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Magnetoresistance oscillation in a two-dimensional electron gas under periodic modulation of electric and magnetic fields

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Abstract

We have studied oscillatory magnetoresistance (Weiss oscillation) in a two-dimensional electron gas (2DEG) subjected to a one-dimensional periodic modulation of both electric and magnetic fields. The relative amplitude of the two types of modulation can be controlled by applying a bias voltage to a gate consisting of a periodic array of ferromagnetic metal stripes. Allowing the magnetic modulation to dominate by applying +500 mV to the gate, we succeeded in observing magnetic Weiss oscillation which is characterized by peak/valley inversion in the magnetoresistance oscillation and not with regard to its well-known electric counterpart. The oscillation curve shows continuous phase shift with smaller gate biases, until it reaches the peak/valley location of electric Weiss oscillation at about −250 mV.

Keywords: Electrical transport; Electrical transport measurements; Gallium arsenide; Heterojunctions; Magnetic phenomena; Nickel; Semiconductor–semiconductor heterostructures

A high-mobility two-dimensional electron gas (2DEG) formed in a modulation-doped GaAs/AlGaAs heterostructure, combined with modern lithography techniques, has made it possible to artificially introduce a potential variation in the lateral length scale which is comparable to or less than the electron mean free path. A one-dimensional periodic electrostatic potential modulation thus introduced is now known to give rise to oscillatory magnetoresistance (so-called "electric" Weiss oscillation) periodic in $1/B$, with the minima of resistivity ρ_{xx} occurring at

$$2R_c = a(n - \tfrac{1}{4}) \qquad (n = 1,2,3,\ldots). \qquad (1)$$

Here x denotes the direction of the modulation, a the period, $R_c = \hbar k_F/eB = \sqrt{2\pi n_e}\, l^2$ the cyclotron radius of an electron at the Fermi level, with k_F the Fermi wave-number, n_e the electron density, and $l = \sqrt{\hbar/eB}$ the magnetic length [1–6]. The oscillation is well accounted for by the classical commensurability between a and $2R_c$.

A magnetic analogue of such periodic modulation is theoretically predicted to reproduce a similar oscillatory magnetoresistance but with the peak/valley structure inverted [7–9]; the positions of ρ_{xx} minima obey the formula

$$2R_c = a(n + \tfrac{1}{4}) \qquad (n = 1,2,3,\ldots). \qquad (2)$$

An initial attempt to observe the magnetic Weiss oscillation experimentally was made by Yagi and

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Iye [8], using an array of ferromagnetic metal (nickel) stripes as a source of magnetic field modulation. However, a native electric modulation brought about by the presence of striped gates (through elastic strain and/or Fermi level pinning at the surface) exceeded the magnetic one, and hindered an unambiguous interpretation of their result. We therefore made an electrical connection among all the nickel stripes for an otherwise similar device to that of Yagi and Iye, so that we can apply a bias to the striped gates in an attempt to compensate the unwanted "built-in" electric modulation. By adjusting the gate bias, we succeeded in suppressing the electric modulation to observe the magnetic Weiss oscillation [10]. Furthermore the gate-biasing technique turned out to be a convenient way to vary the relative amplitude of electric and magnetic modulations by modifying the electric amplitude with respect to a fixed magnetic one [11].

The structure of devices used in our study are shown schematically in the inset of Fig. 1. The devices were fabricated from MBE-grown GaAs/AlGaAs single heterojunction with electron density $n_e \approx 4 \times 10^{15}\ \mathrm{m}^{-2}$ and low-temperature mobility $\mu \approx 60\ \mathrm{m}^2/\mathrm{V \cdot s}$. A standard Hall bar was formed by photolithography and wet etching, and nickel striped gates were deposited on the top defined by an electron-beam lithography and lift-off process.

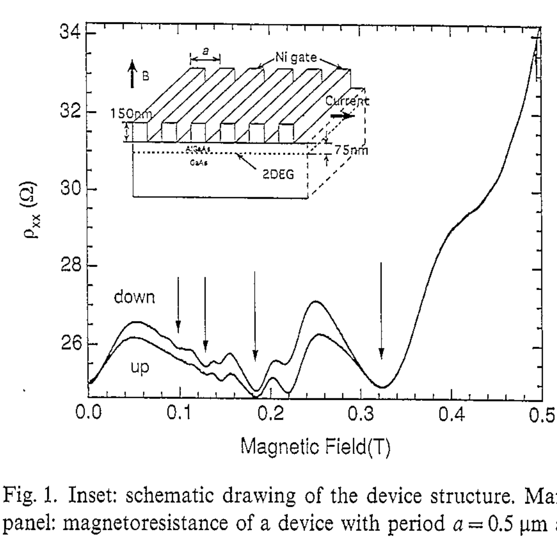

Fig. 1. Inset: schematic drawing of the device structure. Main panel: magnetoresistance of a device with period $a = 0.5$ μm at $T = 4.2$ K. The gate bias $V_g = +500$ mV. Up-sweep and down-sweep traces are shown.

It is worth noting that this lift-off process, not completed in the previous work [8], seems to have contributed to the reduction of electrostatic potential modulation by eliminating elastic strain arising from the differential contraction between GaAs and the electron-beam resist. The width and spacing of the stripes are designed to be equal for the devices used in this study. All the stripes are electrically connected with a thin line of nickel (not shown in Fig. 1) running parallel to the current direction.

Magnetotransport measurements were carried out at $T = 4.2$ K using a standard low-frequency AC technique. The main panel of Fig. 1 shows the magnetoresistance $\rho_{xx}(B)$ for a device with $a = 0.5\ \mu$m when the gate bias $V_g = +500$ mV is applied. The gate bias was chosen to suppress the native electric modulation most efficiently. Two traces, those of up-sweep and down-sweep of the magnetic field, are shown. Both traces show oscillatory behavior with the minima well explained by Eq. (2). This means that we observed magnetic Weiss oscillation by making the magnetic modulation dominate in our device. (The traces in Fig. 1 contain minima which cannot be explained by Eq. (2). Their origin is not known at present.) The magnetoresistance displays hysteretic behavior: the down-sweep trace, representing stronger magnetic modulation, shows larger ρ_{xx} than the up-sweep trace. The hysteresis loop closes at $B \approx 0.3$ T, indicating that the magnetization of the nickel gates saturate around this field. To confirm the magnetic origin of the oscillation, we took the difference between up- and down-sweeps, $\Delta\rho_{xx}(B) = \rho_{xx}(B,\mathrm{down}) - \rho_{xx}(B,\mathrm{up})$, as plotted in Fig. 2, which obviously is associated only with magnetic modulation. The positions of the ρ_{xx} minima expected from Eq. (2) for $n = 1$–5 are marked with arrows in Fig. 2, showing excellent agreement with those observed experimentally.

For smaller V_g, the compensation of the electric modulation is less complete. A situation is realized where both electric and magnetic modulations are simultaneously present in the device. In addition, the two modulations are likely to be spatially in phase, since both originate from the nickel stripes. Fig. 3 shows the magnetoresistance curves (normalized by zero-field resistivity) of the same device as

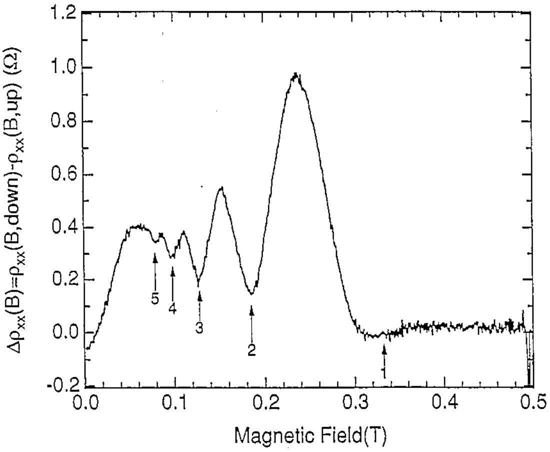

Fig. 2. The difference between up- and down-sweeps $\Delta\rho_{xx}(B)=\rho_{xx}(B,\text{down})-\rho_{xx}(B,\text{up})$, shown in Fig. 1. The arrows indicated the expected positions of resistivity minima for magnetic Weiss oscillation (Eq. (2)).

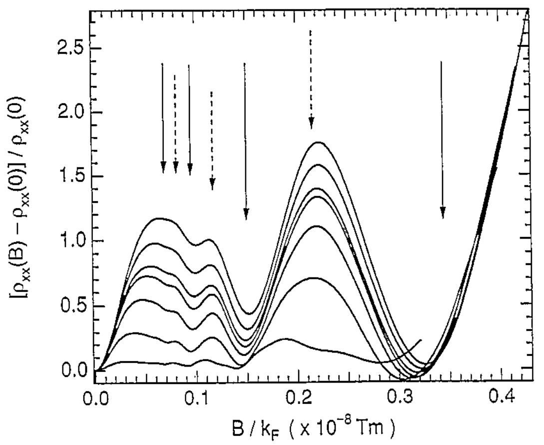

Fig. 3. Magnetoresistance of a device with $a=0.5\,\mu$m at $T=4.2$ K for different gate bias voltages $V_g=+50$ (bottom), -50, -110, -125, -150, -175, and -200 (top) mV. The expected positions of resistivity minima for electric and magnetic Weiss oscillation (Eqs. (1) and (2)) are marked with solid and dashed arrows, respectively.

Fig. 1 for $V_g=+50$, -50, -110, -125, -150, -175 and -200 mV. The electron densities n_e determined by Hall measurements are 3.87, 3.62, 3.46, 3.37, 3.30, 3.19, and $3.11\times10^{15}\,\text{m}^{-2}$, respectively, and the zero-field mobilities μ are 59.3, 51.5, 47.3, 45.3, 43.2, 41.4, and 39.3 $\text{m}^2/\text{V}\cdot\text{s}$ for each gate bias, respectively. The horizontal axis is taken as B/k_F in order to scale the magnetoresistance traces of different electron densities. For clarity, only down-sweeps, which represent saturated magnetization of the nickel gates as mentioned, are shown in Fig. 3. Expected locations of the resistivity minima for electric and magnetic positions (Eqs. (1) and (2)) are indicated by solid and dashed arrows for $n=1$–3 and $n=1$–4, respectively. It can be seen that with decreasing V_g, the resistivity minima shifts continuously from magnetic toward electric Weiss minima.

Peeters and Vasilopoulos [9] considered magnetoresistance in the case where both electric and magnetic modulations are present simultaneously. For the in-phase sinusoidal electrostatic-potential and magnetic-field modulations, $V(x)=V_0\cos[(2\pi/a)x]$ and $B_z(x)=B_0\cos[(2\pi/a)x]$, their calculation gives (for $\omega_c\tau\gg1$)

$$\frac{\rho_{xx}(B)-\rho_{xx}(0)}{\rho_{xx}(0)}=\frac{ak_F}{2\pi^2}\frac{\hbar\omega_0}{\hbar\omega_c}\frac{\hbar\omega_0}{E_F}(\omega_c\tau)^2(1+\delta^2)\times\left[1-A(T/T_a)+A(T/T_a)\times\sin^2\left(\frac{2\pi R_c}{a}-\frac{\pi}{4}+\phi\right)\right],\tag{3}$$

where $\omega_0=eB_0/m^*$, $\omega_c=eB/m^*$ with m^* the electron effective mass, E_F the Fermi energy, $\tau=m^*\mu/e$ is the scattering time, $k_B T_a=(\hbar\omega_c/4\pi^2)ak_F$, $A(x)=x/\sinh x$, and

$$\delta\equiv\frac{2\pi V_0}{ak_F\hbar\omega_0}=\tan\phi\tag{4}$$

is a dimensionless parameter characterizing the relative amplitude of electric and magnetic modulations. δ can be deduced from the amplitude of the experimental oscillation traces using Eq. (3). On the other hand, ϕ can be directly read from the same traces. The plot of δ versus ϕ for the largest oscillation ($n=1$) for each V_g is shown in Fig. 4, derived from the traces shown in Fig. 3 and traces for $V_g=0$, -100 and -250 mV in a different run (not shown). The agreement of the plots with the relation $\delta=\tan\phi$ (dotted curve) is quite good, indicating that our experimental oscillation ampli-

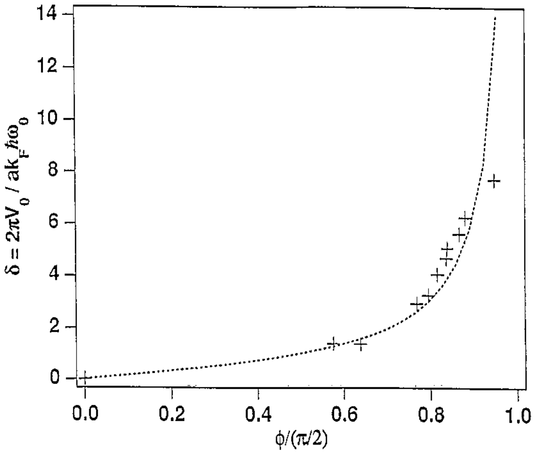

Fig. 4. Plot of relative amplitude parameter δ versus the phase ϕ of the magnetoresistance oscillation. δ is deduced from the amplitude of experimental oscillation traces using Eq. (3) and ϕ is directly read from the traces. The dotted curve depicts the relation $\delta = \tan\phi$.

tude and phase shift is well explained by the formulation by Peeters and Vasilopoulos [9].

In summary, we have observed a magnetic Weiss oscillation for 2DEG with a one-dimensional periodic array of nickel striped gates, suppressing stray electrostatic potential modulation by applying +500 mV to the gates. (We have learned that similar magnetic Weiss oscillation has been observed by Carmona et al. [12] and Ye et al. [13] using superconducting lead stripes and dysprosium stripes for magnetic modulation, respectively.) The electric modulation can be restored by decreasing the gate bias. By changing the relative strength of the two modulations with the gate bias, we have observed continuous phase shift of the oscillatory magnetoresistance, whose amplitude and the shift are in agreement with the theory of Peeters and Vasilopoulos [9].

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