

Asymmetric field variation of magnetoresistance in Permalloy honeycomb nanonetwork

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The magnetic properties of two-dimensional network comprising a Permalloy wire-based honeycomb structure were investigated by magnetic force microscopy and magnetoresistance measurement. These results indicate that the magnetization of the wire behaves homogeneously like a binary bit and that the magnetic interaction at the vertex governs this magnetization. This allows us to achieve a magnetoelectronic device, based on the magnetic interaction among the wires.

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I. INTRODUCTION

Recently, there has been extensive coverage of the study of laterally defined nanoscale magnetic structures due to advances in lithographic and magnetic measurement techniques.^{1–6} The main motivation for studying nanoscale magnetic materials is the dramatic change in the magnetic properties that occurs when the magnetic length scale governing certain phenomenon is comparable to the magnetic element size. We have already revealed that ferromagnetic wire-based nanonetwork with honeycomb pattern shows frustration due to the magnetic interaction among the wires when the magnetic moment in the wire behaves coherently like a spin.^{7,8} However, the frustration disappears in response to a decrease in the magnetic interaction at the vertices.⁹ In this paper, we clarify that asymmetric field variations of magnetoresistance in the Permalloy honeycomb system are derived from the domain wall location in each vertex. These results imply a potential application for magnetoelectronic devices, based on the frustration.

II. EXPERIMENT

Figure 1 shows a scanning electron microscope image of part of the Permalloy honeycomb nanonetwork system. The sample was fabricated by the lift-off technique. A thin poly-methyl methacrylate resist (ZEP-520) layer, 100 nm thick, was spin coated onto a thermally oxidized Si substrate. After prebaking, the desired pattern was drawn with electron beam lithography, followed by resist development. Subsequently, Permalloy film was deposited at a rate of 0.1 nm/s by the electron beam (EB) evaporator in a vacuum of 1×10^{-8} Torr. The sample was obtained after the resist mask was removed in solvent. The size of the honeycomb network is as follows; width=50 nm, length=400 nm, and thickness=20 nm. The network system consists of 60×60 unit cells of the honeycomb structure.

The magnetic domain structure of the sample was observed by means of magnetic force microscopy (MFM),

SPI4000/SPA300HV). A CoPtCr low moment probe was used in order to minimize the influence of the stray field from the probe to the magnetic structure of the system. A scanning probe microscope system, equipped with an evacuated (1.0×10^{-6} Torr) sample chamber, was used in dynamic force mode with an optimized quality factor of the probe of around 3000.¹⁰ To measure the resistance of the system, two Cu electrodes were deposited at the edges of the network. All magnetoresistance (MR) measurements were performed at 77 K by applying a dc of 80 mA along the direction of **J**, as shown in Fig. 1.

III. RESULTS AND DISCUSSION

Figure 2(a) shows a MFM image for the remanent state after the application of an external magnetic field (10 kOe) perpendicular to the film plane. In the MFM image, a leakage field signal caused by a domain wall is clearly observed at each vertex and no domain wall features are observed in the wire parts. These results indicate that the magnetization in the wire behaves coherently and that the magnetic property of the ferromagnetic network can be described in terms of the uniform magnetization in each wire and the magnetic interaction among the wires at the vertex.

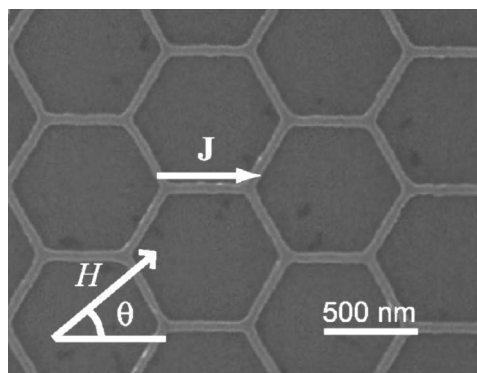


FIG. 1. A scanning electron microscope image of a Permalloy honeycomb nanonetwork. The size of the wire system is as follows; wire width=50 nm, length=400 nm, and thickness=20 nm, respectively. **J** denotes the current direction for magnetoresistance measurements.

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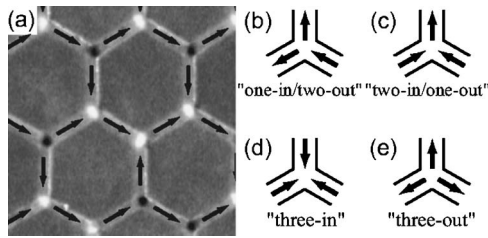


FIG. 2. (a) A magnetic force microscope image of a Permalloy honeycomb nanonetwork. The arrows denote the magnetization in the wires. [(b)–(e)] The possible magnetic configurations at the vertex.

The intensity of each black or white contrast is almost equal, while there are four possible magnetic configurations at the vertex, as shown in Figs. 2(b)–2(d), 2(d), and 2(e). Consider that the intensity of the contrast varies with the leakage field corresponding to the magnetic configuration at the vertex. This indicates that the latter magnetic configuration is required to minimize the exchange energy. The magnetization M_i in the i th wire, is determined to be the vector sum of M_i for the three wires jointed at the N th vertex must not be zero vector. We describe the magnetic configuration as a “one-in/two-out” or “two-in/one-out” magnetic configuration [see Figs. 2(b) and 2(c)]. The “three-in” or “three-out” magnetic configurations, in which the vector sum of M_i at N th vertex is zero vector, are unstable because of the large magnetic energy loss due to the abrupt magnetization rotation at the vertex [see Figs. 2(d) and 2(e)]. The micromagnetic simulation using OOMMF code was carried out in one vertex.¹¹ The cell size, the saturation magnetization M_S , and the damping parameter α are 5 nm, 1 T, and $\alpha=0.01$, respectively. Figures 3(a) and 3(b) show the results of the micromagnetic simulations for the vertex of the system. The configurations in Figs. 3(a) and 3(b) are the “one-in/two-out” and “two-in/one-out” magnetic configurations, respectively. The three-in or three-out magnetic configurations are unrealizable in the simulation results. These results indicate that the magnetic interaction among the wires predominates over the magnetic configuration. Recently we clarified that these magnetic properties of the honeycomb system stably appear when the wire length of the honeycomb network is shorten.

Figure 4(a) shows a MR curve of the system at the field angle $\theta=30^\circ$, where θ denotes the angle between the current \mathbf{J} and the projection of the field H onto the film plane (see Fig. 1). Before the MR measurement, the magnetic configurations were arranged by applying a magnetic field H_{ini} (5 kOe) for $\theta=0^\circ$. The magnetic configuration after the application of the field H_{ini} is shown in Fig. 4(e). After applying the magnetic field $H=-1.4$ kOe, the resistance increases

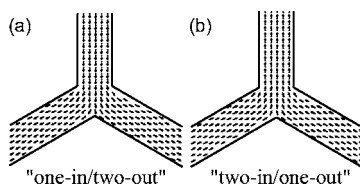


FIG. 3. Magnetic configurations at the vertex part of the honeycomb system from micromagnetic simulations (OOMMF code). (a) The “one-in/two-out” configuration. (b) The “two-in/one-out” configuration.

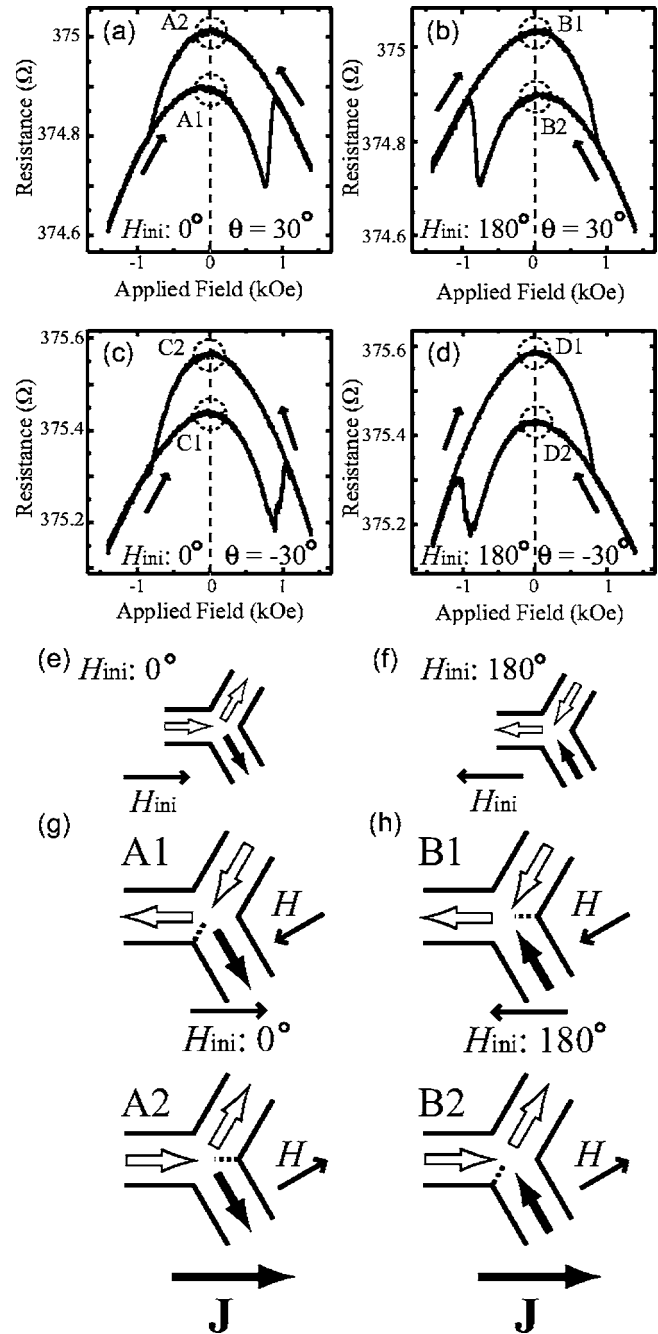


FIG. 4. [(a)–(d)] The magnetoresistance of the network system at the field angle of $\theta=30^\circ$ or -30° . Before the MR measurements, the magnetic configurations are arranged by applying magnetic field H_{ini} for $\theta=0^\circ$ or 180° . (g) The magnetic configurations at points A1 and A2. (h) The magnetic configurations at the points B1 and B2. The dashed lines in (g) and (h) denote the magnetic domain walls. The magnetization characterized by black arrows in (g) and (h) does not reverse in the MR measurement. \mathbf{J} denotes the current for magnetoresistance measurements.

monotonically with increasing magnetic field and reaches the value of 374.9 Ω at $H=0$ kOe (point A1). The resistance is decreased with the field variation from negative to positive sense, and it shows a steep jump at $H=0.76$ kOe. After reaching $H=1.4$ kOe, the field is decreased with a peak of 375 Ω at $H=0$ kOe (point A2). The resistance also exhibits a jump at $H=-0.86$ kOe. This MR is interpreted by the anisotropic magnetoresistance effect which is produced by the rapid reversals of the magnetization in the wires.¹

This MR curve appears asymmetrical. This asymmetry is due to the position of the magnetic domain wall at the vertex. Due to the shape magnetic anisotropy, a high magnetic field is needed to reverse the magnetization in the wire, which creates a right angle with the magnetic field H [black arrows in Fig. 4(g)]. Thus it would appear that this magnetization stayed unchanged in the MR measurement. Figure 4(g) shows the magnetic configurations at points A1 and A2 in Fig. 4(a). The broken line in Fig. 4(g) indicates the position of magnetic domain walls. At point A1, the magnetic domain walls lie in the current flow \mathbf{J} and strongly affect the resistance of the system. At point A2, the current flow \mathbf{J} was blocked by the magnetic domain walls. Thus the magnetic domain walls contribute relatively little to the resistance. The position of the magnetic domain wall at the vertex brings about the difference of the resistance at $H=0$ kOe. The origin of asymmetry is attributed to the minor loop while measuring the MR. Notable is that each magnetic configuration in Figs. 4(g) and 4(h) is stabilized. These asymmetric field variations of the MR in a zigzag structure has been reported.²

Figure 4(b) shows the MR curve for $\theta=30^\circ$ after applying a magnetic field H_{ini} (5 kOe) along $\theta=180^\circ$. Before the MR measurement, the magnetic configurations at the vertices are arranged, as shown in Fig. 4(f). The magnetic configurations at points B1 and B2 are shown in Fig. 4(h). As well as the case of Fig. 4(g), the magnetic domain walls lie on the different positions and the MR curve shows asymmetric variation. The MR curve in Fig. 4(a) has mirror symmetry with that in Fig. 4(b), while each of the MR measurements is performed by applying the magnetic field at $\theta=30^\circ$. This is due to the difference in the position of the magnetic domain wall at the vertex. When comparing the magnetic configuration at A1 with that at B1, the positions of the magnetic domain walls at the vertices are different due to the magnetization vector perpendicular to the magnetic field H , indicating that the domain walls act different effects on magnetoresistance.

As well as the MR measurements at $\theta=30^\circ$, part of the

wires is perpendicular to the magnetic field H when the field H is applied along $\theta=-30^\circ$. Figures 4(c) and 4(d) show the MR for $\theta=-30^\circ$ at the initial magnetic fields H_{ini} along $\theta=0^\circ$ and $\theta=180^\circ$, respectively. The MR curves appear asymmetrical. These MR curves can be explained by the position of the magnetic domain walls without contradiction.

IV. SUMMARY

The magnetic properties of the Permalloy honeycomb nanonetwork were investigated by the MFM and MR measurement. These results reveal that the magnetization in the wire is a single domain and that it behaves like a binary bit. The magnetic energy at the vertex is dominant to the magnetization in the wire and the magnetization in the wires interacts with each other. We revealed that the asymmetric MR curves for $\theta=30^\circ$ and -30° are due to the position of the magnetic domain wall.

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