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## OBSERVATION OF DOUBLE CYCLOTRON RESONANCE AND INTERBAND TRANSITIONS IN InAs–GaSb MULTI-HETEROJUNCTIONS

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Magneto-absorption experiments are performed in an InAs–GaSb multi-heterojunction where both electrons and holes are simultaneously confined at the interfaces. Oscillatory characteristics are observed and interpreted in terms of interband transitions from the single hole subband to the two lowest electron subbands, and of cyclotron resonances associated with these subbands. Two electron masses are obtained, arising directly as a consequence of the heterojunction potential.

THERE IS NOW great interest in two-dimensional electron or hole gases at semiconductor heterojunction interfaces, primarily in modulation-doped GaAs–GaAlAs structures [1] where high carrier mobilities can be obtained. Another interesting system is the InAs–GaSb heterojunction [2], which in fact is quite unique in that two-dimensional gases of both electrons and holes are spontaneously created in the InAs and GaSb sides of the interface, respectively.

In such a system, the top of the valence band of GaSb is 150 meV above the bottom of the conduction band of InAs. Electrons transfer from GaSb to InAs, the number of transferred electrons being of course equal to the number of holes left behind. This process causes band bendings and, consequently, the formation of potential wells and quantum subbands therein. The resulting energy diagram is illustrated in Fig. 1(a) from calculations to be described below, where  $E_1$  is the ground subband of electrons,  $H_1$ , that of holes, and  $E_F$  is the Fermi level. Several electron subbands ( $E_1, E_2, E_3$ ) are actually involved, as can be seen in Fig. 1(a). Thus, without any impurity doping and external electric fields, there is an electron accumulation layer in InAs and a hole accumulation layer in GaSb, so that two-dimensional gases of both carriers are formed and coexist at the interface. The situation is thus quite different from the

GaAs–GaAlAs heterojunction, where only one two-dimensional gas is present.

We report here the first far-infrared (FIR) transmission experiments under magnetic field ( $B$ ) in the InAs–GaSb multi-heterojunction structure. For each photon energy, the transmission signal vs  $B$  exhibits oscillations, interpreted as being due to (i) interband transitions from Landau levels of the hole subband  $H_1$  up to those of the electron subbands  $E_1$  and  $E_2$ , referred to as  $IS_1$  and  $IS_2$ ; (ii) double cyclotron transitions of electrons associated with the two subbands, noted as  $CR_{e1}$  and  $CR_{e2}$ ; and (iii) cyclotron resonance associated with the hole subband, noted as  $CR_h$ . These transitions are indicated in Fig. 1(b), the energy diagram under magnetic field, and are identified in Figs. 2 and 3 where the absorption spectra are shown and analyzed. Unlike transport measurements where electrons and, in fact, only those associated with the ground subband, dominate the observed properties, our results involve both electrons and holes, and demonstrate directly their coexistence. The effect of conduction band nonparabolicity is reflected unambiguously through the observation of the double cyclotron transitions, the first such observation in a heterojunction structure.

The sample used here was grown by molecular beam epitaxy on (100) GaSb substrate. The total thickness of the overgrowth is 2  $\mu\text{m}$ , consisting of undoped, periodic layers of InAs and GaSb, each being 1000 Å thick. In this case, as can be seen in Fig. 1, each interface is largely independent of the others and the structure in essence

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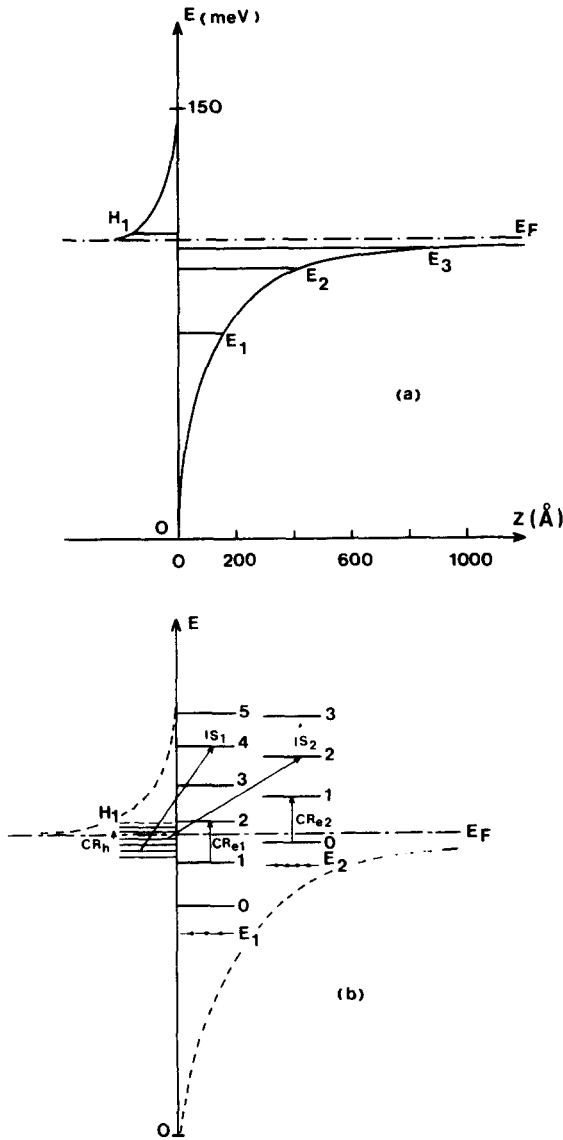


Fig. 1. (a) Potential and subband energies calculated as described in the text for an InAs-GaSb heterojunction. The interface is at  $z = 0$ , InAs and GaSb being respectively on the right- and left-hand side of the interface. (b) Landau levels of  $E_1, E_2$  and  $H_1$ . The potential energy wells are given by the dashed lines, and  $E_F$  is the Fermi level. Arrows indicate interband transitions ( $IS_1$  and  $IS_2$ ) and cyclotron resonance of electrons ( $CR_{e1}$  and  $CR_{e2}$ ) and holes ( $CR_h$ ).

becomes a series of heterojunctions. The use of this multiple, instead of the single heterojunction, offers the advantage of suppressing the effect of the bulk and enhancing that of the interface in which we are interested. In our experiments, the transmission of the sample was measured at 5 K at fixed photon energies as a function of  $B$ . The radiation was propagating perpendicular to the interfaces and parallel to  $B$ . It was provided by an optically pumped FIR laser generating

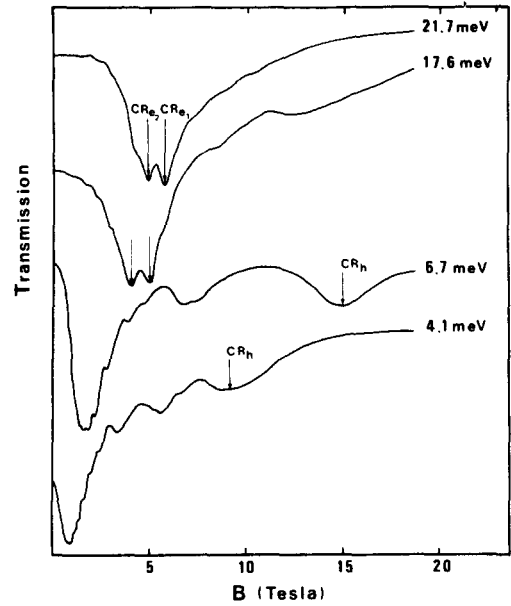


Fig. 2. Typical transmission signals vs  $B$  for different infrared photon energies.

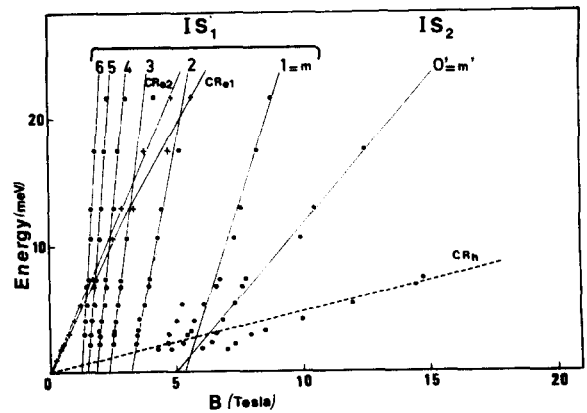


Fig. 3. Position of the transmission minima as a function of  $B$  and infrared photon energies (full dots and crosses). The solid lines are theoretical calculations, and the dashed line corresponds to heavy-hole cyclotron resonance with an effective mass of  $0.26m_0$ .

wavelengths from 70 to 1217  $\mu\text{m}$ . The transmission signals were detected by a Ge bolometer at 1.2 K and the magnetic field was provided by a bitter magnet, continuously variable from 0 to 20 T.

The transmission spectra shown in Fig. 2 exhibit, for each photon energy, a number of minima, corresponding of course to absorption maxima. The energies  $h\nu$  at which these minima occur are plotted vs  $B$  in Fig. 3, and, as will be seen below from theoretical analyses, depend almost linearly on  $B$ . The most pronounced minima are attributed to cyclotron transitions of electrons, which split and become experimentally resolvable

at high fields. The minima noted CR<sub>h</sub>, which are broad and less pronounced in intensity, are believed to be associated with the cyclotron transition of holes. All other features are assigned to interband transitions involving various Landau levels of the electron and hole subbands. Since  $E_1$  and  $E_2$  are spatially separated from  $H_1$  and transitions are made possible only by the overlap of their respective wavefunctions near the interface, such transitions are expected to be weak, appearing as fine structure in the spectra.

To calculate the subband energies and Landau levels, we use the Bohr quantization relation in a potential well given by the Thomas–Fermi approximation [3], a method similar to that introduced by Antcliffe *et al.* [4] for HgCdTe inversion layers. The quantization condition is

$$\int_0^{z_t} k_z dz = \pi(n + \gamma), \quad (1)$$

where  $k_z$  is the momentum along the direction  $z$  perpendicular to the interface,  $n$  is an integer,  $z_t$  is the classical turning point, and [5]  $\gamma = 3/4$ . The conduction band nonparabolicity of bulk InAs is taken into account by using the simplified Kane model [6], so that the dispersion relation is  $E_b(1 + E_b/E_g) = \hbar^2(k_z^2 + k_s^2)/2m_e^*$  where  $k_s$  is the parallel momentum to the interface,  $E_g$  is the band gap of bulk InAs, and  $m_e^*$  is its band edge mass. For the potential profile  $e\Phi(z)$  on the InAs side, corresponding to the bottom of the conduction band, we use the Thomas–Fermi approximation [3, 7],  $e\Phi(z) = e\Phi(\infty)[1 - (1 + z/z_0)^{-4}]$ , with  $e\Phi(\infty) = E_F$ , all the energies being measured in this work from the InAs band edge at  $z = 0$ . The parameter  $z_0$  is given by [3]

$$\Phi(\infty)z_0^4 = 400(3\hbar^3\epsilon/8\pi e)^2/(m_e^*e)^3, \quad (2)$$

where  $\epsilon$  is the InAs dielectric constant, and  $e$ , the electronic charge. The energy of an electron in the potential well is  $E = E_b + e\Phi(z)$ , and substituting these equations into equation (1) gives the quantization condition,

$$\int_0^{z_t} \left[ \frac{2m_e^*}{\hbar^2} [E - e\Phi(z)] \left( 1 + \frac{E - e\Phi(z)}{E_g} \right) - k_s^2 \right]^{1/2} \times dz = \pi(n + \gamma). \quad (3)$$

Strictly speaking, equation (3) is only an approximation. A more rigorous method has been developed [8] for surface space charge layers in narrow-gap semiconductors, yielding an expression similar to equation (3) with additional terms in the integrand. These terms, however, are negligible in the situation considered here where  $e\Phi(z)$  remains small with respect to  $E_g$ . For heavy holes

in the GaSb potential well, using again the Thomas–Fermi approximation, a relation similar to equation (3) can be readily obtained. The simple parabolic relation for the bulk valence band of GaSb is used,  $E_b = \hbar^2(k_z^2 + k_s^2)/2m_h^*$ , where  $m_h^*$  is the heavy-hole mass at the band edge. To obtain the energies of the electron and hole subbands, we calculate for electrons and holes in the InAs and GaSb sides, respectively, the corresponding integrals as a function of  $E$ , assuming an initial value for  $E_F$ . The electron (or hole) subband energies  $E_n$  (or  $H_n$ ) are given by the values of  $E$  for which the integral is equal to  $\pi(n + 3/4)$ . Through iteration, a self-consistent solution is reached when densities of electrons and holes, calculated from their respective two-dimensional density of states, become equal. Setting  $k_s = 0$  and using [9]  $m_e^* = 0.023 m_0$ ,  $m_h^* = 0.33 m_0$ ,  $E_g(\text{InAs}) = 410$  meV,  $E_g(\text{GaSb}) = 810$  meV,  $\epsilon(\text{InAs}) = 14.5$ , and  $\epsilon(\text{GaSb}) = 15.7$ , these calculations yield three electron subbands,  $E_1 = 72$  meV,  $E_2 = 95$  meV,  $E_3 = 102.5$  meV, a single hole subband,  $H_1 = 107.5$  meV, and the Fermi energy  $E_F = 104$  meV. These energies together with the resulting potential profiles have been used in the construction of Fig. 1(a). These results are in close agreement with those obtained earlier from the Schrödinger equation in conjunction with the Thomas–Fermi approximation [2], but the present method is advantageous for its convenience in obtaining the Landau-level energies which are required to account for the observed double cyclotron masses. Using  $m$  as the Landau level index,  $E_{n,m}$  and  $H_{n,m}$  can be attained by following the same procedure with the exception of replacing  $\hbar^2 k_s^2/2m_e^*$  and  $\hbar^2 k_s^2/2m_h^*$  in equation (3) by  $(m + \frac{1}{2})\hbar\omega_e$  and  $(m + \frac{1}{2})\hbar\omega_h$ , respectively, where  $\omega_e = eB/m_e^*$  and  $\omega_h = eB/m_h^*$  are the cyclotron frequencies.

Having established the subband energies, the interband transitions can be readily calculated. Assuming the selection rule [10],  $\Delta m = 0$ , the transition energies for the two electron subbands are given by  $h\nu = E_{1,m} - H_{1,m}(\text{IS}_1)$  and  $h\nu = E_{2,m'} - H_{1,m'}(\text{IS}_2)$ . The results are shown in solid lines in Fig. 3 [11]. For the IS<sub>1</sub> series, transitions from  $m = 1$  up to  $m = 6$  are obtained; they all converge to  $E_1 - H_1 = -35.5$  meV at  $B = 0$ . In the case of IS<sub>2</sub>, the transition involves the ground Landau levels,  $m' = 0'$ , which intercepts at  $E_2 - H_1 = -12.5$  meV at  $B = 0$ . The overall agreement between the calculations and the data points is quite remarkable. That transitions of  $E_2$  with high Landau indices are not observed can be understood, since they are supposed to fall in the energy and field ranges with dense transitions of  $E_1$ , and, therefore, are masked. The complexity of the data points at  $h\nu \lesssim 5$  meV and  $B \simeq 5$  T is likely to result from a combination of two effects. Electron–phonon interaction, or polaron effect [12], can be important in

this region where the separation between  $m = 0$  and  $m = 1$  Landau levels of  $E_1$  is close to the LO-phonon energy [9]; and this effect has been shown theoretically to be enhanced in two-dimensional systems [13]. The other effect arises as a result of the crossing of Landau levels  $E_{1,1}$  and  $E_{2,0}$ . The cyclotron transitions ( $CR_{e1}$  and  $CR_{e2}$  in Fig. 3) can likewise be calculated from the subband energies. They correspond, respectively, to  $h\nu = E_{1,m+1} - E_{1,m}$  and  $h\nu = E_{2,m+1} - E_{2,m}$  where  $E_{1,m}$  (or  $E_{2,m}$ ) is below and  $E_{1,m+1}$  (or  $E_{2,m+1}$ ) above  $E_F$ . The agreement between the calculated solid lines and the data points is also quite satisfying; the double cyclotron resonance occurring as predicted. From the slopes of the lines, two electron masses of the two subbands can be defined and evaluated:  $m_{e1}^* = 0.029 m_0$  and  $m_{e2}^* = 0.026 m_0$ . The fact that  $m_{e1}^* > m_{e2}^*$ , although contrary to what one would expect intuitively, can be understood by considering the effect of conduction band non-parabolicity of InAs in the light of the heterojunction potential profile in Fig. 1. Since the mass is measured near  $E_F$ , electrons associated with  $E_1$  are effectively at a higher energy from the band edge than those with  $E_2$  and have, consequently, a more enhanced mass. Observations of multi-cyclotron resonance have hitherto been made only in inversion layers of narrow gap semiconductors such as InSb and HgCdTe [14, 15]. The dashed line in Fig. 3 is drawn through a few data points and the origin. It corresponds to the cyclotron resonance of holes with an effective mass of  $m_h^* = 0.26 m_0$ . This value is smaller than the general accepted value of  $0.33 m_0$ , which was used in our theoretical calculations, but agrees well with that reported [16] for (100) GaSb. Had we used this value in the calculations, the fit to the experimental data would not have changed appreciably, as electrons, with a much lighter mass, played the dominant role in such calculations. While the interpretation of hole cyclotron resonance is reasonable from considerations of carrier scattering and lack of other expected transitions in these energy and field ranges, the apparent deviation of the data from the dashed line (Fig. 3) calls for a more definite confirmation. We have recently initiated experiments by tilting the field away from the surface normal, which may shed light on this and other questions relevant to the two-dimensional properties. Preliminary results have shown that all the transitions under consideration follow essentially the expected cosine angular dependence.

In conclusion, we have presented here FIR magneto-absorption experiments in an InAs–GaSb multi-heterojunction, and also a theoretical model which

accounts for the data. Multiple transitions involving both interband and cyclotron resonance are observed, from which the subband energies are determined. The coexistence of two-dimensional electrons and holes is demonstrated, which is the very origin of the uniqueness of the InAs–GaSb system.

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