Subband–Landau-Level Coupling in a Two-Dimensional Electron Gas

Z. Schlesinger,[a] J. C. M. Hwang,[b] and S. J. Allen, Jr.[a]

Bell Laboratories, Murray Hill, New Jersey 07974

(Received 28 April 1983)

Anti–level-crossing of Landau and the electric subband levels is observed in the high-mobility two-dimensional electron gas at the GaAs/(GaAl)As interface. Coupling between the electron motion parallel and perpendicular to the interface is due to a small parallel component of magnetic field. This novel subband spectroscopic technique determines the electric subband transition energy in this two-dimensional electron system.

PACS numbers: 73.40.Lq, 76.40.+b, 78.20.Ls

The spectrum of electric subband energy levels characterizing the electron motion normal to the interface is fundamental to a quantitative understanding of the two-dimensional (2D) character of semiconductor space-charge layers.[1,2] Absorption spectroscopy, Raman scattering, and magnetotransport have provided information concerning subband excitations in 2D systems.[2-4] In the following we report a measurement of the separation between the ground and first-excited subband states by anti–level-crossing with the cyclotron-resonance transition. This unlikely method of subband spectroscopy provides us with a direct measure of these states in the 2D electron gas at a single GaAs/(GaAl)As interface.

The samples used in the experiment, shown in Fig. 1(a), are grown by molecular-beam epitaxy (MBE).[5,6] When cooled to liquid-helium temperatures in the dark, it is found that the (GaAl)As layer is depleted and that a conducting space-charge layer is generated in the GaAs and bound to the (GaAl)As interface. Figure 1(b) schematically indicates the conduction-band edge in the (GaAl)As and GaAs as a function of distance measured from the sample surface. The space-charge layer is quantized into discrete electric subbands by the surface potential caused by the space-charge layer and the fixed charge trapped in both the (GaAl)As and GaAs. Contacts to the space-charge layer allow one to measure the areal density, n_s, of the electron gas via Shubnikov–de Haas (SdH) oscillations.

To vary the interface potential and electron density (n_s), one of the samples was thinned to ~90 μm and mounted on a sapphire substrate with a thin transparent metallic layer in contact with the back side of the sample.[7] A voltage applied between this metallic film and the space-charge layer allowed us to impose electric fields of ~10^4 V/cm at the interface and vary n_s by ~50%. Unlike previous cyclotron-resonance experiments in this system which were performed at fixed frequency,[8-11] swept-frequency cyclotron resonance was obtained with a Michelson interferometer and a room-temperature Bitter magnet capable of producing fields up to 20 T. The sample was immersed in a pumped liquid-helium bath at ~1.2 K. Each sample is wedged to eliminate Fabry-Perot interference. As a result it is subsequently mounted so that the axis normal to the sample plane is at an angle of 2 to 4 deg with respect to the applied magnetic field. A Ge composite bolometer (noise equivalent power ~10^{13}

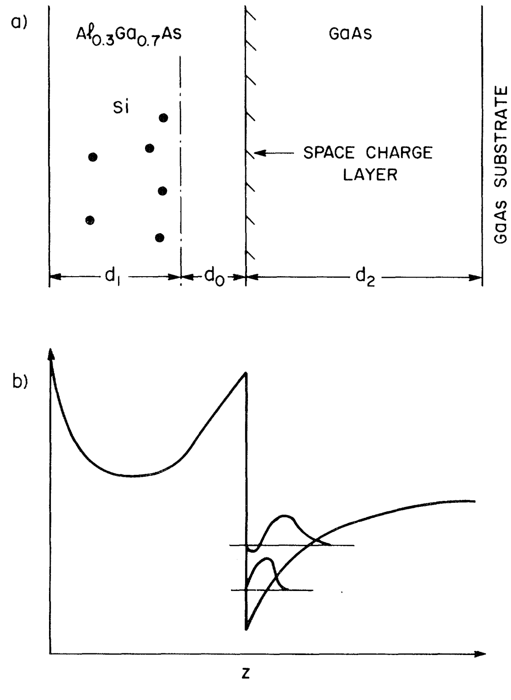

FIG. 1. Selectively doped GaAs/(GaAl)As interface. (a) Geometry of interface including setback distance, d_0, to donor impurities. For the sample discussed in the text $d_0 \simeq 320$ Å, $d_1 \simeq 700$ Å, and $d_2 \simeq 1$ μm. (b) Conduction-band edge and lowest subband levels.

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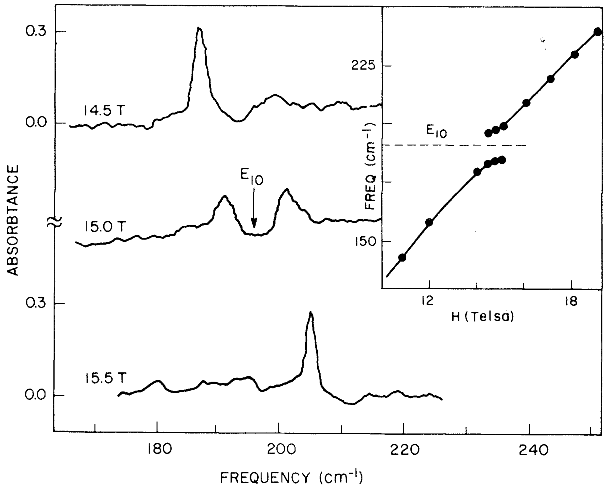

FIG. 2. Cyclotron resonance at level crossing. Three cyclotron-resonance spectra taken at the indicated fixed fields and a gate voltage $V_g = -15$ V are shown. The 2D electron density is 1.45×10^{11} cm^{-2}. At 15 T two absorption peaks of comparable magnitude are present. Inset: The frequency of the observed absorption peaks (at $V_g = 0$ V) as a function of magnetic field. The magnetic field tilt angle is 4 deg.

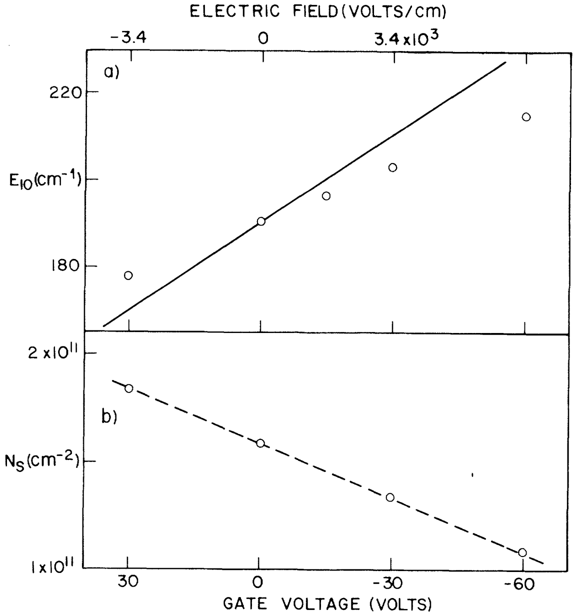

FIG. 3. Stark shift of the 0 → 1 subband transition. (a) The effect of a dc gate voltage on the 0 → 1 subband transition energy, E_{10}. The straight line is the calculated shift for a triangular potential. (b) Areal density of the 2D electron gas as a function of gate voltage.

W/Hz$^{1/2}$) thermally tied to the same bath was used to detect the radiation transmitted through the sample at normal incidence.

In Fig. 2 we show swept-frequency cyclotron resonance at three magnetic fields for a sample which is tilted by 4 deg with respect to the magnetic field. A clear line splitting is observed in the $H = 15$ T spectrum. The inset shows the evolution of the spectra as a function of magnetic field.

In Fig. 3 we show the effect of applying a voltage to the thin metal film on the back side of the device. The magnetic field at which the line splitting occurs increases linearly with negative gate voltage. (The application of a negative voltage is analogous to applying a reverse substrate bias in a metal-oxide-semiconductor field-effect transistor.[2]) The size of the resonant splitting is not changed appreciably by this voltage.

Tilting the sample with respect to the magnetic field does change the observed splitting, however, as illustrated in Fig. 4. Although the magnitude of the tip is not accurately known, the splitting increases with tip angle. The field at which the splitting occurs is independent of this angle.

An estimate of the Stark tuning rate can be obtained by use of a triangular-well model,[1] for which case the 0 → 1 level separation is

$$E_{10} \cong (\hbar^2/2m)^{1/3}(\tfrac{3}{2}\pi e F)^{2/3}[(\tfrac{7}{4})^{2/3} - (\tfrac{3}{4})^{2/3}], \qquad (1)$$

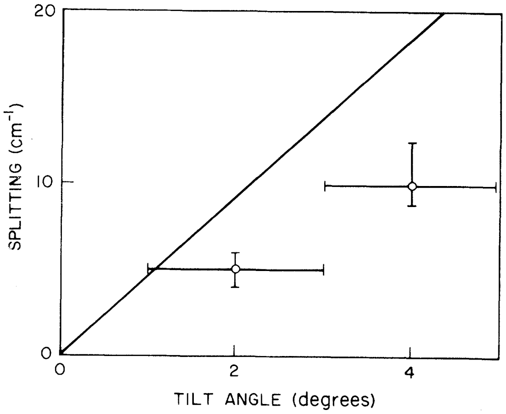

FIG. 4. Splitting vs tilt angle. The splitting of the two peaks observed in the cyclotron-resonance spectrum at the level crossing is shown for two angles. The straight line is an estimated theoretical splitting [Eq. (7)] due to the tilting of the magnetic field away from the surface normal.

where m is the mass, e the electron charge, and F the interface electric field. The Stark tuning rate is then given by

$$\partial E_{10}/\partial F = \tfrac{2}{3} E_{10}/F \tag{2}$$

or, using the level separation $\nu_{10} \simeq 190\ \mathrm{cm}^{-1}$ as in Fig. 2,

$$\partial \nu_{10}/\partial F \sim 6 \times 10^{-3}\ \mathrm{cm}^{-1}/(\mathrm{V/cm}). \tag{3}$$

This tuning rate is indicated by the straight line in Fig. 3.

Since we have neglected the self-consistent or Hartree part of the potential, this estimate is an upper bound for the Stark tuning. Including the Hartree term[4,12,13] should diminish the slope of the line shown in Fig. 3, improving the agreement with experiment.

Coupling between the Landau and subband levels is an elementary consequence of the tipped magnetic field.[3,4] For a magnetic field at an angle θ with respect to the normal to the 2D plane ($\hat{z}$), the vector potential in the Landau gauge can be written

$$A_y = B(x\cos\theta - z\sin\theta), \quad A_x = A_z = 0.$$

The three-dimensional Hamiltonian for an electron at the interface is

$$H = (1/2m)(\vec{P} + e\vec{A}/c)^2 + v(z),$$

where $\vec{P}$ is the momentum operator and $v(z)$ is the perpendicular quantizing potential. To first order in θ we can write

$$H = H_{\theta=0} + H_1 \sin\theta, \tag{4}$$

where $H_{\theta=0}$ is the Hamiltonain for $\theta = 0$ and

$$H_1 = -\omega_c z(P_y + m\omega_c x). \tag{5}$$

The Landau and subband levels are exact eigenstates of $H_{\theta=0}$ but are weakly coupled by H_1 when the magnetic field is tilted. At the level crossing, $\hbar\omega_c = E_{10}$, this perturbation lifts the degeneracy between the Landau and subband levels, giving

$$E_\pm = E_{10} \pm |\langle l=0, n=1|H_1|l=1, n=0\rangle| \sin\theta, \tag{6}$$

where l is the Landau-level index and n is the subband-level index. The in-plane matrix elements, x and P_y, are obtained easily because the Landau levels are harmonic-oscillator states. To approximate the perpendicular matrix element we use the harmonic-oscillator result

$$\langle n=1|z|n=0\rangle = (\hbar^2/2mE_{10})^{1/2}.$$

One then obtains

$$E_\pm = E_{10} \pm \hbar\omega_c(\sin\theta)/\sqrt{2}. \tag{7}$$

This estimated splitting, $E_+ - E_-$, is plotted in Fig. 4. It shows acceptable agreement with experiment considering the approximation used to generate the matrix elements and the experimental uncertainties in angle.

In summary, we have observed an anti-level-crossing between cyclotron resonance and the first subband transition in the 2D electron gas at the GaAs/(GaAl)As interface. The mode interaction is caused by a tipped magnetic field. This level-crossing spectroscopy provides us with a direct measure of the subband levels at a single GaAs/(GaAl)As interface.

These experiments were performed at the Francis Bitter National Magnet Laboratory at the Massachusetts Institute of Technology. The assistance of the Magnet Laboratory staff, especially Bruce Brändt and Larry Rubin, is gratefully acknowledged. It is also a pleasure to acknowledge valuable technical assistance received from Al Savage, Kirk Baldwin, and Frank DeRosa and discussions with P. M. Champion.

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[a] Guest Scientist at Francis Bitter National Magnet Laboratory, Cambridge, Mass. 02139.

[b] Present address: G. E. Electronics Laboratory, Syracuse, N.Y. 13221.

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