Magnetization process in a ferromagnetic disk measured by a semiconductor two-dimensional electron gas

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We have monitored a magnetization process in a ferromagnetic disk by measuring a bend resistance of semiconductor two-dimensional electron gas (2DEG) lying beneath the disk. Annihilation and nucleation of a vortex in the ferromagnetic disk are clearly seen in the trace of the bend resistance as a function of in-plane magnetic field. The large change in the signal is well reproduced by a simulation based on a semiclassical billiard model. © 2007 American Institute of Physics. [DOI: 10.1063/1.2710435]

Artificial ferromagnetic structures in mesoscopic scale make their magnetic states simple and controllable. Interestingly, a vortex structure was found in a ferromagnetic disk. The vortex core shifts from the center of the disk under a finite in-plane magnetic field. The magnetization process in a disk, e.g., annihilation/nucleation of the vortex and vortex chirality, has been studied by various experimental techniques. In our early work, we proposed a method for detection of magnetic states in a ring by using a ballistic transport in two-dimensional electron gas (2DEG). In the present article, we demonstrate the method for the case of a disk.

Detection of magnetic states in an individual microfabricated ferromagnet by using a 2DEG were first conducted a decade ago. They measured a Hall resistance of the 2DEG. We fabricated a NiFe disk with diameter 1 μm, thickness 30 nm on a GaAs/AlGaAs 2DEG cross as shown in Fig. 1(a). The density n and the mobility μ of the 2DEG before processing were 4.3 × 10^15 m^-2 and 77 m^2/V s, respectively. The depth of the 2DEG plane from the surface is 65 nm. Hence the stray field from the disk affects the resistance of the 2DEG. We measured a bend resistance obtained by the current and voltage configuration as shown in Fig. 1(a). We carried out the measurement at 3.5 K.

The bend resistance R_{14,23} as a function of in-plane magnetic field clearly exhibits nucleation/annihilation of a vortex in the NiFe disk as shown in Fig. 2. Here we applied the magnetic field in the x direction and set the excitation current and the mobility of the 2DEG = 10 μA so as to obtain a low-noise signal. The amplitude and the change in the signal decrease a little bit due to an increase of electron temperature in the 2DEG cross. The change in the bend resistance ΔR between the positive and the negative saturations with respect to the resistance without the stray field R_0 is quite large, the ratio ΔR/R_0 is about 70%.

We can estimate the stray field pattern from the NiFe disk in plane of the 2DEG by a simple magnetostatic calculation. We assume the magnetization in the disk by a rigid vortex model as illustrated in Fig. 1(b). In the model, diameter of the vortex core (40 nm) is kept constant with increase of an in-plane magnetic field. The vortex core shifts from the center of the disk with the in-plane magnetic field and then is pushed outside the disk at an annihilation field. The model gives a good approximation of the magnetization in the disk when the vortex core lies in the vicinity of the center.

Figure 3 shows a change in the normal component of the stray field pattern with a shift of the vortex core l. When we apply the magnetic field in the x direction, the vortex core moves in the y direction. A spotlike field is generated be-
neath the vortex core and is accompanied with the vortex core motion. The peak amplitude and the net magnetic flux of the local field are 4 mT and $8.4 \times 10^{-18}$ Wb, respectively.

The main part of the stray field comes from the right and the left edges of the disk under a finite in-plane magnetic field. The sign of the stray field is opposite between the both edges. Hence the net flux of the stray field in the 2DEG cross is canceled out so that we can monitor the magnetization by measuring not Hall resistance but bend resistance. The peak amplitude and the flux beneath the both edges under a saturation of the magnetization are $59$ mT and $1.2 \times 10^{-14}$ Wb, respectively. The flux from the edges is much larger than that from the vortex core, which means that the main contribution of the change in the bend resistance of the 2DEG originates from the magnetization in the disk in the $x$ direction. The effect of the vortex core is negligible comparing with the effect of the outside region.

We simulated the bend resistance behavior in the presence of the stray field from the NiFe disk by a semiclassical billiard model. In the model, electrons are injected from each probe into the 2DEG cross with angular distribution $P(\phi) = \cos \phi / 2$, where $\phi$ is the angle with respect to the probe axis. We assumed that the cross has a square corner and the width $W=1.5 \mu$m. Ballistic electron trajectories are modified by the stray field from the disk. The electron mean free path in the 2DEG is larger than the width $W$ so that we can neglect effect of impurity scattering in the cross. We calculated transmission probabilities between probes and obtained bend resistances by the Landauer-Büttiker formula.

Figure 4 shows the simulated bend resistances as a function of magnetization in the $x$ direction by a billiard model. The experimental change in the bend resistance between positive and negative saturations are shown for two excitation currents 1 and $10 \mu$A.

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