Electron Mass Tunneling along the Growth Direction of (Al,Ga)As/GaAs Semiconductor Superlattices

T. Duffield,[a] R. Bhat, M. Koza, F. DeRosa, D. M. Hwang, P. Grabbe, and S. J. Allen, Jr.[a]
Bell Communications Research, Incorporated, Murray Hill, New Jersey 07974
(Received 26 December 1985)

We have measured the effective mass of electrons tunneling through thin barriers in (Al, Ga)As/GaAs superlattices by performing cyclotron-resonance experiments with the magnetic field oriented perpendicular to the growth direction. The effective mass is shown to increase with the barrier height at a rate that is in rough agreement with a model that includes the change in band mass in the barrier.

PACS numbers: 73.40.Gk, 71.25.Jd, 72.20.My

One of the more remarkable achievements in material science has been the growth of semiconductor single crystals atomic layer by atomic layer. By variation of the composition along the growth direction, control can be exercised over doping and band gaps. Although the understanding and development of these materials has been unusually rapid, the early vision[1] that focused on the engineering of bulk, three-dimensional band structures has been largely forsaken in favor of properties that emerge as a result of confinement of the electron states to two dimensions. In the case of superlattices, a one-dimensional square-wave potential is formed in the growth direction. This results in the Brillouin zone's being divided into a number of minizones and extended states' being restricted to a series of narrow minibands.[1]

Experiments that address quantum transport along the superlattice growth direction are relatively scarce. The original work of Dingle, Gossard, and Wiegmann[2] revealed splittings in excitonic features that were caused by tunneling between quantum wells, but in the limit of a large number of coupled wells the optical-absorption spectra became featureless. More recently Sakaki and co-workers[3,4] have reported measurements of the Fermi-surface geometry in superlattice systems. Sollner *et al.*[5] have observed strong resonant tunneling features in double barriers separated by a thin quantum well. Most relevant to the following discussion is the recent theoretical[6] and experimental[7] work of Maan and co-workers that examines the effect of a magnetic field, perpendicular to the growth direction, on the minibands in the superlattice. In this configuration, interband magnetoluminescence[7] shows a well defined set of Landau levels that disappear when the cyclotron energy exceeds the miniband width.

Here we report the first cyclotron-resonance measurements on extended states in a semiconductor superlattice. As in the interband magnetoluminescence experiment reported by Belle, Maan, and Weimann,[7] the magnetic field is oriented perpendicular to the growth direction and the electrons are forced to execute cyclotron motion by tunneling through the periodic barriers (Fig. 1). The resonance frequency is related to the transport mass along the growth direction. We have measured this mass as a function of barrier height and compare the results with a theory of miniband structure.

The $Al_xGa_{1-x}As/GaAs$ samples used in this study were grown in an organometallic chemical vapor deposition reactor.[8] In every case 6 μm of superlattice was grown directly on a GaAs substrate, oriented 6° off the (100) towards the (111) *A* direction. The period of the superlattice was 10 nm and the thickness of the $Al_xGa_{1-x}As$ barrier was nominally 2 nm. Transmission electron micrographs revealed perfect crystallization and uniform layered structure. However, the barriers were not perfectly sharp and had sloping walls tending to produce a triangular-shaped barrier with a full width at half maximum of ~ 2 nm. The fractional aluminum content, x, in the barrier was varied between nominal values of 0.10 and 0.30 at intervals

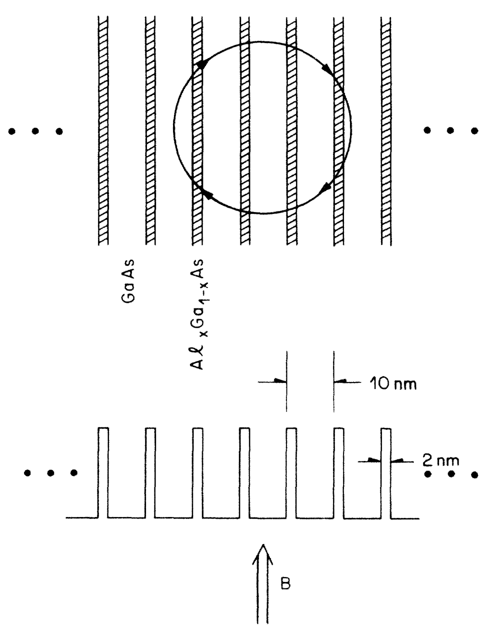

FIG. 1. Schematic diagram of the orientation of the superlattice, magnetic field, and the interesting cyclotron orbit.

of 0.05 to produce a set of five samples. The actual Al content was measured by x-ray fluorescence with a wavelength-dispersive spectrometer attached to a scanning electron microscope.

The carrier concentration was obtained without intentional doping and was n type of the order of $\sim 2\times 10^{15}$ cm^{-3}. Two considerations led to the choice of low donor concentration. Cyclotron resonance with the magnetic field in the plane of the sample does not occur at $\omega_c = eB/m_c$, where e is the electron charge, B the magnetic field, and m_c the cyclotron mass. Rather, it occurs at the combined cyclotron and plasma resonance given by $\omega_0^2 = \omega_c^2 + \omega_p^2$. Here ω_0 is the observed frequency and ω_p is the plasma frequency, which we can estimate from the simple 3D result, $\omega_p^2 = ne^2/\epsilon m$. Here n is the volume density of carriers, ϵ the dielectric constant, and m the electron mass of GaAs. The exact collective plasma modes of superlattices are known to exhibit a rich and varied behavior.[9] But we expect that this 3D result will be a valid measure of the importance of these corrections. If n is kept in the 10^{15} range they can be kept much smaller than the cyclotron frequency and m_c can be accurately measured. Low doping levels also reduce impurity scattering. At liquid-nitrogen temperatures the transport mobility was of the order of 40 000 cm^2/V$\cdot$sec in our samples (cf. 2 000 cm^2/V$\cdot$sec for the superlattices used in the Fermi-surface studies of Sakaki and co-workers[3,4]). The low doping levels require us to perform the resonance experiments at elevated temperature (~ 75 K) to avoid carrier freezeout.

Cyclotron-resonance experiments were performed in magnetic fields to 8 T. The resonance was detected by swept-frequency spectroscopy with a Fourier-transform spectrometer. Resonances were recorded with the magnetic field in the plane of the sample (see Fig. 1), and perpendicular to it. Typical data are shown in Fig. 2. The resonance frequency, ω_0, was squared and plotted versus B^2. In this way the plasma resonance that alters the result when the field is in the plane of the sample appears as a nonzero intercept (in close agreement with the estimates made above), but does not affect the slope of the line which we take as a measure of the cyclotron mass, m_c. The mass determined from these measurements is plotted in Fig. 3 as a function of measured Al concentration, scaled to indicate the Al concentration in the barrier.

The cyclotron mass, m_c, measured with the magnetic field perpendicular to the growth direction is the geometric mean of the transport mass along two orthogonal directions. To extract and display a measure of the transport mass along the growth direction we evaluate $m = m_c^2/m_0$, where m_0 is the mass measured with the field parallel to the growth direction. This mass shows a strong increase with Al content or barrier height. It is apparent, however, that there is

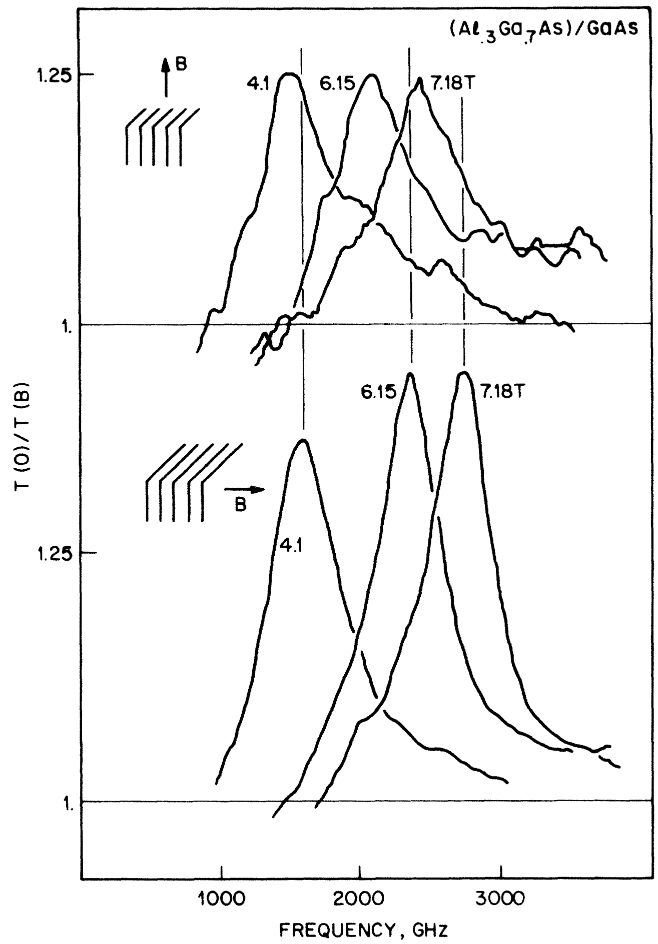

FIG. 2. Transmission ratio vs frequency. Cyclotron resonance in a superlattice at a temperature of 70–80 K, with the magnetic field oriented in two different directions with respect to the growth direction. The labels refer to the applied magnetic field.

scatter in the data that lies outside the uncertainties in determination of the mass and Al content in the barrier. This indicates that there are material parameters beyond our control that influence transport through the barriers. On the other hand, it does demonstrate that these measurements are sensitive and specific to transport through the barrier.

In the largest magnetic field used in these experiments the electrons still execute a cyclotron motion with a diameter that exceeds the superlattice period. (At 8 T the quantum-limit zero-point motion is of the order of 18 nm.) As a result we choose not to consider the interesting complications described by Maan[6] as the cyclotron orbit shrinks inside the period of the superlattice. There may be subtle changes in the cyclotron resonance as the number of superlattice periods embraced by the cyclotron orbit is changed but they are not apparent in the existing data.

There are a number of theoretical discussions that

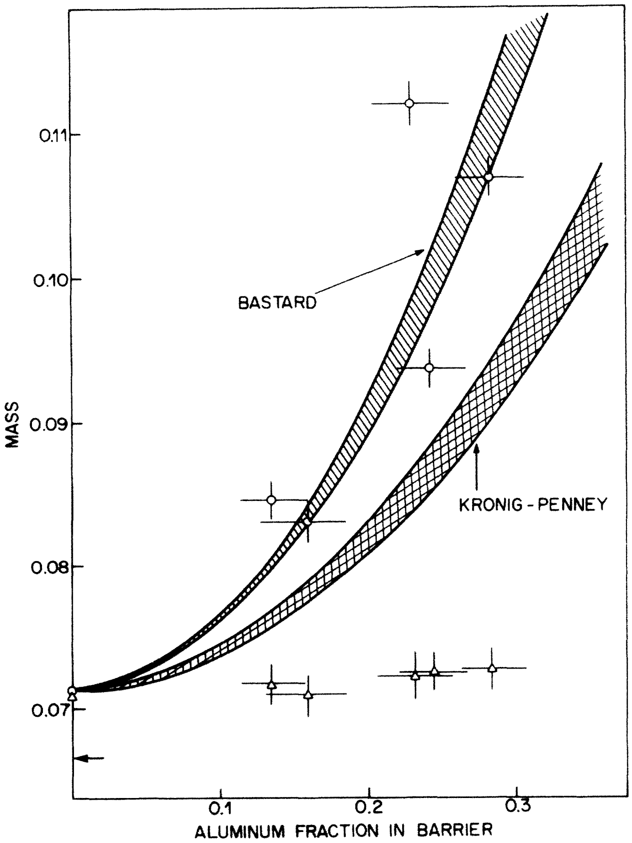

FIG. 3. Electron transport mass in units of the free-electron mass in $Al_xGa_{1-x}As/GaAs$ superlattices: circles, along the growth direction; triangles, perpendicular to the growth direction. Error bars reflect the uncertainty in the measured Al fraction and resonance of calculations (see text) of the transport mass along the growth direction. The arrow indicates the effective mass of bulk GaAs at the conduction-band edge.

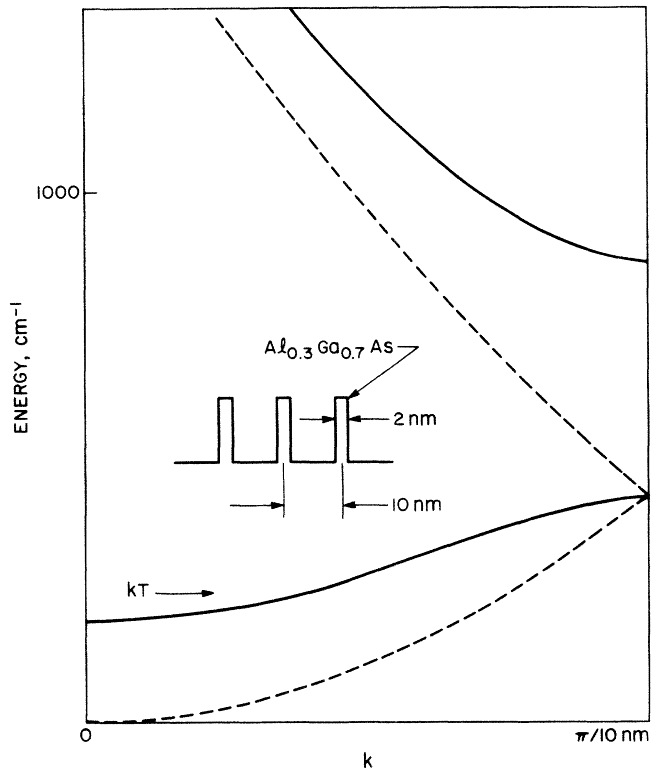

FIG. 4. Miniband structure, reduced to the first minizone, calculated along the growth direction with an Al content in the barriers of $x=0.3$ and for the boundary conditions at the barrier prescribed by Bastard. The dashed line shows the free-electron dispersion which should be a good description of the electron mass perpendicular to the growth direction.

address miniband structure.[1,10-15] It is not the purpose of this paper to assess critically these theories. Rather, we wish to show the efficacy of this experimental approach and reserve for subsequent publication a more detailed discussion and careful comparison with sophisticated theory. Here we take a simple Kronig-Penney potential to model the superlattice and calculate a cyclotron mass, m_c, at an energy k_BT. In a superlattice, in addition to conduction- and valence-band discontinuities, there is also an effective-mass discontinuity at the interfaces between the quantum wells and the barriers. Bastard[15] has shown that this changes the continuity condition for stationary states with probability current, F, to $(1/m)dF/dz$ rather than dF/dz as in the original Kronig-Penney model. We have calculated the miniband structure for our samples using both the Kronig-Penney and Bastard solutions for the potential. We assume that the electron mass in the $Al_xGa_{1-x}As$ barriers, required for the Bastard solution, is m_0 multiplied by the ratio of the direct gap in the barrier to that in GaAs, where m_0 is the mass measured with the field parallel to the growth direction. We also assume that the barrier height is related to the Al concentration by $\Delta E_c=(0.63\pm0.02)\Delta E_g$,[16] where ΔE_c is the conduction-band offset and ΔE_g is the difference in the energy gap between the barrier and GaAs. Figure 4 shows the minibands for an Al content $x=0.3$.

The range of magnetic fields used in these experiments spans the classical and quantum limits. At the highest fields the cyclotron energy exceeds k_BT. Experimentally, however, the mass exhibits no field dependence and we choose to compare experiment with a "classical" calculation that is performed as follows. The cyclotron mass, m_c, at an energy E in the miniband is[17]

$$m_c=(\hbar^2/2\pi)\,dS/dE, \qquad (1)$$

where $\hbar$ is Planck's constant and the derivative on the right-hand side is the rate of change of the orbit area in k space with electron energy. We assume a parabolic band in the direction parallel to the barriers with electron mass m_0. After some manipulation Eq. (1)

may be rewritten as

$$m_c = \frac{\hbar}{\pi}(2m_0)^{1/2}\int_0^{k_m}\frac{dk}{[k_B T - E(k)]^{1/2}}, \qquad (2)$$

where k_m is the wave vector along the growth direction at energy $k_B T$ above the band bottom and $E(k)$ is the dispersion of the miniband along the growth direction (see Fig. 4). The Kronig-Penny and Bastard solutions of the model potential are used to calculate $E(k)$.

We reiterate that two approximations have been made in the above calculation. We have assumed that the low-field result is valid although the data extend to magnetic fields that reach that quantum limit, and that this classical result can be obtained by the consideration of a single orbit at an energy $k_B T$.

With the magnetic field oriented along the growth direction we expect that the resonance will occur close to the GaAs mass. This is expected even for those orbits that spiral along the magnetic field and tunnel through the successive barriers. Under these conditions we expect the mass to be some weighted average of the GaAs well mass and the conduction-band mass in the barrier. The contribution from the barrier is weighted and we expect no larger mass shifts than are seen in confined quantum well structures. Indeed, the results shown in Fig. 3 are relatively insensitive to the Al content in the barriers and do not differ significantly from the bulk mass.

The results of the calculations for the mass along the growth direction are shown as the shaded areas in Fig. 3. For a given Al concentration, the limits represent the uncertainty in ΔE_c with the upper limit given by $\Delta E_c = 0.65\Delta E_g$. Despite the scatter in the data the calculation that includes the change in the band structure as parametrized by Bastard is significantly better than the simple Kronig-Penney model. The agreement between the data and the former calculation is striking considering that we have used a simple classical interpretation of the physics of the experiment and that there are a number of important complications lying below the surface of the simple model of cyclotron resonance under these conditions.

In summary, we have demonstrated that electron cyclotron resonance performed with the magnetic field oriented perpendicular to the growth direction is a sensitive and specific probe of electron transport through barriers in a semiconductor superlattice. In a future publication we look forward to critically testing our understanding of the miniband structure in semiconductor superlattices. In addition to understanding these fundamental issues, it is apparent that one can examine high-field magnetotransport in a regime where the magnetic length scales are comparable to the periodicity. Magnetic breakdown and the collapse of the miniband picture as demonstrated by Maan and co-workers[7] should ensue.

We wish to thank Larry Rubin and Bruce Brandt for their support of the experiments carried out at the Francis Bitter National Magnet Laboratory.

[a]Visiting guest scientist at the Francis Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Mass. 02139.

[1]L. Esaki and R. Tsu, IBM J. Res. Dev. **14**, 61 (1971).

[2]R. Dingle, A. C. Gossard, and W. Wiegmann, Phys. Rev. Lett. **34**, 1327 (1975).

[3]J. Yoshino, H. Sakaki, and T. Furata, in *Proceedings of the Seventeenth International Conference on the Physics of Semiconductors*, edited by D. J. Chadi and W. A. Harrison (Springer-Verlag, New York, 1985), p. 519.

[4]L. L. Chang, H. Sakaki, C. A. Chang, and L. Esaki, Phys. Rev. Lett. **38**, 1489 (1977).

[5]T. C. L. G. Sollner, W. D. Goodhue, P. E. Tannenwald, C. D. Parker, and D. D. Peck, Appl. Phys. Lett. **43**, 588 (1983).

[6]J. C. Maan, in *Two-Dimensional Systems, Heterostructures, and Superlattices*, edited by G. Bauer, F. Kuchar, and H. Heinrich, Springer Series in Solid State Sciences Vol. 53 (Springer, New York, 1984), p. 183.

[7]G. Belle, J. C. Mann, and G. Weimann, in Proceedings of the Sixth International Conference on the Electronic Properties of Two-Dimensional Systems, Kyoto, Japan, Surf. Sci. (to be published), and Solid State Commun. **56**, 65 (1985).

[8]H. M. Manasevit, Appl. Phys. Lett. **12**, 156 (1968).

[9]A. C. Tselis and J. J. Quinn, Phys. Rev. B **29**, 3318 (1984), and references contained therein.

[10]R. Dingle, in *Festkörperprobleme*, edited by H.-J. Queisser (Pergamon, New York, 1975), Vol. 15, p. 21.

[11]G. A. Sai-Halasz, in *Physics of Semiconductors—1978*, edited by B. L. H. Wilson, IOP Conference Proceedings No. 43 (Institute of Physics, Bristol and London, 1979).

[12]G. A. Sai-Halasz, L. Esaki, and W. A. Harrison, Phys. Rev. B **18**, 2812 (1978).

[13]D. Mukherji and B. R. Nag, Phys. Rev. B **12**, 4338 (1975).

[14]G. A. Sai-Halasz, R. Tsu, and L. Esaki, Appl. Phys. Lett. **30**, 651 (1977).

[15]G. Bastard, Phys. Rev. B **24**, 5693 (1981).

[16]T. J. Drummond and I. J. Fritz, Appl. Phys. Lett. **47**, 284 (1985).

[17]C. Kittel, *Quantum Theory of Solids* (Wiley, New York, 1963), p. 225ff.