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CONTROL OF MAGNETIC FIELD MODULATION ON TWO-DIMENSIONAL ELECTRON GAS AT THE GaAs/AlGaAs HETEROINTERFACE BY PARALLEL MAGNETIC FIELD

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Abstract—We have studied the magnetoresistance oscillation (Weiss oscillation) in a two-dimensional electron gas (2DEG) subjected to a one-dimensional periodic modulation of magnetic field. Magnetic field modulation was produced by placing nickel grating on the surface of 2DEG wafer and applying a magnetic field $B_{\parallel}$ *parallel* to the 2DEG plane. We show that the amplitude of the magnetic modulation can be varied by rotating $B_{\parallel}$ with respect to the grating, independent of the perpendicular field $B_{\perp}$ used for the measurement of magnetoresistance. With decreasing magnetic modulation amplitude, the magnetoresistance oscillation loses its amplitude without shifting the phase, until peak-to-valley inversion takes place. This demonstrates that the magnetic modulation thus produced is spatially out-of-phase with the small residual electrostatic potential modulation inevitably brought about by the grating.

1. INTRODUCTION

Two-dimensional electron gas (2DEG) with weak one-dimensional periodic modulation of electrostatic potential and/or magnetic field shows oscillatory magnetoresistance periodic in $1/B$ (Weiss oscillation). The oscillation originates from the commensurability between the spatial modulation period a and the cyclotron radius $R_c = \hbar k_F/eB$, where $k_F = \sqrt{2\pi n_e}$ represents the Fermi wavenumber with n_e the electron density. For magnetic field modulation, minima in resistivity occur at

$$\frac{2R_c}{a} = n + \frac{1}{4} \quad (n = 1, 2, 3, \ldots), \tag{1}$$

while for potential modulation, peaks and valleys interchange their roles and Equation (1) represents the positions of maxima.

Experimentally, magnetic field modulation has been realized by placing a micro-patterned grating of ferromagnet[1–3] or superconductor[4] on the surface of 2DEG wafer. However, the attachment of the grating is inevitably accompanied by electrostatic potential modulation, mainly through the differential thermal contraction between the metal and the semiconductor[5,6]. Therefore the devices fabricated for periodic magnetic modulation usually also contain periodic potential modulation. Recently, Skuras *et al.*[7] have shown that the strain-induced potential mainly arises from piezoelectric coupling and that the effect depends on the orientation of the stripe pattern with respect of the crystal axes of GaAs/AlGaAs. It has been shown that the strain-induced potential can be made minimal by orienting the stripe pattern to the [100] direction. The direction is applied to the study of 2DEG with a spatially varying magnetic field by Nogaret *et al.*[8].

In the present paper, we study 2DEG with a ferromagnetic metal (nickel) grating on top. Magnetic field $B_{\parallel}$ parallel to the 2DEG plane is employed to generate magnetic field modulation. This allows us to manipulate the magnetic modulation independently from the cyclotron motion of 2DEG electrons which is affected only by the field $B_{\perp}$ perpendicular to the 2DEG plane; a distinct advantage over more conventional experimental configuration using only $B_{\perp}$[1–4]. We will show that the modulation amplitude can be controlled by the direction of $B_{\parallel}$ with respect to the grating. In contrast to the conventional configuration, the magnetic field modulation and the remnant potential modulation are out-of-phase with each other, as will be shown. We also use [100] direction to minimize the potential modulation.

2. EXPERIMENTAL

The device used in the present study was fabricated from a molecular beam epitaxy (MBE)-grown GaAs/AlGaAs single heterostructure with electron density $n_e = 2.7 \times 10^{15}\,\text{m}^{-2}$ and mobility $\mu = 60\,\text{m}^2\,\text{V}^{-1}\,\text{s}^{-1}$ at 1.5 K. The 2DEG plane resides at a depth 90 nm from the surface. A stan-

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dard Hall-bar was made by photolithography along the [100] direction. An array of nickel stripes with periodicity $a = 500$ nm ($a/2$ wide and $a/2$ apart) was defined by electron-beam lithography, vacuum deposition and lift-off process.

Magnetotransport measurement was carried out using a standard low-frequency a.c. technique. A cross-coil superconducting magnet system was employed enabling us to independently control $B_{\parallel}$ and $B_{\perp}$.

3. RESULTS AND DISCUSSION

Figure 1 shows the magnetoresistance traces with $B_{\parallel} = 5$ T applied at different angles, φ, ranging from 10° to 80° with respect to the nickel stripes. The azimuthal angle φ is defined in the inset of Fig. 1; $\varphi = 0°$ corresponds to $B_{\parallel}$ parallel to the current direction, while at $\varphi = 90°$ $B_{\parallel}$ is parallel to the nickel stripes. Weiss oscillations are seen in the field range $B_{\perp} < 0.3$ T. Shubnikov–de Haas oscillation is also observed as an oscillation with shorter period at higher $B_{\perp}$.

Hysteretic behavior was not observed between up and down sweeps of $B_{\perp}$, as opposed to our previous experiments[1,2]. This suggests that magnetization of the nickel stripes is unaffected by $B_{\perp}$, as expected from $B_{\perp} \ll B_{\parallel}$. To elucidate the phase of Weiss oscillation, traces in Fig. 1 are replotted in Fig. 2 with their abscissa converted to $2R_c/a$ using the value of n_e determined from Shubnikov–de Haas oscillation for each trace. For traces with $\varphi = 10°$, 40°, 50°, minima are observed at the positions given by Equation (1) (vertical dotted lines in the figure), with their oscillation amplitude decreasing with increasing φ and without substantial shift in positions of minima. At $\varphi = 70°$ almost no oscillation is observed, while for $\varphi = 80°$, oscillation reappears with maxima instead of minima at Equation (1) positions.

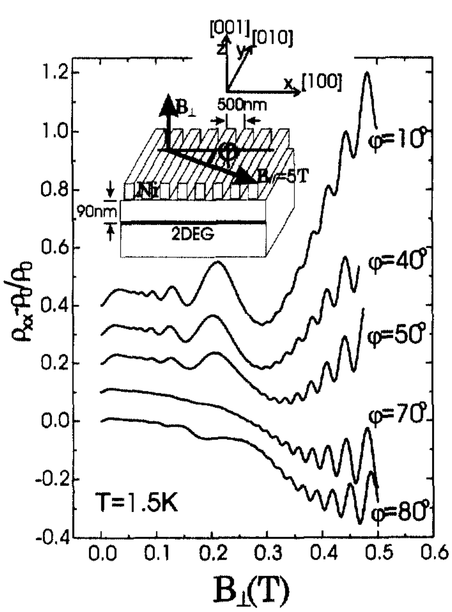

Fig. 1. Magnetoresistance of the device with period $a = 0.5\,\mu$m at $T = 1.5$ K with different angles $\varphi = 10°$ (top), 40°, 50°, 70° and 80° (bottom). The traces are offset for clarity. Inset: Schematic illustration of the device. Definition of azimuthal angle φ is also shown.

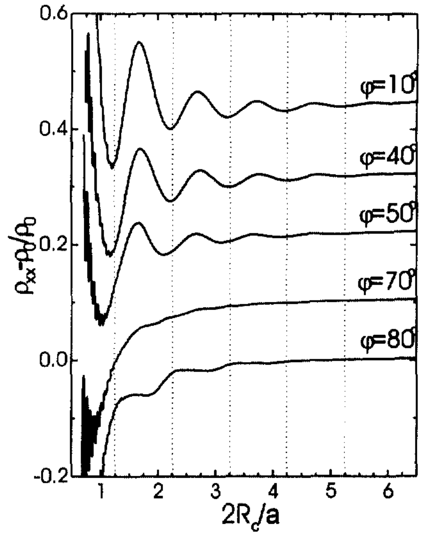

Fig. 2. Traces in Fig. 1 replotted as a function of $2R_c/a$. The traces are offset for clarity. Vertical dotted line depicts the positions given by Equation (1).

Oscillations for $\varphi < 70°$ are interpreted to mainly derive from magnetic field modulation. Increasing φ decreases the amplitude of magnetic modulation felt by 2DEG. As mentioned earlier, however, 2DEG with grating always contains potential modulation as well, which clearly manifests itself as peak/valley inverted oscillation when the magnetic modulation amplitude is sufficiently small (trace for $\varphi = 80°$).

The behavior of Weiss oscillation as a function of relative amplitude of the two types of modulations, magnetic field and electrostatic potential, for the present experiment is distinctly different from our previous experiments using only $B_{\perp}$[1,2]. For the latter, the oscillation phase (positions of minima and maxima in $2R_c/a$) shifted continuously with the relative amplitude between the condition for pure magnetic and pure potential modulation. The difference is attributed to the difference in the relative spatial phase of the two types of modulations. For former experiments, maxima in magnetic field coincide with maxima (or minima) in potential (in-phase modulation, see Fig. 3(a)). Our present experiment can be explained assuming out-of-phase modulation in which maxima (or minima) of the two types of modulation arrive alternatingly (Fig. 3(b)). Theoretical calculation by Peeters and

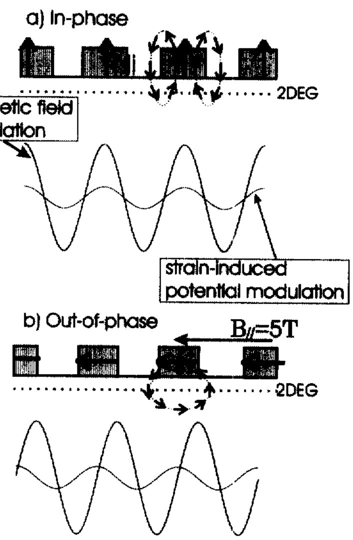

Fig. 3. The profile of magnetic field and electrostatic potential modulation seen by electrons in 2DEG. (a) in-phase modulation (b) out-of-phase modulation.

Vasilopoulos[9] shows that for potential and magnetic field modulation $V(x) = V_0 \cos(2\pi x/a)$ and $B_z(x) = B_0 \sin(2\pi x/a)$, respectively, the oscillatory part of the magnetoresistance is approximated by

$$\frac{2}{\pi^2}\cdot\frac{1}{2R_c/a}\cdot(B_0\mu)^2\cdot(1-\delta^2)\cdot A\left(\frac{T}{T_a}\right)\cdot\sin^2\left(\frac{2\pi R_c}{a}-\frac{\pi}{4}\right) \qquad (2)$$

where μ denotes the mobility, $A(x) = x/\sinh(x)$ and $T_a = E_F/(\pi^2 \cdot 2R_c/a)$ with E_F the Fermi energy. The parameter

$$\delta \equiv \frac{2\pi m^* V_0}{ak_F\hbar eB_0} = \tan(\phi) \qquad (3)$$

represents the relative amplitude of the two types of modulation. Equation (2) predicts that peak to valley inversion takes place without the phase shift of the oscillation; peaks in the pure magnetic case ($\delta = 0$) lose their amplitude with the increase of δ without shifting their positions, change the sign and turn into valleys when $|\delta|$ exceeds unity. This is basically what we observe in Fig. 2. By increasing azimuthal angle φ, the amplitude of the magnetic field modulation B_0 seen by 2DEG decreases while V_0 remains unchanged, resulting in the increase of δ. The observation strongly suggests that magnetic modulation produced by in-plane field is spatially out-of-phase with the remnant potential modulation. Elementary calculation placing magnetic dipole on the nickel stripes[10] also shows that magnetic field modulation in the 2DEG plane is reasonably well approximated as being out-of-phase with the potential modulation, as shown in Fig. 3(b). The behavior is in marked contrast with the case for in-phase modulation where phase factor ϕ given by Equation (3), which also reflects the relative amplitude, enters in the argument of the $\sin^2$ term[1,2,9].

To be more quantitative, we deduce B_0 for each φ, and V_0, taking the oscillation amplitude at $n = 2$ for each trace in Fig. 2 and employing Equations (2) and (3). The deduced value of V_0 was 0.11 meV. This value is an order of magnitude smaller than V_0, typically 1.0 meV, generated by nickel stripes aligned to a more conventional crystallographic direction, the [110] direction[1,2]. The deduced B_0 is plotted in Fig. 4 as a function of φ. The plot displays $\cos(\varphi)$ dependence with the extrapolated value of B_0 at $\phi = 0$ being 19.7 mT. The $\cos(\varphi)$ dependence shows that only the component of magnetization of nickel stripes parallel to the current, $\mathbf{M}_{\text{eff}}$ depicted in the inset of Fig. 4, is relevant to the amplitude of magnetic modulation B_0. Simple explanation can be given by the semiclassical treatment[11] of the Weiss oscillation: the y-component (direction parallel to the nickel stripes) of the guiding-center-drift velocity $v_{d,y}$ results in the longitudinal resistivity ρ_{xx}. The contribution of the y-component magnetic field modulation to $v_{d,y}$ disappears when averaged over one cyclotron orbit, provided the amplitude is much smaller than external field $B_\perp$.

In summary, we have shown that the amplitude of magnetic field modulation felt by 2DEG electrons generated by in-plane field $B_{||}$ varies as $\cos(\varphi)$ of the angle φ between $B_{||}$ and the direction of the one-dimensional period. This offers a unique opportunity to manipulate the amplitude of magnetic modulation independent of $B_\perp$, the field component relevant to the motion of 2DEG electrons. In contrast to a more conventional experimental configur-

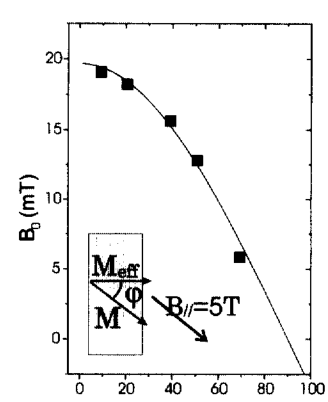

Fig. 4. Amplitude B_0 of the magnetic field modulation as a function of azimuthal angle φ. Solid curve represents $B_{0(\varphi=0)}\cdot\cos(\varphi)$.

ation using $B_{\perp}$ both to generate magnetic field modulation and to measure magnetoresistance, the resulting magnetic field modulation is spatially out-of-phase with the potential modulation generated by the grating.

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