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Magnetization of a two-dimensional electron gas with a second filled subband

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We have measured the magnetization of a dual-subband two-dimensional electron gas, confined in a GaAs/AlGaAs heterojunction. In contrast to two-dimensional electron gases with a single subband, we observe non-$1/B$-periodic, triangularly shaped oscillations of the magnetization with an amplitude significantly less than $1\mu_{\mathrm{B}}^{*}$ per electron. All three effects are explained by a field-dependent self-consistent model, demonstrating that the shape of the magnetization is dominated by oscillations in the confining potential. Additionally, at 1 K, we observe small oscillations at magnetic fields where Landau levels of the two different subbands cross.

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When an extra degree of freedom is added to a two-dimensional electron gas (2DEG), many-body interactions can lead to the formation of novel electronic grounds state at the crossings of the different energy levels in the system.[1] Two-dimensional electron gases with crossing energy levels can be realized in a variety of systems with different relative sizes of orbital and spin effects, Coulomb energy, and different coupling between the components. Their study has lead to the discovery of many correlated quantum hall states,[2–4] and much effort is put into unravelling the energy-level structure of these systems.

One way of realizing such a 2D system is to increase the electron density of a III-V 2DEG such that a second subband becomes occupied. Dual-subband systems realized in a quantum well have recently been studied within this context.[5,6] A similar system is the dual-subband 2DEG in a GaAs/AlGaAs heterojunction. In transport studies, the multisubband 2DEG is generally assumed to be a superposition of single 2DEGs: the Landau-level structure is a superposition of Landau fans, separated by the intersubband spacing calculated self-consistently at zero magnetic field.[7,8]

In this paper we study the magnetization M of a dual-subband 2DEG. This is a way to directly probe a thermodynamic property, the chemical potential μ. For two-dimensional systems, the Maxwell relation between M and μ is reduced to a proportionality. Since the Fermi energy E_{F} is equal to μ at low temperatures, the magnetization directly reveals changes in the size as well as the shape of the Fermi energy: $\Delta M=(N/B)\Delta E_{\mathrm{F}}$, where N is the total number of electrons.

The magnetization of multisubband 2DEG's has already attracted some attention, both theoretically[9,10] and experimentally,[11] however, these studies have focussed on very high-density systems with three or more filled subbands. In this regime changes in the energy gap between the subbands can be ignored. In this paper we focus on the effect of the filling of a only a second electronic subband on the Fermi energy.

Quantum oscillations in the magnetization of a single 2DEG are well known to be characterized by strictly $1/B$-periodic sawtoothlike oscillations with an amplitude of 1 effective Bohr magneton (μ_{B}^{*}) per electron.[12–14] Here we will show that this is no longer the case in a multicomponent system. Due to a self-consistent, magnetic-field dependent redistribution of electrons between the subbands inside the heterojunction, the amplitude of the oscillations becomes considerably reduced, the sawtoothlike steps are broadened into triangles, and the $1/B$ periodicity is lost. Additionally we find that extra magnetization minima appear at low temperature at the Landau-level crossings of the two subbands.

We study the magnetization of two samples with different electron densities, realized in GaAs/AlGaAs heterojunctions grown by molecular-beam epitaxy: a single-subband 2DEG (sample 1) and a high-density 2DEG (sample 2) where two electronic subbands are occupied. Sample 1 has a density of 4.8×10^{11} cm^{-2}, and a mobility of 2.2×10^{6} cm^{2}/V s. Our high electron-density sample 2 has a carrier concentration of 8.0×10^{11} cm^{-2} and a mobility of 1.4×10^{6} cm^{2}/V s. Most of the electrons (7.4×10^{11} cm^{2}, deduced from transport measurements on a reference sample) remain in the lowest subband; the small remaining fraction occupies the second subband. The magnetization experiments were performed using a torsional magnetometer with optical angular detection.[15]

Figure 1 shows the magnetization of sample 1, the single-subband 2DEG, as a function of filling factor ($\nu=hn/eB$). It displays oscillations periodic in ν, i.e., $1/B$-periodic oscillations. The steps at the lowest filling factors, where Landau-level broadening has the least influence, are sawtooth shaped, and, with decreasing temperature, the amplitude saturates to 1 μ_{B}^{*} per electron. Although the steps are rather sharp, even at 1.2 K they still have a small, finite width indicating a finite density of states (DOS) in between Landau levels.[14,16]

Apart from the clear steps assigned to the Landau gap at even integer filling factors, at 1.2 K [Fig. 1(b)] additional features appear at odd integer filling factors. They are attrib-

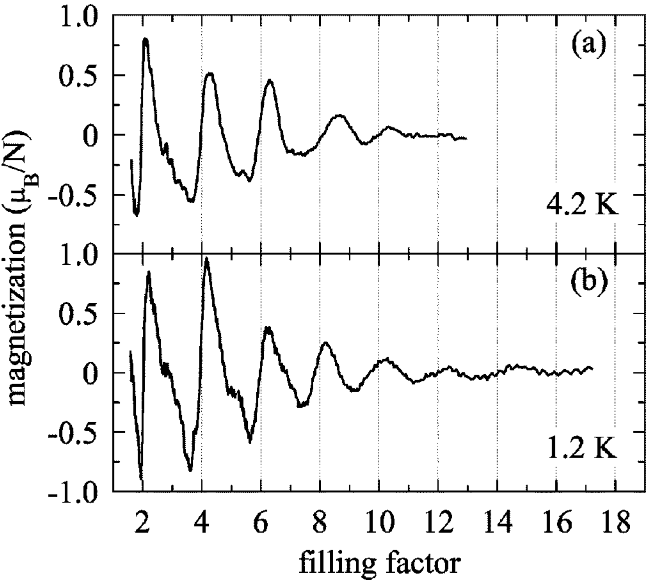

FIG. 1. Magnetization of sample 1 (single 2DEG with $n=4.8\times10^{11}$ cm^{-2}) at 4.2 K (a) and 1.2 K (b). Oscillations are a strictly $1/B$-periodic sawtooth, the amplitude saturates to $1\mu_B^*$ per electron at low ν. Features at filling factors 3 and 5 are related to spin splitting.

uted to the opening of a spin gap, significantly enhanced due to exchange interaction.[17–19]

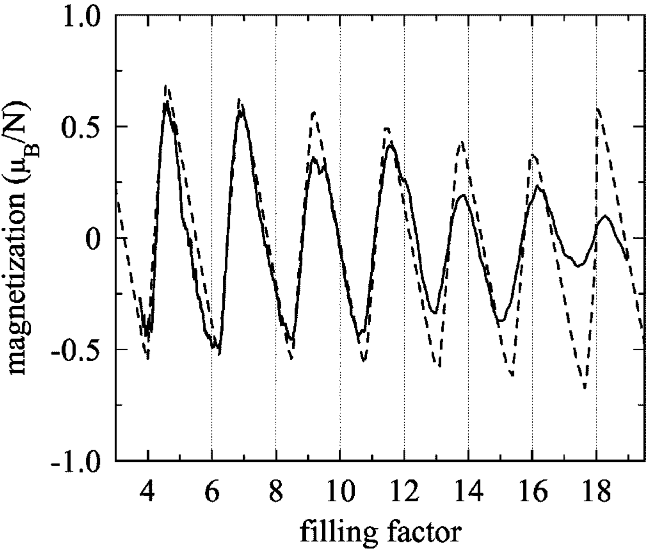

FIG. 2. Magnetization of the dual-subband 2DEG with $n=8.0\times10^{11}$ cm^{-2} at 4.2 K. The dashed line is a self-consistent calculation using a Gaussian Landau-level broadening with $\Gamma=0.2\sqrt{B}$ meV. Note the deviation from $1/B$ periodicity.

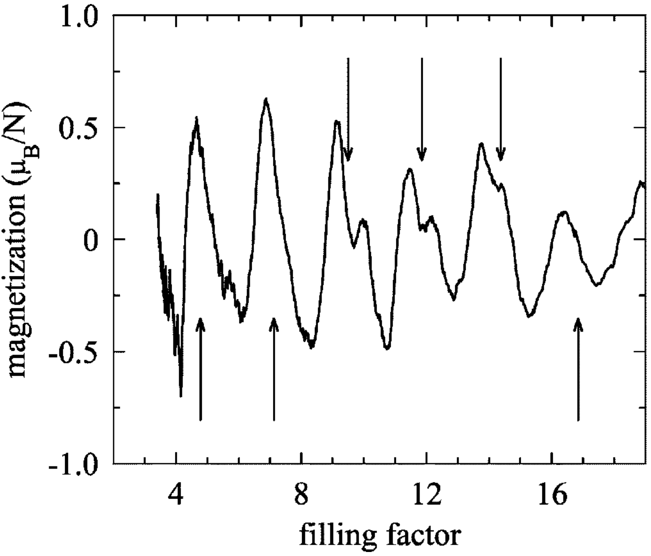

FIG. 3. Magnetization of a dual-subband 2DEG at 1 K. Arrows indicate the positions of Landau-level crossings, additional features can be seen at these positions in intermediate magnetic fields.

The second sample, with two filled subbands, displays the magnetization plotted by the solid line in Fig. 2. The dashed line is a theoretical calculation and will be discussed later. Also, for this sample the magnetization oscillates as a function of inverse magnetic field. Closer inspection of the data, however, reveals three distinct differences compared to the single 2DEG. First, the oscillations are no longer sawtooth-like, but instead they are triangularly shaped. Second, we find that the oscillations are no longer strictly periodic in $1/B$. This becomes clear when we see that while $\nu=4$ coincides with an oscillation minimum, there is an increasing discrepancy, and $\nu=14$ actually coincides with an oscillation maximum. Finally, the amplitude of the oscillation is about $0.5\mu_B^*$ per electron, even for the lowest filling factors. This value is significantly less than the $1\mu_B^*$ per electron observed in Fig. 1(b) for the single 2DEG and it remains at this level even for the lowest temperatures (see Fig. 3).

In order to understand the behavior of the magnetization, it is important to realize that in a heterojunction the confining potential of the 2DEG is formed by the electrons themselves. In a dual-subband 2DEG redistribution of charge over the two subbands can occur when a magnetic field is applied, resulting in a potential that is not fixed as a function of magnetic field. The wave function of the second subband is much more extended than that of the first one, therefore even a small change in its occupation can have profound effects. Since the occupation of the two subbands depends on the magnetic field that quantizes the DOS into Landau levels, and since the shape of the confining potential, the intersubband spacing, and the spacial charge distribution are interdependent, the Schrödinger and Poisson equations have to be solved self-consistently for each value of the magnetic field.[20,21]

In our model we keep the electron density fixed and assume a Gaussian broadened DOS with a width that increases with the square root of the magnetic field. As the (bare) spin splitting is too small to have an effect, it is neglected in the calculations. The Landau-level broadening is our, albeit only, fit parameter. We note that the calculated amplitude decreases with increasing broadening, however, even in the limit of nonbroadened Landau levels, the calculated amplitude of the oscillations is only $0.7\mu_B^*$ per electron.

Using the self-consistent model, we have calculated the Fermi energy as a function of magnetic field, from which the

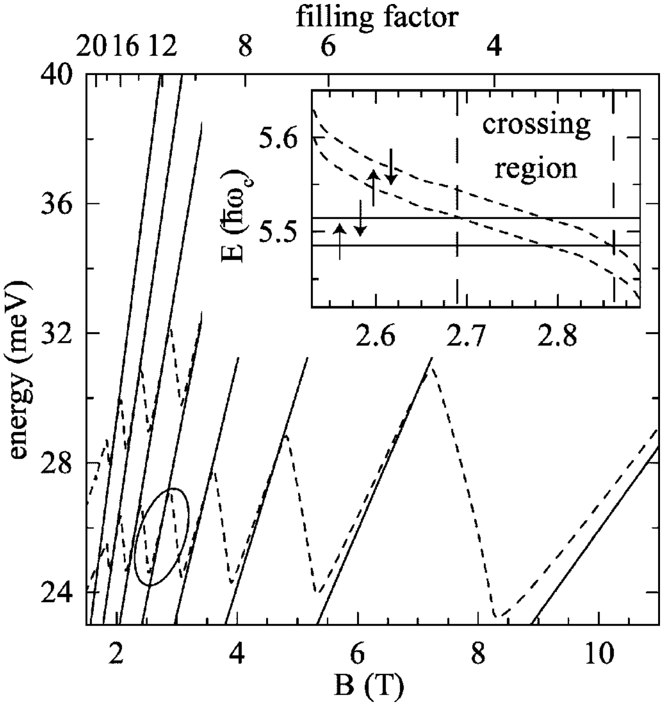

FIG. 4. Landau-level diagram of the dual-subband 2DEG. Solid lines depict levels originating from the lower subband. Dashed lines show the Landau levels of the higher subband. The inset is an enlargement of the circled Landau-level crossing around $\nu=11.9$, normalized to the cyclotron energy.

magnetization follows directly through the Maxwell proportionality. The dashed line in Fig. 2 shows the resulting magnetization for a Gaussian Landau-level broadening with $\Gamma = 0.2\sqrt{B}$ meV. It is in very good agreement with the experimental data as it reproduces all three observed effects: triangular shape, nonperiodicity, and the reduced amplitude.

Inspection of the self-consistent field-dependent modeling of the high-density 2DEG in detail reveals two important points. First, although the number of electrons in the highest subband is small, it remains populated up to high magnetic fields. Second, the shape of the Fermi energy (and thus magnetization) is determined by the oscillations in the intersubband spacing, caused by self-consistent redistribution of electrons over the two subbands. A Landau-level scheme for the dual-subband 2DEG, resulting from the self-consistent model, is depicted in Fig. 4. While levels originating in the lower subband (solid lines) are linear functions of the magnetic field, the Landau levels of the higher subband (dashed lines) oscillate according to the intersubband spacing. Above 1.5 T only the lowest Landau level of the second subband is populated and the Fermi energy lies continuously within it. It can be clearly seen that the oscillations of the confining potential due to the redistribution of the electrons have a large effect on the energy-level structure.

At this stage it is interesting to remark that consequently the width of the magnetization step is mainly caused by this redistribution and not by a finite DOS between two Landau levels as suggested for a single-subband 2DEG.[14,16] Only in the region nearing $\nu=4$ there is, scarcely visible in Fig. 2, a kink followed by a sharp step, whose finite width is related to this small, extra DOS. These features are not at all visible on the other downward slopes, where the width is determined by the electron redistribution, and including the extra DOS does not influence the shape of the calculated Fermi energy.

When reducing the temperature to 1 K, additional minima appear in the 2DEG magnetization (Fig. 3) around filling factor $\nu=9.6$, $\nu=12.0$, and $\nu=14.2$. Interestingly enough these filling factors coincide with positions where two Landau levels originating from the two subbands cross, indicated by down arrows in Fig. 3.

On the flanks of the triangular oscillations a series of crossings occurs between the lowest Landau level of the higher subband and Landau levels with decreasing index of the lower subband as the magnetic field increases (see Fig. 4). The addition of spin splitting to this (single-electron) picture results in energy-level schemes as depicted in the inset of Fig. 4 for one of the crossings. When spin splitting is taken into account, there is not a single level-crossing, but a small region where the levels with different spin consecutively cross each other. In this region spin up and spin-down do not alternate for increasing energy: the two spin-down levels are lowest in energy, the spin-up levels the highest.

Although the Landau levels in Fig. 4 are represented by discrete lines, they are in fact considerably broadened, creating an overlap and giving the electrons some freedom to distribute themselves over the available energy levels. We suggest that this enables electrons to form a novel electronic ground state that is spin polarized in the crossing region. Creation of this polarized state would be favored by the system, because exchange interaction significantly reduces the ground-state energy. When the energy gain exceeds the broadening of the energy levels, the enhanced gap shows up as a minimum in the magnetization.

Although it is evident that at lower magnetic fields (filling factors higher than 14, up arrows indicate the positions of the level crossings) extra structure cannot be seen due to the broadness of the Landau levels, extra structure is also too small to be observed at the Landau-level crossings of the lowest filling factors (up arrows in Fig. 3). Clearly the picture of the crossing region sketched above is not yet complete and further experimental and theoretical investigation of this many-body effect is required.

In summary, we have measured the magnetization of the coupled 2DEGs in a dual-subband 2DEG in a GaAs/AlGaAs heterojunction. We find that the de Haas–van Alphen oscillations are changed in three ways compared to those of the single 2DEG. The shape is triangular, the oscillation amplitude is reduced to $0.5\mu_B^*$, and the oscillations are no longer periodic in $1/B$. This behavior is well described by a self-consistent model, taking into account changes of the confining potential with magnetic field. It shows the shape of the Fermi energy and consequently the magnetization is entirely dominated by the oscillations in this potential due to redistribution of electrons over the two subbands. We observe additional magnetization minima at 1 K, which occur at magnetic fields corresponding to the positions where Landau levels originating in the two different subbands cross. These minima possibly originate from a reduction of the total energy by the formation of a novel, exchange enhanced electronic state at the level crossing.

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