Cyclotron Resonance and Far-Infrared Magneto-Absorption Experiments on Semimetallic InAs-GaSb Superlattices

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Far-infrared magneto-absorption experiments performed in semimetallic InAs-GaSb superlattices are presented. The results are interpreted in terms of cyclotron resonance and interband transitions from the valence subbands to the conduction subbands. The resulting energy gaps of the superlattices are found to be negative, demonstrating directly their semimetallic nature. The observed electron mass is enhanced as a result of the conduction-band nonparabolicity.

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It has been shown theoretically that InAs-GaSb superlattices[1] (SL) undergo a semiconductor-semimetal transition[1-3] when the layer thickness d reaches a critical value d_c in the vicinity of 85 Å. This transition arises primarily from the relative position of the band-edge energies of the host semiconductors, the bottom of the InAs conduction band being at a lower energy than the top of the GaSb valence band. When d is increased, the ground valence subband[4] H_1, which is concentrated in the GaSb layers, is raised while the ground conduction subband E_1, which is largely located in the InAs layers, is lowered. For $d > d_c$, H_1 is at a higher energy than E_1, leading to a semimetallic situation. It follows that the SL energy gap, namely $E_1 - H_1$, is negative. In this case electrons transfer from GaSb to InAs, and the Fermi level E_F lies between E_1 and H_1. Experimentally, this semiconductor-semimetal transition was manifested in the enhancement of carriers from recent Hall measurements[5] as a function of the InAs layer thickness. These investigations gave $d_c \sim 100$ Å, in satisfying agreement with theory.

We report in this Letter the first far-infrared magneto-absorption experiments in semimetallic InAs-GaSb superlattices. For each infrared wavelength used, we observe a series of oscillations in the transmission signal as a function of the magnetic field B. Our data are interpreted in terms of cyclotron resonance of electrons associated with Landau levels of the E_1 subband, and of interband transitions from Landau levels of the H_1 subband up to those of the E_1 subband. The results provide the first experimental determination of the subband energies in semimetallic superlattices; the semimetallic nature being directly demonstrated by the observation of a negative energy gap. The electron cyclotron mass, in addition, is found to be substantially enhanced with respect to the band-edge mass in bulk InAs, indicating the strong nonparabolicity of the conduction band.

The samples used in the present experiments were grown[6] by molecular-beam epitaxy on (100) GaSb substrates with the total thickness of the SL region being typically ~2 μm. The thickness of the InAs and GaSb layers are 120 and 80 Å, respectively, for sample $S1$, and 200 and 100 Å for sample $S2$. The scattering time, as obtained from the electron mobility, is $\sim 10^{-12}$ sec, giving a broadening of $\hbar/\tau \sim 0.6$ meV. The far-infrared magneto-absorption experiments were performed at 1.6 K with radiation near normal incidence to the SL layers,[1] using, as infrared sources, H_2O ($\lambda = 118$ μm), HCN ($\lambda = 337$ μm), and DCN ($\lambda = 198$ μm) molecular lasers, and also carcinotrons ($\lambda = 1$ and 2 mm). The transmission signal, obtained at fixed photon energies, was detected by a carbon bolometer. The magnetic field provided by a superconducting magnet could be varied continuously from 0 to 5.75 T. The oscillatory transmission characteristics were observed when B was perpendicular to the SL layers (Faraday configuration). With B parallel to the layers (Voigt configuration), no oscillations were detected, as expected in such a quasi-two-dimensional electron system.

Figure 1 shows typical oscillatory transmission signals versus B obtained in sample $S1$. Figures 2 and 3 give, as a function of the magnetic field, the infrared energy positions of the transmission

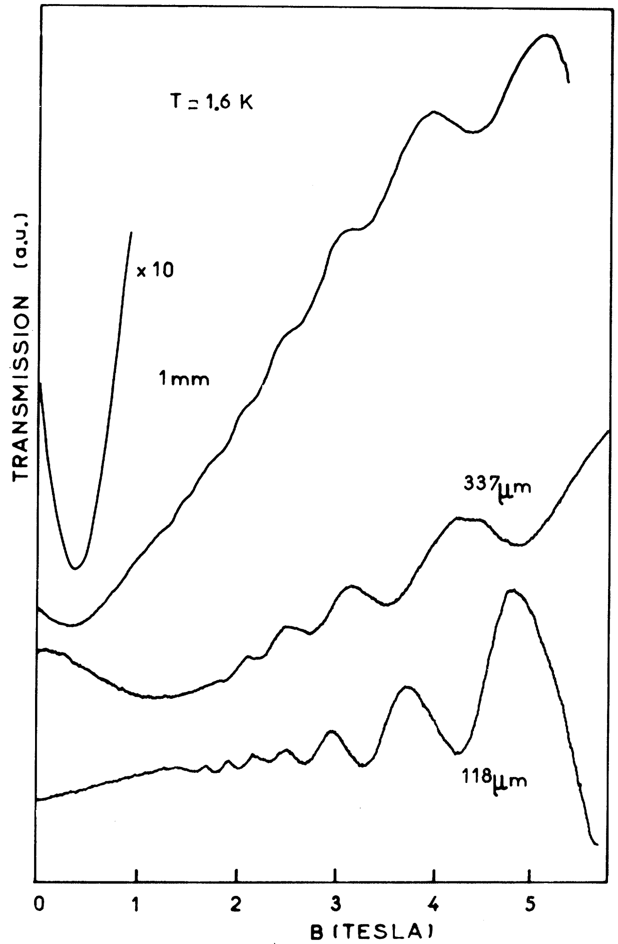

FIG. 1. Transmission signals vs magnetic field B obtained in sample $S1$ for different infrared wavelengths for B perpendicular to the superlattice layers.

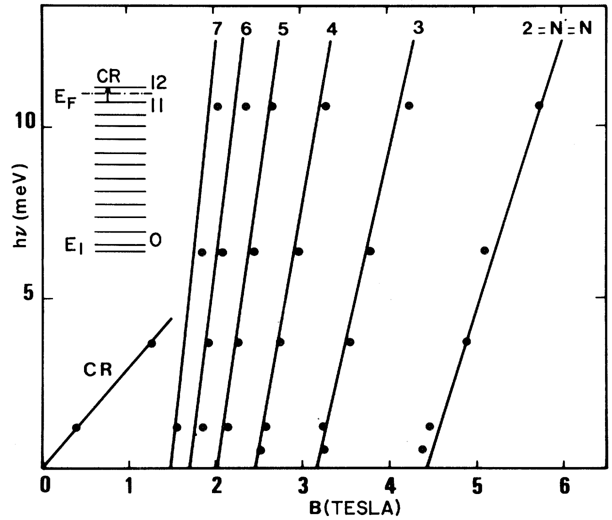

FIG. 2. Position of the minima observed in the transmission signals (see Fig. 1) as a function of the infrared energy $h\nu$ and magnetic field (full dots). The solid lines correspond to theoretical fits as described in the text. The inset shows schematically the E_1 Landau levels at $B = 1$ T to illustrate the transition of cyclotron resonance with level indices $N = 11$ to $N = 12$.

minima from such oscillations. Similar results were also obtained in sample $S2$. From these data, it is apparent that the energies at which absorption maxima occur depend approximately linearly on B, but two kinds of behavior are obtained. As will be seen below from quantitative analyses, one of the lines extrapolates to $h\nu = 0$ at zero magnetic field, while all the others converge to -38 meV. The first one, which is noted CR in Fig. 2, is attributed to electron cyclotron resonance, namely to transitions from the last occupied to the first empty Landau level of the E_1 subband. The other curves are interpreted as being due to interband transitions from H_1 to E_1 Landau levels. That the observed oscillatory characteristics in this energy range are associated with the subband structure is ascertained from their absence in both bulk and semiconducting superlattice samples of thin layers,[7] which have been grown similarly.

To proceed further, we calculate[8] the Landau levels of E_1 and H_1, as done previously in a semiconducting InAs-GaSb SL.[7] The effect of nonparabolicity of the InAs conduction band is taken into account by use of the simplified version of the Kane approximation,[9] which had been found to be quite adequate for the energy range under consideration. If N is the SL Landau level index and $\omega_c = eB/m_e^*$, the electron cyclotron frequency in bulk InAs, where m_e^* is its band edge mass, one obtains readily

$$(N+\tfrac{1}{2})\hbar\omega_c = E_{1,N}(1+E_{1,N}/E_g) - E_1(1+E_1/E_g), \qquad (1)$$

where E_g is the band gap of bulk InAs. All the energies used in this work are referred to the bulk InAs conduction band edge. Equation (1) yields the Landau levels of E_1:

$$E_{1,N} = -\tfrac{1}{2}E_g + [(\tfrac{1}{2}E_g)^2 + E_g D_N]^{1/2}, \qquad (2)$$

with $D_N = (N+\frac{1}{2})\hbar\omega_c + E_1(1+E_1/E_g)$. For the heavy-hole Landau levels $H_{1,N}$, we use the simple quantization relation for a parabolic band:

$$H_{1,N} = H_1 - (N+\tfrac{1}{2})\hbar\omega_v, \qquad (3)$$

where $\omega_v = eB/m_h^*$ is the heavy-hole cyclotron

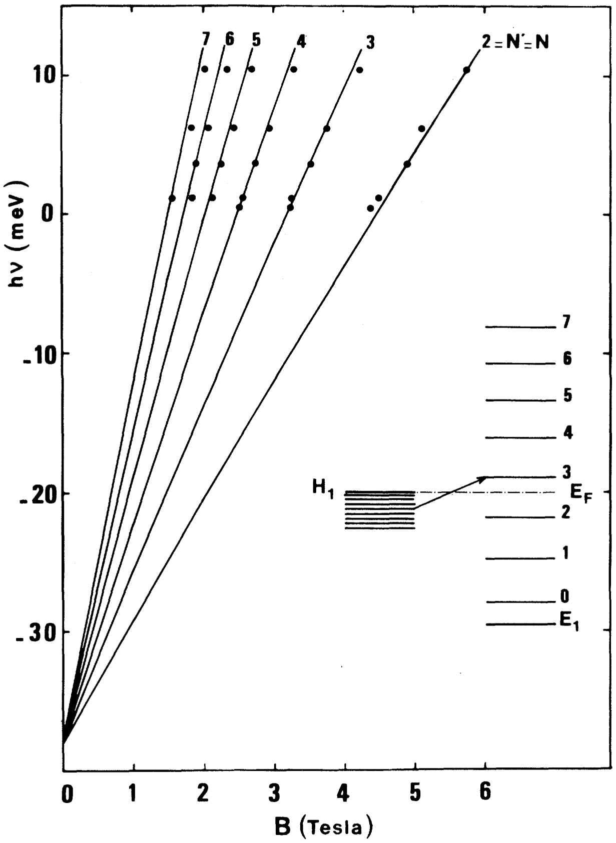

FIG. 3. Magneto-absorption results of Fig. 2 plotted on an enlarged energy scale to indicate the extrapolated negative energy gap of the semimetallic superlattice (full dots: experimental data; solid lines: theory). The inset shows schematically the Landau levels of E_1 and H_1 at $B=4$ T to illustrate interband transitions.

frequency. In the insets of Figs. 2 and 3 are shown, respectively, the calculated electron Landau levels for $E_1 = 115$ meV at $B = 1$ T, and both the electron and hole Landau levels for $E_1 = 115$ meV and $H_1 = 153$ meV at $B = 4$ T; the material parameters[10] used are $m_e^* = 0.023m_0$, $E_g = 410$ meV, and $m_h^* = 0.33m_0$.

Electron cyclotron resonance, for example, that shown in the inset of Fig. 2, corresponds to transitions of $h\nu = E_{1,N+1} - E_{1,N}$ with $E_{N+1} > E_F > E_N$, which can be calculated from Eq. (2) as a function of B. For interband transitions between H_1 and E_1 Landau levels, such as that illustrated in the inset of Fig. 3, the absorbed photon energy is $h\nu = E_{1,N} - H_{1,N}$, and can be similarly calculated from Eqs. (2) and (3). The problem of the selection rules for magneto-optic transitions in such SL structures is rather difficult. However, because of the large heavy-hole mass[10] ($0.33m_0$), taking a selection rule $\Delta N = N - N' = 0$, $+1$, or -1 would lead only to insignificant changes in our numerical results. Also, we have no experimental evidence of any spin effects, which are expected to be small for electrons with energies high above the InAs conduction band edge,[11] as in present investigations. Thus, for the sake of simplicity, we assume in our calculations that these transitions correspond to $\Delta N = 0$, so that we have $h\nu = E_{1,N} - H_{1,N}$. Besides, because of the high density of states of the heavy-hole subband, E_F is close to H_1, and we take thus $E_F = H_1$. Fits of our experimental data to this theoretical model are shown in Figs. 2 and 3 for sample $S1$. The cyclotron resonance (CR) curve starts from the origin, and all the others converge to $E_1 - H_1 = -38$ meV at $B = 0$. The agreement between experiment and theory is rather satisfying, and we obtain for sample $S1$, $E_1 - H_1 = -38 \pm 2$ meV with $E_1 = 115 \pm 15$ meV and $H_1 = 153 \pm 15$ meV. Similar investigations performed in sample $S2$ yield $E_1 - H_1 = -61 \pm 4$ meV with $E_1 = 60 \pm 20$ meV and $H_1 = 121 \pm 20$ meV. From the transmission minima we can also deduce from the CR results the SL electron cyclotron mass m^* defined by $E_{1,N+1} - E_{1,N} = e\hbar B/m^*$. It follows from Eq. (1) that $m^* \cong m_e^*(1 + 2E_F/E_g)$ for $E_{1,N+1} \cong E_{1,N} \cong E_F$. We obtain $m^* = 0.040m_0$ in sample $S1$ and $0.036m_0$ in sample $S2$, with an uncertainty of $\pm 0.002m_0$ in both cases. Thus, it is clear that m is larger than the electron band-edge mass[10] in bulk InAs in accordance with the effect of conduction band nonparabolicity as in other superlattices[7,12]. This observation, indeed, can be taken as an indication that electrons remain concentrated in the InAs layers even when the superlattices become semimetallic.

The subband energies determined experimentally in this fashion can be compared with those calculated theoretically[1,5] by the linear combination of atomic orbitals (LCAO) method. In the semimetallic regime, the effect of electron transfer as mentioned earlier has to be taken into consideration consistently; such transfer, which arises from the fact that H_1 lies in energy above E_1, causes band bending and, in turn, affects the subband energies themselves. Exact solutions have not been carried out, which would require extensive formulation and construction of envelop wave functions to account for the spatial distribution of carriers. Instead, we treat the situation in the framework of the Thomas-Fermi approximation. The band bending and thus the overall superlattice potential are first computed from this approximation for an assumed density of electron transfer. Subsequently, the subband energies are calculated from the LCAO method and the Fermi level determined from the quasi-two-dimensional density of states, subject to the constraint of equal numbers of electrons and holes. A proper solution is reached through iteration when the resulting density of electrons coincides with that assumed initially. These calculations give $E_1 - H_1 = -42$ meV with $E_1 = 87.5$ meV and $H_1 = 129.5$ meV for sample $S1$. For sample $S2$, similar calculations yield $E_1 - H_1 = -68$ meV with $E_1 = 64.5$ meV and $H_1 = 132.5$ meV. Thus, it can be concluded that experimental and theoretical results compare favorably, in particular if we take into consideration the crude nature of the calculations, as well as the uncertainties in the experimental values. We wish also to point out that these calculations give $H_1 - E_F = 2.15$ meV for sample $S1$ and 3.9 meV for sample $S2$. This justifies taking $H_1 = E_F$ in our interpretation of the data, since the fits are not sensitive to the exact value of E_F, as long as it is close to and below H_1.

To summarize, we have described here far-infrared magneto-absorption experiments in semimetallic InAs-GaSb superlattices, from which the energy gaps are shown to be negative. Quantitative interpretation of the experimental data have allowed us to obtain the ground subband energies of both electrons and heavy holes, and to determine the cyclotron effective mass of electrons at the Fermi energy. The effect of conduction band nonparabolicity has been included throughout our consideration to account for the behavior of electrons, indicating their spatial confinement in InAs in semimetallic superlattices.

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