Equilibrium Tunneling from the Two-Dimensional Electron Gas in GaAs: Evidence for a Magnetic-Field-Induced Energy Gap

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Zero-bias tunneling of electrons between a quantum well and an n^+ substrate is studied with excitation voltages smaller than k_BT. At low temperatures and only with magnetic field applied perpendicular to the plane of the electron gas in the well, the tunneling rate develops a novel temperature-dependent suppression. The suppression strength is roughly independent of Landau-level filling for densities 0.5×10^{11} to 6×10^{11} cm^{-2}. The data are interpreted in terms of a magnetic-field-induced energy gap, at the Fermi level, in the single-particle spectrum of electrons in the well.

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Study of the two-dimensional (2D) electron gas formed at the interface of a semiconductor and an insulator has revealed much important physics, the most dramatic being the quantized Hall effects. The work presented here grew from a study intended to probe the modification of the electron density of states (DOS) in the 2D electron gas produced by a magnetic field perpendicular to the plane of the gas, a measurement of "the Landau-level DOS at the Fermi level." The technique used provided two independent measures of the DOS, one a thermodynamic DOS and the other a tunneling or single-particle DOS. The experiment extends earlier capacitance spectroscopy of the Landau-level DOS (Ref. 1) to lower temperatures and, most importantly, also measures the tunneling conductance between the 2D gas and an n^+ substrate. It differs as well from other tunneling measurements[2,3] which determine an I-V characteristic. In our experiment, the Fermi energy in a quantum well is varied in a controlled fashion by application of a gate voltage, and the Fermi energies on both sides of the tunnel barrier are kept within k_BT of one another. We measure the equilibrium tunneling conductance as a function of the Fermi energy in the well, not the differential conductance as a function of the difference in Fermi energies across the barrier.

The experiment shows, in addition to the structure expected from the development of Landau levels, an unexpected suppression of the electron tunneling which is greater than an order of magnitude at a field of 8 T and a temperature of 100 mK. We interpret these data as evidence for the development of a new magnetic-field-induced energy gap forming at the Fermi energy of the 2D gas.

Mesas etched from two wafers grown using molecular-beam epitaxy have been studied. The essential structure of the wafers is shown in Fig. 1(a). One of the wafers (A) has been described in detail previously.[4-6] Both wafers consist of a degenerately n-doped substrate in GaAs, and AlGaAs tunnel barrier, a GaAs quantum well, a thick nonconducting AlGaAs barrier, and a degenerately doped GaAs surface contact region. Wafer A has a Si-doping density in the substrate of 1×10^{17} cm^{-3}. The other wafer, B, has a different Si-doping concentration in the substrate (4×10^{17} cm^{-3}), a different Al mole fraction in the barrier (41% compared to 30% for A), and, unlike A, no dopants in the nonconducting barrier. In both wafers, only the lowest electronic subband of the well is occupied. The electron density in the quantum well can be varied by the application of a gate bias across the sample.

Tunnel barriers in our samples can be regarded as capacitors shunted by a tunneling conductance. These were designed to have RC times which lie within the range of our measurements. The capacitance and the loss tangent of patterned mesas were measured at twenty frequencies between 15 Hz and 30 kHz. Low-pass filtering was employed on sample leads to reduce any noise that might cause spurious voltage excitation across the tunnel barrier. The loss tangent displays a Lorentzian line shape which peaks, and concurrently the measured capacitance decreases, as the measuring frequency is swept through $2\pi/RC$.[6,7] By fitting with the functional

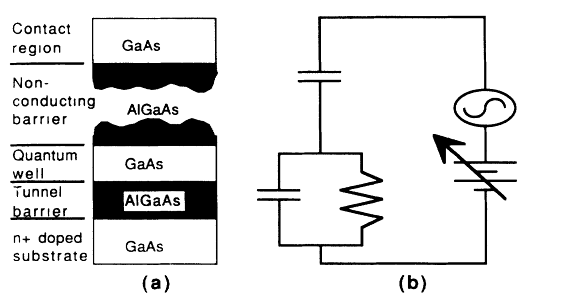

FIG. 1. (a) The essential structure of the samples. Tunneling from the GaAs quantum well to the substrate across the AlGaAs tunnel barrier is observed by means of capacitive coupling through the thick nonconducting barrier. (b) The equivalent model of the sample which is used in curve fitting to extract the tunneling conductance and the density of states in the quantum well.

forms for the capacitance and loss tangent versus frequency given by the simple circuit model shown in Fig. 1(b), the tunneling conductance is extracted from the data.[4,8] The capacitances shown in the model depend on both sample dimensions and the thermodynamic DOS (Ref. 9) in the quantum well which thus can be determined from the capacitance measurements.[6,8] Discussed here are the results of a series of experiments in which the capacitance DOS and the tunneling conductance are measured as a function of the electron density in the quantum well, the temperature of the sample, and the magnetic field strength (applied perpendicular to the plane of the 2D electron gas).

Elastic-scattering times in the well were estimated in both wafers from the widths of the DOS peaks of Landau levels in a magnetic field.[10] Wafer A would have a nominal 4.2-K mobility in the well of approximately 50000 $\mathrm{cm^2 V^{-1} sec^{-1}}$ as defined by this single-particle scattering time; wafer B would have a mobility of 130000 $\mathrm{cm^2 V^{-1} sec^{-1}}$. Actual transport mobilities are expected to be higher.[11] The suppression effect discussed here has been observed in both samples. More data have been taken on wafer A, and for clarity these are the data that will be discussed here. Over 100000 capacitance measurements were taken on one 400-μm-diam mesa from wafer A.

Figure 2 displays the logarithm of the tunneling conductance at 4 T for different temperatures. The highest-temperature curves oscillate about the zero-field curve,[4] indicating the development of Landau-level structure in the DOS in the 2D gas. At lower temperatures, the tunneling conductance is strongly suppressed. In contrast with this behavior in magnetic field, the zero-field tunneling conductance shows no substantial variation with temperature over the range 90 mK–10 K except for electron densities near full depletion ($<5\times10^{10}$ $\mathrm{cm^{-2}}$). The temperature-dependent suppression occurs only in the presence of the magnetic field applied perpendicular to the plane of the 2D electron gas; a magnetic field applied parallel to the plane[5] does not induce a temperature-dependent suppression. We note that the doping levels in the substrate are high enough (10^{17} $\mathrm{cm^{-3}}$) to discount magnetic freezeout[12] as the cause of the effect. Finally, the thermodynamic DOS in the well, as determined from the capacitance values distinct from conductance results, shows no unexpected behavior reflecting the tunneling suppression.

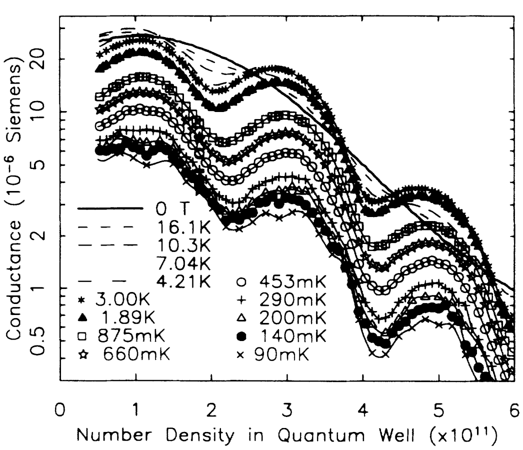

FIG. 2. Tunneling conductance (log scale) vs electron number density in the quantum well for zero field (bold solid curve) and for a variety of temperatures with 4.0-T magnetic field applied perpendicular to the plane of the electron gas in the quantum well. The smooth curves joining the points are guides to the eye.

The temperature dependence suggests that the suppression is due to a tunneling anomaly restricted to energies near the Fermi energy. To explore this idea, a high frequency signal (period shorter than the RC relaxation time of the tunnel barrier) was injected across the sample during capacitance measurements. This signal provides an oscillating Fermi-level offset between the 2D gas and the substrate, allowing tunneling to occur from a band of states of width given by double the amplitude of the injected signal. We find that as the excitation voltage that appears across the barrier due to the injected signal is made larger than k_BT/e, the suppression effects induced by the low temperature of the sample recede. At very low temperatures, where the suppression appears to be saturated, the effect of excitation, of rms amplitude V_e, on conductance is roughly the same as increasing the temperature in the absence of excitation to a value eV_e/k_B. This implies that the suppression would be observed in a conventional I-V characteristic as a zero-bias anomaly, not as a general bias-independent suppression.

The data shown in Fig. 2 are striking in that the suppression is nearly independent of the Landau-level filling number in the well. Also, at low temperatures, where the contrast associated with the Landau levels has developed, the suppression has roughly the same strength when the Fermi level is between Landau levels as when it is at a Landau maximum.

In Fig. 2, tunneling at densities higher than 3.9×10^{11} $\mathrm{cm^{-2}}$ should be forbidden in the absence of scattering. At these densities, the Fermi level is in the third Landau level in the well, whereas in the substrate the third Landau level lies outside of the Fermi surface. Indeed, the tunneling conductance is markedly lower in this range of density. Interestingly, the strength of suppression due to the magnetic field is approximately the same in the forbidden region as it is in the range of densities for which tunneling is allowed. This observation suggests that the suppression is not some consequence of the change in spatial character of the one-electron wave functions associated with the development of Landau states.

To summarize the data for different fields, we average the conductance data over a range of well fillings (over a half-integer or integer number of Landau levels). When $k_B T$ is of order of Landau-level width, the Landau-level structure changes markedly, and the average of the conductance must be taken with respect to Fermi energy in the well, not with respect to well filling, to assure that Landau-level shape changes are not confused with a change in the average value of the tunneling conductance. The capacitance data provide sufficient information to allow a conversion from filling to energy, yielding the conductance as a function of Fermi energy in the well.[8] For all but the 8.5-T data, the average conductance at high temperatures approaches the average of the zero-field conductance, which is taken to be the high-temperature limit. In Fig. 3 the ratio $G(T;B)$ of the average conductance to the high-temperature limit is plotted as a function of temperature. Ambiguities of interpretation of the 8.5-T data at high temperature imply a 10% uncertainty in the normalization of the 8.5-T data.

If one considers an energy gap centered on the Fermi energy in the 2D electron gas as the cause for the suppression, then the appropriate form for $G(T;B)$ would be

$$G(T;B) = -\int_0^\infty \frac{g(E)}{g_0} \frac{\partial f(E;T)}{\partial E} dE \,,$$

where E is the kinetic energy in the 2D gas, $g(E)$ is the 2D DOS, g_0 is the zero-field DOS, and $f(E;T)$ is the Fermi distribution function. For reasons described below, we fit with the following gap:

$$g(E) = \begin{cases} Ag_0 + \dfrac{(1-A)g_0|E-E_f|}{\Delta} & (E \le 2\Delta)\,, \\ g_0 \quad (E > 2\Delta)\,. \end{cases}$$

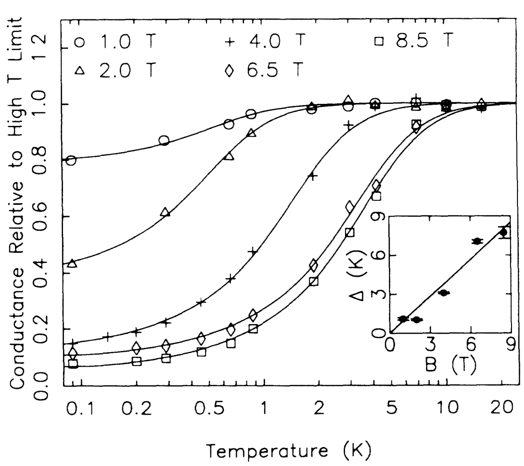

FIG. 3. Averaged conductances relative to the high-temperature limit of the conductance plotted against temperature (log scale). The smooth curves are fits described in the text. Inset: Δ in kelvins plotted against the applied magnetic field. The line is given by $\Delta = 0.047\hbar\omega_c/k_B$.

The fits shown in Fig. 3 are the result using this "linear" gap.

We call attention to a few principal features of the summary data in Fig. 3. (a) For low fields, 1 and 2 T, the width parameter Δ depends little on B, but the depth of the gap $(1-A)$ increases with increasing field. (b) For high fields, 6.5 and 8.5 T, the gap is nearly fully developed in depth and the width is increasing with field, with some indication of saturation at high fields. (c) The data consistently show more temperature dependence in the low-temperature limit than do models in which the gap is nonsingular at the Fermi energy, e.g., square- or smooth-bottomed gap functions. The linear singularity is not unique in giving good fits to the data; a variety of other singular behaviors will do as well. (d) At fields 2 T and higher, the gap width Δ has a value of about 5% of the cyclotron energy, $\hbar\omega_c$. (e) The errors generated in the averaging procedure at high temperatures (>3 K) by the Landau-level shape changes leave the results ambiguous as to whether or not there is temperature dependence of the gap in this temperature regime.

We mention several speculations concerning the suppression mechanism, none of which seems consistent with all features of the data. All relate to interaction effects in the 2D system. Anomalies in the 3D gas should be present for arbitrary orientation of the magnetic field, but the suppression is observed only with the field perpendicular to the 2D gas. Also, density dependence of the suppression is observed near depletion of the 2D gas[8] suggesting the properties of the 2D gas as the source of the suppression effect.

We interpret the results in terms of a gap, rather than of an influence of the field on the single-particle tunneling dynamics, because the temperature and excitation dependences indicate that the tunneling is suppressed only for states near the Fermi energy. Gaps associated with the fractional quantized Hall effect are also a few kelvins wide. However, these occur only at particular Landau-level filling fractions, while the data presented here require a gap tied to the Fermi level. A Coulomb gap, as observed by White, Dynes, and Garno[13] in high-resistivity granular films is more appropriate. The singular nature of the gap observed in such experiments is particularly appealing given that our fits imply the existence of a singular gap. One would expect, however, the strength of the gap to depend upon the thermodynamic DOS which varies by more than a factor of 10 (at the highest fields used here) as the Fermi energy moves from the center of a Landau level to between Landau levels.

Another proposal is the enhancement, by some mechanism involving the magnetic field, of the coupling of the tunneling transition to other excitations of the system, e.g., phonons or plasmons. The limiting value of the suppression at low temperatures would as observed, decrease with increasing field as more tunneling oscillator strength is transferred from the elastic to the inelastic channels. There is no obvious candidate for the coupled excitation which would need to have a characteristic energy of order 0.5 meV in order to explain, even crudely, the temperature dependence of the suppression.

In summary, we have observed a novel temperature-dependent suppression of tunneling from a quantum well induced by a magnetic field. The suppression only occurs when the magnetic field is perpendicular to the plane of the 2D electron gas in the quantum well. The suppression can be characterized by a field-induced gap in the single-particle DOS tied to the Fermi energy of width roughly 5% of $\hbar\omega_c$.

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[1]T. P. Smith, B. B. Goldberg, P. J. Stiles, and M. Heiblum, Phys. Rev. B **32**, 2696 (1985).

[2]E. Böckenhoff, K. v. Klitzing, and K. Ploog, Phys. Rev. B **38**, 10 120 (1988).

[3]B. R. Snell, K. S. Chan, F. W. Sheard, L. Eaves, G. A. Toombs, D. K. Maude, J. C. Portal, S. J. Bass, P. Claxton, G. Hill, and M. A. Pate, Phys. Rev. Lett. **59**, 2806 (1987).

[4]J. A. Lebens, R. H. Silsbee, and S. L. Wright, Appl. Phys. Lett. **51**, 840 (1987).

[5]J. A. Lebens, R. H. Silsbee, and S. L. Wright, Phys. Rev. B **37**, 10 308 (1988).

[6]J. A. Lebens, Ph.D. thesis, Cornell University, 1988 (unpublished).

[7]R. E. Cavicchi and R. H. Silsbee, Phys. Rev. B **37**, 706 (1988).

[8]R. C. Ashoori *et al.* (to be published).

[9]P. A. Lee, Phys. Rev. B **26**, 5882 (1982).

[10]J. P. Eisenstein, H. L. Störmer, V. Narayanmurti, A. Y. Cho, A. C. Gossard, and C. W. Tu, Phys. Rev. Lett. **55**, 875 (1985).

[11]S. Das Sarma and Frank Stern, Phys. Rev. B **32**, 8442 (1985).

[12]T. W. Hickmott, Phys. Rev. Lett. **57**, 751 (1986).

[13]Alice E. White, R. C. Dynes, and J. P. Garno, Phys. Rev. B **31**, 1174 (1985).