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Magnetotransport in 2DEG with magnetic barriers

Masahiro Hara[a,*], Akira Endo[a], Shingo Katsumoto[a,b], Yasuhiro Iye[a,b]

[a] Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan
[b] CREST Project, Japan Science and Technology Corporation, 1-4-25 Mejiro, Toshima-ku, Tokyo 171-0031, Japan

Abstract

We have studied the transport in 2DEG subjected to two different types of magnetic barrier. Excess resistivities due to those magnetic barriers increase as T^2. The resistance as a function of the uniform component of the magnetic field exhibits a positive magnetoresistance and a beating pattern of the Shubnikov–de Haas oscillations.

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Electron transport in inhomogeneous magnetic field has been investigated extensively in recent years. Magnetoresistance in 2DEG subjected to periodic magnetic field (magnetic lateral superlattice) results in an oscillatory magnetoresistance arising from commensurability between the cyclotron radius and the period of the magnetic modulation (magnetic Weiss oscillations) [1–3]. It has been found that the magnetic lateral superlattice gives rise to an excess component of resistivity at zero uniform magnetic field, which varies as $\Delta\rho \sim AT^2 + C$ with increasing temperature. The T^2-term of the excess resistivity is attributed to electron–electron Umklapp scattering process [4,5]. In the present work, we investigate the transport through isolated magnetic barriers and make comparison with periodic case.

Our samples were fabricated from a GaAs/AlGaAs single-heterojunction wafer grown by molecular beam epitaxy. The electron density and mobility of the 2DEG at 4.2 K were $3.0 \times 10^{15}\ \mathrm{m}^{-2}$ and $40\ \mathrm{m}^2/\mathrm{Vs}$, respectively. The depth of the 2DEG plane from the sample surface was 75 nm. An array of cobalt strips was deposited on top of the current arm of a standard Hall bar. The width of the Hall bar is 30 μm, and the separation between the voltage probes is 60 μm. The transport measurements were carried out using a low-frequency AC technique at an excitation current of 1 μA. A cross-coil superconducting magnet system used in the present study consisted of a 6 T split-coil magnet and a homemade 1 T solenoid. It enabled us to control the horizontal and vertical components of the magnetic field independently. The ferromagnetic strips were fully magnetized by applying a strong enough magnetic field parallel to the 2DEG plane.

Two different types of magnetic barrier have been made. Schematic diagrams of sample configuration are shown in Fig. 1. One type, which we call "dipolar magnetic barrier", was created by the fringing field generated by a narrow ferromagnetic wire magnetized perpendicularly to its length and consisted of

* Corresponding author. Tel.: +81-471-36-3301; fax: +81-471-36-3301.
E-mail address: hara@issp.u-tokyo.ac.jp (M. Hara).

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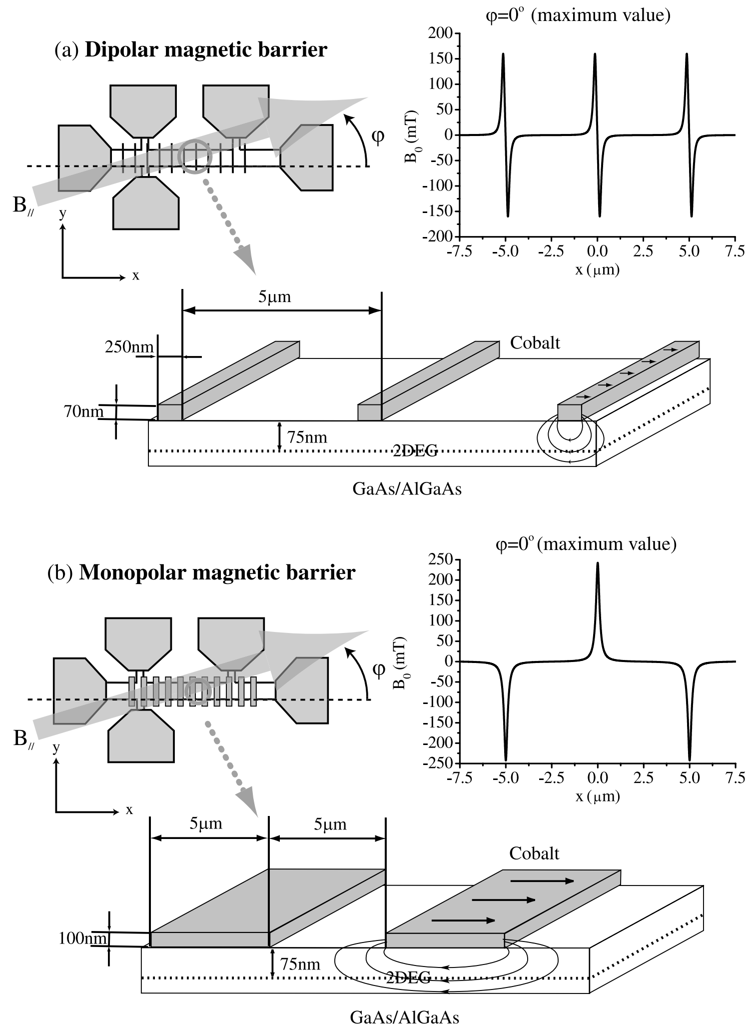

Fig. 1. Schematic diagram of sample configuration and calculated magnetic field profile ($\varphi = 0^\circ$: maximum value) of two different magnetic barriers: (a) dipolar magnetic barriers; (b) monopolar magnetic barriers.

a pair of tightly spaced positive and negative local magnetic field. The other, "monopolar magnetic barrier", was a local magnetic peak of either sign and was generated at the edge of a wide ferromagnetic film. In the actual samples, many such barriers were placed with the mutual separation comparable to or greater than the electron mean free path. The amplitude of the fringing field was precisely controlled by changing the azimuthal angle φ of the horizontal field with respect to the ferromagnetic strips. We were able to sweep the uniform perpendicular magnetic field while keeping the strength of the magnetic barriers constant.

The resistivity of the 2DEG in the absence of uniform magnetic field increases as the magnetic barriers are turned on. We investigated the dependence of the excess resistivity $\Delta\rho$ on the amplitude of the magnetic barrier B_0 which changes as $B_0 = B_0^{\max} \cos\varphi$. In the case of the dipolar barriers, $\Delta\rho$ is proportional to $B_0^{3/2}$. This is similar to what we found for the case of periodic magnetic field modulation. [1] The $B_0^{3/2}$-dependence is in accordance with the theoretical prediction by Matulis and Peeters [6], who consider the semiclassical electron trajectories in the presence of the magnetic barriers. They calculate the critical angle of the incident electron wave vector which separates whether a particular trajectory transmits through or is reflected from the magnetic barrier. For the monopolar barriers, we found a somewhat stronger dependence $\Delta\rho \sim B_0^{\nu}$ with $\nu \sim 1.8$. Similar observation has been reported by Kubrak et al. [7], who found $\Delta\rho \sim B_0^{3/2}$ for dipolar barriers and $\Delta\rho \sim B_0^2$ for monopolar barriers.

Let us now turn to the temperature dependence of the excess resistivity. In the context of the model by Matulis and Peeters [6], thermal fluctuation tends to suppress the excess resistance caused by the magnetic barriers. Experimentally, however, $\Delta\rho$ is found to *increase* with temperature as $\Delta\rho \sim AT^2 + C$. Such quadratic temperature dependences have been commonly observed for both types of magnetic barriers and also for the periodic modulation case [4,5]. In this respect, Kubrak et al. report different results [7]. For the dipolar barrier they found the excess resistance to increase in proportion to the total resistance and hence it was linear in T at low temperatures. For the monopolar barrier, they found no temperature dependence. However, their data points are rather sparse for detailed discussion of the temperature dependence. Fig. 2.

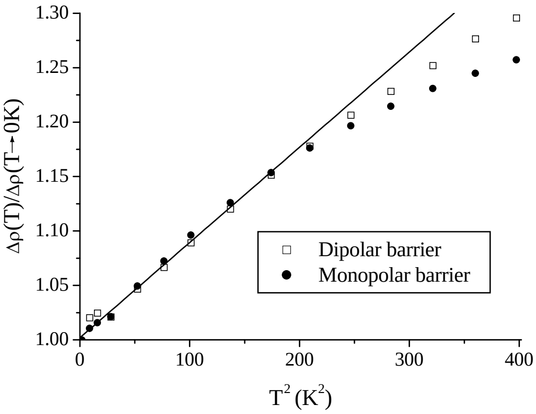

Fig. 2. Temperature dependence of the excess resistivity for the two types of magnetic barriers ($\varphi = 0^\circ$: maximum value). The data is normalized to the value at zero temperature and plotted as a function of T^2.

In our earlier papers, we interpreted the phenomenon for the periodic case in terms of the electron–electron Umklapp process activated by the artificial superperiodicity [4,8,9]. In the present study, similar temperature-quadratic behavior of excess resistivity has been observed also for isolated magnetic barriers. The fact that the origin of the T^2-term lies in electron–electron scattering has been confirmed by studying the warm electron effect as done before [8]. However, the present result implies that the periodicity of modulation per se is not essential for the occurrence of T^2-term. In this respect, it is noteworthy that Sasaki and Fukuyama propose a novel T^2-term due to electron–electron scattering in periodically modulated systems which originates not from Umklapp process but from normal momentum conserving process [10]. When electron–electron scattering occurred under spatially varying magnetic field, total momentum of scattering electrons is conserved, but not the current. This theory also applies to the case of the isolated magnetic barriers.

Fig. 3 shows the resistivity as a function of the uniform magnetic field while the amplitude of magnetic barrier is kept constant by a strong enough parallel magnetic field. We focus on two characteristic features of these traces; positive magnetoresistance (PMR) and beating of the Shubnikov–de Haas (SdH) oscillations. The PMR is thought to be of classical origin since its temperature dependence is weak. The PMR in the dipolar barrier sample evolves in two steps. The low field PMR, which is attributed to the so-called snake orbit [11], saturates at ~ 0.1 T. The overall PMR curve is concave upward. By contrast, the PMR curve in the monopolar barrier sample has no low field features and is concave downward. In a semiclassical picture, the magnetoresistivity is derived from the average electron drift velocity [12].

$$\frac{\Delta\rho_{xx}}{\rho_0} \simeq \omega_c^2\tau^2\frac{\Delta\sigma_{yy}}{\sigma_0} \simeq \omega_c^2\tau^2\frac{\langle v_d^2\rangle}{v_F^2/2} \quad (\omega_c\tau \gg 1), \tag{1}$$

[1] In our earlier paper [4], we reported $\Delta\rho \sim B_0^2$. But we carried out more precise measurements recently and obtained $\Delta\rho \sim B_0^{3/2}$ for the periodic case.

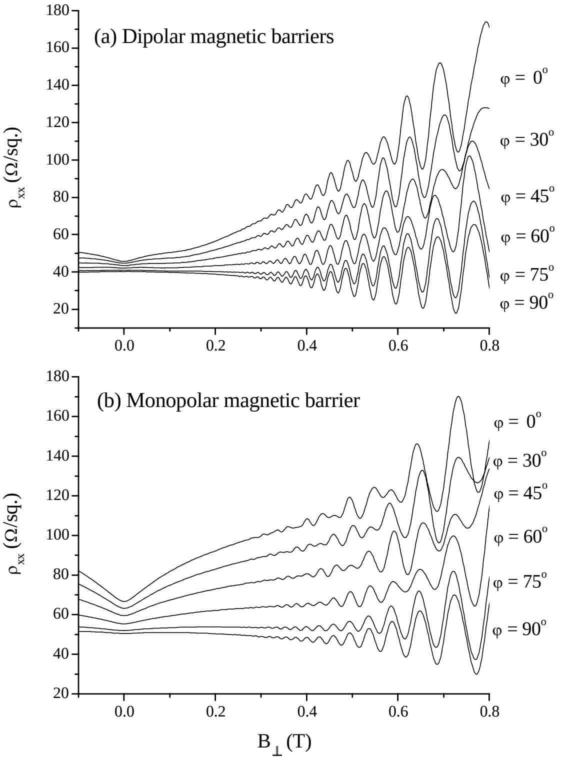

Fig. 3. Magnetoresistivity with magnetic barriers for different settings of the amplitude of magnetic barriers by changing the azimuthal angle φ of the parallel magnetic field.

where ρ_0 is the resistivity at zero uniform magnetic field, ω_c is the cyclotron frequency, τ is the classical scattering time, and v_F is the Fermi velocity. We numerically calculated various electron orbits in the presence of magnetic barriers whose shape was simply assumed to be rectangular (Fig. 4). For the monopolar magnetic barrier, drift motion of electrons monotonically decreases with increasing uniform magnetic field. On the other hand, for the dipolar one, those trajectories trapped along the center line of the barrier make significant contribution to the drift motion at higher fields. Fig. 5 shows the magnetoresistivity curves numerically calculated on the basis of this semiclassical model. The difference in the PMR behavior between the two types of barrier is qualitatively agreement with the experimental results.

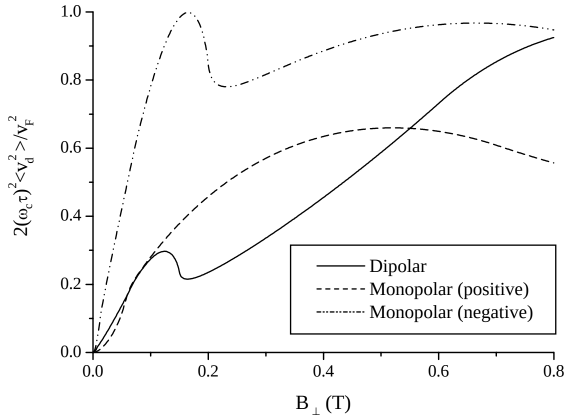

Fig. 5. Numerical calculation of the normalized magnetoresistivity in Eq. (1). Drift velocity of electron $\langle v_d^2 \rangle$ was averaged out within 2.5 μm of the center of the barrier. For monopolar barrier, we observe the average of "positive" and "negative" in this experiment.

As seen in Fig. 3, the SdH oscillations develop a beating pattern as the magnetic barrier amplitude is

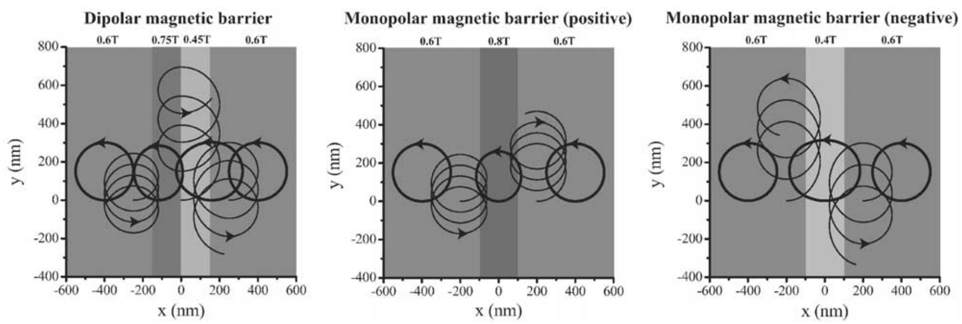

Fig. 4. Electron orbits in the presence of simplified rectangular magnetic barriers at uniform magnetic field $B_\perp = 0.6$ T. For monopolar barrier, "positive" means that the direction of magnetic barrier is same as the uniform magnetic field, "negative" means opposite.

increased. Component of the oscillations between 0.4 and 0.8 T as a function of the inverse of the uniform magnetic field $B_{\perp}$ is Fourier transformed. It revealed spectra consisting of a central peak and a side band on each side for the both types of magnetic barriers. The former corresponds to the cyclotron orbits in the homogeneous region between the barriers. The latter is attributed to the stationary trajectories as shown in Fig. 4 in the region of the magnetic barriers. The position of the central peak is independent of the barrier amplitude. On the other hand, the side band splits off from the central peak as the magnetic barriers are turned on. The left-hand side band (lower frequency) is more clearly observed than the right-hand side band (higher frequency). It is consistent with the fact that SdH oscillations are clearly observed with increasing perpendicular magnetic field. Unlike the case of spatially varying electron density, the splitting of the SdH frequency in this case is dependent on the strength of the uniform magnetic field.

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