Resonant microwave photoconductivity of periodic layered Bi-Sb composites with a network of misfit dislocations: manifestation of a miniband spectrum?

V. A. Gerasimenko, V. V. Zorchenko, V. V. Kondratenko, A. I. Fedorenko, D. D. Khalameĭda, and V. M. Yakovenko
Institute of Radiophysics and Electronics, Academy of Sciences of the Ukrainian SSR

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A sharp peak has been discovered in the negative microwave photoconductivity as a function of the magnetic field H in periodic layered Bi-Sb composites. The photoconductivity is resonant in the frequency. The position of the peak along the H scale is determined by the radiation power and the current through the sample.

Layered structures consisting of semimetals and substances with narrow band gaps have attracted considerable research interest in recent years. Such substances hold promise for microwave and IR technological applications.

In this letter we report a study of periodic layered composites based on the semimetals Bi and Sb. The composites are grown through the alternate vapor deposition of Bi and Sb on a mica substrate in a vacuum of 10^{-6} Pa. The period of the composites (~ 10 nm) and the thicknesses of the layers are determined by the known procedure which involves the positions of satellite peaks on a diffraction pattern.[1] The periodic layered composites (the dimensions of the samples are 13×1 mm) have 15 periods. At the Bi-Sb interface there are misfit dislocations, which form an ordered triangular network.[2] The samples are immersed in liquid helium and attached to a flange of the waveguide in such a way that their central part is irradiated. The contacts are positioned outside the waveguide. The static magnetic field H is in the plane of the com-

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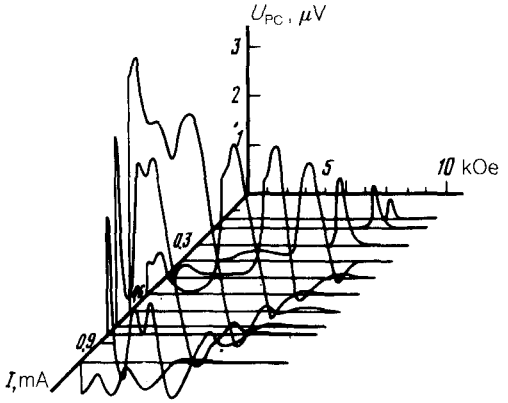

FIG. 1. Photoconductivity versus the magnetic field and the current at $f = 135.35$ GHz, at a radiation power $W = 50$ mW, and at $T = 4.2$ K.

posite and perpendicular to the current through the sample, I. The electric field of the wave is parallel to H. The sample is irradiated with square microwave pulses with a length equal to half the repetition period. The repetition frequency of the pulses is either 30 Hz or 15 kHz. The additional voltage which arises across the composite during the irradiation, u_{PC}, is measured with a calibrated 232V tuned nanovoltmeter, which is tuned to the modulation frequency. The current through the sample is held constant. The microwave power incident on the sample ranges up to 50 mW, so there is no heating of the sample. The radiation frequency f is varied from 131.5 to 137.7 GHz.

Figure 1 shows the photoconductivity of one of the samples (with a period $d = 8.6$ nm and with Bi layers of thickness $d_{Bi} = 4.32$ nm) versus H and I. At small values of I and at $H = 0$, the composites have essentially no photosensitivity. The imposition of a magnetic field gives rise to a sharp peak in the negative photoconductivity, with a maximum at $H = H^*$. As the current is increased, the peak shifts down the H scale, and its height simultaneously increases. At $H = 0$, the maximum of the photoconductivity is reached at a certain current I_0. A further increase in the current causes the decay and disappearance of the photoconductivity. At a fixed value of I, the photoconductivity maximum is reached in the field H^* which satisfies the empirical relation

$$I = I_0 [1 - (H^*/H_0^*)^2] , \tag{1}$$

where H_0^* is the limit of H as $I \to 0$.

At $I \gtrsim 300$ μA, the main peak is followed immediately by a region with a positive photoconductivity, while at $I \gtrsim 450$ μA the main peak is accompanied by an additional peak, which—like the main peak—moves down the H scale as I is increased. Expression (1) is plotted in Fig. 2, which also illustrates the degradation of the composites after repeated cycles of cooling from room temperature to liquid-helium temperature. For a sample with $d = 8.6$ nm and $d_{Bi} = 4.32$ nm, the photoconductivity peak shifts in a nonlinear way down the H scale as the radiation power is increased. As the radiation frequency is reduced, the current I_0 increases, while the parameter H_0^*

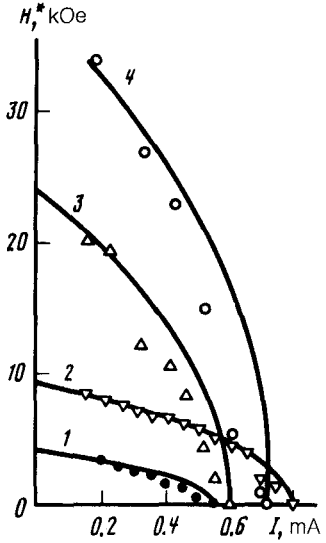

FIG. 2. Relationship between H^* and I for samples with the following parameter values. 1 (●)—$d = 11.2$, $d_{Bi} = 3.84$ nm; 2 (▽), 3 (△), 4 (○)—$d = 8.6$, $d_{Bi} = 4.32$ nm ($W = 50$ mW). 1, 2) Measurements after the first cooling of the sample from 290 K to 4.2 K; 3, 4) measurements after the second and third such coolings.

decreases, so the photoconductivity peak may shift either up or down the H scale, depending on the magnitude of the current. At a fixed current $I \sim 500\ \mu$A, a frequency deviation $\sim 2\%$ results in the complete disappearance of the photoconductivity peak in a magnetic field, although for a sample with $d = 11.2$ nm the photoconductivity peak is observed at all the frequencies used in the experiments. The current-voltage characteristics of the samples are essentially linear; for the sample corresponding to Fig. 1 we find $R = 204\ \Omega$. The change in the resistance upon the imposition of the microwave field does not exceed 0.01%. The photoconductivity shows no response to a reversal of the direction of H or I.

It would be extremely difficult to explain the observed effects on the basis of a heating of the current carriers or on the basis of effects of an acoustoelectric type,[3] in view of the resonant nature of the photoconductivity and the low value of the electric fields. The essential problem is to reach an understanding of the nature of the photoconductivity at $H = 0$ and of the role played by the magnetic field in the observed effects. It may be that the electron spectrum is a miniband spectrum in these samples. This suggestion makes it possible to explain the fact that the photoconductivity is resonant in the frequency and also to explain the dependence of the position of the peak on the magnitude of the current, under the assumption that the electrons partially fill a lower miniband. At a photon energy sufficient to scatter electrons into a higher miniband, a photoconductivity should be observed (and its sign will depend on the relation between the mobilities of the electrons in the bands). If, on the other hand, the frequency of the radiation is too low for this process, a static electric field could shift the Fermi energy distribution by an amount $\delta\epsilon$ and "tune" the energy gap to the photon energy. The shift $\delta\epsilon$ can be found from the relation $\delta\epsilon \sim eEl$, where E is the static electric field, and l is the mean free path of the electrons between inelastic collisions. An estimate of l from the shift of I_0 upon a change in f yields $l \sim 14\ \mu$m

(this value agrees in order of magnitude with the mean free path between electron-electron collisions in films of antimony[4]). For the width of the higher miniband, determined from the current interval ($H = 0$), in which the photoconductivity is observed, we find a value roughly half the photon energy (5.6×10^{-4} eV at $f = 135.5$ GHz). As the temperature is lowered, the photoconductivity decreases, and it disappears at $T \sim 1.7$ K, probably because of a decrease in the spreading of the Fermi distribution.

The role played by a magnetic field is not clear. At this point we cannot explain the nature of the resonance of the photoconductivity in the magnetic field or the origin of relationship (1) between I and H^*. It is interesting to note that the parameter H_0^* increases n-fold (the frequency and power of the radiation are held constant) after a thermal cycling of the samples.

If a superlattice does indeed form, the miniband nature of the spectrum would apparently result from both the layered nature of the structure and potential wells for electrons in Sb at the sites of the ordered network of misfit dislocations (a three-dimensional superlattice), since the energy characteristics of the minibands in the case of one-dimensional superlattices would be two orders of magnitude higher than the characteristic energies in these experiments. The hypotheses advanced in this letter require further research; for the time being, the nature of the effects seen here must remain an open question.

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