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Magnetoresistance Oscillation in Two-Dimensional Electron Gas under Spatially Modulated Magnetic Field

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We have obtained clear experimental evidence for the oscillatory magnetoresistance effect in a two-dimensional electron gas under the influence of a spatially modulated magnetic field, which has been theoretically predicted. The magnetoresistance curve contains an oscillatory component due to the magnetic modulation as well as one due to the potential modulation, and their relative amplitudes can be changed by adjusting the gate bias.

KEYWORDS: two-dimensional electron gas, GaAs/AlGaAs heterojunction, magnetoresistance, Weiss oscillation, vector potential

Recent developments in semiconductor crystal growth and microfabrication techniques have opened new opportunities for "designed" experiments. In particular, two-dimensional electron gas at the GaAs/AlGaAs heterointerface with a structured gate electrode has been used in various experiments. One of the phenomena observed in such systems is an oscillatory magnetoresistance due to the geometrical resonance between the cyclotron radius and superstructure periodicity. The case of a one-dimensionally modulated potential (washboard potential) is called Weiss oscillation.[1-3] The effect manifests itself as oscillations in the $\rho_{xx}(B)$ curve, x being the direction of potential modulation, which is periodic in $1/B$. The minima of ρ_{xx} occur at

$$\frac{2R_c}{a} = n - \frac{1}{4} \qquad n = 1, 2, 3 \ldots. \tag{1}$$

Here, a is the modulation period, and $R_c = \hbar k_F/eB = (2\pi n_e)^{\frac{1}{2}}\ell^2$ is the cyclotron radius of an electron at the Fermi level. k_F and n_e are the Fermi wave number and the areal electron density, and $\ell = (\hbar/eB)^{\frac{1}{2}}$ is the magnetic length. Within a semiclassical picture, the phenomenon is understood as due to quenching of the guiding center drift motion when the commensurability condition, eq. (1), is fulfilled.[4] Calculation based on a quantum Boltzmann equation formalism gave essentially the same results.[5]

The effect of periodically modulated magnetic field on the energy spectrum of two-dimensional electron gas was theoretically treated by Yoshioka and Iye.[6] A *magnetic* analog of the Weiss oscillation, i.e. oscillatory magnetoresistance arising from a spatially modulated *vector* potential, was proposed by Xue and Xiao,[7] Yagi and Iye[8] and Peeters and Vasilopoulos.[9] Theoretical models predict that instead of eq. (1) for the usual *electric* case, the ρ_{xx} minima in the case of *magnetic* modulation are given by

$$\frac{2R_c}{a} = n + \frac{1}{4} \qquad n = 1, 2, 3 \ldots. \tag{2}$$

Thus, the hallmark of the *magnetic* Weiss oscillation is inversion of the peak/valley structure as compared to the *electric* counterpart.

Yagi and Iye[8] made an experimental attempt to observe this type of phenomenon by use of a system similar to the one used in the present study. However, it was found that the oscillation component caused by strain-induced potential modulation was dominant in their devices, and this hindered accurate interpretation of the magnetoresistance data. In the present study, we have succeeded in unambiguous demonstration of the *magnetic* Weiss oscillation by use of samples with higher electron mobility and an improved device fabrication processing. Part of the work presented here was published previously.[10]

Devices used in the present study were fabricated from molecular beam epytaxy (MBE)-grown GaAs/AlGaAs single heterojunction samples with electron density $\sim 4 \times 10^{11}$ cm^{-2}, and electron mobility $\sim 6 \times 10^5$ cm^2/V s at 4.2 K. The device structure shown in Fig. 1 was fabricated by the following process. A standard Hall-bar pattern was first defined on a GaAs/AlGaAs chip by photolithography and wet etching. A striped gate pattern of ferromagnetic metal was then defined by electron beam lithography, vacuum deposition, and the lift-off process. Nickel film of thickness ~150 nm was used in the present study. The stripes were perpendicular to the direction of current path of the Hall bar. The striped gate was actually comb-shaped, i.e., all stripes were electrically connected by a line (not shown in the figure) running parallel to the current direction, so as to ensure that all parts of the striped gate had the same electrical potential. Four devices with different gate modulation periods were prepared. The spacing of the strips was

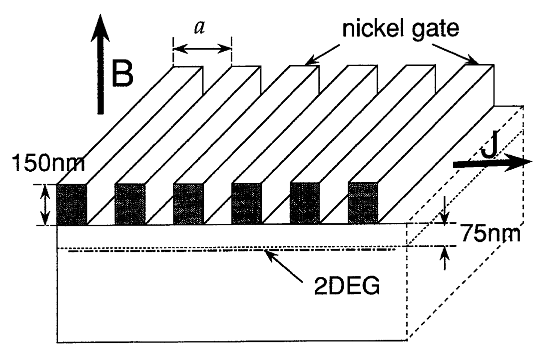

Fig. 1. Structure of the device used in the present study. The array of ferromagnetic stripes produces spatial modulation of magnetic field for the two-dimensional electrons at the GaAs/AlGaAs heterointerface.

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equal to their width in all the presently used devices. The GaAs/AlGaAs heterointerface was ~75 nm from the surface. Magnetoresistance and Hall resistance were simultaneously measured by a standard low-frequency *a.c.* technique. All the measurements reported in this paper were performed at $T = 4.2$ K.

Even at zero bias, the presence of structured gate metal by itself causes spatial modulation of the scalar potential by strain-induced deformation potential modulation, and by surface level pinning at the metal-semiconductor contact. Although the strength such a *built-in* potential modulation is rather difficult to estimate, it can be partially compensated by an appropriate choice of gate bias. The magnetic field modulation is produced by the magnetization of the ferromagnetic gate. The magnetization shows hysteretic behavior and depends on the maximum value of magnetic field excursion.

The upper panel of Fig. 2 shows the magnetoresistance for the device with $a = 0.5$ μm, at a gate bias $V_g = +500$ mV. The magnetoresistance in the field range $B < 0.3$ T is hysteretic. This hysteretic part is obviously associated with the magnetization of the ferromagnetic gate, and reflects the fact that the magnetic field modulation imposed on the two-dimensional electrons is stronger in the down-sweep of the field than the up-sweep. The lower panel of Fig. 2 shows $\Delta\rho_{xx}(B) = \rho_{xx}(B, \text{down}) - \rho_{xx}(B, \text{up})$, i.e. the difference between the two traces in Fig. 2(a). The solid arrows mark the expected position of ρ_{xx} minima for the *magnetic* modulation. The good agreement between the expected and observed positions of resistivity minima establishes that the *magnetic* Weiss oscillation is realized in this device.

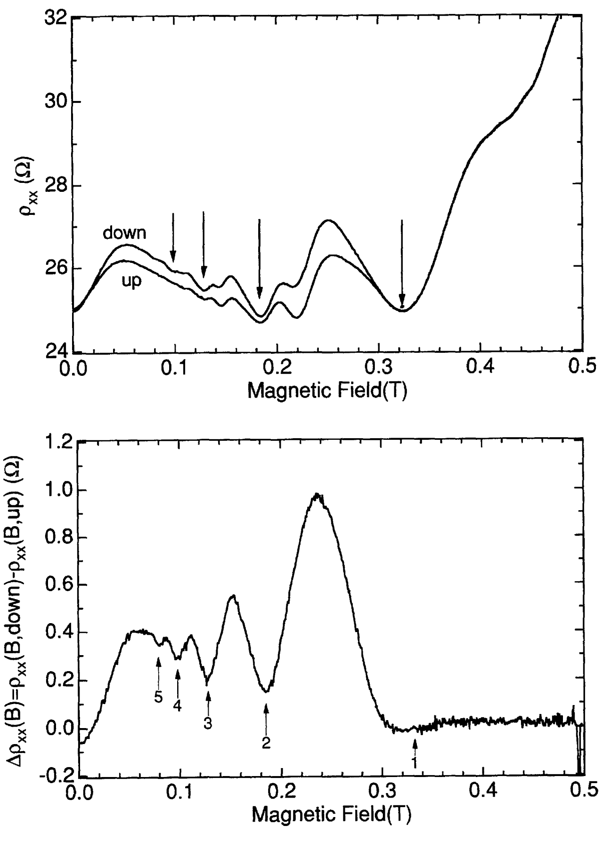

Fig. 2. *Upper panel*: Magnetoresistance of a sample with microstructured nickel gate of period $a = 0.5$ μm with the gate bias set at $V_g = +500$ mV. The $\rho_{xx}(B)$ curve shows hysteretic behavior with respect to the magnetic field excursion. The solid (dashed) arrows mark the positions of resistivity minima for the magnetic (electric) Weiss oscillation. *Lower panel*: The difference between the down- and up-sweep traces of $\rho_{xx}(B)$ which clearly shows the magnetic Weiss oscillation.

As mentioned earlier, the magnetoresistance trace contains oscillatory components of electric as well as magnetic origin. The relative amplitude of the two components of the Weiss oscillation is changed with the gate bias. The case of coexisting electric and magnetic modulations is theoretically by Peeters and Vasilopoulos.[9] When the electric and magnetic modulations are in phase, as in the present case, the positions of the ρ_{xx} minima change between eq. (1) and eq. (2) as the relative amplitude of the electric and magnetic modulations is changed. This is seen in Fig. 3 which shows three traces for gate bias $V_g = -250$, -100, and 0 mV.

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 $\rho(0)$ 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. 2), the *built-in* potential modulation is most effectively compensated, so that most of the oscillatory component of ρ_{xx} is of magnetic origin. As the gate bias becomes more negative, the electric modulation component increases. As seen in Fig. 3, the oscillatory component of ρ_{xx} increases in amplitude and shifts along the horizontal axis. At $V_g = -250$ mV, the oscillatory component is almost purely of *electric* origin.

Assuming that the Weiss 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 am-

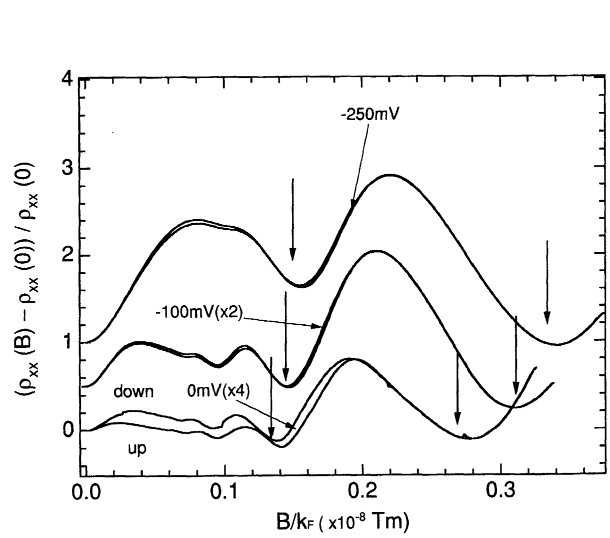

Fig. 3. $\rho_{xx}(B)$ curves for different values of gate bias $V_g = 0$, -100, and -250 mV. The vertical arrows indicate the positions of ρ_{xx} minima calculated by the procedure described in the text. Note that the traces are vertically offset for clarity.

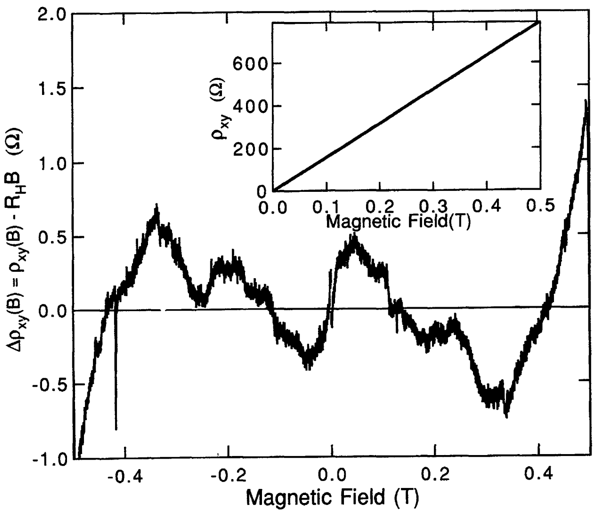

Fig. 4. Hall resistivity, $\rho_{xy}(B)$, taken under the same conditions as Fig. 2. The curve in the main panel, obtained by subtracting the B-linear component, exhibits the Weiss oscillation.

plitude with a theoretical expression given by Peeters and Vasilopoulos.[9] For example, the modulation amplitude is estimated as $B_1 \approx 13$ mT at $B = 0.25$ T on the down-sweep. In a similar way, one can estimate the amplitude of potential modulation the two-dimensional electrons feel when the ρ_{xx} oscillation is dominated by the electric effect. For the three traces in Fig. 3, the potential modulation amplitude is estimated as $eV_0 \approx 0.31$, 0.85, and 1.8 meV for $V_g = 0$, -100, and -250 mV, respectively. The magnetic modulation amplitude is always the same as the case of $V_g = +500$ mV. Knowing the amplitude of the electric and magnetic modulation amplitudes, we can calculate the *phase* term of Weiss oscillation. It is -0.21 for $V_g = -250$ mV, which is close to $-1/4$ for the pure electric case. For $V_g = -100$ and 0 mV, the calculated values of the phase are -0.15 and -0.02, respectively. The corresponding positions of ρ_{xx} minima are marked with vertical arrows in Fig. 3. The good agreement with the experimental data proves the validity of the model.

The Weiss oscillation is also expected in resistivity tensor components other than ρ_{xx}, albeit of much smaller magnitude. The inset in Fig. 4 shows the Hall resistivity, $\rho_{xy}(B)$, which looks perfectly linear on this scale.

In order to detect deviation from linearity, a B-linear component is subtracted from the experimental $\rho_{xy}(B)$, which is plotted in the main frame of Fig. 4. In this way, it is seen that the Hall resistivity also shows the Weiss oscillation.

To summarize, with the use of a microstructured gate of ferromagnetic substance, we have succeeded in observation of the theoretically predicted *magnetic* Weiss oscillation. Oscillatory magnetoresistance consists of both electric and magnetic modulation components whose relative amplitude can be changed by adjusting the gate bias. We have also observed the Weiss oscillation in the Hall resistivity component.

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