Resistance oscillation in wide single quantum wells subject to in-plane magnetic fields

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We report transport measurements in wide single quantum wells subject to magnetic fields parallel to the plane of the two-dimensional electron gas. The observed resistance oscillation is associated with singularities in the parallel magnetic-field-dependent density of states of a coupled bilayer electron system. While the tight-binding model fails to predict accurately the position of the resistance oscillation, self-consistent numerical calculations are in good quantitative agreement with the experimental data. [S0163-1829(97)01428-8]

Bilayer two-dimensional (2D) electron systems have been of great research interest in studying properties of low-dimensional systems subject to strong quantizing magnetic fields. Introducing an extra degree of freedom, represented by the layer index, results in remarkable one-electron and many-body physics. The electron-electron interactions are particularly important when a strong magnetic field is applied perpendicular to the 2D layer plane as it quenches the kinetic energy by the Landau quantization. There have indeed been several reports of different, highly correlated states with strong interlayer interactions,[1,2] such as quantum Hall ferromagnets at filling factor $\nu=1$,[3–5] or fractional quantum Hall states at even-denominator filling factors[5,6] and insulating phases strongly suggestive of a bilayer Wigner crystal phase.[7]

Applying the magnetic field parallel to the plane of the 2D electron layers can also lead to remarkable transport phenomena.[8,9] Here the essence of the physics is captured by a simple tight-binding approximation (TBA) model for an electron moving in a 2D layer and having a nonzero probability of hopping from one layer to the other.[8] The model predicts that in parallel magnetic fields the one-electron energy subbands corresponding to individual electron layers are shifted in opposite directions in the wave vector space and that the layer dispersion curves anticross. As a result, Fermi lines acquire ''peanut'' and ''lens'' shapes when the system is subject to intermediate fields. When the magnetic field is further increased, the lens is emptied followed by a splitting of the peanut into two disjunctive circles belonging to individual electron layers. Depopulation of the lens gives rise to a step in the magnetic-field dependence of the density of states (DOS) at the Fermi energy; splitting of the peanut results in a van Hove divergence in the DOS.

Resistance oscillation associated with the singularities in the DOS was recently observed in GaAs/$Al_xGa_{1-x}As$ double quantum wells.[9] In these structures, a high and hard-wall $Al_xGa_{1-x}As$ barrier separates two narrow GaAs quantum wells so that the bilayer electron system consists of two narrow and weakly coupled layers. The experimental positions of both the minimum of the resistance (step in the DOS) and maximum of the resistance (the van Hove singularity in the DOS) are in quantitative agreement with TBA calculations assuming two purely 2D electron layers and a magnetic-field-independent hopping parameter t. These experiments were recently extended to a trilayer electron system in a triple-quantum-well structure and the results were found to be in good quantitative agreement with the TBA calculations.[10]

In this paper we present magnetoresistance data $R(B)$ measured in wide single quantum wells subjected to a parallel magnetic field B. The charge distribution in a wide single quantum well (see Fig. 1) is more subtle than the one in the double quantum well. Here the Coulomb repulsion of the electrons in the well leads to a barrier (inside the well), which in turn results in a bilayer electron system.[2,4–7] For this structure, the R vs B traces exhibit a pronounced oscillation indicating the bilayer nature of the electron system. We analyze the data using both the analytical TBA model and self-consistent numerical simulation of energy spectra as a function of parallel B and show that only the latter can quantitatively explain the position of the experimental $R(B)$ oscillation.

Our samples were grown by molecular-beam epitaxy and consist of a GaAs well bounded on each side by an undoped $Al_{0.35}Ga_{0.65}As$ spacer and a Si δ-doped $Al_{0.35}Ga_{0.65}As$ layer. Front-side and back-side gates were used to obtain balanced charge distribution in the sample, i.e., a symmetric distribution of the 2D electron gas with respect to the center of the quantum well. Changing the pair of front-gate and back-gate bias voltages, we measured Shubnikov–de Haas

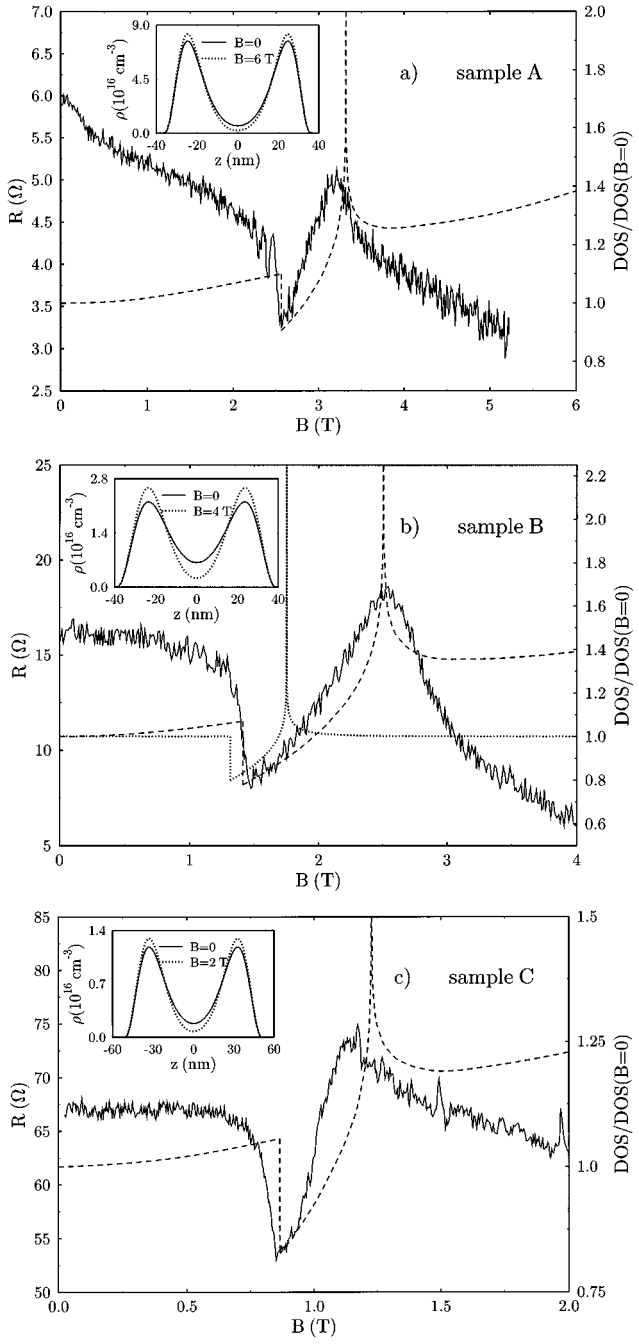

FIG. 1. Experimental dependence of resistance on the parallel magnetic field (solid line) and the DOS at the Fermi energy calculated in the SCLDA (dashed line) for the three samples whose parameters are detailed in Table I. For comparison, the DOS calculated according to the TBA is shown in (b) for sample B. The insets show the charge distribution in the quantum wells at $B=0$ and at the indicated parallel magnetic field.

oscillations and from their Fourier transform we obtained the gap separating the two lowest-lying energy levels in the quantum well. The balanced charge distribution is the one where this energy gap has a minimum value $\equiv\Delta_{SAS}$. (Δ_{SAS} corresponds to the energy gap $2t$ that separates the symmetric and antisymmetric states in the tight-binding model.) To accurately determine the width of the quantum well w we fitted the experimental dependence of Δ_{SAS} on the electron sheet density N_s to the Δ_{SAS} vs N_s curve calculated self-consistently with w as the free parameter.[5,6] The deduced values for w differ by about 10–20 % from w expected from the nominal growth parameters. Given that the substrates were not rotated during the epitaxial growth, this difference is reasonable based on our calibrations. Three samples from different wafers were prepared to measure the parallel magnetic-field-dependent resistance. The parameters for these samples are listed in Table I.

Experimental resistance data for the three samples are shown in Fig. 1. In each trace a strong resistance oscillation is observed with a minimum at B_{min} and a maximum at B_{max}. To compare the data with theory we first evaluate the TBA model expressions[9] for the mean position $B_{mean}\equiv(B_{min}+B_{max})/2$ and the difference $\Delta B\equiv B_{max}-B_{min}$ between the minimum and maximum of the resistance oscillation:

$$B_{mean}=\frac{2\hbar\sqrt{\pi N_s}}{|e|d}, \tag{1}$$

$$\Delta B=\frac{4mt}{|e|d\hbar\sqrt{\pi N_s}}, \tag{2}$$

where $\hbar$ is the Planck's constant, e is the electron charge, and $m=0.067m_e$ is the effective electron mass in GaAs. The distance between two peaks in the charge distribution calculated self-consistently in a zero magnetic field replaces the layer separation d and the hopping parameter $t=\Delta_{SAS}/2$. The values of B_{mean} and ΔB, calculated for the three samples using Eqs. (1) and (2), are listed in Table I under the TBA. As an example, in Fig. 1(b) we have also included the DOS oscillation expected from this model for sample B. Table I and Fig. 1(b) clearly show that the TBA model does not provide accurate B_{mean} and ΔB values for these samples: the model predicts a lower B_{mean} and a much smaller ΔB compared to the experimental data.

To quantitatively explain the position of the observed $R(B)$ oscillation we performed numerical calculations of the electronic structure in the self-consistent, local-density-functional approximation (SCLDA).[11] The Hamiltonian for an electron moving in the quantum well and the parallel magnetic field, the $B\|\hat{y}$ axis, can be written as

$$H=\frac{1}{2m}(\mathbf{p}+|e|\mathbf{A})^2+V_{conf}(z), \tag{3}$$

where the vector potential $\mathbf{A}=(Bz,0,0)$ and the confining potential of the quantum well V_{conf} is a sum of the Hartree potential V_H and the exchange-correlation term V_{xc}. The Hartree potential is given by the Poisson equation

$$\frac{d^2V_H}{dz^2}=\frac{|e|\rho(z)}{\varepsilon}, \tag{4}$$

where $\rho(z)$ is the electron charge distribution in the quantum well and ε is the dielectric constant in GaAs. For the exchange-correlation term we used the expression calculated in the local-density-functional approximation by Hedin and Lundquist:[12]

TABLE I. Sample parameters are listed together with B_{mean} and ΔB observed experimentally, calculated using Eqs. (1) and (2) (the TBA) and obtained from the self-consistent simulations (the SCLDA).

						Experiment		TBA		SCLDA	
Sample	w (nm)	N_s (10^{11} cm^{-2})	μ (10^6 cm^2/V s)	d (nm)	Δ_{SAS} (meV)	B_{mean} (T)	ΔB (T)	B_{mean} (T)	ΔB (T)	B_{mean} (T)	ΔB (T)
A	69	2.5	0.31	49.3	0.51	2.9	0.7	2.37	0.13	2.94	0.76
B	75	0.98	1.0	47.2	0.98	2.0	1.0	1.55	0.43	1.95	1.09
C	99	0.61	0.35	65.8	0.38	1.0	0.3	0.88	0.15	1.04	0.35

$$V_{xc}(z) = -0.611\frac{e^2}{4\pi\varepsilon}\left(\frac{4\pi\rho(z)}{3}\right)^{1/3}. \quad (5)$$

In each loop of the self-consistent procedure we solve numerically the Schrödinger equation with the Hamiltonian (3) to obtain the electron charge distribution. Then a new V_{conf} is calculated from Eqs. (4) and (5), which enters the next loop of the procedure.

Fermi contours of occupied states, calculated in the SCLDA model for sample B at several values of the magnetic field are plotted in Fig. 2. One reason for the failure of the TBA model to explain quantitatively the position of the magnetoresistance oscillation is clearly seen from this figure. In the TBA model, the electron layers are assumed to have zero thickness. The electronic structure of an ideal, zero-thickness 2D electron system is unaffected by the parallel magnetic field; the Fermi contour remains a circle. In a wide single quantum well, however, the bilayer system consists of *finite-width* electron layers as they are confined in a shallow and approximately triangular quantum well at the GaAs/$Al_xGa_{1-x}As$ heterojunction. In earlier studies of the single heterojunction it was found that the Fermi contour acquires an egglike shape when the electron system is subject to strong parallel magnetic fields.[13] Figure 2 shows how, in a wide single quantum well, the TBA-model-like modification of Fermi contours (lens and peanut) of the bilayer system is accompanied by the egglike distortion of the individual layers' Fermi contours. SCLDA simulations of energy spectra at different magnetic fields are plotted in Fig. 3. Here we see another unrealistic assumption of the TBA model for the wide single-quantum-well structures. In the TBA model the B-independent hopping parameter t yields a constant partial energy gap[8,9] $E_g = 2t$ separating the symmetric and antisymmetric energy subbands at $k_x = 0$. However, for the bilayer system in the wide single quantum well, E_g strongly increases with B, as shown in Fig. 3(b).

Dashed lines in Fig. 1 represent SCLDA model calculations of the DOS for the three samples. The step in the DOS and the van Hove singularity match, with a high accuracy, B_{min} and B_{max} of the measured resistance oscillation. Given the noise and the rounded extrema in the experimental $R(B)$ traces and approximately 2% error in the determination of the well width from the Shubnikov–de Haas measurements, one can easily explain the small discrepancy between the experimental data and the self-consistent calculations. Varying other parameters of the quantum well, such as the conduction-band offset at the GaAs/$Al_xGa_{1-x}As$ interface

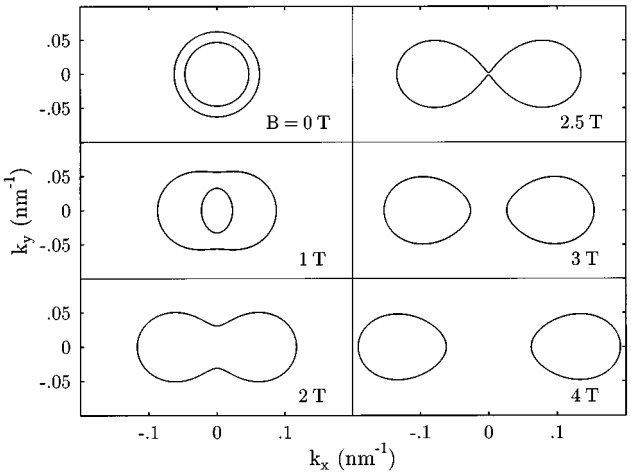

FIG. 2. SCLDA calculations of Fermi lines for occupied states at different parallel magnetic fields for sample B.

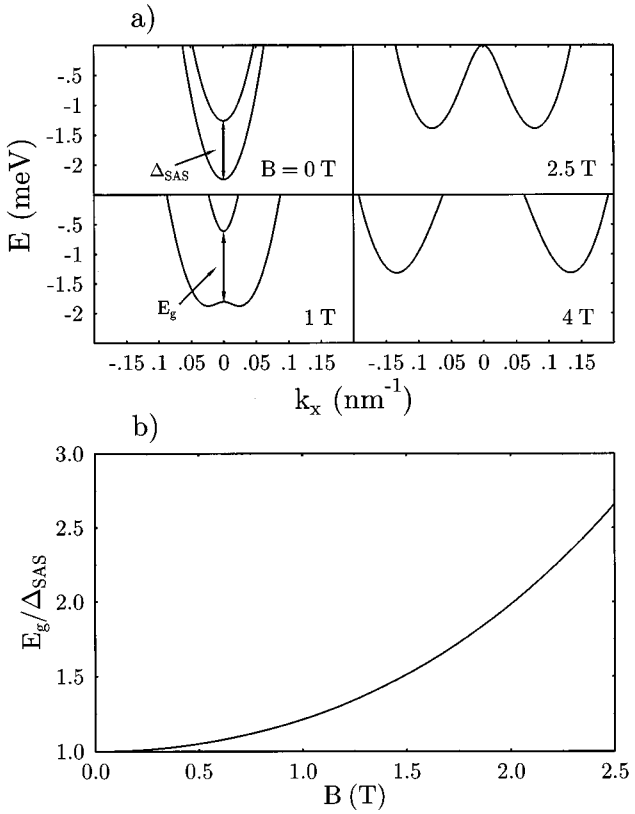

FIG. 3. (a) SCLDA calculations of energy subbands for occupied states at different parallel magnetic fields for sample B (Fermi energy ≡ 0). (b) Partial energy gap as a function of the magnetic field relative to its zero-field value ($\equiv \Delta_{SAS}$).

or the residual impurity concentration, within their estimated uncertainty, had a negligible effect on the theoretical results. The values for B_{mean} and ΔB obtained from self-consistent simulations are also included in Table I to make the comparison between the experiment and the two model calculations easier.

In conclusion, we observe an oscillation, as a function of parallel magnetic field, in the resistance of bilayer electron systems confined to wide, single GaAs quantum wells. Qualitatively, the oscillation can be explained within a simple tight-binding model for coupled bilayer electron systems. A quantitative explanation of the experimental position of the resistance oscillation, however, requires self-consistent numerical simulations. We performed such simulations, and the good agreement with the experimental data attests to the validity of the self-consistent method for calculating the electronic structure of wide single quantum wells in parallel magnetic fields. The discussion of the overall shape of the resistance curves would include, besides the electronic structure analysis, also the theory of transport in parallel magnetic fields, which has not been well established yet.[14] We hope that our results will stimulate further progress in building up this theory so that a more complete interpretation of the experimental data will be possible.

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