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# Magnetotransport in periodic magnetic fields

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**Abstract**

By depositing an array of ferromagnetic dysprosium wires on top of a high-mobility two-dimensional electron gas (2DEG) we generate a one-dimensional periodic magnetic field with periods between $a = 500$ nm and 1 $\mu$m, giving rise to magnetic commensurability oscillations of the magnetoresistance $\rho_{xx}$. Here we study the commensurability oscillations as a function of the angle $\theta$ between the Dy wires and the Hall bar. For parallel orientation of the wires we find pronounced anomalies at intermediate magnetic fields which we ascribe to overlapping, modulation-broadened, Landau bands.

*Keywords:* Dysprosium; Electrical transport; Electrical transport measurements; Gallium arsenide; Heterojunctions; Quantum effects

## 1. Introduction

The resistance of a 2DEG subjected to a weak (modulation amplitude $B_m < B_0$) periodic magnetic field, which oscillates on a length scale which is small compared to the mean free path of the electrons, is expected to oscillate as a function of an externally applied field $B_0$ [1]. This effect, closely related to the commensurability oscillations observed in a 2DEG with superimposed electrostatic periodic potential [2–4], was recently verified experimentally by using either patterned ferromagnetic [5,6] or superconducting [7] gates placed on top of a 2DEG. In our experiment [5], we deposited an array of ferromagnetic dysprosium (Dy) wires on top of high-mobility GaAs–AlGaAs heterojunctions to generate a one-dimensional (1D) magnetic-field modulation. By varying the maximum applied "conditioning" field, the strength of the magnetization of micromagnets, and hence the amplitude of the periodic magnetic field, was tuned. For a sufficiently high amplitude $B_m$ (periodic magnetic field component normal to the 2DEG), $\rho_{xx}$ oscillates and minima appear at $2R_c = (\lambda + \frac{1}{4})a$ with $\lambda = 1,2,\ldots$ if the current flows perpendicular to the grating. This reflects the interplay of the two characteristic lengths of the system, the cyclotron radius $R_c$ at the Fermi energy and the period $a$ of the magnetic superlattice. In contrast, in the presence of a 1D periodic electrostatic field modulation, minima appear whenever $2R_c = (\lambda - \frac{1}{4})a$ holds. Here, we study the dependence of the magnetic commensurability oscillations on the period $a$ and on the angle of the Dy wires with respect to the current flow (see inset to Fig. 2).

## 2. Experimental

Our samples were prepared from high-mobility GaAs–AlGaAs heterojunctions where the 2DEG

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was located approximately 100 nm underneath the sample surface. The carrier density $n_s$ and electron mobility $\mu$ at 4.2 K were $\sim 2.2 \times 10^{11}$ cm$^{-2}$ and $1.3 \times 10^6$ cm$^2$/V·s, respectively, corresponding to an elastic mean free path of $\sim 10$ $\mu$m, which is much longer than the period of the magnetic field modulation. 50 $\mu$m wide Hall bars with AuGe/Ni ohmic contacts were fabricated by standard techniques. A 10 nm thin NiCr film, evaporated on top of the devices, defines an equipotential plane to avoid electric modulation of the 2DEG. However, strain due to different thermal expansion coefficients of the ferromagnetic grating and the heterojunction always results in a weak electric periodic potential as the sample is cooled down to cryogenic temperatures [8]. The Dy gratings with period $a = 500$ nm and 1 $\mu$m were defined by electron beam lithography and lift-off technique on top of NiCr gates. Four-point resistance measurements were performed in a $^4$He cryostat with superconducting coils using standard ac lock-in techniques. For all experiments, the external magnetic field $B_0$ was applied normal ($z$ direction) to the plane of the 2DEG.

## 3. Results and discussion

In Fig. 1 we compare the magnetoresistance trace of 1D magnetic superlattices with period $a =$ 500 nm (solid lines) and 1 $\mu$m (dashed line). The traces labeled 0 T, 4 T and 8 T are taken after the initial cooling and after the magnetic field was ramped up to a maximum field $B_{max} = 4$ and 8 T, respectively. By increasing $B_{max}$ to 4 and 8 T, the magnetic polarization $J$ of the Dy strips and hence the strength of the resulting stray field can be increased. Note that $B_m$ also depends on $B_0$ (or $a/R_c$ in Fig. 1), reflecting the magnetization traces of Dy [5]. In Fig. 1 a dramatically enhanced resistance peak can be found at $a/2R_c = 1.8$ for an increased strength of the magnetic modulation. The positions of the oscillation minima of the 4 and 8 T $\rho_{xx}$ traces closely follow the theoretical prediction, marked by filled triangles. On the normalized magnetic-field scale, the magnetic commensurability oscillations measured in the 500 nm and 1 $\mu$m gratings are in phase, reflecting the expected scaling behavior. The oscillations in the 0 T trace are predominantly due to the electrostatic potential modulation caused by the strain. The open triangles in Fig. 1 mark the second harmonic of the grating-induced potential which dominates here (see e.g. Ref. [8]). The evolution from electric commensurability oscillations to magnetic ones with increasing strength $B_m$ was systematically investigated in Ref. [5]. From the amplitude of the maximum at $a/2R_c \approx 1.8$ we estimate, assuming a field modulation of the form $B_m \cos[(2\pi/a)x]$, the field amplitude $B_m$ from Ref. [5] to be

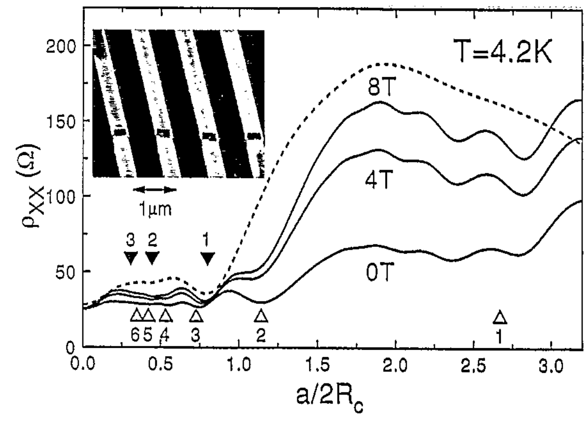


Fig. 1. $\rho_{xx}$ versus $a/2R_c$ for different $B_{max}$ sweeps. Filled triangles, with positions defined by Eq. (1), mark the flat-band condition in a periodic magnetic field. Open triangles mark the flat-band condition of the second harmonic of the strain-induced electrostatic potential. Dashed curve: $\rho_{xx}$ for $a = 1$ $\mu$m. Solid traces: $\rho_{xx}$ for $a = 500$ nm. Inset: electron micrograph of the Dy strips evaporated across a mesa edge: $a = 1$ $\mu$m, height of a Dy strip: 200 nm.

$$\frac{\Delta\rho_{xx}}{\rho_0} = \frac{2}{\pi}\frac{e^2}{h^2}\frac{a}{R_c n_e} l_e^2 B_m^2 \sin^2\left(\frac{2\pi}{a}R_c - \frac{\pi}{4}\right), \qquad (1)$$

where $\rho_0$ is the zero-field resistivity of the unmodulated 2DEG, $n_s$ is the electron density and $l_e$ is the mean free path. For the $B_{max} = 8$ T trace of the sample with $a = 500$ nm, we estimate from Eq. (1) $B_m \approx 30$ mT, and for the 4 T trace, $B_m \approx 23$ mT.

The oscillations in $\rho_{xx}$ described above are due to the formation of Landau bands whose widths oscillate as a function of the Landau index $n$ and $B_0$. For high quantum numbers $n$, we approximate the width $W_m$, given by Ref. [1], by

$$W_m = \hbar\omega_m \frac{ak_F}{2\pi} J_1\left(\frac{2\pi}{a} R_c\right), \tag{2}$$

where $J_1(x)$ is a Bessel function. The band formation and the resulting band conductivity contribution [3,4,9] dominate the commensurability oscillations if the current flows perpendicular to the magnetic grating (these band-conductivity oscillations can also be understood semi-classically for the case of 1D electric potentials [10]). Minima in $\rho_{xx}$ appear when the band-width goes to zero and the band conductivity vanishes. However, commensurability oscillations for electric 1D modulation were also observed for a current flow parallel to the grating [2,3]. These oscillations are due to the modified density of states (DOS) displaying maxima when the Landau bands become flat (DOS maxima at $W_m \approx 0$).

In Fig. 2 we investigate the commensurability oscillations for different angles of the Dy grating with respect to the current flow (see inset). To account for the different mobilities of the samples investigated, we scaled $\rho_{xx}$ by $(a/l_e)^2$ (see Eq. (1)). As the angle $\theta$ is changed from 90 to 0°, the amplitude of the oscillations decreases characteristically. In the simplest case, we expect

$$\Delta\rho'_{xx} = \Delta\rho_{xx} \sin^2\theta \tag{3}$$

to hold. This scaling, ignoring the positive magnetoresistance contributions in experiment, is roughly fulfilled by the traces in Fig. 2. For the $\theta = 0°$ case, we surprisingly do not observe the expected "antiphase" oscillations which, in the case of a weak electrostatic periodic potential, are smaller by a factor of 5–10 than the 90° oscillations. The reason for this could be that the grating is not exactly aligned along the Hall bar, so that band-conductivity contributions still dominate.

The effects of the modified DOS become pronounced, however, at higher magnetic field, slightly beyond the commensurability regime. This is shown by the $\rho_{xx}$ traces in Fig. 3, where we changed the strength of the magnetic modulation by varying the maximum field $B_{max}$ from 1 to 10 T. Here, the Dy wires are aligned parallel to the Hall bar ($\theta = 0°$). With increasing strength of magnetic-field modulation, the amplitude of the Shubnikov–de Haas oscillations decays. This can be understood qualitatively as a consequence of Landau-band formation, which reduces the maximum density of states of a Landau level by modulation broadening. Apart from the reduced amplitude of the SdH oscillations, we observe a characteristic shift of the SdH minima to higher magnetic fields, and even additional oscillatory features (see trace 10 T between 0.5 T and 0.7 T) for increasing magnetic modulation. We ascribe this behavior to overlapping modulation-broadened Landau bands. This assumption is supported by an estimate of the bandwidth $W_m$ at $B_0 = 0.6$ T from previously published data (inset of Fig. 3a [5]). By extrapola-

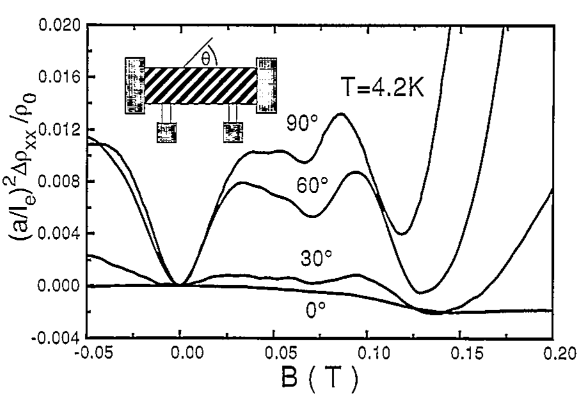


Fig. 2. $(a/l_e)^2\Delta\rho_{xx}/\rho_0$ as a function of the external magnetic field $B_0$ for different angles $\theta$. The amplitude of the oscillations decreases when the grating is tilted from 90 to 0°.

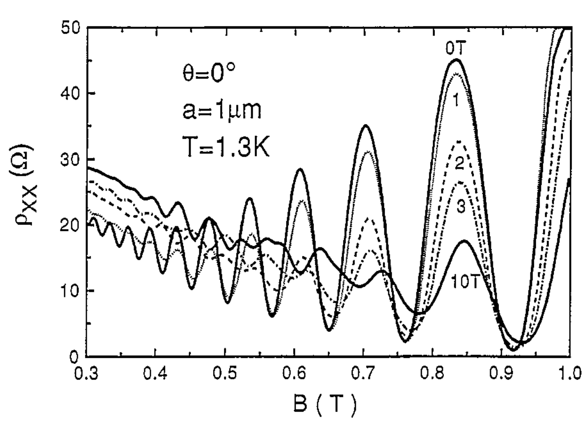


Fig. 3. $\rho_{xx}$ as a function of the external magnetic field $B_0$ with the maximum applied field $B_{max}$ varied between 0 and 10 T. Here, the Dy wires are aligned parallel to the Hall bar.

tion we obtain $B_m = 25$ mT (1 T), 33 mT (2 T), 45 mT (3 T), 65 mT (10 T) at $B_0 = 0.6$ T corresponding to $2W_m = 0.59$, 0.78, 1.06 and 1.53 meV derived from Eq. (2). The latter two values are larger than the Landau gap $\hbar\omega_0 = 1.03$ meV at $B_0 = 0.6$ T. We expect a shift of the SdH minima to higher magnetic field when, while sweeping to higher $B_0$, the next lower Landau band gets depopulated before the upper band is completely empty. However, more refined calculations are necessary to clarify this point.

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