The following full text is a publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/115611

Please be advised that this information was generated on 2019-12-20 and may be subject to change.
OBSERVATION OF DOUBLE CYCLOTRON RESONANCE AND INTERBAND TRANSITIONS IN InAs–GaSb MULTI-HETEROJUNCTIONS

Y. Guldner, J.P. Vieren, P. Voisin, M. Voos
Groupe de Physique des Solides* de l’Ecole Normale Supérieure, 24, rue Lhomond, 75005 Paris, France

J.C. Maan
Max-Planck Institut für Festkörperforschung, 38042 Grenoble, France

and

L.L. Chang and L. Esaki
IBM T.J. Watson Research Center, P.O. Box 218, Yorktown Heights, NY 10598, U.S.A.

(Received 10 October 1981 by M. Balkanski)

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 \( CR_{1\pi} \) and \( CR_{2\pi} \); 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 \( \mu \)m, consisting of undoped, periodic layers of InAs and GaSb, each being 1000 \( \AA \) thick. In this case, as can be seen in Fig. 1, each interface is largely independent of the others and the structure in essence

---

* Laboratoire associé au CNRS.
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 wavelengths from 70 to 1217 $\mu$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 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 CRh, 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

\[
\int_{z_t}^{z} k_z \, dz = \pi (n + \gamma),
\]

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 \( \gamma = 3/4 \). The conduction band
nonparabolicity of bulk InAs is taken into account by
using the simplified Kane model [6], so that the dispersion
relation is \( E_b(1 + E_b/E_g) = \hbar^2 (k_x^2 + k_y^2)/2m_e^* \)
where \( k_x \) 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],

\[
e\Phi(z) = e\Phi(\infty) [1 - (1 + z/z_0)^{-\gamma}],
\]

yielding an expression similar to equation (3) with
(\( m + 1/2 \)) \( \hbar \omega_e \) and \( (m + 1/2 \)) \( \hbar \omega_h \), 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 \( \hbar \nu = E_1, m - H_1, m(\text{IS}_1) \) and \( \hbar \nu = E_2, m' - H_1, m'(\text{IS}_2) \). The results are shown in solid lines in Fig. 3 [11]. For the IS1 series, transitions from \( m = 1 \) up to \( m = 6 \) are obtained; they all converge to \( E_1 - H_1 = -35.5 \text{ meV} \) at \( B = 0 \). In the case of IS2, the transition involves the ground Landau
levels, \( m' = 0' \), which intercepts at \( E_2 - H_1 = -12.5 \text{ meV} \) 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 \( \hbar \nu \leq 5 \text{ meV} \) and \( B \approx 5 \text{ T} \) is likely to result from a combination of two effects. Electron–phonon interaction, or polaron effect [12], can be important in

\( m_e^* = 0.023 m_0, m_h^* = 0.33 m_0, E_g(\text{InAs}) = 410 \text{ meV}, E_g(\text{GaSb}) = 810 \text{ meV}, \epsilon(\text{InAs}) = 14.5, \) and \( \epsilon(\text{GaSb}) = 15.7 \), these calculations yield three electron subbands,
\( E_1 = 72 \text{ meV}, E_2 = 95 \text{ meV}, E_3 = 102.5 \text{ meV}, \) a single
hole subband, \( H_1 = 107.5 \text{ meV}, \) and the Fermi energy
\( E_F = 104 \text{ meV} \). 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 \( \hbar^2 k_x^2/2m_e^* \)
and \( \hbar^2 k_y^2/2m_h^* \) in equation (3) by \( (m + 1/2) \hbar \omega_e \) and \( (m + 1/2) \hbar \omega_h \), respectively, where \( \omega_e = eB/m_e^* \) and \( \omega_h = eB/m_h^* \) are the cyclotron frequencies.

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, \( E_b = h^2 (k_x^2 + k_y^2)/2m_h^* \), 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 \( k_x = 0 \) and using [9]
\( m_e^* = 0.023 m_0, m_h^* = 0.33 m_0, E_g(\text{InAs}) = 410 \text{ meV}, E_g(\text{GaSb}) = 810 \text{ meV}, \epsilon(\text{InAs}) = 14.5, \) and \( \epsilon(\text{GaSb}) = 15.7 \), these calculations yield three electron subbands,
\( E_1 = 72 \text{ meV}, E_2 = 95 \text{ meV}, E_3 = 102.5 \text{ meV}, \) a single
hole subband, \( H_1 = 107.5 \text{ meV}, \) and the Fermi energy
\( E_F = 104 \text{ meV} \). 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 \( \hbar^2 k_x^2/2m_e^* \)
and \( \hbar^2 k_y^2/2m_h^* \) in equation (3) by \( (m + 1/2) \hbar \omega_e \) and \( (m + 1/2) \hbar \omega_h \), 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 \( \hbar \nu = E_1, m - H_1, m(\text{IS}_1) \) and \( \hbar \nu = E_2, m' - H_1, m'(\text{IS}_2) \). The results are shown in solid lines in Fig. 3 [11]. For the IS1 series, transitions from \( m = 1 \) up to \( m = 6 \) are obtained; they all converge to \( E_1 - H_1 = -35.5 \text{ meV} \) at \( B = 0 \). In the case of IS2, the transition involves the ground Landau
levels, \( m' = 0' \), which intercepts at \( E_2 - H_1 = -12.5 \text{ meV} \) 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 \( \hbar \nu \leq 5 \text{ meV} \) and \( B \approx 5 \text{ T} \) 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 \( hv = E_{1, m+1} - E_{1, m} \) and \( hv = E_{2, m+1} - E_{2, m} \) 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.

Acknowledgement – The IBM group acknowledges partial sponsorship of the work under U.S. Army Research Office contract.

REFERENCES

5. L.D. Landau & E.M. Lifshitz, Quantum Mechanics, Ch. 7. Addison-Wesley, Reading, Massachusetts (1958).
7. The calculations of [3] do not take into account the conduction band nonparabolicity, but we have checked that including this effect leads to minor corrections.
10. Taking \( \Delta m = 0, \pm 1 \) lead in fact to insignificant changes in the numerical results.
11. We have taken into account the charge redistribution occurring when the last Landau levels \((m = 0)\) are swept across \( E_F \).