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Huge magnetoresistance oscillations in periodic magnetic fields

P.D. Ye[a,c,*], D. Weiss[a,b], R.R. Gerhardts[a], K. von Klitzing[a], S. Tarucha[c]

[a] *Max-Planck-Institut für Festkörperforschung, D-70569 Stuttgart, Germany*
[b] *Experimentelle und Angewandte Physik, Universität Regensburg, D-93040 Regensburg, Germany*
[c] *NTT Basic Research Laboratories, 3-1 Morinosato Wakamiya, Atsugi-shi, Kanagawa-ken, 243-01, Japan*

Abstract

By depositing ferromagnetic gratings on top of two-dimensional electron gases (2DEG), it is possible to generate periodic magnetic fields on a submicron scale in the plane of the electrons. Here, we show that the amplitude of the periodic magnetic field can be notably enhanced if the externally applied magnetic field B_0 is tilted towards the plane of the 2DEG while kept normal to the gratings.

Keywords: Commensurability effects; Dysprosium; Periodic magnetic fields

By means of patterned ferromagnetic [1,2] or superconducting [3] layers on top of two-dimensional electron systems, it is possible to study the electron motion in inhomogeneous magnetic fields varying on a length scale small compared to the mean free path l_e of electrons. By periodically arranging ferromagnetic "wires" with submicron diameters on top of a high-mobility GaAs–AlGaAs heterojunction, it is possible to generate a one-dimensional (1D) periodic magnetic field in the plane of the two-dimensional electron gas (2DEG). The effect of a weak periodic magnetic field on a 2DEG results in an oscillatory magnetoresistance, which reflects the commensurability between the period a of the magnetic field modulation and the classical diameter $2R_c$ of the electrons at the Fermi energy E_F [4–6]. For a weak 1D magnetic modulation with modulation amplitude $|B_m|$ much smaller than the external magnetic field $|B_0|$, the magnetoresistance ρ_{xx} oscillates with minima appearing at magnetic fields given by $2R_c = (\lambda + \frac{1}{4})a$ where $\lambda = 1, 2, \ldots$ is an integer oscillation index and a is the period of the 1D modulation. In general, the magnetic modulation is accompanied by an electrostatic one due to the strain caused by the different thermal expansion coefficients of the ferromagnetic material (here dysprosium) and the semiconductor layers [7,8]. However, to understand the experiments below it is sufficient to consider the classical motion of electrons in periodic magnetic fields only as the strain effects are weak compared to the magnetic modulation. Averaging the modulation-induced drift of the guiding centres over the unperturbed cyclotron orbits at field

* Corresponding address: NTT Basic Research Laboratories, 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa-ken, 243-01, Japan. Fax: 0081 462 40 4723; e-mail: ye@will.brl.ntt.co.jp.

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B_0 [9,10], we obtain a change in the resistivity

$$\frac{\Delta\rho_{xx}}{\rho_0} = \frac{B_m^2\mu^2 a}{\pi^2 R_c}\sin^2\left[KR_c - \frac{\pi}{4}\right], \tag{1}$$

where $\rho_0 = 1/en_s\mu$ is the zero-field resistivity of the unmodulated 2DEG with the electron mobility μ. Eq. (1) directly relates the observable resistivity changes to the amplitude of the magnetic modulation B_m. In this paper we report a method to enhance the magnetic modulation dramatically by tilting the direction of the externally applied magnetic field with respect to the normal of 2DEG. Such an enhanced amplitude of the periodic magnetic stray field is of interest, e.g., for studying tunnelling through magnetic barriers or the investigation of chaotic electron motion in sufficiently strong modulated magnetic field [11,12].

Our samples were prepared from high-mobility GaAs–AlGaAs heterojunctions where the 2DEG was located approximately 100 nm underneath the sample surface. The carrier density n_s and electron mobility μ at 4.2 K were $\sim 2.2 \times 10^{11}\,\mathrm{cm}^{-2}$, and $1.3 \times 10^6\,\mathrm{cm}^2/\mathrm{V\,s}$ in dark, corresponding to an elastic mean free path of $\sim 10\,\mu\mathrm{m}$. 50 μm wide Hall bars were fabricated by standard photolithographic techniques. The Dy gratings with period a of 500 nm and 1 μm were defined by electron beam lithography on top of one of the Hall bars. More details of the fabrication process can be found in Ref. [13].

Fig. 1a displays the resistivity ρ_{xx} at 1.3 K as a function of the externally applied magnetic field B_0. The data were taken for six different tilt angles from $\theta = 0°$ to $\theta = 84°$. The angle θ can be determined, e.g., from the $\cos\theta$ shift of the Shubnikov–de Haas oscillations on the magnetic field scale according to $B_\perp = B_0\cos\theta$. A more accurate way, used here, is to determine θ by Hall measurements at low fields (0–0.5 T). With increasing tilt angle the positive magnetoresistance grows dramatically and reaches values of up to 10 kΩ. The origin of the huge positive magnetoresistance becomes clear if we plot ρ_{xx} versus $B_\perp$, shown in Fig. 1b. The huge magnetoresistance bump below 1 T (of $B_\perp$) obviously belongs to the last commensurability

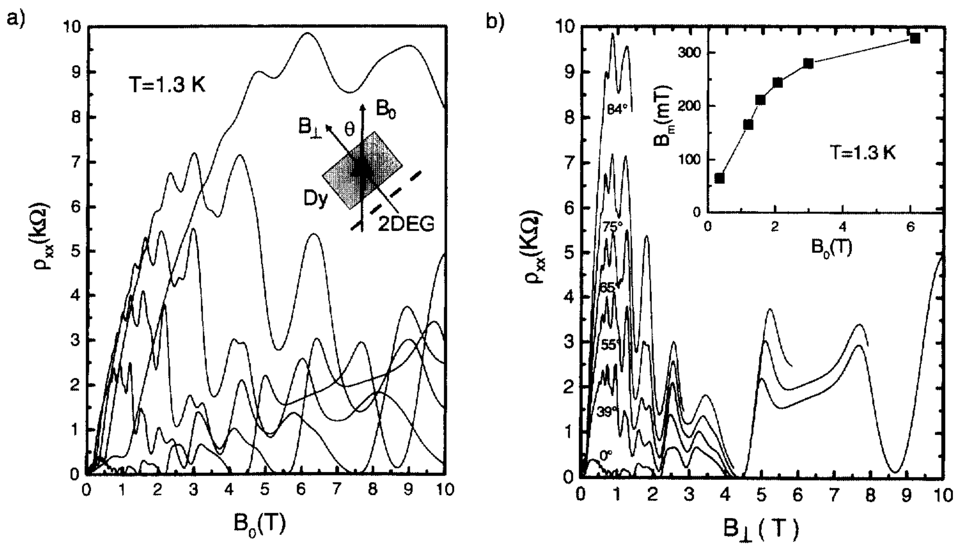

Fig. 1. (a) Magnetoresistance ρ_{xx} as a function of the external magnetic field B_0 at various angles θ (see inset). The six traces (from bottom to top) are taken at angles $\theta = 0°, 39°, 55°, 65°, 75°, 84°$, respectively. The inset showing a cross-section of Dy-wire and 2DEG illustrates the direction of the applied field. The orbital motion of the electrons is only affected by the normal component $B_\perp$ of the applied field. Here, the period of the grating was 1 μm. (b) ρ_{xx} at various tilt angles θ with respect to the sample normal as a function of perpendicular field $B_\perp = B_0\cos\theta$. The inset displays the strength B_m of the stray field normal to the 2DEG estimated from the ρ_{xx} maxima at $B_\perp \sim 0.6\,\mathrm{T}$ (Eq. (1)) for different θ.

maximum at about 0.3 T. The amplitude of this bump increases from 400 Ω at $\theta = 0^\circ$ to $\sim$10 kΩ at $\theta = 84^\circ$ by a factor of 25. With increasing maximum value of the resistivity peak, its position shifts to higher magnetic fields, which indicates an increasing amplitude of the modulation field [14]. This is the consequence of the hard magnetic behaviour of our evaporated dysprosium films. The magnetisation of these films saturates only at high magnetic fields of a few T [1]. Only if the magnetic wires have reached their full saturation magnetisation the amplitude of the periodic stray field is maximum. For our $\theta = 0^\circ$ trace the magnetizing field at the bump position is only 0.3 T but 6 T for the $\theta = 84^\circ$ trace. Only in the latter case we are close to saturation. The impact of the increased stray field on the resistivity is huge as the oscillation amplitude $\Delta\rho_{xx}$ increases with B_m^2 according to Eq. (1). We can estimate the amplitude of the magnetic modulation from the maximum of the peak height according to Eq. (1), which is plotted in the inset of Fig. 1b. The peak-to-peak modulation of the periodic magnetic field at $\theta = 84^\circ$ reaches more than 0.6 T at $B_0 = 6$ T. At such high values for B_m the approximation of a weak magnetic modulation ($B_m \ll B_\perp$) is close to breakdown, since $B_\perp \sim 0.8$ T and $B_m \sim 0.3$ T. The strong modulation leads to overlapping, modulation-broadened, Landau bands. This might complicate the analysis of the SdH oscillations on top of the magnetoresistance maximum. An additional small peak appearing at about $B_\perp \sim 1$ T in trace $\theta = 65^\circ$ indicates some anomalous behaviour. Similar effects were also observable with a current flow parallel to the magnetic superlattices [15]. The spin splitting at about $B_\perp = 1.8$ T in Fig. 1b disappears with increasing modulation and can also be ascribed to overlapping spin-split Landau bands. Note that this behaviour is in contrast to tilted field experiments in conventional 2DEGs where the spin splitting is enhanced by increasing the tilt angle as the Zeeman energy depends on the total magnetic field, but not on the normal component.

In Fig. 2 we display the temperature dependence of ρ_{xx} taken from another device with period $a = 500$ nm at a tilt angle of 68°. At low temperatures again rich oscillatory structure sitting on top of the last commensurability maximum is observed.

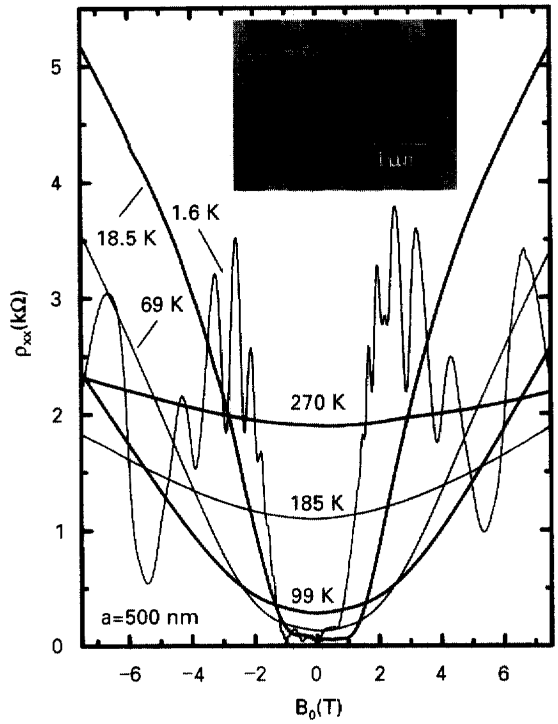

Fig. 2. Temperature dependence of the magnetoresistance between 1.6 and 270 K at a fixed tilt angle $\theta = 68^\circ$. The traces for 1.6, 99 and 270 K are recorded from 7.5 to −7.5 T, while the traces for 18.5, 69 and 185 K are taken from −7.5 to 7.5 T. Inset: electron micrograph of the Dy strips evaporated across a mesa edge: $a = 1$ μm, height of a Dy strip: 200 nm.

At about 18.5 K the commensurability oscillations are nearly washed out. A similar weak temperature dependence was also measured previously for magnetic commensurability oscillations in the $\theta = 0$ case [16]. A positive magnetoresistance sustains higher temperatures up to room temperature, i.e. above the Curie temperature of Dy which is 88 K.

If the 2DEG is aligned parallel ($\theta = 90^\circ$) to the external magnetic field, the orbital motion of the electrons is only affected by the normal component of the stray field generated by the periodic micromagnet array (see inset of Fig. 3). If the 2DEG is perfectly parallel to B_0, the Hall resistivity ρ_{xy} is zero in any magnetic field. By carefully rotating the sample, the Hall resistivity can be controlled to remain smaller than 100 Ω in the 10 T region, which reflects a deviation smaller than $\pm 0.02^\circ$ from 90°.

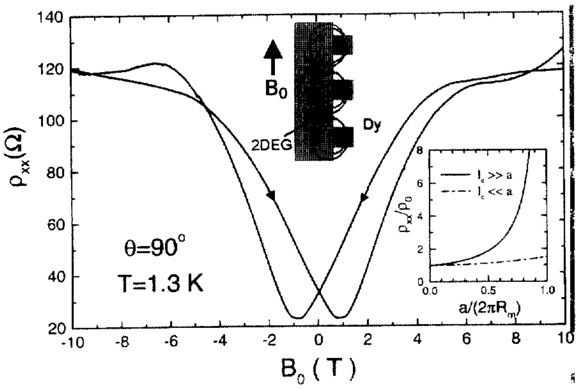

Fig. 3. Magnetoresistivity ρ_{xx} as a function of the external magnetic field B_0 for $\theta = 90°$ tilt. The inset illustrates the magnetic stray field which delivers the only perpendicular magnetic field components (with respect to the 2DEG). The bottom inset displays calculated resistance traces versus B_m for vanishing average field.

A corresponding experiment is shown in Fig. 3 displaying a pronounced positive low-field magnetoresistance with hysteretic behaviour. The 2DEG coupled with the magnetized micromagnets works as a detector, which supplies direct information on the ferromagnetic properties of the strips. The field value at the resistance minimum reflects the coercive field B_c of about 0.8 T, which is consistent with magnetisation measurements [1]. The minimum resistance of 23 Ω reflects the zero-field resistance $\rho_{xx}(0)$ without modulation, while the increased resistance of 30 Ω at $B_0 = 0$ reflects the influence of the built-in remnant magnetic field. Both values are consistent with $\rho_{xx}(0)$ measurements for the $\theta = 0°$ case. The resistance trace becomes flat above 5 T, as the magnetization of the Dy strips gets saturated. The inset of Fig. 3 shows the calculated resistance of a 2DEG in the magnetic field $B_z(x) = B_m \cos 2\pi x/a$ versus B_m (R_m is the cyclotron radius in a homogeneous field of strength B_m) for two limits of the electron mean free path l_e [14]. From this we estimate, since $l_e \gg a$, that an increase of ρ_{xx} by a factor of 6 requires a modulation amplitude $B_m \approx 0.4$ T.

In summary we have shown a pronounced increase of the amplitude of a periodic stray field in the tilted field experiments. Similar angle-dependent measurements have been performed recently for the Ni-wires [17].

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