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Strain-induced potential modulation versus magnetic field modulation on two-dimensional electron gas at the GaAs/AlGaAs heterointerface

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Abstract

We have studied the magnetoresistance oscillation (magnetic Weiss oscillation) in a two-dimensional electron gas (2DEG) subjected to a one-dimensional periodic modulation of magnetic field. We estimated the amplitudes of strain induced potential modulation and the magnetic field modulation by independently controlling the magnetic field components parallel and perpendicular to the 2DEG plane.

Keywords: Magnetoresistance oscillation; GaAs/AlGaAs; heterostructures

1. Introduction

Magnetic Weiss oscillation is an oscillatory magnetoresistace phenomenon in 2DEG under one-dimensional periodic modulation of magnetic field [1–5]. The periodicity in $1/B$ originates from the commensurability between the spatial modulation period and the cyclotron diameter. The series of minima in resistivity, when the resistivity is measured with current parallel to the direction of modulation, occurs at

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

Here, a is the period of the modulation and $R_c = \hbar k_F/eB = \sqrt{2\pi n_e \ell^2}$ is the cyclotron radius of an electron at the Fermi level with k_F the Fermi wave number, n_e the electron density, and $\ell = \sqrt{\hbar/eB}$ the magnetic length. Eq. (1) contrasts with the condition $2R_c/a = n - \frac{1}{4}$ $(n = 1, 2, 3, \dots)$ for the case of potential modulation (electric Weiss oscillation).

Magnetic Weiss oscillation has been observed experimentally [2,4,5]. In those experiments a spatially varying magnetic field was produced by placing a suitably micro-patterned ferromagnet

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or superconductor on the surface of the 2DEG specimen.

In the course of those studies, it has been recognized that placing a patterned metal on the surface generates a strain-induced potential modulation due to differential thermal contraction of the metal and GaAs [1,6]. The Weiss oscillation component originating from this strain-induced potential modulation admixtures to and often prevails over the magnetic Weiss oscillation. In our previous work, this strain-induced potential modulation amplitude was found to be typically ~ 1 meV [2,3]. 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 [1 0 0] direction. The direction is applied to the study of 2DEG with spatially varying magnetic field by Nogaret et al. [8].

In the present work, we investigate the change in the amplitude of the magnetic field modulation by the orientation of the external magnetic field. We control independently the magnetization of the ferromagnet and the motion of electrons with the magnetic field component parallel and perpendicular to 2DEG plane, respectively. We also employ the [1 0 0] direction to minimize the remnant 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 $n_e = 2.4 \times 10^{15}\,\mathrm{m}^{-2}$ and mobility $\mu = 60\,\mathrm{m}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$ at 4.2 K. The 2DEG plane resides at a depth of 70 nm from the surface. A standard Hall-bar was made by photolithography along the [1 0 0] 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 AC technique. A cross-coil superconducting magnet system enabled us to independently control the magnetic field components parallel and perpendicular to the 2DEG plane. The parallel magnetic field $B_{\parallel}$ was used to manipulate the magnetization of the nickel stripes, while the perpendicular magnetic field $B_{\perp}$ was used to measure the magnetoresistance of the 2DEG. By rotating $B_{\parallel} = 6$ T in the plane of 2DEG with respect to the nickel stripes, we can control the amplitude of magnetic field modulation.

3. Results and discussion

Fig. 1 shows the magnetoresistance for the device in the absence of parallel magnetic field $B_{\parallel}$. Two traces, up-sweep and down-sweep of $B_{\perp}$ display hysteretic behavior due to that of the magnetization of the nickel stripes. The down-sweep trace shows a larger oscillation amplitude, indicating a stronger magnetic modulation than that of the up-sweep trace.

In Fig. 2, the down-sweep trace in Fig. 1 is replotted with their abscissa converted to $2R_c/a$ using

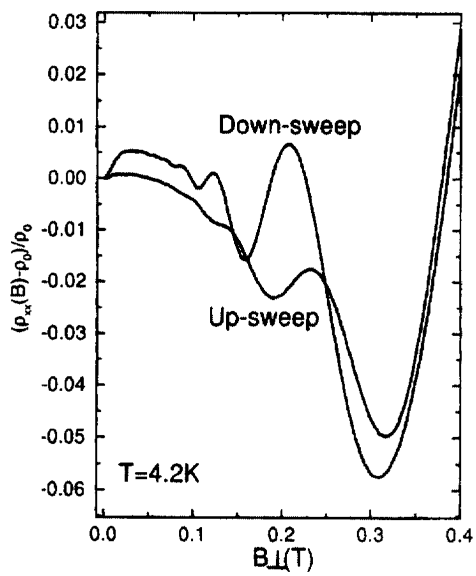

Fig. 1. Magnetoresistance of the device with period $a = 0.5\,\mu\mathrm{m}$ at $T = 4.2$ K. Up-sweep and down-sweep traces are shown, as indicated.

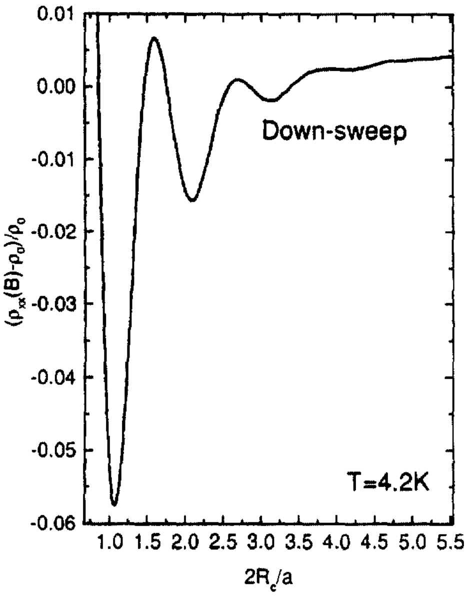

Fig. 2. Down-sweep trace in Fig. 1 replotted as a function of $2R_c/a$.

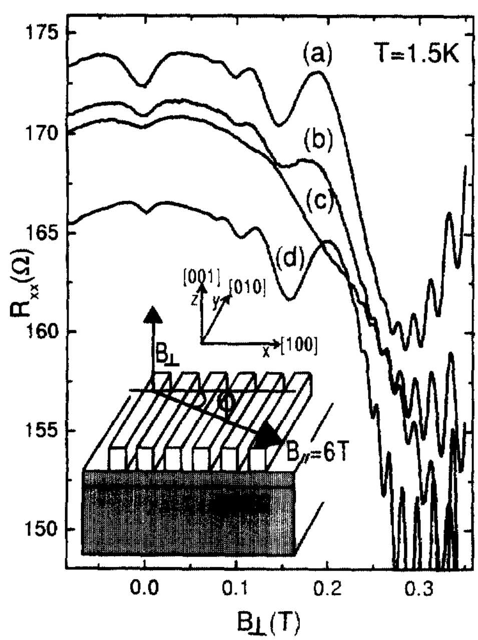

Fig. 3. Magnetoresistance of the device with period $a = 0.5$ μm at $T = 1.5$ K with different angles $\varphi = 0$ (trace (a)), 45° (trace (b)) and 90° (trace (c)). Trace (d) shows the magnetoresistance without $B_\parallel$. Inset: Schematic illustration of the device.

the value of n_e determined from the Shubnikov–de Haas oscillation. It is found that the positions of minima in the magnetoresistance are close to those given by Eq. (1) for the case of purely magnetic modulation. This confirms that the strain-induced potential modulation is relatively small in this sample. There is, however, a small deviation from Eq. (1), indicating the presence of a residual potential modulation in phase with the magnetic one. We return to this point later when we estimate the modulation amplitudes.

Fig. 3 shows the magnetoresistances at $T = 1.5$ K with $B_\parallel = 6$ T applied at different angles φ ranging from 0° to 90° with respect to the nickel stripes as shown in the inset (traces (a)–(c)) and a trace without $B_\parallel$ (trace (d), down sweep). In contrast to Fig. 1, traces (a)–(c) in Fig. 3 show no hysteretic behavior. Magnetization of the nickel stripes is unaffected by $B_\perp$ as expected from $B_\perp \ll B_\parallel$. When $B_\parallel = 6$ T was applied perpendicular to the stripes ($\varphi = 0°$, trace (a)), the maximum magnetic modulation was obtained as evidenced by the largest amplitude of the magnetic Weiss oscillation. The amplitude of the magnetic field modulation was estimated to be 10.4 mT from the oscillation amplitude, employing Eq. (28) in Ref. [9] (see below). Trace (b) with $\varphi = 45°$ shows much smaller amplitude of magnetic Weiss oscillation. When $B_\parallel = 6$ T is applied parallel to the stripes ($\varphi = 90°$, trace (c)), the magnetization of the nickel stripes generates no magnetic field modulation at the 2DEG plane. The oscillation with much smaller amplitude and with inverted peak/valley structure as compared with traces (a) and (b) is ascribed to *electric* Weiss oscillation resulting from the residual strain-induced potential modulation. The amplitude V_0 of the modulation is estimated as 0.07 meV from the oscillation amplitude [10,11]. This value is an order of magnitude smaller than V_0 generated by nickel stripes aligned to a more conventional crystallographic direction, the [1 1 0] direction [2,3].

In Fig. 4, the traces in Fig. 3 are replotted with their abscissa converted to $2R_c/a$. While the positions of minima in the magnetoresistances for $\varphi = 0°$ (trace (a)) and $\varphi = 45°$ (trace (b)) agree with

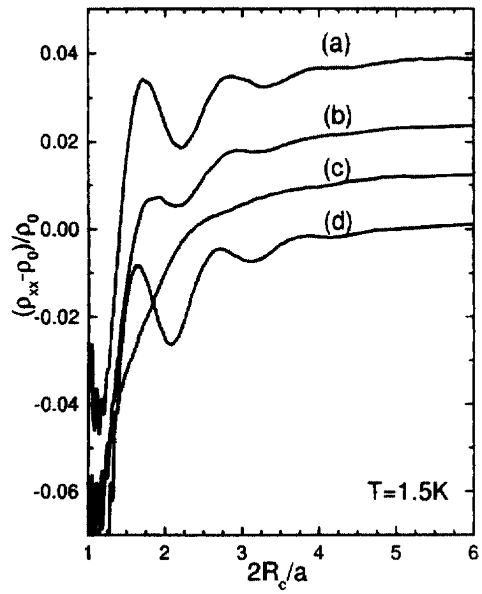

Fig. 4. Traces in Fig. 3 replotted as a function of $2R_c/a$. The traces are offset for clarity.

those given by Eq. (1), those in trace (d) show slight discrepancy. This can be explained by the relative spatial phase of the magnetic field modulation and the residual potential modulation.

When both an electrostatic potential modulation $V(x) = V_0 \cos(2\pi x/a)$ and a magnetic field modulation $B_z(x) = B_0 \cos(2\pi x/a)$ are present (with an identical spatial phase), the minima in resistivity ρ_{xx} occur at [9]

$$\frac{2R_c}{a} = n + 1/4 - \phi/\pi \quad (n = 1, 2, 3, \ldots),$$

$$\delta \equiv \frac{2\pi V_0}{a k_F \hbar \omega_0} = \tan(\phi), \tag{2}$$

where $\omega_0 = eB_0/m^*$ with m^* the electron effective mass. The parameter δ represents the ratio of the electric field modulation to the magnetic one, and determines the phase ϕ of the magnetoresistance oscillation. The positions of minima and maxima shift continuously as a function of δ. Small deviation in minima positions of Fig. 2 and Fig. 4d from Eq. (1) can be attributed to the presence of residual potential modulation which is spatially in phase with the magnetic field modulation. In fact, the phase deviation $\phi = 0.16\pi$ read from Fig. 2 or Fig. 4d shows quite good agreement with $\phi = 0.16\pi$ and 0.17π calculated by the second equation in Eq. (2), using $B_0 = 7.2$ and 6.8 mT deduced from the oscillation amplitude of each trace, respectively, using Eq. (23) in Ref. [9].

On the other hand, when potential and magnetic field modulations are spatially out-of-phase to each other, namely $V(x) = V_0 \cos(2\pi x/a)$ and $B_z(x) = B_0 \sin(2\pi x/a)$, theoretical calculation [10] 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, changes the sign and turn into valleys. This is basically what we see in Fig. 3a–c. 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 that peaks in trace (a) lose their amplitude in (b) and turn into valleys in (c) without shifting their positions strongly suggests that magnetic modulation produced by in-plane field is spatially out-of-phase with the remnant potential modulation.

In Fig. 5, we plot φ dependence of the magnetic modulation amplitude B_0 deduced from the oscillation amplitude and the value $V_0 = 0.07$ meV obtained from trace (c), employing Eq. (28) in Ref. [9] (formula for out-of-phase modulation). The $\cos(\varphi)$ dependence shows that only the component of $B_{\parallel}$ parallel to the current, i.e., perpendicular to the nickel stripes counts for the amplitude of magnetic modulation B_0.

In summary, we have found that the azimuthal angle of the in-plane field $B_{\parallel}$ can be used to control the strength B_0 of magnetic field modulation felt by 2DEG. Especially when $B_{\parallel}$ is parallel to the nickel stripes, we can nullify the magnetic field modulation even in the presence stripes of the ferromagnets and observe very small residual strain-induced potential modulation. In contrast to more conventional experimental configuration using $B_{\perp}$ to generate magnetic field modulation, the resulting magnetic field modulation is out-of-phase with the strain-induced potential modulation.

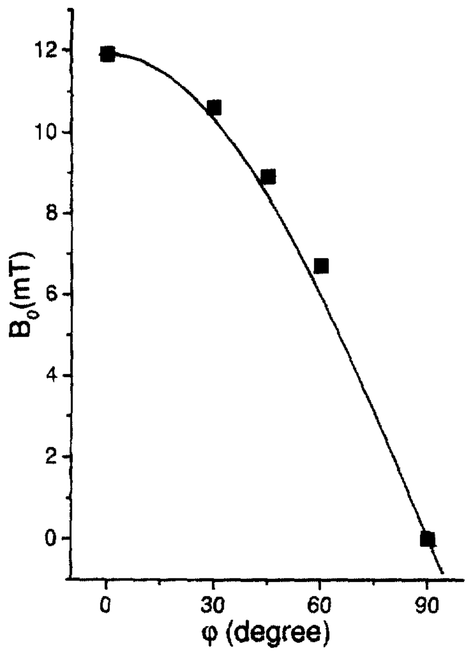

Fig. 5. Amplitude B_0 of the magnetic field modulation as a function of azimuthal angle φ. Solid curve represents $B_0(\varphi = 0)\cos(\varphi)$.

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