RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 43, NUMBER 15 15 MAY 1991-II

Measurement of Fermi-surface distortion in double quantum wells from in-plane magnetic fields

G. S. Boebinger, A. Passner, L. N. Pfeiffer, and K. W. West
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 1 February 1991)

In double quantum wells with interwell tunneling, we find that a small in-plane magnetic field substantially alters the beating observed in Shubnikov–de Haas oscillations. This phenomenon is attributed to distortion of the Fermi surface due to mixing of the symmetric and antisymmetric double-well states. The measured magnitude of the distortion is in good quantitative agreement with a calculation of the symmetric and antisymmetric mixing from the in-plane magnetic field.

Fabrication of multiple two-dimensional (x,y) electron layers in close proximity is one technique to control the introduction of degrees of freedom associated with the third dimension (z). The double quantum well (DQW) is a simple multilayer structure which retains two attractive features of the single heterojunction: (i) high electron mobilities due to remotely positioned donors and (ii) external gate-bias control of the electron density in each two-dimensional layer. In a DQW, unlike a single heterojunction, the electrons have one more degree of freedom: they can occupy the left or right well states or (in the presence of interwell tunneling) the symmetric or antisymmetric states. Control of this additional degree of freedom comes primarily through the fixed height and width of the interwell barrier, which determines not only the energy gap between symmetric and antisymmetric states but also the strength of interwell Coulomb interactions.

As a result, several interesting Coulombic effects have recently been observed in DQWs. In particular, it has been found that large magnetic fields perpendicular to the wells are capable of destroying the energy gap between the symmetric and antisymmetric states[1] This phenomenon, observed in the regime of quantized Hall states has been attributed to Coulomb-driven interwell electron-density fluctuations,[2,3] and thus relies critically on the presence of the DQW degree of freedom. Also, frictional drag between two isolated layers of a DQW has been measured; a current constrained to flow in one well induces a voltage in the opposite well. The induced voltage is found to be in qualitative agreement with calculations of interwell Coulomb scattering.[4]

In this paper, we demonstrate that magnetotransport in double quantum wells with interwell tunneling is dramatically altered by application of an in-plane magnetic field, $B_{\parallel}$. The in-plane field mixes the symmetric and antisymmetric electron states and thereby distorts the Fermi surfaces of the double quantum well. We are able to measure this distortion through shifts in the beating of the Shubnikov–de Haas oscillations in a small perpendicular magnetic field, $B_{\perp}$. Quantitative agreement is found with a calculation of the symmetric and antisymmetric mixing resulting from the in-plane magnetic field.

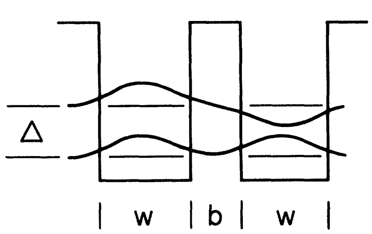

FIG. 1. Symmetric and antisymmetric states of the double quantum wells.

The data are from two DQW samples consisting of nominally identical quantum wells separated by barriers of different widths. The samples are grown by molecular-beam epitaxy and consist of two GaAs wells of width $w=140$ Å, separated by a $Al_{0.3}Ga_{0.7}As$ barrier of thickness $b=28$ or 40 Å (see Fig. 1). The electrons are provided by remote δ-doped donor layers ($N_{Si}=6\times10^{11}$ cm^{-2}) set back from each side of the DQW by 500–600-Å-thick $Al_{0.3}Ga_{0.7}As$ spacer layers. The data are taken at $T=0.3$ K in a superconducting magnet using standard lock-in techniques at $f=10$ Hz.

As demonstrated explicitly in Ref. 5, application of an external gate bias can bring the electron densities in each well into balance. In this balanced condition, there is substantial interwell tunneling for these samples. The two eigenfunctions are the symmetric and antisymmetric DQW states separated by an energy gap Δ (see Fig. 1). Table I contains the gap Δ, the electron density per well n ($2n$ is the total electron density), and the electron mobility μ, at $T=0.3$ K for the two samples. For all data presented in this paper, the electron density in the two wells is balanced.[6]

The higher electron density in the symmetric state, compared to the antisymmetric state, results in a beating of the Shubnikov–de Haas oscillations in the longitudinal resistance R_{xx} vs $B_{\perp}$, as shown in the top panel of Fig. 2 for the $b=40$ Å sample. The nodes (arrows in Fig. 2) occur when phases of the oscillations from the two elec-

TABLE I. Sample parameters.

b (Å)	Δ (K)	N (cm^{-2})	μ (cm^2/V s)
28	17.3	2.1×10^{11}	0.74×10^{6}
40	8.1	2.0×10^{11}	1.00×10^{6}

tron states differ by an odd multiple of π:

$$\pi h n_1/eB_\perp = \pi h n_2/eB_\perp + j\pi , \qquad (1)$$

where j is an odd integer and $n_{1,2}$ are the electron densities in the two states. It follows that the node positions for a given density difference of the two electron states, $\delta n = n_1 - n_2$, are

$$B_{\perp,j} = h\delta n/je . \qquad (2)$$

The nodes in the top trace of Fig. 2 represent the $j=3$ and $j=5$ nodes and yield a value $\delta n = 0.21\times10^{11}$ cm^{-2} for the $b=40$ Å sample. This measured value of δn is in excellent agreement with a value of $\delta n = (\Delta/E_F)n$, calculated using $\Delta=8.1$ K, and $E_F=77.2$ K which result from a self-consistent solution of the one-dimensional Schrödinger equation including the Hartree potential for this sample. Similarly, good agreement is found for the $b=28$ Å sample.[1]

To study the Fermi-surface distortion resulting from an in-plane magnetic field, ideally one would apply a fixed in-plane field, $B_\parallel$, while sweeping the perpendicular field, $B_\perp$. Instead, we recorded a series of traces of R_{xx} vs B_{total} with the plane of the quantum wells tilted at a fixed angle θ, relative to the total magnetic field. On each sample, 50 traces were recorded from $\theta=0°$ to $\theta\sim80°$ at angular intervals ranging from 6° (at small angles) to $\sim0.5°$ (at large angles). The resulting array of data on a given sample is sufficiently dense to extract a trace of R_{xx} vs $B_\perp$ for fixed $B_\parallel$. Examples of these traces from the $b=40$ Å sample are given in Fig. 2 for various $B_\parallel$.

Figure 3 contains the $B_\perp$ node positions (arrows in Fig. 2) versus $B_\parallel$ for both the (a) $b=28$ Å and (b) $b=40$ Å samples. Note that the nodes shift to higher $B_\perp$ as the in-plane magnetic field increases. From Eq. (2), we conclude that the in-plane magnetic field is increasing the density difference between the two occupied electron states.

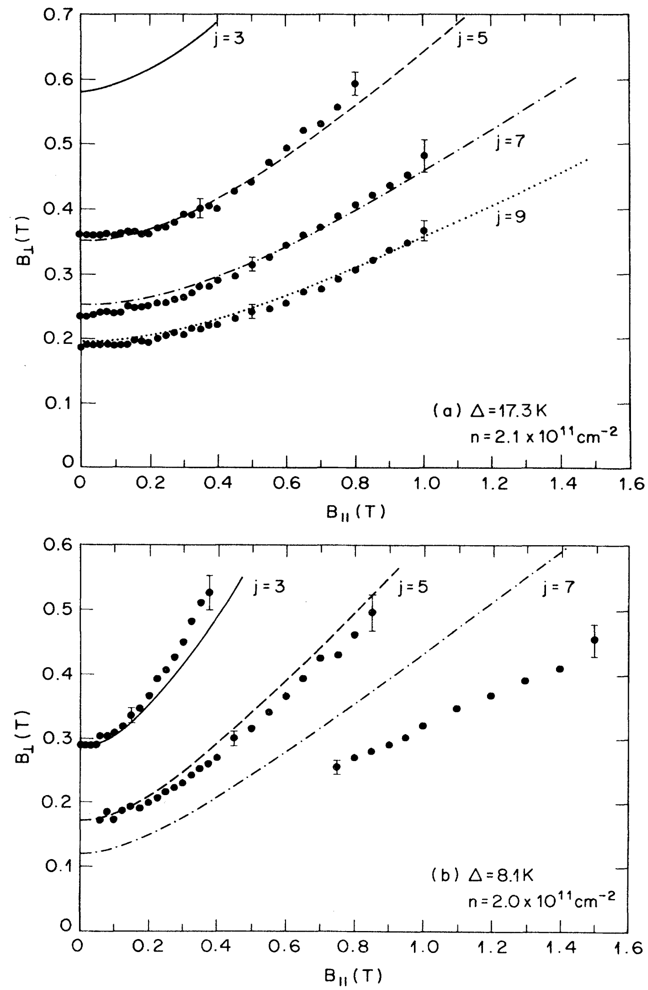

FIG. 3. Node positions (arrows in Fig. 2) as function of $B_\parallel$ for samples with barrier thickness of (a) $b=28$ Å and (b) $b=40$ Å. The lines are calculated node positions as described in the test [j refers to Eq. (2)].

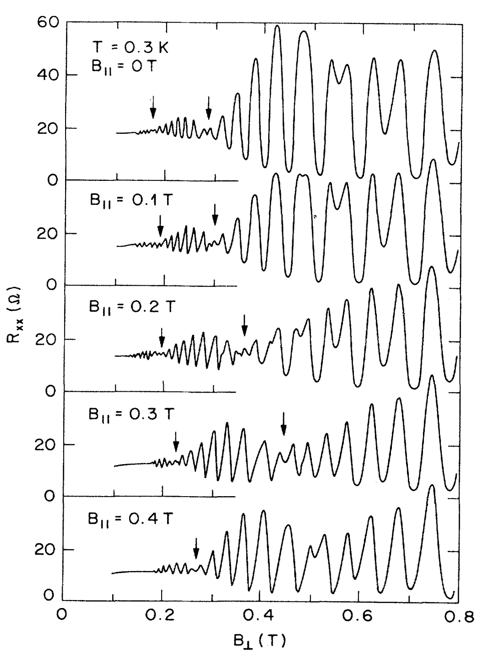

FIG. 2. Beating in the Shubnikov–de Haas oscillations for a different fixed in-plane magnetic field, $B_\parallel$. Arrows indicate the node positions plotted in Fig. 3.

To gain a quantitative understanding of the data of Figs. 2 and 3, consider the DQW Hamiltonian with an in-plane magnetic field, $\mathbf{B}=(B_\parallel,0,0)$ in the Landau gauge, $\mathbf{A}=(0,-zB_\parallel,0)$:

$$\mathrm{H} = \frac{\hbar^2k_x^2}{2m^*} + \frac{\hbar^2}{2m^*}\left(k_y - \frac{ezB_\parallel}{c\hbar}\right)^2 - \frac{\hbar^2\delta_z^2}{2m^*} + V(z) , \qquad (3)$$

where $V(z)$ is the confining DQW potential which includes the Hartree potential self-consistently. In this calculation, we ignore the small perpendicular magnetic field and discuss the limitations of this approximation near the end of the paper.

The contribution to the Hamiltonian from $B_\parallel$ is

$$\mathrm{H}_\parallel = -\hbar\omega_\parallel k_y z + (m^*/2)\omega_\parallel^2 z^2 , \qquad (4)$$

where $\omega_{\parallel}=eB_{\parallel}/m^*c$ is the cyclotron frequency associated with the in-plane magnetic field. We use the two-state basis of the occupied symmetric and antisymmetric DQW states, which are the eigenfunctions of the final two terms of Eq. (3) with energies $\varepsilon_{\mathbf{k}}\pm\Delta/2$, where $\varepsilon_{\mathbf{k}}$ is the in-plane kinetic energy. Note that the second term of Eq. (4) does not mix the symmetric and antisymmetric states and contributes only an overall energy shift with no observable effect. Diagonalization of the secular equation associated with the first term of Eq. (4) yields the following eigenvalues:

$$\varepsilon_{1,2}=\varepsilon_{\mathbf{k}}\pm[\Delta^2/4+(\hbar\omega_{\parallel}k_yz_0)^2]^{1/2}\,, \qquad (5)$$

where $\varepsilon_{\mathbf{k}}=\hbar^2(k_x^2+k_y^2)/2m^*$ and $z_0=\langle\Psi_{\text{symm}}|z|\Psi_{\text{antisymm}}\rangle \gtrsim(b+w)/2$. The k_y dispersion relations of Eq. (5) are plotted in the bottom panels of Fig. 4 for $B_{\parallel}=0$ and $B_{\parallel}=1.5$ T. Note from Eq. (5) that the k_x dispersion relations remain parabolic, independent of $B_{\parallel}$.

We summarize the effects of the in-plane magnetic field: Eq. (3) and Fig. 4 show that the two parabolic k_y dispersions are shifted by $\pm ez_0B_{\parallel}/c\hbar$. In addition, the interwell tunneling removes any degeneracy between the two electron states by opening an energy gap of size Δ. Thus, for $B_{\parallel}=0$, tunneling lifts the degeneracy at all k_y. In contrast, once $B_{\parallel}\neq 0$, the only degeneracy to be removed is at $k_y=0$, where the eigenstates remain the unperturbed symmetric and antisymmetric states. As $|k_y|$ increases, the eigenstates tend increasingly toward the left and right single quantum-well states.

In this sense, the in-plane magnetic field acts as an effective electric field applied in the z direction, with a magnitude that is proportional to $k_yB_{\parallel}$. Note that $B_{\parallel}$ gives rise to an interesting trajectory for an electron in a $B_{\perp}$-induced cyclotron orbit. If $B_{\parallel}=0$, this electron would occupy the symmetric state and follow a circular orbit in the plane of the DQW. Once $B_{\parallel}\neq 0$, however, the orbiting electron occupies the symmetric state only when $k_y=0$. As k_y becomes positive, a field $B_{\parallel}\gtrsim 0.5$ T is sufficiently large to push the electron entirely into one well. The orbiting electron returns to the symmetric state as k_y becomes zero, only to be pushed entirely into the opposite well when k_y becomes negative.

The in-plane magnetic field also distorts the cylindrical Fermi surfaces of the DQW. By numerically integrating the density of states resulting from the dispersion relations of Eq. (5), we determine the Fermi energy (dotted lines in Fig. 4) and Fermi surfaces for the two DQW eigenstates (plotted in the top panels of Fig. 4). The Fermi-surface cross-sectional areas yield a calculated electron-density difference, δn from which Eq. (2) yields the expected node positions in the Shubnikov-de Haas oscillations. These $B_{\perp,j}$ are plotted as the lines in Fig. 3 for the indicated odd-integer values of j. The agreement is quite good with no adjustable parameters for the data from the $b=28$ Å sample. However, it is less satisfying for the $b=40$ Å data, most likely because the calculation has ignored the presence of a perpendicular magnetic field.

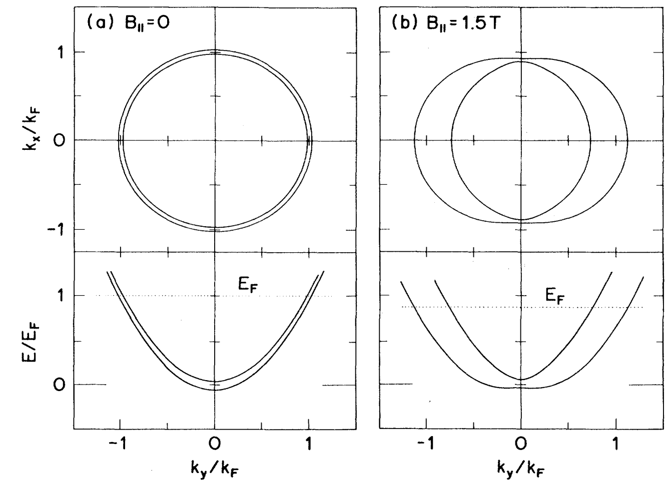

FIG. 4. Calculated Fermi surfaces (top panels) and dispersion relations (bottom panels) for an in-plane magnetic field of (a) $B_{\parallel}=0$ and (b) $B_{\parallel}=1.5$ T for the $b=40$ Å sample. E_F (dotted lines) are the Fermi energies calculated from numerical integration of the density of states. The closed curves of the Fermi surface give the electron cyclotron orbits in k space.

We expect our calculation to become inadequate once the cyclotron energy associated with the perpendicular magnetic field becomes comparable to Δ (which occurs at $B_{\perp}\sim 0.9$ T for $b=28$ Å and $B_{\perp}\sim 0.4$ T for $b=40$ Å). In this regime, the symmetric and antisymmetric states have broken into discrete Landau levels which are coupled by the in-plane magnetic field. At a fixed $B_{\perp}$, the inter-Landau-level coupling (and, hence, the expected deviation from our calculation) will increase as $B_{\parallel}$ increases.

Of course, even for $B_{\perp}=0$, our calculation breaks down once $B_{\parallel}$ is sufficiently large so that the corresponding cyclotron-orbit diameter becomes comparable to the well width, $2l=2(\hbar c/eB_{\parallel})^{1/2}\sim w$ ($B_{\parallel}\sim 14$ T for our samples). A larger $B_{\parallel}$ would mix in higher quantum-well subbands[7] and create edge states within the individual quantum wells.[8]

To summarize, we find that the additional electron degree of freedom offered by the double quantum well yields substantial changes in magnetotransport upon application of a fixed in-plane magnetic field. Observations of beating Shubnikov-de Haas oscillations probe the resulting distortion of the Fermi surface of the double quantum well. A calculation with no adjustable parameters, which is applicable in a well-defined regime of a small applied magnetic field, is found to be in good agreement with the observations made in this regime.

We thank P. M. Platzman, A. H. MacDonald, Jun Hu, and J. P. Eisenstein for valuable interactions.

[1]G. S. Boebinger, H. W. Jiang, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **64**, 1793 (1990).

[2]A. H. MacDonald, P. M. Platzman, and G. S. Boebinger, Phys. Rev. Lett. **65**, 775 (1990).

[3]Luis Brey, Phys. Rev. Lett. **65**, 903 (1990).

[4]T. J. Gramila, J. P. Eisenstein, A. H. MacDonald, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **66**, 1216 (1991).

[5]G. S. Boebinger, in *High Magnetic Fields in Semiconductor Physics III,* edited by G. Landwehr, Springer Series in Solid-State Sciences (Springer-Verlag, Berlin, in press).

[6]If the in-plane current is applied perpendicular to the in-plane magnetic field, $B_{\parallel}$, the Lorentz force could drive a Hall voltage and set up a density imbalance between the two wells. In fact, this effect is vanishingly small; experiments with $I \perp B_{\parallel}$ and $I \parallel B_{\parallel}$ yield indistinguishable results.

[7]Subband mixing has been studied in a single heterojunction: D. R. Leadley, R. J. Nicholas, J. J. Harris, and C. T. Foxon, in *Proceedings of the 20th International Conference on Physics of Semiconductors, Thessaloniki, Greece, 1990,* edited by E. M. Anastassakis and J. D. Joannopoulos (World Scientific, Singapore, 1990), Vol. 2, pp. 1609-1612.

[8]Edge states have been studied in single-barrier tunneling: 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).