Magnetic Anisotropy of a One-Dimensional Electron System

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We have discovered a novel anisotropy in a quasi-one-dimensional electronic system in the presence of a magnetic field. The density of states changes dramatically when a magnetic field is applied along different axes of the sample. Further, we do not observe spin splitting of one-dimensional levels in magnetic fields up to 20 T, indicating that enhancement of the Landé g factor is also anisotropic. These results provide new insight into the underlying properties of quantum-confined electrons.

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Anisotropy is inherent in low-dimensional systems, and can be manifested in many different ways. One of the most powerful probes of this anisotropy is a magnetic field. For more than twenty years anisotropy of the Shubnikov–de Haas effect has been used to characterize two-dimensional systems.[1] The Landau-level separation is determined by the component of the magnetic field perpendicular to the plane of the two-dimensional electron gas. Although there are also magnetic field effects associated with the component parallel to the two-dimensional layer, they are fairly subtle. Recently, a great deal of work has been done to further reduce the dimensionality of electronic systems by imposition of additional confinement on two-dimensional systems.[2] However, in most schemes the inversion layer or heterojunction confinement is still predominant. Magnetic field studies of these quasi-one-dimensional systems have focused on effects when a magnetic field is perpendicular to the original 2D plane.[3] In this orientation results can be interpreted by way of extension from two dimensions. An important, but as yet unanswered, question is whether additional confinement leads to additional magnetic anisotropy.

In this Letter we present the first evidence for such phenomena. If a magnetic field is applied perpendicularly to the original two-dimensional plane, we see the expected transition from electric to magnetic quantization. On the other hand, if the magnetic field is oriented in the plane of the dominant quantization, a novel anisotropy is observed. A magnetic field perpendicular to the quantum wires produces a rigid diamagnetic shift of the quasi-one-dimensional levels, while a magnetic field parallel to the wires destroys the electric quantization.

The samples used in this study are GaAs-AlGaAs heterojunction capacitors with 0.2-, 0.3-, or 0.4-μm lines etched in the top surface to provide lateral confinement. The details of their fabrication have been given previously.[2] The electrons are confined in the $\hat{z}$ direction (see the inset in Fig. 1) by the heterojunction to a triangular well about 100 Å wide, and by the grating to a square well (or parabolic well depending on the carrier concentration) about 1000–3000 Å wide. Electrons are free to move in the remaining orthogonal direction. Thus the potential energy of electrons in these samples is different in all three directions.

The application of a magnetic field results in two different types of effects. A magnetic field applied along

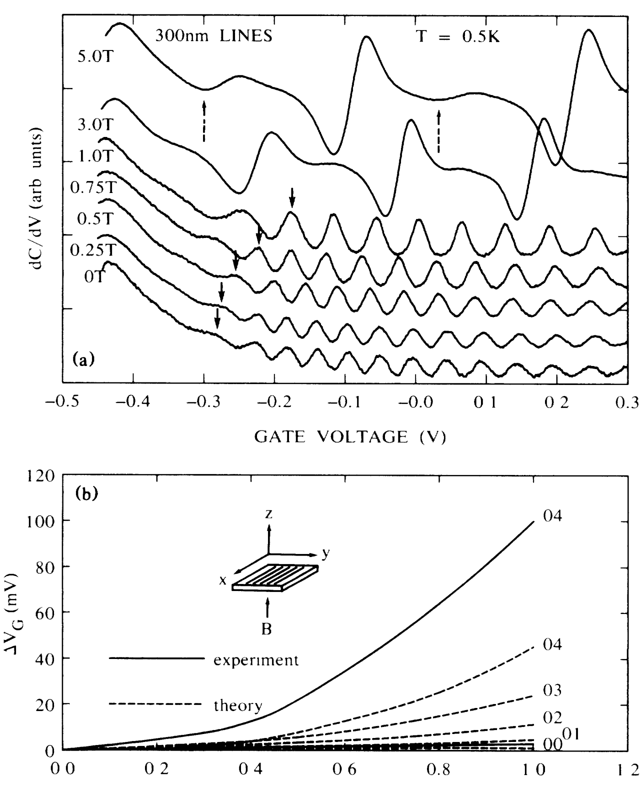

FIG. 1. (a) The derivative of the capacitance vs gate voltage in the presence of a magnetic field. The sample was oriented such that the magnetic field was along the $\hat{z}$ axis (see inset). The solid arrows indicate the position of the 04 level as it shifts as a function of magnetic field. For convenience, the data at 3 and 5 T are scaled down by a factor of 4. The dashed arrows point out the spin splitting of Landau levels at 5 T. (b) The calculated and experimental shifts in the positions of the first five energy levels as a function of magnet field.

either of the confinement directions couples the free motion (in the $\hat{\mathbf{x}}$ direction) with the remaining confined motion, hybridizing these states and eventually condensing the electrons into zero-dimensional states if the magnetic field strength is high enough. In contrast, a magnetic field applied parallel to the $\hat{\mathbf{x}}$ direction couples the two confinement potentials. Electrons remain free in this direction (essentially one dimensional) but the $\hat{\mathbf{y}}$ and $\hat{\mathbf{z}}$ eigenstates are mixed, changing the density of states. Since these effects can be masked by other phenomena in transport measurements, it is preferable to study the thermodynamic properties directly, and capacitance measurements constitute an ideal probe. The measured capacitance is directly related to the thermodynamic density of states. We can probe the density of states by varying the bias applied to the gate electrode and thus changing the Fermi energy.

Figure 1(a) shows experimental traces of dC/dV versus gate voltage, V_G, for a sample with 0.3-μm lines when the magnetic field is parallel to the $\hat{\mathbf{z}}$ direction. This is the most familiar configuration and will provide a foundation for our new results. In this orientation the 1D levels and magnetic levels are coupled. Below 1 T [where the magnetic length, $\lambda_M = (\hbar/eB)^{1/2}$, is comparable to or larger than the effective width of the lateral potential confinement], the quasi-1D levels are still observed. However, they shift in gate voltage and increase in strength with increasing magnetic field. At high magnetic fields the magnetic length becomes smaller than the effective width of the wires and the electrons condense into Landau levels. The Landau quantization is much stronger than the lateral quantization and the effects of the lateral confinement are obscured so that one sees capacitance oscillations, reflecting the presence of zero-dimensional states. The two uppermost curves in Fig. 1 show this. It is important to note that we also see spin splitting of the Landau levels. This is highlighted with dashed arrows. The oscillations observed in our capacitance measurements are related to changes in the Fermi energy and occur when the Fermi energy crosses a one-dimensional subband. The intensity of these oscillations is related to the shape of the density of states and its broadening. A complete analysis of the hybridization of electric and magnetic states implies a detailed study of charge transfer in the presence of the magnetic field. While a full numerical solution to this problem may ultimately give the best quantitative results, a great deal of insight into this problem can be obtained with a few judicious approximations. In the weak magnetic field limit ($\omega_c\tau < 1$, where $\omega_c = eB/mc$, and τ is the scattering time) neither the Fermi energy nor the electrostatic potential change significantly. In this case, shifts in the capacitance oscillations primarily reflect diamagnetic shifts in the energy levels. When the magnetic field is applied along the $\hat{\mathbf{z}}$ axis the Hamiltonian can be written as follows:

$$\mathcal{H} = \frac{1}{2m}\left[\left(p_x + \frac{\hbar y}{\lambda_m^2}\right)^2 + p_y^2 + p_z^2\right] + V(y,z)\,, \qquad (1)$$

where we use the gauge $\mathbf{A} = (-yH,0,0)$. The potential $V(y,z)$ includes the electrostatic potential originating from the presence of donors in AlGaAs, and the charge transfer to the GaAs. It is obtained from self-consistent calculations in the absence of a magnetic field.[4] On the basis of our assumptions, changes in this potential due to the magnetic field are ignored. Since the confinement in the $\hat{\mathbf{z}}$ direction is much stronger than in the $\hat{\mathbf{y}}$ direction, we can also use the decoupled approximation[5,6] to obtain the eigenfunctions. We assume that the threshold voltage (taken to be the large peak in dC/dV) is related to the ground level (00 level). Because the threshold voltage occurs at low carrier concentrations, when the $\hat{\mathbf{y}}$ direction is more confined than at more positive biases,[7] the effect of the magnetic field will be relatively small and this will be reflected in the changes in the threshold voltage. However, the higher-lying quantum levels will have a wider spatial extent due to the larger carrier concentration and effective width, and the magnetic field effects will be larger. This will be reflected as changes in

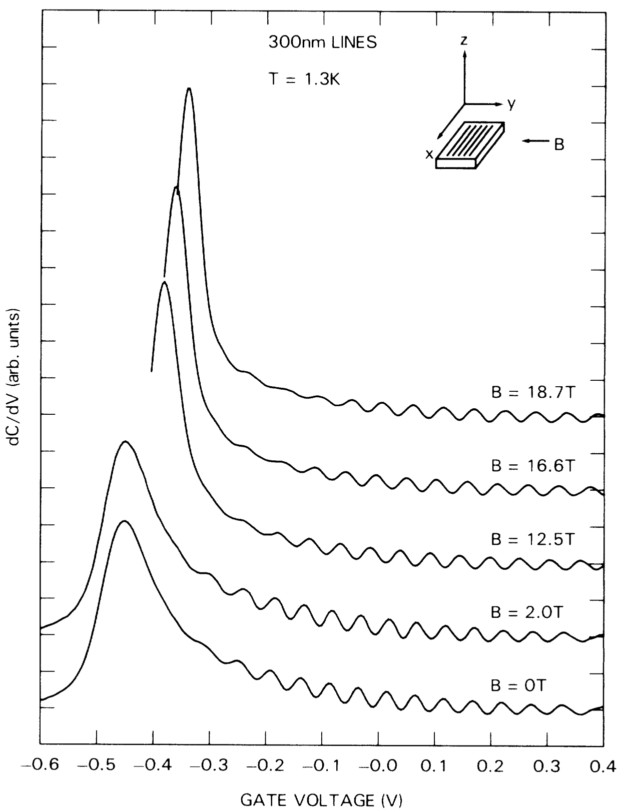

FIG. 2. The derivative of the capacitance vs V_G with the magnetic field oriented along the $\hat{\mathbf{y}}$ axis. We observe a rigid shift in the positions of the energy levels, but there is little or no change in the amplitude of the oscillations in this configuration, nor is there any spin splitting of the levels.

the relative positions of the oscillations in dC/dV due to coupling of the $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ motions. This is what we observe experimentally. In Fig. 1(b) we plot the measured shift of the threshold and the fourth excited excited level (04 level) as solid lines and the calculated shifts in the oscillation positions as dashed lines. The calculated shifts are smaller than the observed behavior of the corresponding levels, but the overall agreement is satisfactory. The shifts in the levels increase with level index. In addition, for the same quantum level, the magnitude of the shift increases with the width of the lateral confinement. Again, this is in agreement with our calculations and is not surprising since a weaker confinement implies greater freedom of motion for the carriers and hence more sensitivity to external fields.

When the magnetic field is applied parallel to the $\hat{\mathbf{y}}$ direction the magnetic field couples the $\hat{\mathbf{z}}$-confined motion with the free motion. In this case, there should be a diamagnetic shift of the eigenstates created by the heterojunction but little change in the states created by the lateral confinement. Figure 2 shows dC/dV vs V_G for a sample with 0.3-μm lines in this configuration. There is a shift in the threshold voltage, V_θ, but the positions of the oscillations with respect to V_θ do not change appreciably, and their amplitude remains fairly constant up to 20 T. The magnitude of the threshold voltage shifts increases systematically as the width of the lines increases. We calculated the shift in the energy levels observed in this configuration, using the approximations described above. The Hamiltonian for this configuration is very similar to Eq. (1) except that $\mathbf{A}=(Hz,0,0)$. In the first-order decoupled approximation, the positions of the oscillations relative to V_θ do not change with the magnetic field. It is important to point out that the energy of each eigenstate depends strongly on the position of the center of the magnetic orbit. We assume that the oscillations observed in the capacitance are related to the center of orbit with the minimum energy, and that these are the first states occupied. Although our calculations capture all the essential features of our experiments, the quantitative agreement is not that good. For example, at 10 T, for the samples with 0.2-μm lines, we calculated a shift of 10 mV in the threshold voltage, whereas the experimental value is about 40 mV. This discrepancy may reflect the importance of magnetic field effects on the Fermi energy and the charge transfer. While we are effectively in the weak-field regime (since the cyclotron orbits are larger than the $\hat{\mathbf{z}}$ confinement) the magnetic

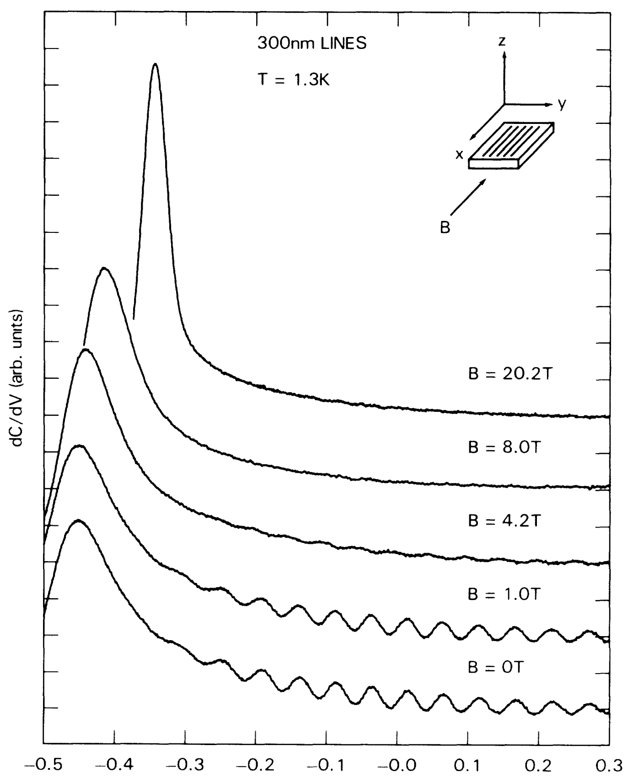

FIG. 3. dC/dV vs V_G with the magnetic field along the $\hat{\mathbf{x}}$ axis. The oscillations in the derivative of the capacitance are completely damped by the magnetic field above 8 T.

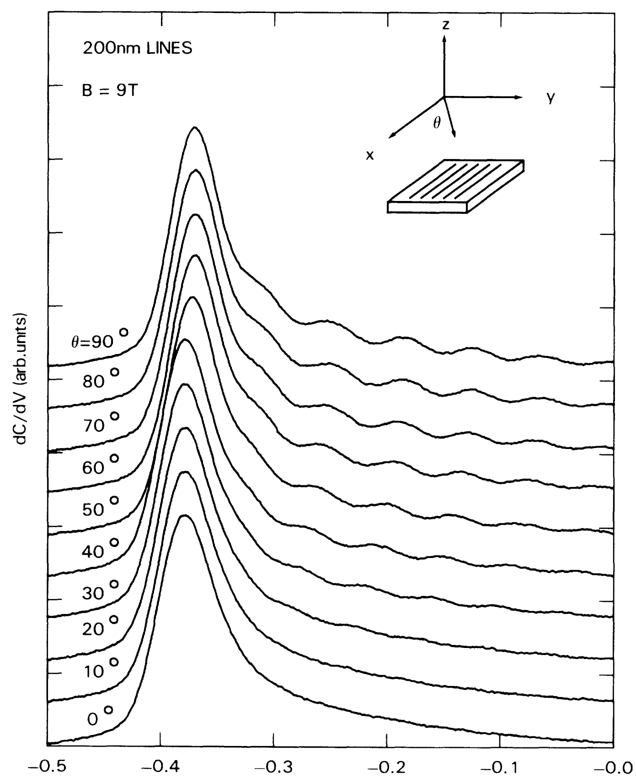

FIG. 4. The damping of the 1D levels is dependent on B_x. This is demonstrated by the angular dependence of the amplitude when the sample is rotated in the x-y plane with respect to the magnetic field.

fields are sufficiently large to change the electrostatics.

Despite the fact that the Hamiltonian for the first two configurations is essentially the same, the difference in the extent of confinement gives rise to an additional anisotropy. While we observe spin splitting of Landau levels at high magnetic fields when $\mathbf{B} \parallel \hat{\mathbf{z}}$, we do not see any splitting of the one-dimensional states when $\mathbf{B} \parallel \hat{\mathbf{y}}$. The absence of spin splitting at magnetic fields as high as 20 T indicates that the g factor is not enhanced as it is in the first orientation. Enhancement of the g factor in 2D electron systems has been explained in terms of an imbalance in the number of spin-up and spin-down electrons.[8] This enhancement also depends on the fact that the Landau-level spacing is much greater than the level broadening. Since the one-dimensional level spacings are relatively small (5 meV or less) the same mechanism may not be effective when $\mathbf{B} \parallel \hat{\mathbf{y}}$. Thus the g factor may be close to its bulk value (-0.44 for GaAs),[9] and at 20 T the spin splitting would only be $\simeq 0.5$ meV and not resolved. However, this explanation ignores other effects of one-dimensional confinement which require further study.

Even more intriguing and unexpected are the effects of a magnetic field applied in the $\hat{\mathbf{x}}$ direction (see Fig. 3). Rather than a monotonic increase or shift in the oscillations, we observe a damping of the oscillations as the magnetic field strength increases. For all three line sizes the amplitude of the oscillations decreases linearly with increasing magnetic field. The amplitude of the oscillations decreases at about the same rate for all of the line sizes and the oscillations are completely damped out at about 8 T. We also observe a diamagnetic shift in the energy levels as a function of magnetic field. However, the shift is somewhat smaller than the shift when the magnetic field is perpendicular to the lines. This can be seen more clearly in Fig. 4 where the derivative of the capacitance is shown as a function of angle in the x-y plane. $\theta = 0$ when the magnetic field is parallel to the $\hat{\mathbf{x}}$ direction. The diamagnetic shift increases with angle with the largest change occurring between 40° and 50°, and this is consistent with our theoretical calculations. In this configuration the magnetic field is competing with both the $\hat{\mathbf{z}}$ and $\hat{\mathbf{y}}$ confining potentials, and both directions are now strongly coupled.

Coupling of the heterojunction potential with the lateral confinement potential may also be responsible for the damping of the oscillations. While it is not obvious that coupling of the $\hat{\mathbf{y}}$ and $\hat{\mathbf{z}}$ states introduces additional broadening, it is this coupling which distinguishes this configuration from the other two, and its importance cannot be ignored. The magnetic field also couples adjacent one-dimensional levels in our perturbation calculations. Again, we cannot be sure that this will lead to additional smearing of the one-dimensional density of states, but it is a possibility. Finally, damping out of the oscillations may be due to enhancement of the boundary effects. The magnetic field may increase the importance of the potential fluctuations associated with variations in the width and profile of the lines. Rather than generating additional broadening, the magnetic field may simply boost the role of existing broadening mechanisms.

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