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# Transport in ferromagnet/semiconductor 2DEG hybrid network structure

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## Abstract

We have investigated transport in a network of narrow two-dimensional electron gas (2DEG) channel under a gradient magnetic field which is generated by a network of cobalt film deposited on the surface. Resistance of the 2DEG network changed with the magnetization of the cobalt network. The gradient magnetic field breaks the symmetry of the system with respect to the direction along the channel. We have found that the differential resistance under a finite DC bias current depends on the current direction. Magnetoresistance as a function of uniform perpendicular magnetic field while keeping the gradient field constant exhibits an overall shift and modulation of Shubnikov de-Haas oscillations.

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*Keywords:* Gradient magnetic field; Snake orbit; Magnetoresistance

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## 1. Introduction

Mesoscopic ferromagnet/two-dimensional electron gas (2DEG) hybrid structures attract much interest not only as an experimental stage of novel magnetotransport phenomena but also as a prototype of future devices. We can study such systems from two different physical viewpoints; the magnetization process of a sub-micron scale ferromagnet and the transport in 2DEG under spatially varying magnetic field. In past works, the magnetization of a small ferromagnetic element was detected by use of the local Hall effect of a narrow 2DEG channel [1,2]. The transport in 2DEG under 1D periodic magnetic modulation [3–6] and magnetic barrier [7,8] causes the resistance behaviour which reflects the ballistic transport under inhomogeneous magnetic fields. In the present work, we investigate electronic transport in a novel hybrid structure which consists of a cobalt network and a GaAs/AlGaAs 2DEG network to explore the above-mentioned two aspects.

The resistance of the 2DEG network sensitively detects changes in the stray magnetic field produced by the cobalt wire on the surface. We could introduce a gradient magnetic field into the 2DEG channel by magnetizing the cobalt film perpendicular to the channel direction. The energy spectrum of the channel under a magnetic field gradient is asymmetric with respect to the sign of wave number $k$, i.e. the time-reversal symmetry is broken [9,10]. Electronic states which are confined near the line of zero magnetic field correspond to the so-called snake states in semiclassical picture, which propagates along the line in the direction determined by the sign of the gradient. Experimentally Nogaret et al. reported a resonance peak due to the snake states confined by the magnetic

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field gradient in the device with a ferromagnetic strip deposited above the center line of the channel [11].

## 2. Experimental method

Our samples were fabricated from a GaAs/AlGaAs single-heterojunction wafer grown by molecular beam epitaxy. The density and mobility of the 2DEG before processing at 1.3 K were $3.1 \times 10^{15}\ \mathrm{m}^{-2}$ and $67\ \mathrm{m}^2/\mathrm{Vs}$, respectively. The depth of the 2DEG plane from the sample surface was 65 nm. We fabricated a hybrid network structure schematically shown in Fig. 1 by the following procedure. First, we made a network of GaAs/AlGaAs single heterojunction by mesa etching, which has a period 6 µm and a width 1.5 µm. Then, we placed a network of cobalt wire of width 0.5 µm on top of the 2DEG network. The sample has $15 \times 40$ cells of a network, thus a total width 90 µm. The separation between two voltage probes to measure a longitudinal resistance $R_{xx}$ of the 2DEG network was 180 µm. The transport measurements were carried out using a low-frequency AC lock-in technique at an excitation current of 100 nA at $T = 1.3$ K.

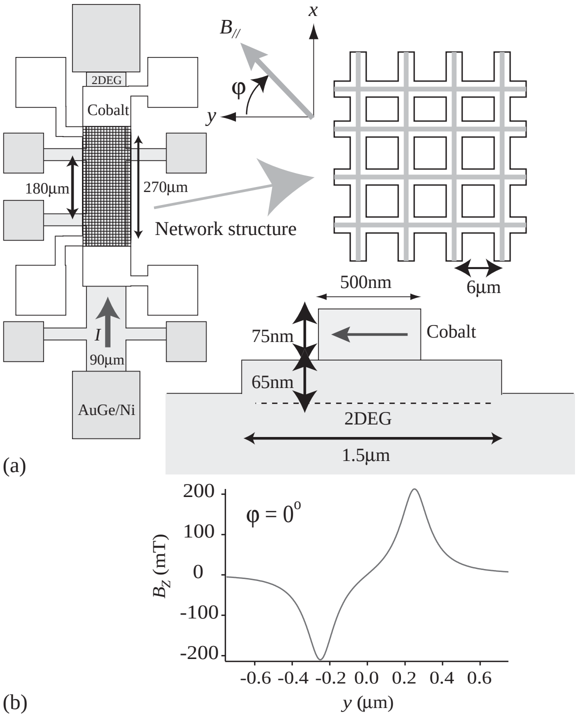

Fig. 1. (a) Schematic diagram of a sample configuration. (b) Calculated magnetic field profile $B_z$ inside a 2DEG channel with an in-plane magnetic field applied perpendicular to the channel direction. Saturation magnetization of cobalt film was assumed to be 1.8 T.

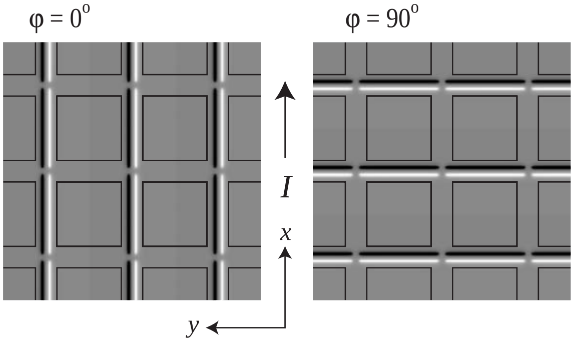

Fig. 2. Field patterns of an inhomogeneous magnetic field for $\varphi = 0°$ and $\varphi = 90°$. In the bright (dark) area, normal component of a stray magnetic field $B_z$ from a cobalt film is upward (downward). For $\varphi = 0°$, electron trapped by a gradient magnetic field (snake states) propagates along $\langle +x \rangle$ direction.

The present system is similar to the device studied by Nogaret et al. [11] except that the ferromagnet/2DEG hybrid forms a network rather than a single wire. The device was fabricated in such a way that the electronic transport in the cobalt network itself could be measured simultaneously as that in the 2DEG network. Use of a cross-coil magnet system consisting of a 7 T split coil and 1 T solenoid enabled us to control the horizontal and vertical magnetic field components independently. By applying an in-plane magnetic field to magnetize a cobalt film, a spatially varying magnetic field is generated inside the channel. The field patterns in the case of $\varphi = 0°$ ($B \perp I$) and $\varphi = 90°$ ($B \| I$) are as shown in Fig. 2. Here, $\varphi$ is the azimuthal angle of the in-plane magnetic field defined in Fig. 1. The bottom panel of Fig. 1 shows a magnetic field profile across the 2DEG channel calculated by a simple magnetostatic model. The amplitude of the normal component of the stray field $B_z$ is about 0.2 T.

## 3. Resistance change associated with the magnetization process

First, we set the magnetic field within the 2DEG plane at different values of azimuthal angle $\varphi$. We precisely adjusted the tilt angle of the external magnetic field parallel to the 2DEG plane by probing the Hall

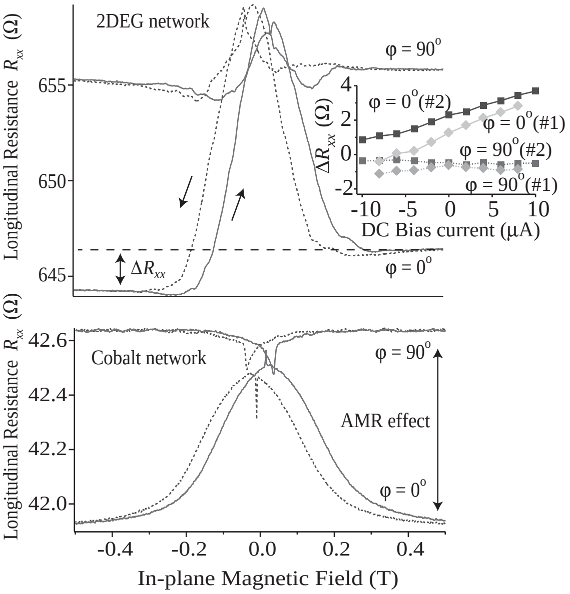

Fig. 3. Resistance behaviour of 2DEG network and cobalt network sweeping an in-plane magnetic field for $\varphi = 0°$ and $\varphi = 90°$. Inset shows DC bias current dependence of the change of a differential resistance $\Delta R_{xx}$ for two different samples (#1,#2) fabricated in the same condition.

voltage at the non-etched region. Fig. 3 shows the longitudinal resistance of the 2DEG network and cobalt network for two orientations of the in-plane magnetic field $\varphi = 0°$ and 90°. The resistance of the cobalt network exhibits the so-called anisotropic magnetoresistance (AMR) effect with hysteresis. The corresponding change in the resistance of the 2DEG is caused by the stray field. For $|B| > 0.3$ T the magnetization of the cobalt network is saturated, and the resistance of 2DEG becomes constant. The gradient magnetic field from the cobalt wire enhances the conductivity in the narrow 2DEG channel.

In the case of $\varphi = 0°$, the so-called snake orbits running along the line of zero magnetic field are parallel to the current direction. These orbits propagate in the direction determined by the sign of the magnetic field gradient. The contribution of the snake orbits to the conduction can be inferred from the behaviour of the differential resistance under finite DC bias current. Inset in Fig. 3 shows the change in the resistance difference between the positive and negative in-plane magnetic field $\Delta R_{xx} = \Delta(\mathrm{d}V/\mathrm{d}I)$ defined in the main panel of Fig. 3 as a function of the DC bias current $I$. For $\varphi = 0°$, $\Delta R_{xx}$ changes linearly with the DC bias current in such a manner that the resistance is smaller when the current carrying direction of the snake states is the same as the DC bias current. For $\varphi = 90°$, such effect is absent. This asymmetric behaviour of the differential resistance may originate from the asymmetry of the system with a gradient magnetic field. However, the detail of the mechanism is unclear at the moment. Recently, Lawton et al. reported a similar rectification effect in the device with a single wire [12]. They propose that the phenomenon is due to anisotropic electron–phonon interaction arising from an asymmetry in the energy dispersion of the 2DEG channel under a gradient magnetic field, which occurs when the electron temperature is raised by bias current. In our samples, the amplitude of magnetic modulation is much smaller than that assumed in their model, so their theory cannot be directly compared with our result. We would like to point out that the observed linear dependence of $\Delta R_{xx}$ implies that the voltage difference caused by inverting the gradient magnetic field is proportional to the temperature difference between the electrons and the lattice.

## 4. Magnetoresistance under a uniform perpendicular magnetic field

Second, we measured the magnetoresistance as a function of uniform perpendicular magnetic field while fixing the profile of the spatially varying magnetic field from the cobalt network by applying a relatively large in-plane magnetic field 5 T (Fig. 4). The spatial modulation of the magnetic field in the 2DEG network channel causes an overall shift of magnetoresistance and modulation of Shubnikov de-Haas (SdH) oscillations. Since the channel width is smaller than the electron mean free path, the boundary scattering plays an important role in the magnetoresistance near zero magnetic field. Perpendicular magnetic field forms a skipping orbit along the boundary and suppresses the backscattering, which reduces the resistance. Moreover, in the case of a narrow channel under a magnetic field gradient, snake orbit and cycloid orbit enhance the conductivity along the channel. For $\varphi = 90°$, the enhancement of the conductivity along the $y$-direction shifts the magnetoresistance upward with respect to that for $\varphi = 0°$. We estimated the enhancement of conductivity due to the field gradient quantitatively by using the following relation between

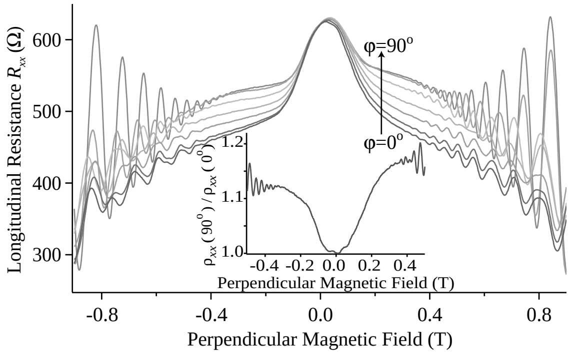

Fig. 4. Magnetoresistance of a 2DEG network as a function of the uniform perpendicular magnetic field for different settings of the azimuthal angle $\varphi$ (15° step) of the parallel magnetic field 5 T which keeps the spatially varying magnetic field from a cobalt network constant. Inset shows the value $\rho_{xx}(\varphi=90^\circ)/\rho_{xx}(\varphi=0^\circ)$.

conductivity and resistivity for different settings of the in-plane field direction $\varphi$,

$$\sigma_{xx}(0^\circ) = \sigma_{yy}(90^\circ) = \rho_{xx}(90^\circ)/S,$$

$$\sigma_{yy}(0^\circ) = \sigma_{xx}(90^\circ) = \rho_{xx}(0^\circ)/S,$$

where $S = \rho_{xx}(0^\circ)\rho_{xx}(90^\circ) + \rho_{xy}(0^\circ)\rho_{xy}(90^\circ)$.

The calculated $\sigma_{xx}(0^\circ)/\sigma_{yy}(0^\circ) = \sigma_{yy}(90^\circ)/\sigma_{xx}(90^\circ) = \rho_{xx}(90^\circ)/\rho_{xx}(0^\circ)$ is shown in the inset of Fig. 4. It increases with the perpendicular magnetic field and saturates at 0.3 T. Snake orbits trapped in the line of zero magnetic field disappear when the uniform perpendicular magnetic field cancels the oppositely directed stray magnetic field, which occurs at $\sim$ 0.2 T in the present sample. Cycloid orbits appear also in the spatial region without alternating sign of magnetic field, thus at higher uniform magnetic field. The observed behaviour of magnetoresistance reveals that the enhancement of conductivity is mainly caused by the cycloid orbit rather than by the snake orbit.

Cyclotron diameter becomes smaller than the channel width above 0.2 T, where SdH oscillations are observed. Since the length scale of the magnetic field gradient from the cobalt film is comparable to the cyclotron radius and the spatial variation of magnetic field is on the same order of magnitude as the uniform component, Landau subband mixing occurs. SdH oscillations originates from the collisional term of conductivity which describes the hopping between the localized states and reflects density of states of the system [13]. For $\varphi = 0^\circ$, in which case the channel along the current direction is subjected to the gradient magnetic field, the SdH oscillations are heavily modulated while for $\varphi = 90^\circ$ modulation is absent. This indicates that the contribution of the collisional term results almost exclusively from the channel along the current direction. On the other hand, the channel under a gradient magnetic field perpendicular to the current direction makes a significant contribution to the diffusion term, as evidenced by the reduction of negative magnetoresistance in $\varphi = 90^\circ$ trace.

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