CYCLOTRON RESONANCE IN AN InAs-GaSb SUPERLATTICE

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Optical transmission in the far infrared region in an InAs-GaSb superlattice is studied as a function of magnetic field and frequency. Cyclotron resonance is observed for electrons confined in the InAs conduction band whose ground state is shifted to higher energy due to the periodic superlattice potential. These measurements confirm the calculated quantisation of the energy levels in a superlattice by ascertaining the effective mass directly.

A superlattice is a structure consisting of ultrathin, periodic layers of two different semiconductors (layer thickness in the order of 100 Å which is about 20 lattice constants per layer). This artificially introduced one-dimensional periodic potential leads to a strong modification of the original band structure of the host materials in the superlattice direction. The original Brillouin zone is divided into subzones with subzone boundaries at wave-vector values corresponding to the superlattice periodicity. The superlattice as a whole can be considered as a completely new, highly anisotropic material whose electronic and optical properties are determined not only by the band parameters of the basis material, but also by the superlattice periodicity, which can be varied at will^{1,2}. Most of the work up to now has been restricted to the relatively simple structures of GaAs-Ga_{1-x}Al_xAs¹⁻³. Recently a new class of superlattices consisting of consecutive layers of InAs and GaSb has been considered⁴. Shubnikov-de Haas measurements⁵ on this type of superlattice show clearly the extreme anisotropy of the superlattice system, and good agreement is found between the measured and the calculated Fermi energy. However, the agreement between the calculated effective mass and the effective mass determined indirectly from the temperature dependence of the Shubnikov-de Haas oscillations was not satisfactory for all samples.

In this paper we report the first observation of cyclotron resonance in a superlattice, and therefore the first direct and accurate determination of the effective mass. The superlattice under investigation was that of InAs and GaSb. This structure is especially interesting because due to the strong energy dependence of the effective mass, its determination provides direct information about the energy levels in the superlattice.

The periodic arrangement of two semiconductors in a superlattice gives rise to a one-

dimensional periodic potential. Therefore the problem of calculating the band structure strongly resembles the well known Kronig-Penney problem for free electrons in a rectangular periodic potential. However, in the case of a superlattice, Bloch wave functions should be used instead of free electron wave functions. Taking into account this fact and matching the wave functions of different materials and their derivatives at the successive boundaries of the superlattice potential taken to be along the z-direction, one gets⁴

$$\cos(kd_0) = \cos(k_1d_1)\cos(k_2d_2) - \frac{1}{2} \left(\frac{ik_1 + \tilde{u}_1/u_1}{ik_2 + \tilde{u}_2/u_2} + \frac{ik_2 + \tilde{u}_2/u_2}{ik_1 + \tilde{u}_1/u_1} \right) \sin(k_1d_1)\sin(k_2d_2) \quad (1)$$

Here, the subscripts 1 and 2 refer to the two different materials, k_1, k_2 are the original k_z wave vectors of the host materials, k is the wave vector of the superlattice, d_0 is the superlattice periodicity, d_1, d_2 are the layer thicknesses of the host materials, and u_1, u_2 are the cell-periodic parts of the Bloch function at an arbitrary boundary. Eq. (1) implies the well known fact that not all original k_z values of the host materials are allowed anymore by the superlattice periodicity. More specifically, the lowest allowed k_z value is non-zero. Knowing the dispersion relation of the basis materials, the energy bands can be calculated once the allowed k_z values are known. Since $k_z = 0$ is not allowed anymore, this leads to a shift in energy of the band edges in a superlattice. For an InAs-GaSb superlattice the lowest conduction subband and the highest valence subband calculated in this way results from matching at the boundaries of the light hole GaSb valence band wave function to the light electron InAs conduction band wave function. Since we are interested in electrons

only we do not consider the heavy hole valence band which does not couple to the other two bands. The heavy hole bands in a superlattice have to be considered separately⁴. The Fermi energy can be obtained by integration of the density of states of each subband, knowing the total electron concentration n_e . This calculated Fermi energy can be verified by means of the Shubnikov-de Haas effect^{5,6}.

Table I summarizes the relevant characteristics of the investigated sample. The carrier concentration and the mobility were derived from Hall measurements. The subband energies and width of the two lowest conduction bands and the Fermi energy were calculated as described above. The material parameters used for this calculation are 0.42 eV and 0.81 eV for the energy gaps, band edge masses m^*/m of electrons of 0.023 and 0.048, and for the light holes of 0.025 and 0.052 for InAs and GaSb respectively, while the bottom of the InAs conduction band is taken to be 0.1 eV below the top of the GaSb valence band⁷. The Fermi energy is calculated as $E_F = 39$ meV above the lowest subband edge, which implies that only this band is occupied. This band originates from the InAs conduction band which is shifted to higher

lattice potential are in the z-direction, Eq. (2) is modified in the following way: The bottom of the band in a superlattice is given by Eq. (2) for $k_x = 0$, $k_y = 0$, and k_z has the lowest value allowed by the superlattice periodicity. The energy corresponding to this level is E_1 , which is just the shift in the InAs conduction band. In a magnetic field, the remaining quantum numbers k_x and k_y are replaced by $(N + \frac{1}{2}) \frac{\hbar e B}{m^* \omega_c}$; here N is the Landau level number.

Combining with Eq. (2) one obtains the energy levels of a superlattice in a magnetic field

$$(N + \frac{1}{2}) \frac{\hbar e B}{m^* \omega_c} = E_N(1 + \frac{E_N}{E_G}) - E_1(1 + \frac{E_1}{E_G}), \quad (3)$$

and an effective mass

$$m^*(E_1, B) = m^*_0(1 + \frac{E_{N+1}(E_1, B) + E_N(E_1, B)}{E_G}) \quad (4)$$

where m^* is again the effective mass at the bottom of the conduction band of the bulk InAs; $E_N(E_1, B)$ can be calculated from Eq. (3). Therefore, a determination of the effective mass provides a direct means to verify the calcula-

Table I

Superlattice sample characteristics.

InAs layer thickness	d_1	65 Å
GaSb layer thickness	d_2	80 Å
number of periods	n	125
carrier concentration (Hall effect)	n_e	$4.8 \cdot 10^{17} \text{ cm}^{-3}$
carrier mobility (Hall effect)	μ	$7300 \text{ cm}^2/\text{VS}$
first subband energy (subband width)(calculated)	$E_1(\Delta E_1)$	186 (10) meV
second subband energy (subband width)(calculated)	$E_2(\Delta E_2)$	465 (6) meV
calculated Fermi energy above first subband	$E_{F\text{calc}}$	39 meV
measured Fermi energy above first subband (Shubnikov-de Haas effect, using $m^* = 0.043 m_0$)	$E_{F\text{meas}}$	40 meV

energies by an amount E_1 . This implies that in a cyclotron resonance experiment the observed mass has to be related to the InAs conduction band mass. All other masses occur at energies relatively far away from the Fermi level. We now focus on this band to calculate the energy levels of the superlattice in a magnetic field. In a two band model, using the k.p method, the approximate expression of the dispersion relation for the InAs conduction band valid over the energy range of the present experiments, is given by⁸

$$\frac{\hbar^2 k_x^2}{2m^*_0} + \frac{\hbar^2 k_y^2}{2m^*_0} + \frac{\hbar^2 k_z^2}{2m^*_0} = E(1 + \frac{E}{E_G}) \quad (2)$$

where E is the energy measured with respect to the InAs conduction band edge, and E_G and m^* are the InAs band gap and the band edge effective mass. In a superlattice and in a magnetic field where both magnetic field and super-

lattice potential are in the z-direction, Eq. (2) is modified in the following way: The bottom of the band in a superlattice is given by Eq. (2) for $k_x = 0$, $k_y = 0$, and k_z has the lowest value allowed by the superlattice periodicity. The energy corresponding to this level is E_1 , which is just the shift in the InAs conduction band. In a magnetic field, the remaining quantum numbers k_x and k_y are replaced by $(N + \frac{1}{2}) \frac{\hbar e B}{m^* \omega_c}$; here N is the Landau level number.

Combining with Eq. (2) one obtains the energy levels of a superlattice in a magnetic field

and an effective mass

where m^* is again the effective mass at the bottom of the conduction band of the bulk InAs; $E_N(E_1, B)$ can be calculated from Eq. (3). Therefore, a determination of the effective mass provides a direct means to verify the calcula-

ted shift E_1 in the InAs conduction band. For this purpose we measured the effective mass by measuring the change in the Far Infrared Radiation (FIR) transmission due to cyclotron resonance as a function of frequency and magnetic field.

The FIR transmission experiments were done at three different wavelengths ($\lambda = 118.8 \mu\text{m}$, $\lambda = 70.6 \mu\text{m}$ and $\lambda = 57 \mu\text{m}$) using an optically pumped FIR laser system. The magnetic fields were generated by one of the Bitter coils of the Nijmegen High Magnetic Fields Installation. The transmitted radiation was detected by a He-cooled Si-bolometer. The transmission signal was normalized by means of a reference signal to eliminate fluctuation of the laser output power.

Fig. 1 shows the observed change in transmission for the three different wavelengths investigated. A clearly resolved though fairly broad resonance is observed. The inset in Fig. 1 shows the peak positions vs FIR energy and mag-

Fig. 1 : Transmission signal for an InAs-GaSb superlattice as a function of magnetic field for different frequencies. The field is parallel to the direction of the super lattice potential. The inset shows the transmission minima as a function of the magnetic field and photon energy. The drawn line represents the fit of an effective mass of $0.043 m_0$ to the data.

netic field. From the slope of the observed linear dependence, an effective mass of $0.043 m_0$ is derived. Using this effective mass a Fermi energy can be derived from the periodicity of the observed Shubnikov-de Haas oscillations. This results in a Fermi energy of 40 meV which agrees very well with the calculated value of 39 meV. For bulk InAs the energy dependence of the effective mass is given by $m^*(E) = m_0^* (1 + \frac{2E}{E_g})$. Using this equation the observed effective mass would occur at an energy of 182 meV whereas for the superlattice sample under investigation the Fermi energy is only 40 meV. The observed effective mass there-

fore directly demonstrates the lifting of the bulk conduction band due to the superlattice periodicity.

In order to identify the relevant cyclotron resonance transitions, we show in Fig. 2 the calculated splitting of the subbands as a function of magnetic field using Eq. (3). Transitions occur between conduction band states below and above the Fermi level, and the observed transitions are indicated in the figure. The effective masses at the three resonant fields can be calculated by using Eq. (4), and can be compared with the observed values (Table II). Considering that the calculation contains no adjustable parameters (only commonly accepted literature values for the bulk material are used) and that spinsplitting and energy dependence of the g-factor⁹ are completely neglected, the agreement between measured and calculated masses is quite satisfactory.

Fig. 2 : Calculated energy levels of an InAs-GaSb superlattice in a magnetic field. The vertical solid lines represent the measured cyclotron resonance transition. For the energy scale, the bulk InAs conduction band edge is taken as the zero level.

Table II

Comparison between measured and calculated effective masses.

Resonance Field B (Tesla)	m^* calculated	m^* measured
3.95	0.0476	0.044 ± 0.001
6.39	0.0468	0.042 ± 0.001
8.16	0.0480	0.044 ± 0.001

It should be noted that both the calculated and observed masses are somewhat lower for 6.39 T than for the other two fields. The reason for this may lie in the relative positions of the Fermi energy with respect to the Landau levels: The transition at this field occurs at a somewhat lower energy than those at the other two fields, as can be seen from Fig. 2.

In conclusion it may be stated that for the first time cyclotron resonance in a superlattice has been observed. The measured effective mass can only be explained by taking into account the shift in the energy band brought

about by the quantisation caused by the superlattice periodicity. This observation therefore is a direct demonstration of the quantisation of the energy bands in a superlattice.

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