Magnetoresistance and Cyclotron Mass in Extremely-Coupled Double Quantum Wells Under In-Plane Magnetic Fields*

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Abstract. We experimentally investigate the transport properties of an extremely-coupled AlGaAs/GaAs double quantum well, subject to in-plane magnetic fields ($B_{\parallel}$). The coupling of the double quantum well is sufficiently strong that the symmetric-antisymmetric energy gap (Δ_{SAS}) is larger than the Fermi energy (E_F). Thus for all $B_{\parallel}$ only the lower energy branch of the dispersion curve is occupied. In contrast to systems with weaker coupling such that $\Delta_{SAS} < E_F$ we find: (1) only a single feature, a maximum, in the in-plane magnetoresistance, (2) a monotonic increase with $B_{\parallel}$ in the cyclotron mass up to 2.2 times the bulk GaAs mass, and (3) an increasing Fermi surface orbit area with $B_{\parallel}$, in good agreement with theoretical predictions.

1. Introduction

Coupled double quantum well (DQW) systems have shown interesting transport properties under the application of an in-plane magnetic field, $B_{\parallel}$. Due to the presence of inter-well tunneling, $B_{\parallel}$ causes the dispersion curves of the individual QWs to shift in **k**-space, and a partial energy gap to open at their anticrossing point, whose width is given by the symmetric-antisymmetric gap Δ_{SAS} of a balanced DQW at $B_{\parallel}$=0. The Fermi surface (FS) of this unusual system thus continuously evolves from two concentric circular orbits at $B_{\parallel}$=0, to a large hour-glass shaped orbit and a much smaller lens-shaped orbit at higher $B_{\parallel}$. In contrast to the constant density of states (DOS) exhibited by a single 2D electron layer, this system exhibits additional singularities in the DOS at the upper and lower edges of the anticrossing gap. [1] Because the energy position of the anticrossing gap depends on $B_{\parallel}$, the DOS singularities can be made to pass through the chemical potential μ, producing two large features, a minimum followed by a maximum, in the in-plane magnetoresistance. [2] Simmons *et al.* [3] previously measured the cyclotron mass m_c of electrons in the lens orbit by adding a small perpendicular magnetic field $B_{\perp}$ and measuring the dependence of the Shubnikov-de Haas (SdH) oscillations on temperature T. The lens m_c was found to decrease strongly with $B_{\parallel}$, in agreement with theoretical calculations. [4] Lyo has also predicted that, in contrast to the lens orbit, electrons in the hourglass orbit will exhibit an m_c that *increases* with $B_{\parallel}$. [4] However, Simmons *et al.* were unable to reliably determine the m_c of electrons in the large area hourglass orbit over a significant field range, since the hourglass SdH oscillations were obscured by the much stronger SdH oscillations arising from the small area lens orbit.

In this work, we investigate the transport properties of an *extremely* coupled DQW: whereas in almost all DQW systems previously studied Δ_{SAS} was smaller than the Fermi energy E_F, in this work $\Delta_{SAS} > E_F$. Thus at $B_{\parallel} = 0$ the upper energy branch (or anti-symmetric sub-band) is entirely unoccupied. As a result, *for all $B_{\parallel}$ only the lower energy branch, or hour-glass orbit, is occupied*, enabling its transport properties to be readily determined. This system displays markedly different behavior than a system with both branches occupied. (While Millard *et al.* [5] have recently studied a system with only lower branch occupation, the extreme built-in density imbalance between the two QWs makes interpretation of the data much less straightforward.) In contrast to Ref. 3, we find (1) a single peak in the in-plane

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magnetoresistance at high $B_{\parallel}$, (2) an enhancement by more than a factor of two in the cyclotron mass of electrons in the lower branch, and (3) a steadily increasing FS orbit area. These results agree with the predictions of Lyo for a system with only the lower branch occupied.

2. Samples and experimental method

Our sample was grown by molecular beam epitaxy and consisted of two identical 125 Å GaAs quantum wells separated by a 10 Å $Al_{0.3}Ga_{0.7}As$ barrier. Self-consistent Hartree calculations on this structure without gate bias yielded a Δ_{SAS} of 8.5 meV. A metallic top gate was placed over the DQW in order to control the total density *n*. At gate voltage $V_G = 0.0$ V, the total mobility was 9.4 x 10^3 cm^2/Vs, and *n* was 1.2 x10^{11} cm^{-2}, corresponding to an E_F of 4.3 meV. At V_G=0.5 V the total mobility increased to 2.2 x 10^4 cm^{-2}, and *n* became 2.9 x 10^{11} cm^{-2}, increasing E_F to 10.3 meV. Due to the conduction band minima offset, the upper-lower branch energy difference E_{u-l} became 12.8 meV. These values of E_F are both below the calculated E_{u-l}, therefore the upper energy branch is expected to be unoccupied for all $B_{\parallel}$. Fourier analysis of the SdH oscillations in a pure $B_{\perp}$ show only one frequency component, verifying that only one energy branch is occupied. An in-situ sample tilting stage was used to introduce both $B_{\parallel}$ and $B_{\perp}$ components, enabling measurements of m_c. Magnetoresistance measurements were made via standard four terminal low frequency lock-in techniques at temperatures between 0.3 and 10 K.

3. Measurement results and discussion

3.1 In-plane magnetoresistance

Fig. 1(a) shows the in-plane magnetoresistance R_{xx} of the sample as a function of $B_{\parallel}$ for $V_G = 0.0$ V and $B_{\perp} = 0$. While previous work [3] on samples with $\Delta_{SAS} < E_F$ showed two features, a large minimum followed at higher $B_{\parallel}$ by a smaller maximum, this extremely coupled sample exhibits only a single feature, a large maximum, occuring at $B_{\parallel}$ = 10.8 Tesla. The occurence of only a maximum in the in-plane magnetoresistance can be understood by considering the action of $B_{\parallel}$ on the shape of the dispersion

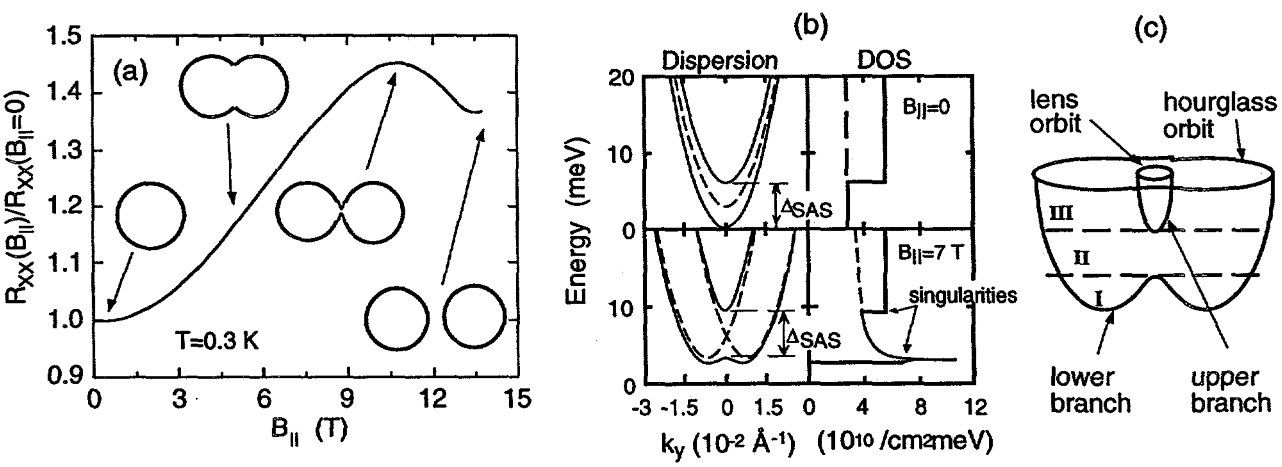

Fig. 1. (a) In-plane magnetoresistance of the extremely coupled DQW. Insets show sketchs of the Fermi surface for different characteristic regions. (b) Sketch of dispersion (left) and density of states (right) for $B_{\parallel}$=0 (top) and $B_{\parallel} \approx 7$ T (bottom). (c) Sketch of dispersion, with the three different Fermi surface cases depending on the position of μ.

curve. Fig. 1(b) shows a sketch of both the dispersion and DOS for our density-balanced coupled DQW, for the two cases $B_{\parallel}$=0 and $B_{\parallel}$≈7 T. At $B_{\parallel}$=0, the symmetric (lower energy branch) and antisymmetric (upper energy branch) dispersions each form identical paraboloids offset by DSAS. The DOS at $B_{\parallel}$=0 is thus constant for each branch. The primary effect of a finite $B_{\parallel}$ is to induce a linear shift $\Delta k_y = edB_{\parallel}/h$ in the canonical momenta of electrons in one QW relative to those in the other, where d is the distance between the electron layers and $B_{\parallel}$ is in the x-direction. The shifted dispersion curves then form an anticrossing gap of width Δ_{SAS}, yielding a highly non-parabolic dispersion. New singularities in the DOS appear at the upper and lower edges of this gap. The shape of the FS is given by the intersection of μ with the dispersion, as illustrated in Fig. 1(c). Three distinctly different cases occur, depending on the energy range in which μ falls: two separated Fermi circles (I); an hour-glass shaped orbit only (II); and both an hour-glass orbit and a much smaller lens-shaped orbit enclosed within it (III). As $B_{\parallel}$ is increased, the gap rises in energy relative to μ. For samples with $\Delta_{SAS}<E_F$, the FS changes from case III to case II, and finally to case I. The magnetoresistance features occur at the two transitions between these three cases. When the upper edge of the energy gap crosses μ, a magnetoresistance minimum occurs. This is because a step decrease in the DOS exists at this point, causing an abrupt decrease in the available scattering states as electrons empty out of the lens orbit. [1,2] At higher $B_{\parallel}$ the lower edge of the energy gap crosses μ. Because the lower gap edge is a saddle point in the dispersion, a logarithmic singularity in the DOS exists here, all of whose states have zero Fermi velocity. Electrons are thus rapidly scattered into these non-current-carrying states, producing a magnetoresistance maximum. In the extremely coupled DQW investigated here, however, $\Delta_{SAS} > E_F$. Thus μ never resides in region III, causing the upper energy branch to be unoccupied for all $B_{\parallel}$ and yielding only a single feature in the magnetoresistance, a maximum corresponding to the lower gap edge crossing μ.

Using the model of Ref. 2 and assuming balanced densities in the two QWs, we estimate the $B_{\parallel}$ at which we expect the maximum to occur. The lower edge of the anticrossing gap will cross m when the the momentum offset Δk_y is such that the undistorted QW dispersion curves cross at an energy $E_F + \Delta_{SAS}/2$. Hence $edB_{\parallel}/h = 2[2m^*(E_F+\Delta_{SAS}/2)]^{1/2}/h$. Using d = 135 Å, this yields a position of $B_{\parallel}$ = 11.9 T, differing by only 10% from the experimental value.

3.2 Cyclotron mass

In order to measure m_c, the sample was rotated to θ=10° from a purely $B_{\parallel}$ so as to introduce a small $B_{\perp}$. For several different T, sweeps of total field B_T were then performed, resulting in simultaneous variation of $B_{\perp} = B_T\sin\theta$ and $B_{\parallel} = B_T\cos\theta$. The mass measurement was performed for both V_G=0.0 V and 0.5 V. Following Simmons *et al.* [3], m_c was extracted from the T-dependence of the SdH oscillation amplitude using a form of the Ando formula, $\Delta R(T)/\Delta R(T_0) = T\sinh[\beta T_0(m_c/m_0)/B_{\perp}] \;/\; T_0\sinh[\beta T(m_c/m_0)/B_{\perp}]$. Here $\Delta R = R(B_{\perp}) - R(B_{\perp}=0)$, T_0 is the base temperature, $\beta = 2\pi^2 k_B m_0/he$ and m_0 is the free electron mass.

Fig. 2(a) shows fits of this expression to the measured $\Delta R(T)/\Delta R(T_0)$ for $B_{\parallel}$ = 4.2 and 9.7 T, at V_G=0.5 V, with m_c the only fit parameter. At 4.2 T the extracted value of $m_c = 0.069\ m_0$ is very close to that of bulk GaAs, $m^*_{GaAs} = 0.067\ m_0$. However, at 9.7 T we find that m_c has increased to 0.113 m_0, or ~1.7 times m^*_{GaAs}. Repeating this procedure for several SdH extrema, in Fig. 2(b) we show m_c as a function of $B_{\parallel}$ for the two V_G values. For V_G=0.5 V, m_c increases monotonically to ~1.7 times m^*_{GaAs}, while for V_G=0 V mc reaches a value over 2.2 times m^*_{GaAs}. This is contrast to previous work, in which the lens orbit m_c *decreased* monotonically with $B_{\parallel}$, and the hourglass orbit m_c could not be fully determined. In the present work the absence of the lens orbit enables the ready determination of the hourglass m_c over a broad field range. Our data agrees well with the theory of Lyo for a DQW with only lower-branch occupation, as shown by tight-binding calculations for our sample (solid lines). [4]

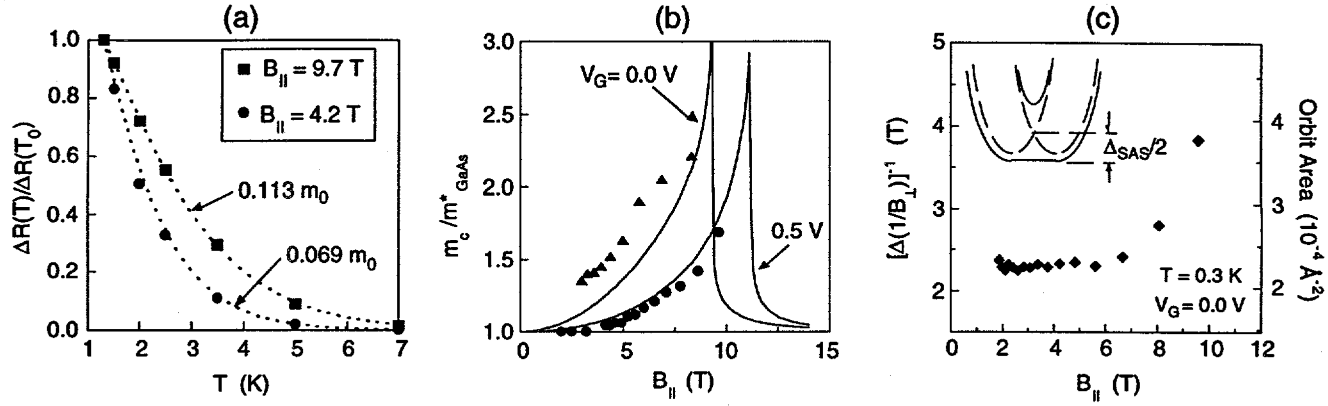

Fig. 2. (a) Amplitude of SdH oscillations vs. temperature at $B_{\parallel}$=4.2 and 9.7 T. Dotted lines show fits to the Ando formula, yielding m_c=0.069 and 0.113 m_0 respectively. (b) Summary of mass data vs. $B_{\parallel}$ for V_G= 0 V (triangles) and 0.5 V (circles). Lines show theory. (c) Area of hourglass orbit vs. $B_{\parallel}$. Inset shows condition under which saddle point begins to form.

Although we could not reliably extract m_c for $B_{\parallel} > 10$ T, we expect that at higher $B_{\parallel}$ the lower gap edge would cross μ, causing m_c to return to the bulk GaAs value. This has been observed in Ref. 5.

3.3 Fermi surface orbit area

We also measured the $B_{\parallel}$-dependence of the area in **k**-space of the hourglass orbit, given experimentally by $A = (2\pi e/h)[\Delta(1/B_{\perp})]^{-1}$, where $\Delta(1/B_{\perp})$ is the reciprocal spacing of the extrema of the SdH oscillations. In Fig. 2(c) we plot A as a function of $B_{\parallel}$ for V_G=0. The data shows a nearly constant area until about 7 T, after which it increases rapidly. At 9.7 T, A reaches a value over 60 % larger than at 2 T. This increase in A with $B_{\parallel}$ is in agreement with our picture of a system with lower branch occupation only. The hourglass orbit is elongated by the action of $B_{\parallel}$, causing a corresponding increase in the area. Again, this is in contrast to the previous measurements of Simmons *et al.*, [3] which allowed measurement of only the lens orbit area, since its strong oscillations obscured those of the hourglass orbit. In that work, the lens orbit area was shown to *decrease* with $B_{\parallel}$. We note that the hourglass orbit's area remaining relatively constant until ~7 T is also consistent with a large Δ_{SAS}: although the orbit will change *shape* at small values of $B_{\parallel}$, its area will not change significantly until the saddle point begins to develop. Roughly, this will occur when the momentum offset Δk_y is such that the two undistorted QW dispersion curves cross at an energy $\Delta_{SAS}/2$ above the dispersion minimum. That is, $\Delta k_y = edB_{\parallel}/\hbar = 2[m^*\Delta_{SAS}]^{1/2}/\hbar$. For Δ_{SAS}=8.5 meV, this expression yields 8.5 T, in fair agreement with the data.

References

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