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Breakdown of Shubnikov–de Haas oscillations in a short-period 1D lateral superlattice

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Abstract

Magnetic breakdown is observed in a two-dimensional electron system subject to a strong, atomically precise, one-dimensional potential with a period of 15 nm. The transition from closed to open electron orbits is studied in magneto-transport experiments by continuously changing the Fermi energy of the superlattice within and above the first miniband. Shubnikov–de Haas oscillations quench for Fermi energies close to the miniband gap but recover at higher magnetic fields. The density of states is clearly altered from a conventional 2D system which manifests itself in aperiodic magnetooscillations when sweeping the Fermi energy at fixed magnetic fields. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Man made periodic potentials have long been of great interest for fundamental research and in view of applications. On the one hand, epitaxially grown semiconductor superlattices have revealed a large variety of effects in electronic transport, but so far research has mainly concentrated on systems with Fermi energy close to the miniband minimum. Additionally, for a given sample the Fermi energy is usually fixed [1]. On the other hand, in surface lateral superlattices the Fermi energy is adjustable, but at the price of a rather large periodicity and shallow potential modulation which leads to a large number of occupied bands [2]. We have extended a sample structure developed by Störmer et al. [3] to combine attractive features of both: A two-dimensional electron system (2DES) resides in an atomically precise superlattice, the Fermi energy of which can continuously be adjusted over a wide range by a gate, and the bandstructure of which can be engineered by heterostructure MBE growth. This sample design allows us to study superlattice DC transport as well as magnetotransport properties of a single partially or fully filled band. Results of magnetotransport experiments are the topic of the present paper.

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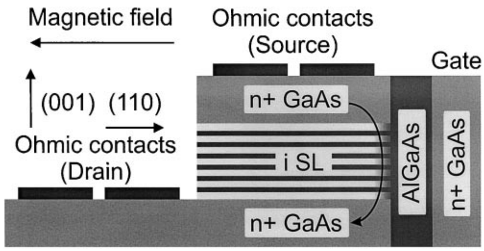

Fig. 1. Sample structure as obtained by MBE cleaved edge overgrowth.

2. Sample design

Our sample consists of an MBE-grown undoped $100 \times (119$ Å GaAs/31 Å $Al_xGa_{1-x}As)$ superlattice ($x = 0.32$) sandwiched between two highly doped n^+ GaAs contacts grown on semi-insulating (0 0 1) GaAs substrate, as shown in Fig. 1. After in situ cleaving the sample, an $Al_xGa_{1-x}As$ spacer layer is grown on the freshly exposed (1 1 0) plane, followed by a highly doped n^+ GaAs gate. By applying a positive gate voltage with respect to the superlattice contacts a 2DES can thus be induced which resides at the interface between the superlattice and the $Al_xGa_{1-x}As$ barrier. A simple Kronig–Penney calculation yields a width for the first miniband of 3.8 meV, separated from the second miniband by a 60 meV one-dimensional minigap. The first excited level of the triangular field effect potential is expected at about 15 meV above the first miniband.

3. Experimental results

Our measurements are performed in a quasi-four-probe geometry between the superlattice contacts with standard lock-in technique at liquid helium temperatures, while magnetic fields up to 14 T are applied perpendicular to the 2DES. First we discuss the Shubnikov–de Haas (SdH) oscillations in the longitudinal magnetoresistance obtained when sweeping the magnetic field strength at fixed gate voltage, i.e. at fixed electron density, see Fig. 2. For gate voltages > 150 mV SdH oscillations are observed. The zero field resistance decreases for increasing gate voltages due to an increasing carrier density, and the magnetic field B_0, where SdH oscillations become visible, de-

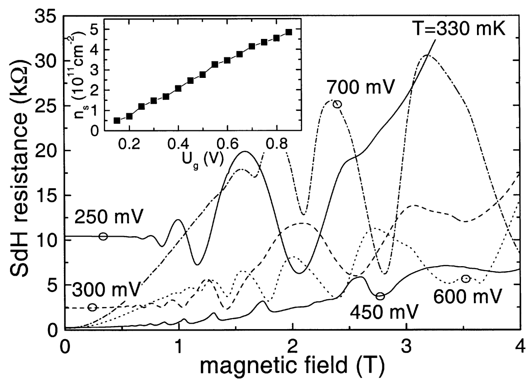

Fig. 2. Shubnikov–de Haas measurement. For gate voltages above 450 mV a positive magnetoresistance, quenching of SdH oscillations and magnetic breakdown can be observed. The inset shows the dependence of the electron density n_s on the gate voltage U_g as found by evaluation of the SdH oscillations.

creases, indicating an increasing effective mobility. At a gate voltage of 375 mV the field B_0 has a minimum of 250 mT. From this value we can estimate a lower bound for the electron mobility of 40 000 cm^2/V s. For larger gate voltages the field B_0 increases again. A drastic change of the magnetoresistance is observed starting at a gate voltage of 450 mV. SdH oscillations at low magnetic fields are quenched in a region of strong positive magnetoresistance which is proportional to the square of the magnetic field. At high magnetic fields, SdH oscillations are recovered.

We now proceed to the analysis of these results. We find that the positions of the minima of the SdH oscillations are periodic if plotted against the inverse magnetic field for *all* gate voltages above 150 mV. By the usual evaluation of the obtained Landau plot or by Fourier transformation we find an almost linear apparent electron density dependence on the gate voltage of $(6.4 \pm 0.1)10^{11}$ cm^{-2} V^{-1}, as shown in the inset of Fig. 2. This value compares well with the capacity per area and charge of 6.7×10^{11} cm^{-2} V^{-1} obtained by taking the sample as a simple capacitor with appropriate dielectric constant. Note that a linear dependence of the electron density on the gate voltage does not imply that the density of states is constant. It may seem surprising that in our evaluation of the SdH oscillations so far no sign of the artificial band structure came into play. The artificial band structure and the presence of a minigap, though, manifest themselves most strikingly in two ways. First in

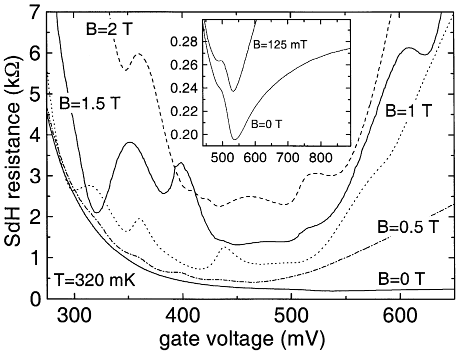

Fig. 3. Magnetooscillations for fixed magnetic fields and variable Fermi energy. The inset shows the increase of the zero field resistance when the Fermi energy is raised above the miniband. The displayed quantities and units are the same as in the main graph.

the appearance of a strong, quadratic, positive magnetoresistance for gate voltages above 450 mV, which is exactly what is expected when open orbits become present [4]. This means that at a gate voltage of 450 mV the Fermi energy is raised above the first miniband into the one-dimensional minigap. Second, the minigap manifests itself in the quenching of the SdH oscillations in that regime, which is because of the absence of closed orbits in k-space, so that at low magnetic fields SdH oscillations are quenched. However, at higher magnetic fields, SdH oscillations are recovered due to magnetic breakdown [5]. In this regime, Bragg reflections are suppressed due to Lorentz force induced by magnetic fields and electrons tunnel in k-space such that closed orbits are recovered. Magnetic breakdown has been observed in metals [6], in 'bulk' superlattices [7], in density-modulated 2DES [2] and in double quantum wells [8]. To our knowledge we show the first example of magnetic breakdown in the first miniband of a modulated 2DES.

Second, we discuss the magnetooscillations observed when sweeping the Fermi energy from within the miniband into the minigap through the Landau levels while keeping the magnetic field strength constant. A selection of traces of our experimental results are displayed in Fig. 3. For zero magnetic field and for increasing gate voltages up to 500 mV, the longitudinal resistance sharply drops to a minimum of 195 Ω due to an increasing electron density. At 500 mV, though, a W-shaped structure is observed in the resistance, and for larger gate voltages the resistance subsequently increases (see inset). When a magnetic field larger than 500 mT is applied, magnetooscillations are observed. These are quenched for gate voltages larger than 450 mV while the magnetoresistance increases again for increasing gate voltages. For larger magnetic fields magnetooscillations are again observed for gate voltages above 450 mV. Most importantly, the spacing of the magnetooscillations is far from regular.

We now try to give an explanation for the W-shaped longitudinal resistance at zero magnetic field. For a conventional 2DES of free Bloch electrons the longitudinal resistance continuously decreases with increasing electron density as long as only the ground state is occupied. In our system, though, as the Fermi energy approaches the top of the first miniband, the density of states becomes very large and then decreases when the Fermi energy is in the minigap. Therefore close to the minigap electron scattering and thus the longitudinal resistance are enhanced. As the Fermi energy is raised into the minigap, the electron density further increases, which leads to a reduced resistance again. At the same time the Fermi surface begins to extend beyond the first Brillouin zone and flattens out, such that the mean electron velocity decreases, which at last leads to an increase in resistance. This behavior of the longitudinal resistance at zero magnetic field can again be taken as direct evidence for the existence of a minigap.

When a sufficiently large magnetic field is present, for a 2DES Landau levels are resolved in the magnetoresistance with a constant energy spacing of $\hbar\omega_c$ where ω_c is the cyclotron frequency. In contrast we find magnetooscillations which are not equally spaced in gate voltage, although the electron density in our sample linearly depends on the gate voltage. For a given magnetic field the spacing in gate voltage is larger when measured close to the minigap. Again this observation can be explained by a density of states which becomes large in the vicinity of the miniband edge. A detailed analysis of the density of states per Landau level, taking into account a non-constant electron mass, the non-trivial shape of the orbits in k-space and the spin splitting of the Landau levels is beyond the scope of the present paper.

In summary, we have presented a novel electronic system which bridges the gap between conventional ‘bulk’ semiconductor superlattices and density-modulated two-dimensional electron systems. Bandstructure parameters in our sample are entirely known and can be tailored to atomic precision through MBE growth. Additionally, the Fermi energy can continuously be controlled by a gate. In magneto-transport experiments the calculated Kronig–Penney bandstructure is directly evidenced. Aperiodic magnetoresistance oscillations for fixed magnetic fields are observed when sweeping the gate voltage. SdH oscillations are found for electron densities below 2.5×10^{11} cm^{-2} as in a conventional high electron mobility 2DES. For higher electron densities SdH oscillations are quenched within a region of strong positive magnetoresistance. SdH oscillations are recovered for high magnetic fields, which we attribute to magnetic breakdown in the minigap. The minigap also becomes visible in the longitudinal resistance when sweeping the Fermi energy above the first miniband at zero magnetic field.

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