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Magnetotransport in modulated and magnetic fields

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Abstract

We study the effect of spatially periodic magnetic field on the transport in a two-dimensional electron gas in GaAs/AlGaAs heterojunctions.The magnetoresistance curve contains an oscillatory component due to the magnetic modulation as well as one due to the electric potential modulation, and their relative amplitudes can be varied by adjusting the gate bias or the maximum field of field cycling.

Keywords: Magnetotransport; Modulated fields; Magnetic fields

Spatially periodic potentials (by lattices, CDW, etc.) have given new stages for electrons. Recent progress in micro-fabrication has enabled human to design novel artificial stages. Especially transport properties of a two-dimensional electron gas (2DEG) at semiconductor hetero-interfaces are sensitive to various mesoscopic decorations on the surface of the devices and serve opportunities for us to test the effect of artificial potentials. One of the phenomena observed in such systems is a magnetoresistance oscillation due to the geometrical resonance between the cyclotron radius and superstructure periodicity. The one induced by a one-dimensional electro-static potential modulation is called "Weiss oscillation" [1–3]. The effect manifests itself as oscillations of $\rho_{xx}(B)$, which is periodic in $1/B$, x being the direction of potential modulation.

The minima of $\rho_{xx}(B)$ occur at

$$\frac{2R_c}{a} = n + \varphi, \quad n = 1, 2, 3, \ldots. \tag{1}$$

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Here, a is the modulation period; $R_c \equiv \hbar k_F/eB = \sqrt{2\pi n_e} l^2$ is the cyclotron radius of an electron at the Fermi level; k_F is the Fermi wave number; n_e is the aerial electron density; $l \equiv \sqrt{\hbar/eB}$ is the magnetic length; φ is "phase term", which is equal to $-\frac{1}{4}$ for the case of electric potential modulation, within a semiclassical picture, the phenomenon is understood as quenching of the guiding center drift motion when the commensurability condition Eq. (1) is fulfilled [4, 5]. This phenomenon is now well established both theoretically and experimentally.

Recent efforts are concentrated on the replacement of the electric potential modulation with a magnetic field modulation, i.e., a vector potential modulation [6–12]. This is a new situation for electrons, in which they feel a regular "potential" modulation without changing kinetic energies. For weak modulation limit, theories predict a similar magnetoresistance oscillation but the phase term $\varphi = \frac{1}{4}$, i.e., the "magnetic Weiss oscillation" is out-of-phase with the electric Weiss oscillation. In the present study, we have succeeded in unambiguous demonstration of the magnetic Weiss oscillation [10].

GaAs/AlGaAs heterojunctions with the junction depth of 75 nm were fabricated by molecular beam epitaxy. The areal electron concentration of the 2DEG was $4 \times 10^{11}\,cm^{-2}$ and the electron mobility was $6 \times 10^5\,cm^2/Vs$ at 4.2 K. A schematic view of the sample structure is shown in the inset of Fig. 1. For convenience, we fix the directions of x, y, and z-axes as shown in the figure henceforth.

A standard Hall-bar pattern was defined on a GaAs/AlGaAs wafer by photolithography and wet mesa-etching. A striped gate pattern was then formed on PMMA resist by electron beam lithography. The gate was actually comb shaped, i.e., all stripes were electrically connected by a line (not shown in the figure) running along the x-axis, so as to ensure that all the gates were at the same electrical potential. Ferromagnetic metal (nickel) was then deposited by vacuum evaporation to a thickness of 150 nm. The process was completed by lift-off. Magnetotransport measurements were performed at 4.2 K by use of a conventional low-frequency AC technique.

The scalar potential modulation inevitably has various sources, e.g., the Fermi energy pinning effect at the surface, surface strain induced by metal–semiconductor contacts, etc., which we collectively call "built-in" potential modulation. Hence the periodic gate of ferromagnetic metal causes both scalar and vector potential modulation, which situation makes the data analysis complicated. In order to make the analysis simpler and to get sound evidence of magnetic Weiss oscillation, we used the gate bias and the magnetic field excursion.

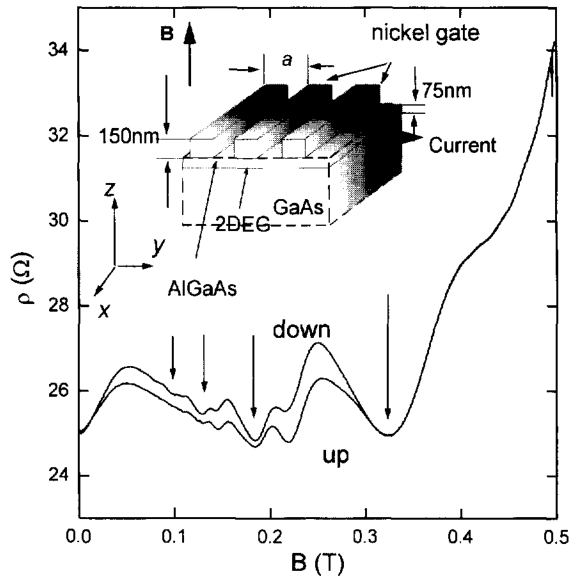

Fig. 1. Magnetoresistance of a sample with a gate-period of 0.5 μm. $V_g = +500$ mV. The two traces correspond to the up- and down-sweep of the field.

The gate bias changes not only the amplitude of the scalar potential modulation but also the average strength, which determines the density of 2DEG. In the analysis of the experiments of bias voltage variation, this effect should be taken into account by measuring the Hall resistance. Detailed form of the built-in potential should be different from that of bias-controllable part. Hence it is impossible to cancel out the built-in potential modulation completely. However it can be largely reduced by an appropriate choice of gate bias. This was confirmed by the samples with striped gates made of pure gold, in which purly electric Weiss oscillations were observed.

Magnetic field cycling affects the hysteretic magnetization of the ferromagnetic gate, which depends on the maximum value of the field. The difference in the potential modulation between up-sweep and down-sweep of the field should be purely magnetic in its origin. A problem in this method is the difficulty in quantitative estimation of the modulation amplitude. Measurement of the magnetization of such tiny ferromagnetic gate metals is difficult. Hence we use here both methods to cover these points.

Fig. 1 shows the magnetoresistance of the device with $a = 0.5$ μm, at a gate bias $V_g = +500$ mV. The magnetoresistance is hysteretic below 0.33 T. Above 0.33 T, the magnetization of the nickel gate is reversible. The hysteretic part is obviously associated with the magnetization of the ferromagnetic gate, and due to the stronger magnetic field modulation imposed on the 2DEG in the down-sweep. It is not easy to estimate the saturation field of such micro-fabricated thin ferromagnetic film, but we confirmed that the saturation field is about 0.4 T in the as-deposited film by measuring the anomalous Hall resistance. Considering the effects of the size and the form, the saturation around 0.33 T in the striped gates is reasonable.

Fig. 2 shows the difference between the two traces in Fig. 1 ($\Delta\rho_{xx}(B) = \rho_{xx}(B, \text{down}) - \rho_{xx}(B, \text{up})$). In the approximation that the total resistance oscillation is the superposition of electric-Weiss part and magnetic part, this difference should show a pure magnetic oscillation. The solid arrows mark the expected position of predicted ρ_{xx} minima for the magnetic modulation. The good agreement between the expected and the observed positions establishes that the magnetic Weiss oscillation is realized and the above-mentioned approximation is not bad for the present conditions. Simultaneous measurements of Hall resistivity have indicated that the screening of the uniform external magnetic field, which would cause a shift in the abscissa, is negligible.

We can see the growth of the magnetic part of the oscillations by changing the maximum value of the field cycling $B_{\max}$ Fig. 3 shows the measurements for another sample with a gate period $a = 1$ μm In the cycling with $B_{\max} = 0.25$ T, for which the nickel gate is not fully saturated, the oscillation is weak in $\Delta\rho_{xx}$ while it is distinct for $B_{\text{ma}} = 0.5$ T due to the

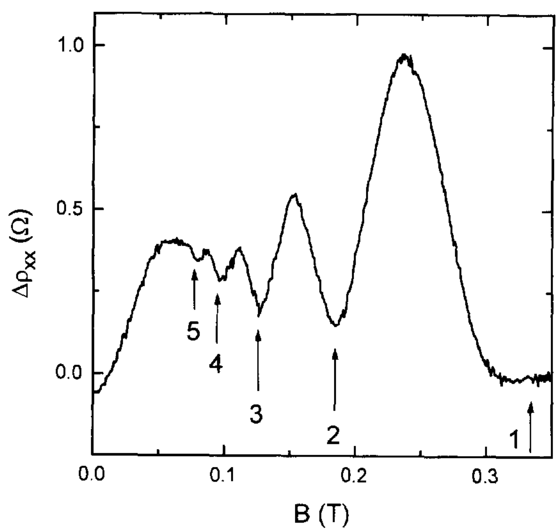

Fig. 2. Hysteretic component of the magnetoresitance $\Delta\rho_{xx}(B) = \rho_{xx}(B, \text{down}) - \rho_{xx}(B, \text{up})$, extracted from the curve in Fig. 1. The arrows indicate the expected positions of resistivity minima for magnetic Weiss oscillation.

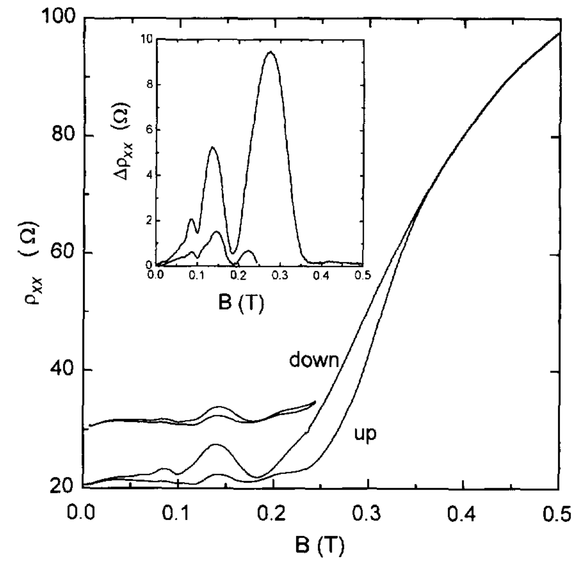

Fig. 3. Magnetoresistance curves for a sample with a 1-μm-period gate. The two curves differ in the maximum value of field cycling. The inset shows the hysteretic component extracted from the curves in the main panel.

increase in the periodic magnetic field modulation. Note that the positions of the minima in the oscillation does not change with the change of $B_{\max}$. This further confirms that the hysteretic part of the magnetoresistance purely reflects the change in the amplitude of the magnetic modulation.

In the next step, we go into the analyses of the total magnetoresistance oscillations, which are associated with both scalar and vector potential modulation. The case of coexisting electric and magnetic modulations is theoretically studied by Peeters and Vasilopoulos [9]. When the two types of modulations are in-phase, as in the present case, φ in (1) varies between $-\frac{1}{2}$ and $\frac{1}{4}$ as the relative amplitude of the electric and magnetic modulations is changed. This cannot account for every detail of the observed oscillation in our samples, in which each type of modulation has various high frequency components, but is expected to explain shift of large structure with the change in the ratio of the two kinds of modulation. In order to study the effect of the electric/magnetic ratio, gate-bias variation is better because it can bring wide change in the amplitude of the electric modulation. Fig. 4 shows three traces for gate bias $V_g = -250$, -100, and 0 mV.

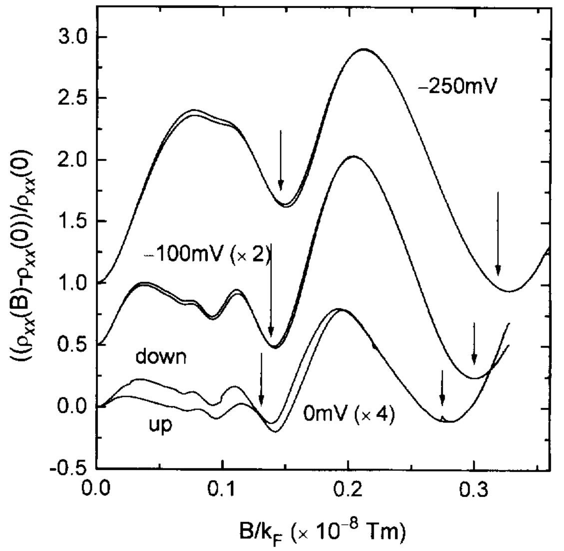

Fig. 4. ρ_{xx} curves for different values of gate bias $V_g = 0$, -100, and -250 mV. The arrows indicate the calculated positions of minima. The curves are offset for clarity.

The electron densities as determined by the Hall measurement are 2.84, 3.48, and 3.75×10^{11} cm^2, and the zero field resistivities $\rho_{xx}(0)$ are 66.5, 35.7, and 24.8 Ω, respectively. In order to scale the magnetoresistance traces for different electron densities, the quantity B/k_F, which is proportional to the inverse cyclotron radius is taken as the horizontal axis. When $V_g = +500$ mV (Fig. 1), the built-in potential is best compensated so that most of the oscillatory component of ρ_{xx} is of magnetic origin.

As seen in Fig. 4, the positions of the two distinct minima shift to larger values of B/k_F. At $V_g = -250$ mV, these are almost at the positions predicted in Eq. (1) with $\varphi = -\frac{1}{4}$, i.e., the potential modulation is almost purely electric.

Assuming that the oscillation for $V_g = +500$ mV is purely of magnetic origin, we can estimate the amplitude of magnetic field modulation at the two-dimensional electron sheet by comparing the relative oscillation amplitude with the theoretical expression. For example, the modulation amplitude is estimated as $B_1 \approx 13$ mT at $B = 0.25$ T on the down-sweep. The magnetic modulation amplitude should be constant against the gate-bias. In a similar way, one can estimate the amplitude of potential modulation, assuming that ρ_{xx} is dominated by the electric modulation for the bias-voltages lower than 0 V. For the three traces shown in Fig. 4, the electric potential modulation is thus estimated as 0.31, 0.85, and 1.8 meV for $V_g = 0$, -100, and -250 mV, respectively. Knowing the amplitudes of both types of modulations, we can evaluate the "phase term" in the oscillations. It is 0.21 for $V_g = -250$ mV, which is close to $-\frac{1}{4}$ for the pure electric case. For $V_g = -100$ and 0 mV, it is -0.15 and -0.02, respectively. The corresponding positions of ρ_{xx} minima are marked with the vertical arrows in Fig. 4. The good agreement with the date proves the validity of the model.

The angle between the external magnetic field and the device, is expected to affect the magnetization of the nickel gates strongly while only its component normal to the 2DEG plane is effective for the unperturbed (i.e., without modulation) motion of the electrons. We studied this effect of the magnetizing direction by applying constant magnetic fields parallel to the 2DEG plane.

Fig. 5 shows the results for the fields B_x, B_y, which are parallel to x- and y- axes, respectively. Increasing B_x, the magnetic Weiss oscillation for down-sweep diminishes. On the contrary, the oscillation for up-sweep grows with increment of B_y, indicating that the magnetization parallel to the 2DEG plane and perpendicular to the lines of nickel gates causes stronger field modulation onto the 2DEG. This result is in qualitative agreement with a numerical calculation based on a simple single domain model of the magnetization of nickel gates, suggesting a possibility of using the present system to investigate properties of small magnets.

The Weiss-type oscillation is also expected in resistivity tensor component other than ρ_{xx}, albeit of much smaller amplitude. The inset in Fig. 6 shows the Hall resistivity taken under the same conditions as Fig. 2, which looks perfectly linear on this scale. However after subtracting the B-linear term, an oscillation anti-symmetric to the magnetic field appears as shown in Fig. 6. We believe, from the period and the magnetic field dependence of the amplitude, this oscillation is also of Weiss-type. Also, the oscillation is in-phase with ρ_{xx}, in accordance with theoretical prediction by Peeters et al.

In summary, we have succeeded in observing magnetoresistance oscillation due to regular magnetic

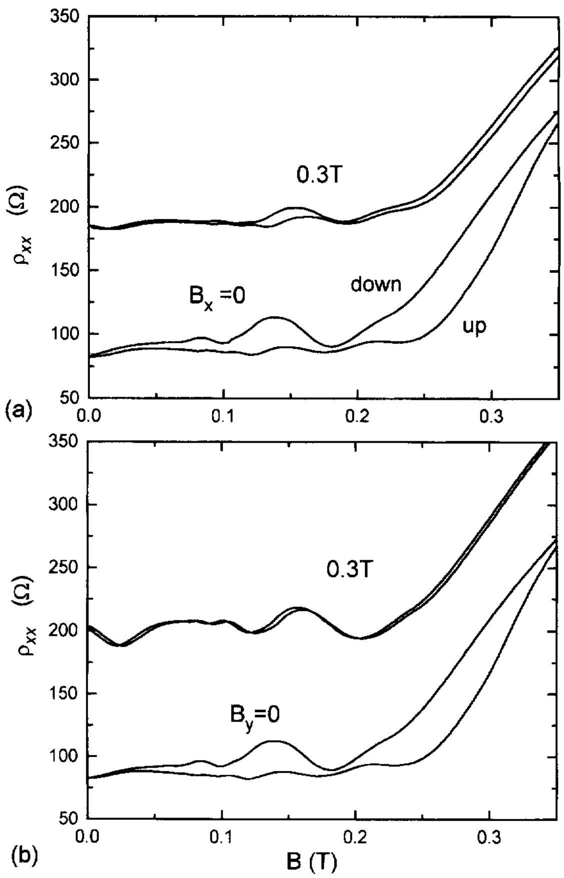

Fig. 5. Effect of magnetic field parallel to the sample plane on the magnetic Weiss oscillation. (a) The field is parallel to the stripe of the nickel gate. (b) The field is perpendicular to the stripe.

field modulations. Oscillatory magnetoresistance consists of both electric and magnetic components whose relative amplitude can be adjusted by the gate bias or the maximum field of field cycling.

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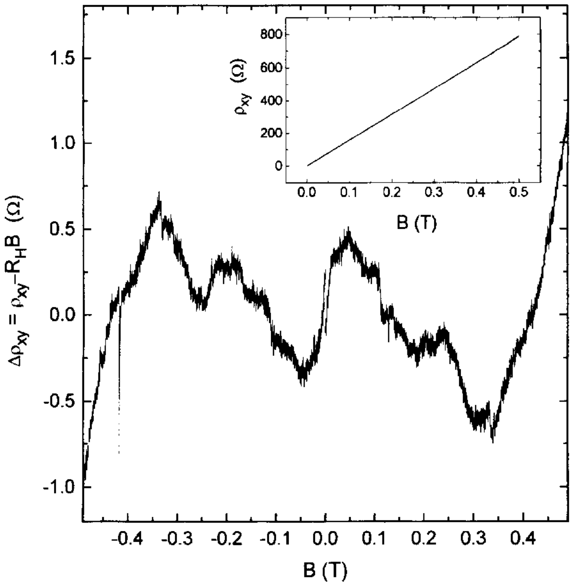

Fig. 6. Hall resistivity ρ_{xy} taken under the same conditions as Fig. 2. The curve in the main panel, obtained by subtracting the B-linear component, exhibits the Weiss oscillation.

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