. Appl. Phys. **44**, 4717 (1973).
2. G. Nimtz, Phys. Rep. **63**, 265 (1980).
3. G. A. Mironova, M. V. Sudakova, and Ya. G. Ponomarev, Zh. Eksp. Teor. Fiz. **78**, 1830 (1980) [Sov. Phys. JETP **51**, 918 (1980)].
4. G. A. Mironova, M. V. Sudakova, and Ya. G. Ponomarev, Fiz. Tverd. Tela (Leningrad) **22**, 3628 (1980) [Sov. Phys. Solid State **22**, 2124 (1980)].
5. J. C. McGroddy and M. I. Nathan, J. Phys. Soc. Jpn. (Suppl.) **21**, 437 (1966).
6. G. E. Smith, G. A. Baraff, and J. W. Rowell, Phys. Rev. **135**, A1118 (1964).
7. H. B. Brandt, S. M. Chudinov, and V. G. Karavaev, Zh. Eksp. Teor. Fiz. **70**, 2296 (1976) [Sov. Phys. JETP **43**, 1198 (1976)].

Translated by Dave Parsons
Edited by S. J. Amoretty