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GIANT EFFECTIVE MASS DEVIATIONS NEAR THE MAGNETIC FIELD-INDUCED MINIGAP IN DOUBLE QUANTUM WELLS

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ABSTRACT

We report major deviations in the electron effective mass m^* near the partial energy gap, or minigap, formed in strongly coupled double quantum wells (QWs) by an anticrossing of the two QW dispersion curves. The anticrossing and minigap are induced by an in-plane magnetic field $B_{||}$ and give rise to large distortions in the Fermi surface and density of states, including a Van Hove singularity. Sweeping $B_{||}$ moves the minigap through the Fermi level, with the upper and lower gap edges producing a sharp maximum and minimum in the low-temperature in-plane conductance, in agreement with theoretical calculations. The temperature dependence of Shubnikov-de Haas (SdH) oscillations appearing in a tilted magnetic field yield a decreased $m^* \leq 1/3 m_{GaAs}^*$ near the upper gap edge, and indicate an increase in m^* near the lower gap edge.

In a double quantum well (DQW) system, a magnetic field $B_{||}$ applied parallel to the plane of the QWs shifts the canonical momenta of electrons in one well with respect to those in the other well. When $B_{||}$ and the QW coupling are sufficiently strong, the dispersion curves produce an anticrossing, resulting in a minigap.¹ The minigap is passed through the Fermi level by sweeping $B_{||}$. The electronic density of states and group velocities are dramatically distorted near the edges of the minigap; this results in the appearance of sharp features in the in-plane conductance $G_{||}(B_{||})$.^{2,3} The distortion of the Fermi surface is also expected to result in dramatic changes in the electron effective mass $m^*(B_{||})$. Our measurements of $m^*(B_{||})$ through the temperature dependence of the Shubnikov-de Haas (SdH) oscillation amplitudes show a decrease in m^* by more than a factor of three for electrons near the upper edge of the minigap, and indicate an increase in m^* near the lower minigap edge.

An MBE-grown structure, consisting of a modulation-doped pair of GaAs QWs of equal width $w=150$ Å separated by an $Al_{0.3}Ga_{0.7}As$ barrier of thickness $t=25$ Å, was studied. Each QW had a density of $n \approx 1.5 \times 10^{11} \text{ cm}^{-2}$ and a mobility $\mu \approx 2.5 \times 10^5 \text{ cm}^2/\text{V-s}$. Standard four-terminal low-frequency lock-in measurements were performed on a 0.2 mm wide Hall bar, with the excitation current flowing in a direction parallel to $B_{||}$. Measurements were done at 12 different temperatures ranging from 0.5 K to 3.0 K in a

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^3He cryostat. The SdH measurements required a magnetic field $B_{\perp}$ perpendicular to the growth plane, while $B_{\parallel}$ was needed to move the minigap through the Fermi level. This experimental configuration was achieved by mounting the sample in a uniform magnetic field B_T at a small angle θ from parallel, with rotation *in situ* possible. The angles $\theta=0.0, 2.5, 3.0$, and 3.5° were studied.

Fig. 1 shows $G_{\parallel}(B_{\parallel})$ for $\theta=0^\circ$. A sharp maximum appears at $B_{\max} = 5.9$ T, followed by a sharp minimum at $B_{\min} = 6.5$ T. The maximum and minimum correspond respectively to the upper and lower edges of the minigap crossing the Fermi level. The origin of these features can be understood with the results of a tight-binding calculation, shown in Fig. 2, for a DQW structure with $w = 140$ Å, $t = 60$ Å, and unequal QW depths of 280 and 277 meV. (These parameters, while somewhat different from those of the experiment, illustrate the essential physics nicely.) The left column shows the two lowest eigenenergies $\epsilon_{\pm}(k_y)$, the middle column the density of states $D(E)$, and the right column a sketch of the Fermi surface for chemical potential $\mu = 5$ meV. The three rows are (a) $B_{\parallel}=0$ T, (b) 2 T, and (c) 6 T. At $B_{\parallel}=0$ the $\epsilon_{\pm}(k_y)$ curves are parabolic and $D(E)$ is constant for each energy branch, with the energy splitting mainly due to the unequal QW depths. The other two $B_{\parallel}$ values were chosen so that with no coupling the Fermi circles touch tangentially on the inside and outside, respectively, at the same $\mu \approx 5$ meV. This corresponds to $\Delta k_y = k_1 \pm k_2$, where k_1 and k_2 are the Fermi wavevectors of the top and bottom QWs. When coupling is present, these two cases exhibit two types of anticrossing: In the first, at 2 T, the slopes of $\epsilon_{\pm}(k_y)$ deviate but do not change sign, changing the group velocity near the anticrossing only slightly. No minigap appears, and the slight changes in $D(E)$ due to each energy branch cancel one another.

In the second type of anticrossing, at 6 T, the slopes of $\epsilon_{\pm}(k_y)$

FIG. 1. Normalized $G_{\parallel}$ vs. $B_{\parallel}$ showing effect of the anticrossing.

FIG. 2. Calculated dispersion $\epsilon(k_y)$ (left); calculated density of states $D(E)$ (middle) for lower energy branch (dotted line) and both energy branches (solid line); and sketch of Fermi surface for $\mu \approx 5$ meV (right); for $B_{\parallel}=(a)$ 0 T, (b) 2 T, and (c) 6 T.

change sign, and a minigap of width E_G appears. E_G is insensitive to $B_{\parallel}$ and $\approx \Delta_{SAS}$, the $B_{\parallel} = 0$ symmetric-antisymmetric gap existing when the QW depths (densities) are equal. At the upper gap edge the dispersion is nearly parabolic and a sharp step-like reduction appears in $D(E)$. States at the upper gap edge have low velocities and contribute little current, yet make significant contributions to the scattering rates of electrons elsewhere on the Fermi surface. As $B_{\parallel}$ increases, pushing the upper gap edge through μ , electrons are no longer scattered into these states, yielding a sharp decrease in scattering and producing the observed maximum in $G_{\parallel}$. The lower gap edge, by contrast, has a saddle-shaped dispersion $\epsilon(k_x, k_y) = \epsilon_0 + (\hbar k_x)^2/2m^* - (\hbar k_y)^2/2m'$, where ϵ_0 is the saddle-point energy, and m' is determined by the saddle-point curvature. This type of dispersion produces a Van Hove singularity at ϵ_0 of the form $D(E) \propto -\ln|\epsilon - \epsilon_0|$. Since the saddle point states have zero group velocity, when $B_{\parallel}$ is swept and the lower gap edge passes through μ , electrons are divergently scattered into states that carry no current, yielding the sharp minimum in $G_{\parallel}$.

The effective mass can in one sense be viewed as inversely proportional to the curvature of the dispersion curves. With this in mind, we would expect deviations in the transverse m^* due to the anticrossing. When the Fermi level is in the upper branch near the gap a small m^* is expected, while far from the gap $m^*_{GaAs} = 0.07 m_0$, where m_0 is the free electron mass, is expected because the dispersion curves are not distorted by the anticrossing. The situation is more complicated at the saddle-point where $\epsilon(k_x, k_y)$ bends down in the k_y -direction and curves up in the k_x -direction, yielding negative off-diagonal mass components.

The experimental arrangement did not permit $B_{\parallel}$ and $B_{\perp}$ ($\ll B_{\parallel}$) to be swept independently, therefore the SdH oscillations were mixed with the anticrossing features of Fig. 1. To partially remove this mixing, $\Delta R(B_{\parallel}, \theta) = R(B_{\parallel}, \theta) - R(B_{\parallel}, \theta=0)$ was studied. Fig. 3 shows $\Delta R(B_{\parallel}, \theta=3.0^\circ)$ for several temperatures. The SdH oscillations are uniform up to ≈ 6.0 T; then both the period in $1/B_{\perp}$ and the oscillation amplitudes change significantly. This indicates that the effective $m^*(B_{\parallel})$ is going through drastic changes. To determine $m^*(B_{\parallel})$, the oscillation amplitudes at a given $B_{\parallel}$ are fit to the equation:⁴

$$\frac{A(T)}{A(T_0)} = \frac{T \sinh(\beta T_0 (m^*/m_0)/B_{\perp})}{T_0 \sinh(\beta T (m^*/m_0)/B_{\perp})} \quad (1)$$

where $A(T)$ is the oscillation amplitude, determined by taking $\Delta R_{\text{peak}} - \Delta R_{\text{valley}}$ and subtracting the linear background, $B_{\perp} = B_T \sin \theta$ is the field at which $A(T)$ is used, T_0 is the base T of 0.5 K, and $\beta = 2\pi^2 k_B m_0 / \hbar e$. Two

FIG. 3. Plot of $\Delta R(B_{\parallel}, \theta=3.0^\circ)$ vs. $B_{\parallel}$ for several temperatures. The SdH oscillations are uniform up to ≈ 6 T, then change amplitude significantly. Inset shows experimental setup.

FIG. 4. Plot shows fit of SdH amplitude data to Eq. (1) for $\theta=3.0^\circ$ for two $B_\perp$ values.

FIG. 5. m^* vs. $B_\parallel$ for three angles θ . Dotted line is GaAs m^* , solid line is $G_\parallel(B_\parallel)$.

typical fits to this equation are shown in Fig. 4. The fits are quite good; with the lower mass fits having smaller error.

Fig. 5 shows m^* plotted versus $B_\parallel$. At low $B_\parallel$, m^* is significantly lower than m^*_{GaAs} , and decreases as $B_\parallel$ approaches the anticrossing, reaching $0.025 m_0$ near the bottom of the upper branch. Near the saddle point $m^* \approx 0.095 m_0$ and decreases rapidly to m^*_{GaAs} as $B_\parallel$ increases, separating the Fermi circles of the two QWs. The resolution in $B_\parallel$ of our method is given roughly by the $B_\parallel$ -spacing of the SdH oscillations. Thus the technique works well for the $B_\parallel$ ranges where m^* is changing slowly, yielding errors in m^* on the order of 10%. For the single data point at $B_\parallel \approx 6.5$ T, where μ lies in the minigap and m^* is changing rapidly, the error is considerably larger. More accurate m^* measurements in this regime will require the ability to sweep $B_\perp$ independently of $B_\parallel$.⁵

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