Journal of the Physical Society of Japan
Vol. 64, No. 3, March, 1995, pp. 706–710

Magnetoresistance Oscillation in Two-Dimensional Electron Gas under Spatially Modulated Vector Potential

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(Received December 22, 1994)

We have observed an oscillatory magnetoresistance effect in a two-dimensional electron gas in GaAs/AlGaAs heterojunctions subjected to a periodically modulated magnetic field generated using a striped gate electrode of ferromagnetic metal. The hysteretic part of magnetoresistance clearly shows oscillations analogous to the so-called Weiss oscillation with the phase relation predicted for the case of vector potential modulation.

[Weiss oscillation, GaAs/AlGaAs, heterostructure, two-dimensional electron gas, magnetoresistance]

In the last several years, a novel class of magnetotransport phenomena associated with periodic superstructures both artificial and natural, has been uncovered. They manifest themselves as oscillation of magnetoresistance as a function of magnetic field strength or field angle with respect to the crystalline axes. An example of the former is the so-called Weiss oscillation,[1-3] where a two-dimensional electron gas in a GaAs/AlGaAs heterojunction subjected to a weak one-dimensional periodic potential modulation created by a striped gate electrode, exhibits magnetoresistance oscillations periodic in $1/B$. An example of the latter is the angular-dependent magnetoresistance oscillation (ADMRO) effect observed in a few layered metallic systems,[4-9] where vertical resistivity ρ_{zz} shows oscillation periodic in $\tan\theta$, θ being the magnetic field angle with respect to the z-axis normal to the layer plane. The common physical essence of these effects lies in periodic occurrence of matching between the cyclotron orbit and the periodic superstructure.

Here we focus on the Weiss-type oscillation. In the usual Weiss oscillation effect, the minima of ρ_{xx}, x being the direction of the one-dimensional potential modulation, occur at

$$2R_c = a\left(n - \frac{1}{4}\right) \quad (n: 1, 2, 3\cdots), \tag{1}$$

where a is the modulation periodicity, $R_c = \hbar k_F/eB = (2\pi n_e)^{1/2} l^2$ is the cyclotron radius of an electron at the Fermi level, with k_F the Fermi wavenumber, n_e the electron density, and $l = (\hbar/eB)^{1/2}$ the magnetic length. There are a few different (basically equivalent) lines of interpretation for this phenomenon. The semiclassical interpretation by Beenakker[10] is as follows. A sinusoidally modulated potential gives rise to a spatially alternating local electric field component in the x-direction. With a magnetic field in the z-direction, electrons acquire alternating local drift velocity $(\boldsymbol{E}\times\boldsymbol{B})/B^2$. The net drift motion of electrons, given by the local drift velocity averaged over different cyclotron orbits $\langle\boldsymbol{E}\times\boldsymbol{B}\rangle/B^2$, is enhanced or suppressed, depending on the commensurability between R_c and a. Weiss *et al.*[1,2] have shown that the presence of a modulated potential results in periodic occurrence of flat (dispersionless) subbands. When the Fermi level coincides with the energy range of such flat subbands, quenching of the drift motion occurs. Similar calculation based on a quantum Boltzmann equation formalism is carried out by Vasilopoulos and Peeters.[11]

A *magnetic* analog of the Weiss oscillation, namely oscillatory magnetoresistance due to a

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spatially modulated *vector* potential, has been envisaged by Xue and Xiao,[12] Yagi and Iye[13] and Peeters and Vasilopoulos.[14] It has been predicted that instead of eq. (1) for the *electric* Weiss oscillation, the magnetoresistance minima in the *magnetic* Weiss oscillation are given by

$$2R_c = a\left(n + \frac{1}{4}\right) \quad (n\colon 1, 2, 3\cdots). \qquad (2)$$

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

Yagi and Iye[13] made an experimental attempt to observe this type of phenomenon by use of a system similar to the one used in the present study. The result, however, was not conclusive because the Weiss oscillation component caused by strain-induced potential modulation turned out to be dominant in their devices, which obscured the interpretation of the magnetoresistance traces. In the present study, we have succeeded in unambiguous demonstration of the *magnetic* Weiss oscillation by use of higher electron mobility samples and improved device fabrication processing.

Devices used in the present study were fabricated from MBE-grown GaAs/AlGaAs single heterojunction samples with electron density $\sim 4\times 10^{11}$ cm^{-2} and low-temperature electron mobility $\sim 6\times 10^{5}$ cm^2/V s. The structure of the devices is as shown in the inset of Fig. 1. The GaAs/AlGaAs heterointerface, where the two-dimensional electrons reside is $\sim$75 nm away from the surface. The device fabrication process was as follows. A standard Hall-bar pattern was defined on a GaAs/AlGaAs chip by photolithography and wet etching. A striped gate pattern as shown in the inset of Fig. 1 was then defined on PMMA resist by electron beam lithography. Ferromagnetic metal (nickel) was then deposited by vacuum evaporation to a thickness of $\sim$150 nm. The fabrication of the striped gate was completed by a lift-off process. 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

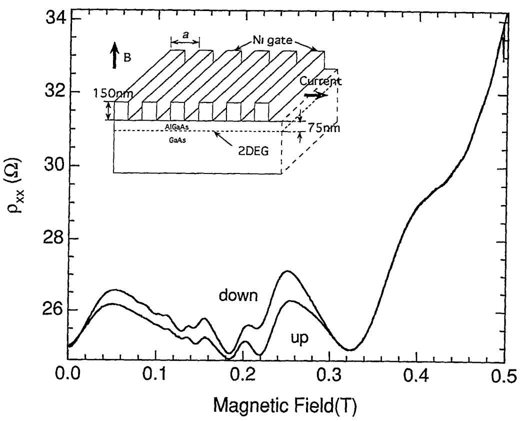

Fig. 1. *Inset*: Schematic drawing of the device structure. *Main Panel*: Magnetoresistance of a device with a 0.5-μm-period gate at T=4.2 K. The gate bias is V_g = +500 mV. The two traces correspond to the up- and down-sweep of the magnetic field. The maximum field excursion for this curve is 0.5 T.

ensure that all parts of the striped gate were at the same electrical potential. A few devices with different gate modulation periods were prepared. The width and the spacing of the stripes were made equal for the presently used devices.

Magnetotransport measurements were performed by use of a standard low-frequency *a.c.* technique. All the measurements reported in this paper were performed at T=4.2 K. In general, the oscillatory magnetoresistance contains both scalar and vector potential modulation components. In order to distinguish the magnetic Weiss oscillation effect from the electric counterpart, we used the gate bias and the magnetic field excursion as two controlling parameters. The effect of changing the gate bias is twofold. On one hand, it changes the two-dimensional electron density as determined by simultaneous measurement of the Hall resistivity. On the other hand, it changes the amplitude of the electric potential modulation. As we learned in the previous study,[13] the scalar potential modulation component arises not only from the usual electric field modulation but also from the strain-induced potential modulation. The latter effect is not easy to quantify because it depends on the detailed strain distribution in the actual device. We found empirically that the strain-induced potential modulation can be partially compensated by adjusting the gate bias so as to make the electric potential modulation counteract it. It turned out that for the presently studied devices, positive bias voltage worked so as to reduce the total (electric plus strain) scalar potential modulation. The magnetic field excursion affects the hysteretic magnetization of the ferromagnetic gate. As seen below, the magnetoresistance trace exhibits distinct hysteresis, from which we can extract information on the influence of the microstructured ferromagnetic substance on the two-dimensional electrons. We also fabricated, for the purpose of comparison, devices with similar structure except that the gate is made of gold, which exhibited the usual Weiss oscillation, as expected.

The graph in Fig. 1 shows the magnetoresistance in one of the devices with a gate of period $a=0.5\ \mu$m, at a gate bias $V_g=+500$ mV. The magnetoresistance in the field range $B<0.3$ T exhibits a clear hysteresis. This hysteretic part is obviously related to the magnetization of the ferromagnetic gate. The hysteresis loop closes above $B\sim 0.3$ T, above which the magnetization of the nickel gate is reversible. The field excursion for this measurement was up to 0.5 T, which was high enough to bring the nickel gate to saturation. The magnetic field modulation imposed on the two-dimensional electrons is stronger during the down-sweep than during the up-sweep. We stress that the hysteretic behavior is associated with the difference in the strength of the field *modulation* between the up and down sweeps, and not with the difference in the *uniform* magnetic field. Simultaneous measurements of Hall resistivity have indicated that the screening of the uniform magnetic field, which would cause a shift in the horizontal magnetic field axis of this figure, is completely negligible in the present context.

We extract the magnetoresistance component explicitly dependent on the hysteretic magnetization of the ferromagnetic gate by taking the difference, $\Delta\rho_{xx}(B)=\rho_{xx}(B, \text{down}) - \rho_{xx}(B, \text{up})$, between the up/down sweeps as plotted in Fig. 2. The $\Delta\rho_{xx}(B)$ curve shows distinct oscillations. $\Delta\rho_{xx}(B)=0$ above ~ 0.3 T because the hysteresis vanishes there. The arrows indicate the expected positions of resistivity minima for the *magnetic* Weiss oscillation. The excellent agreement between the expected and observed positions of resistivity minima firmly establishes that the *magnetic* Weiss oscillation is realized in this device.

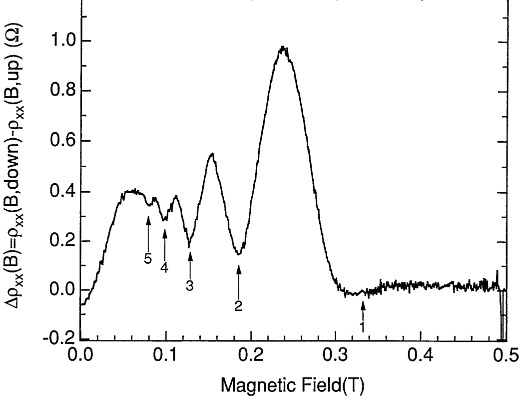

Fig. 2. Hysteretic component of the magnetoresistance, $\Delta\rho(B)=\rho(B, \text{down})-\rho(B, \text{up})$, extracted from the curve in Fig. 1. The arrows indicate the expected positions of resistivity minima for *magnetic* Weiss oscillation.

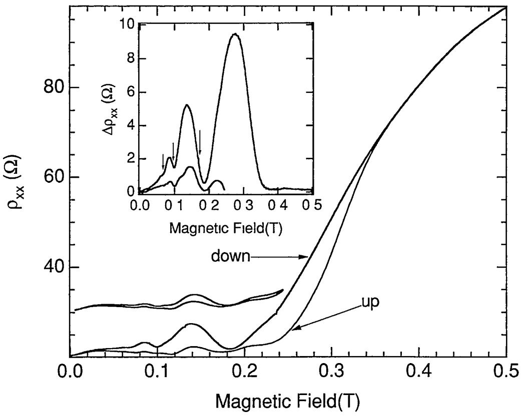

Fig. 3. *Main Panel*: Magnetoresistance curves for a device with a 1-μm-period gate. The two curves differ in the maximum value of field excursion, 0.25 T and 0.5 T. *Inset*: The hysteretic component, $\Delta\rho(B)$ extracted from the curves in the main panel. The arrows indicate the expected positions of resistivity minima for the *magnetic* Weiss oscillation.

The above conclusion is further supported by measurements on other devices with different gate modulation periods. Figure 3 shows the result for a device with a floating gate of period $a=1\ \mu$m. The electron density is

4.28×10^{11} cm^{-2}. This figure shows two hysteretic traces similar to Fig. 2 for different maximum values of field excursion. The inset shows the difference curve. The saturation field for the gate of this device is $B\sim0.35$ T, as judged from the closure of the hysteresis loop. The difference curve with the excursion field $B_{max}=0.5$ T exhibits distinct oscillations with minimum positions consistent with those predicted. The oscillation amplitude is considerably reduced for a field excursion to $B_{max}=0.25$ T, for which the Ni gate is not fully saturated. However, the positions of the $\Delta\rho_{xx}(B)$ minima remain the same, which provides further confirmation that the screening of the uniform magnetic field is negligible.

It is obvious that the hysteretic part of the magnetoresistance curve is to be attributed to the magnetic field modulation. However, the converse is not true, i.e., the hysteretic part is not the whole of the magnetic-field-modulation-induced magnetoresistance oscillation. In fact, it is concluded from the following observation that the major part of the oscillatory magnetoresistance in Fig. 1 should be attributed to the *magnetic* Weiss oscillation. Figure 4 shows the magnetoresistance curves of the same device as in Fig. 1 for three values of 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 are $\rho(0)=66.5$, 35.7, and 24.8 Ω, respectively. In order to scale the magnetoresistance traces for different electron densities, the quantity B/k_F is taken as the horizontal axis. Note that the oscillation amplitude changes significantly with the gate bias, so that each curve is scaled accordingly. The magnetoresistance oscillation for $V_g=-250$ mV is almost purely *electric*, as seen from the positions of minima. As the negative gate bias is decreased, the positions of reisitivity minima shift toward those expected for the *magnetic* Weiss oscillation and at the same time relative weight of the hysteretic component of the magnetoconductivity increases. When the gate bias is set $V_g=+500$ mV (Fig. 1), the *magnetic* Weiss oscillation becomes the major part.

To summarize, we have obtained clear experimental evidence for the *magnetic* Weiss oscillation. The relative magnitude of the *electric* and *magnetic* Weiss oscillations can be changed to some extent by adjusting the gate bias. In the present systems, the amplitude of the magnetic field modulation depends, in a rather complicated way, on the applied field strength and its history, because the ferromagnetic domain structure in the nickel strips can be quite complicated. In order to make a detailed comparison with the theoretical curve for the magnetoresistance, it is preferable to choose a ferromagnetic gate material with simple domain structure and a strain-free device structure.

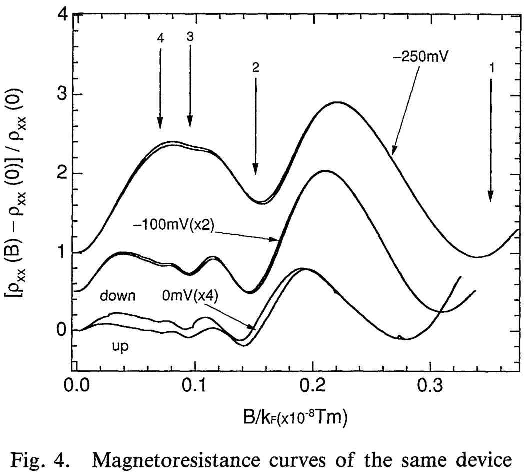

Fig. 4. Magnetoresistance curves of the same device as in Fig. 1, for different gate bias voltages. The values of zero field resistivity are $\rho(0)=66.5$, 35.7, and 24.8 Ω for the gate bias $V_g=-250$, -100 and 0 mV, respectively. The expected positions on the horizontal axis, B/k_F, of resistivity minima for the *electric* Weiss oscillation are marked with arrows.

Acknowledgments

We thank Dr. R. Yagi for collaboration in the early stage of this work and for valuable discussions. This work was supported by Grant-in-Aid for Scientific Research on Priority Areas, "Quantum Coherent Electronics", from the Ministry of Education, Science and Culture.

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