Novel critical field in magneto-resistance oscillation of 2DEG in asymmetric GaAs/Al$_{0.3}$Ga$_{0.7}$As double wells measured as a function of the in-plane magnetic field

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We have investigated the magnetoresistance of strongly asymmetric double-well structures formed by a thin Al$_{0.3}$Ga$_{0.7}$As barrier grown far from the interface in the GaAs buffer of standard heterostructures. In magnetic fields oriented parallel to the electron layers, the magnetoresistance exhibits an oscillation associated with the depopulation of the higher occupied subband and with the field-induced transition into a decoupled bilayer. In addition, the increasing field transfers electrons from the triangular to rectangular well and, at high enough field value, the triangular well is emptied. Consequently, the electronic system becomes a single layer which leads to a sharp step in the density of electron states and to an additional minimum in the magnetoresistance curve.

73.20.Dx, 73.40.-c, 73.50.-h

I. INTRODUCTION

A magnetic field $B_{\parallel}$ applied parallel to the quasi-two-dimensional systems of electrons confined in double-well structures is known to couple strongly to the electron orbital motion and to change dramatically the electron energy spectra. The magnetoresistance oscillation observed on coupled double quantum wells represents a striking manifestation of the two distinct van Hove singularities in the $B_{\parallel}$-dependent density of states, corresponding to the depopulation of the antibonding subband at a critical field $B_{\parallel} = B_{c,1}$, and to the splitting of the Fermi see into two separated electron sheets at a second critical field $B_{c,2}$.

The structures investigated here were prepared by inserting a thin Al$_{0.3}$Ga$_{0.7}$As barrier (of a thickness $D$) into the GaAs buffer layer of a standard modulation-doped GaAs/Al$_{0.3}$Ga$_{0.7}$As heterostructure, in a distance $d$ from the interface. The resulting double-well system consists of a nearly rectangular well of a width $d$ and of a triangular well, both coupled through a thin barrier. With a proper choice of growth parameters, one can control the occupancy of the two wells and simultaneously tune the position of two lowest energy subbands (bonding and antibonding). Provided that the majority of electrons is in the bonding subband, it is possible to study the transfer of electrons between the subbands and/or across the barrier separating both wells under the influence of the in-plane magnetic field.

Unlike bilayers realized in conventional double wells or wide single wells, our system is highly asymmetric. At $B_{\parallel} = 0$, the bonding subband electrons, with concentration $n_b$, have a dominant weight in the rectangular well, while the electrons from the antibonding subband, with concentration $n_a$, are more likely to occupy the triangular well. In our samples $n_b > n_a$ and the corresponding Fermi contours are two concentric circles. Applying the in-plane field $B_{\parallel}$ induces a transfer of antibonding electrons to the bonding subband and, therefore, also from the triangular well into the rectangular one. The Fermi contour of the antibonding subband changes its shape and shrinks; at a critical field $B_{c,1}$ it disappears and all electrons occupy only the lowest, bonding subband. The system behaves as a wide single-layer with electrons distributed between the two coupled quantum wells. The magnetoresistance approaches a pronounced minimum (see Fig. 1).

Upon further increasing $B_{\parallel}$, a neck in the peanut-like Fermi contour narrows which, eventually, results into splitting of the contour at $B_{\parallel} = B_{c,2}$. At this second critical field, the system undergoes a transition from a single-layer to a bilayer state, corresponding to a sharp maximum on the magnetoresistance curve (see Fig. 2). Above $B_{c,2}$, electrons of the larger contour have a dominant weight in the rectangular well, while the smaller contour electrons occupy the triangular well. The asymmetry of charge distribution between the two wells increases with $B_{\parallel}$. At a third critical field $B_{c,3}$ all electrons are transferred into the rectangular well and the 2D system re-enters the single-layer state. It is the aim of this paper to study, if the corresponding van Hove singularity in the DOS can be detected on the magnetoresistance curve as well.

In the following sections we establish a correspondence between the van Hove singularity in the DOS at $B_{c,3}$ and a minimum on a measured magnetoresistance curve.

II. EXPERIMENTS

The growth parameters of our GaAs/Al$_{0.3}$Ga$_{0.7}$As have been designed to allow for the detection of expected anomalies within the experimentally accessible range of
in-plane magnetic fields. The structure described here has been grown by MBE with \( d = 39 \) monolayers (11.04 nm) and \( D = 9 \) monolayers (2.55 nm). These parameters are fitted to give the best agreement between the critical fields \( B_{c,1}, B_{c,2} \) determined from experiments and the self-consistent field calculations for measured \( n, n_b \) and \( n_a \). The \( d \) is larger then its nominal value by approximately 10\%, the nominal value of \( D \) was 12 monolayers.

![Graph showing changes induced by parallel magnetic field \( B_\parallel \) in DOS, \( \Delta g/g \), and longitudinal resistivity \( \Delta \rho_{xx}/\rho_{xx} \).](image)

**FIG. 1.** Changes induced by parallel magnetic field \( B_\parallel \) in DOS, \( \Delta g/g \), and longitudinal resistivity \( \Delta \rho_{xx}/\rho_{xx} \).

The magnetoresistance has been recorded at \( T = 0.4 \) K in magnetic fields up to 23 T. The sample of a standard Hall bar geometry has been mounted into a rotating sample holder, allowing to adjust the angle \( \alpha \) between \( B \) and 2DEG plane to any value between the perpendicular (\( \alpha = 90^\circ \)) and parallel (\( \alpha = 0^\circ \)) configurations. In all cases, however, the in-plane of \( B \) was perpendicular to the measuring current. A standard a.c. lock-in technique \( (f = 13 \) Hz \) has been used to simultaneously determine both longitudinal (\( \rho_{xx} \)) and Hall (\( \rho_H \)) resistivities as a function of applied magnetic field. The low-field slope of the Hall resistivity, compared to the slope at \( \alpha = 90^\circ \), has been used to calculate the tilt angle.

The basic characteristics of 2DEG have been extracted from the data taken in perpendicular magnetic fields. The total electron concentration \( n = 3.3 \times 10^{15} \) m\(^{-2} \) was from the low-field Hall resistivity. Measured \( \rho_H \) and \( \rho_{xx} \), give the electron mobility \( \mu_H = 11.6 \) T\(^{-1} \) m\(^2\)V\(^{-1}\)s\(^{-1} \). While the occupancy of two subbands was evident from the Shubnikov-de Haas oscillations, the concentration of electrons in the second (antibonding) subband was apparently very small, causing only a weak modulation of the oscillations originating from the bonding subband. Fourier analysis could therefore reliably provide only the concentration of the bonding electrons \( n_b = 3.0 \times 10^{15} \) m\(^{-2} \). It implies, that only about 9\% of all available carriers resides in the antibonding subband, i.e., in the triangular well in a zero in plane field.

**III. RESULTS AND DISCUSSION**

Longitudinal magnetoresistance of the sample adjusted to nearly parallel configuration \((|\alpha| < 0.1^\circ)\) is presented in Fig. 1 together with the calculated field dependence of the density of states. In addition to the van Hove singularities related to \( B_{c,1} \) and \( B_{c,2} \), there is another minimum on the magnetoresistance curve that can be associated with the third singularity of the density of states at \( B_{c,3} = 7.25 \) T. We were not able to reliably detect the third singularity of the density of states at \( B_{c,3} = 7.25 \) T. Full lines represent results of the theoretical calculation, experimental points have been determined from the \( \rho_{xx}(B) \) curves measured in magnetic fields slightly tilted from the 2D plane \((|\alpha| < 4^\circ)\). Low tilt angles guarantee, that \( B_{c,1} << B_\parallel \), which justifies the approximations used in the calculation. The perpendicular component of the field induces Shubnikov-de Haas (ShH) oscillations and makes it possible to estimate the 2D electron densities. In lowest magnetic fields, \( B_\parallel < B_{c,1} \), only the oscillations arising from antibonding electrons can be seen, which is due to their lower effective mass. Their concentration is, however, very low and only few peaks could be identified on all measured curves. The value of \( B_{c,1} = 5.0 \) T, defined by extrapolation \( n_a \rightarrow 0 \), is therefore less certain. Unlike samples with narrower barriers measured in Ref. 4, we were not able to reliably detect any oscillations, that could be attributed to the "single-layer" regime at \( B_{c,1} < B_\parallel < B_{c,2} \), since here the interval of fields is much narrower.

The oscillations observed at high parallel fields \((B_\parallel > B_{c,2} = 7.25 \) T\) arise from two separated Fermi seas of
electrons with concentrations \( n_{RW} \) and \( n_{LW} \), localized in the right (triangular) and left (rectangular) wells, respectively. Since \( n_{LW} \gg n_{RW} \) and electrons in the triangular well have much larger effective mass, dominant SdH oscillations arise from the left well and the other electrons are responsible only for a weak modulation of the SdH data. Since both concentrations are field-dependent, the observed oscillations are not periodic in \( 1/B_{\perp} \) and Fourier analysis cannot be employed to determine the periods. Instead, following procedure has been used to estimate \( n_{LW}(B_{\parallel}) \) from the curves measured at low tilt angles.

We assume that the concentration \( n_{LW}(B_{\parallel}) \) does not change within one SdH peak. From the known value of \( \alpha \) we find \( B_{\perp} \) and convert the data to the \( \rho_{xx} \) vs \( 1/B_{\perp} \) dependence. We identify the distance between any two subsequent minima with the period in \( 1/B_{\perp} \), calculate corresponding electron concentration and assign it to the position of particular SdH peak on the \( B_{\parallel} \) axis. This procedure gave the experimental points shown in Fig. 2 for three different tilt angles. The discrepancy between data points corresponding to different tilt angles is due to the fact, that SdH peaks are markedly asymmetric and therefore their width cannot be determined unambiguously on the \( 1/B_{\perp} \) scale. The increase of \( n_{LW} \) as \( B_{\parallel} \) approaches \( B_{c,3} \) is, however, evident.

**FIG. 3.** Longitudinal magnetoresistance at smallest tilt angles \( \alpha \). For clarity, middle and uppermost curves have been shifted upwards by 5 \( \Omega \) and 10 \( \Omega \), respectively.

The behavior of the sample above \( B_{c,2} \) is extremely sensitive to the tilt angle. This is illustrated in Fig. 3, where we compare curves for two smallest measured tilt angles with that obtained at \( \alpha = 0^\circ \). For clarity, the upper two curves in the graph have been shifted upwards by 5 \( \Omega \) and 10 \( \Omega \), respectively. At \( \alpha > 1^\circ \), the minimum accompanying \( B_{c,3} \) disappeared.

**IV. CONCLUSIONS**

We have reported on a novel anomaly in the magnetoresistance of an asymmetric double quantum well system exposed to strong magnetic fields parallel to the GaAs/AlGaAs interface. A minimum is observed on the \( \rho_{xx}(B_{\parallel}) \) curve positioned at a new critical field \( B_{c,3} \). This field agrees quantitatively with the calculated singularity in the DOS of the DQW, that accompanies a depletion of the triangular well. Above \( B_{c,3} \), electron system behaves as a single layer 2DEG.

Unlike the lower critical fields \( B_{c,1} \) and \( B_{c,2} \), that have been observed and explained before, the novel critical field is much more sensitive to a proper choice of the growth parameters. It can be observed in experimentally accessible magnetic fields only if the DQW is highly asymmetric in the sense, that the population of the higher, antibonding subband is only a small fraction of the overall electron concentration.

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