Domain structures and magnetic ice-order in NiFe nano-network with honeycomb structure

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The magnetic domain configurations and the magnetization processes in a permalloy wire-based honeycomb nano-network have been investigated by means of magnetic-force microscopy and magnetoresistance measurement. The magnetic structure is mainly governed by the magnetic interaction among the magnetic pole on the vertices, being similar to the so-called "ice-rule." The magnetization vector in a wire behaves coherently. The present results seem to give a direct analogy between the honeycomb network and an Ising system on a kagomé lattice. The ice-rule type interaction, however, disappears with reducing magnetic energy at the vertices. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1854572]

I. INTRODUCTION

One of the most exciting developments in magnetics has been the use of nano-sized fabrication techniques to form nanoscale magnets. Interest in this area comes partly from data storage technologies and partly because nanomagnets provide a highly controlled experimental system for studying fundamental phenomena in the micromagnetism. Therefore magnetic properties of nanoscale magnetic structures have been studied in detail.[1–10] Until now few studies have focused on the interaction among the ferromagnetic wires. Understanding the interaction is important when it will be applied to new magnetic devices, e.g., magnetic-logic computer.[5] In this paper we present magnetic properties of a permalloy honeycomb nano-network. We show that the magnetization in the wire behaves coherently, which gives a direct analogy between the honeycomb network and an Ising system on a kagomé lattice. We also show that the magnetic interaction among the wires is controllable with varying magnetic energy at the vertices.

II. EXPERIMENT

The permalloy ($Ni_{81}Fe_{19}$) honeycomb nano-network was fabricated by means of an electron-beam lithography. The desired pattern was drawn in a spin-coated layer of resist (ZEP520) on a thermally oxidized Si substrate. After developing the resist pattern, permalloy was deposited by electron-beam evaporation in a high vacuum. With the succeeding lift-off process the resist was removed and the network system remained on the substrate surface. A scanning electron microscope image of the system is shown in Fig. 1. The dimension of the system is as follows: the width of the wire is 50 nm, the length of the wire is 400 nm, and the thickness is 20 nm. The network system consists of 60×60 unit cells of the honeycomb structure.

A magnetic domain observation at a remanent state was carried out with high-sensitive magnetic-force microscopy (MFM, SPI4000/SPA300HV, SII NanoTechnology Inc.). A CoPtCr low moment probe was used to minimize the influence of the stray field from the probe. To improve the response of the MFM, the quality factor of the cantilever was optimized to be around 3000. This was achieved via implementation of an electric feedback loop in the cantilever's driver which controls the effective quality factor of the cantilever automatically. To measure the resistance of the network, two Cu electrodes were deposited at the edges of the network. The resistance was measured by flowing an electric current **J** as shown in Fig. 1. The magnetoresistance measurement was performed by applying external magnetic field whose in-plane and out-of-plane components are $H_{\parallel}$ and $H_{\perp}$, respectively.

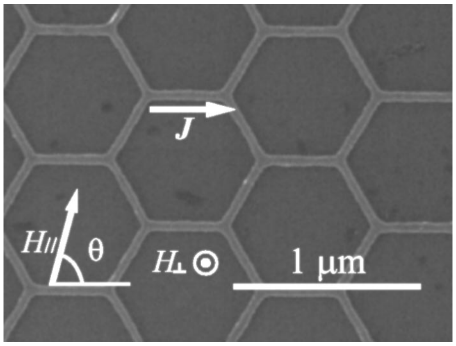

FIG. 1. A scanning electron microscope image of the system. The size of the wire system is as follows: wire width=50 nm, wire length=400 nm, and wire thickness=20 nm, respectively. **J** denotes the current for magnetoresistance measurements. $H_{\parallel}$ and $H_{\perp}$ denote the in-plane and out-plane of the film plane magnetic field.

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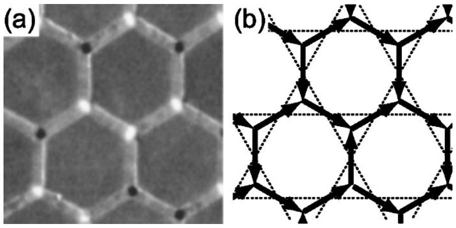

FIG. 2. (a) A magnetic-force microscope image for a part of the permalloy wire-based honeycomb structure. (b) The Ising spin model on a kagomé lattice which is magnetically equivalent to the magnetic structure of (a).

III. RESULTS AND DISCUSSION

Figure 2(a) shows a MFM image of the system at remanence after the application of an external magnetic field (10 kOe) perpendicular to the film plane. White or black contrasts, which indicate the presence of magnetic charge on the domain wall, are clearly observed at every vertex. No domain wall features are observed in the wire parts. It indicates that the vertex traps the domain wall firmly and that the magnetization in the wire part is homogeneous. The result suggests that the magnetic property of the ferromagnetic network is described in terms of not only the uniform magnetic moment in the wire but also the interaction among the wires at the vertex.

Notable is that the amplitude of each contrast is almost equal, while there are several possible magnetization configurations at the vertex. Consider that the amplitude of the contrast varies by the leakage field corresponding to the magnetization configuration at the vertex. This indicates that the magnetic configurations are determined in order to minimize the exchange energy at the vertices. The magnetization $\mathbf{M}_i$ in the ith wire is determined as that of the vector sum of $\mathbf{M}_i$ for three wires jointed at Nth vertex must not be zero vector, that is, $\Sigma_{i\in N}\mathbf{M}_i \neq 0$. We call the magnetic configuration as "two-in, one-out" or "one-in, two-out" magnetic configuration. The "three-in" or "three-out" magnetic configurations ($\Sigma_{i\in N}\mathbf{M}_i = 0$) are unstable because of the large magnetic energy loss due to the abrupt magnetization rotation at the vertex.

The magnetic configuration of the present system can be analyzed as a frustrated system constructed by magnetic moments in the wires. For every vertex, there are six possible magnetic configurations under the two-in, one-out or one-in, two-out rule. This rule has an analogy with the so-called "ice-rule" which is the local condition that defines whether a magnetic configuration in the wire lies within the ground state manifold.[11,12] Therefore the magnetic configuration of the system has a large number of degenerate ground states, and the magnetic properties of the honeycomb nano-network system corresponds to the Ising-spin model on a kagomé lattice [see Fig. 2(b)].

Figure 3 shows the magnetoresistance of the system at 77 K without applying perpendicular magnetic field $H_\perp$. The angle θ between the current **J** and the projection of the field onto the film plane $H_\parallel$ is 75°. After applying the magnetic field of −1.4 kOe, the resistance increases monotonically with increasing magnetic field and reaches the maximum at $H_\parallel = 0.2$ kOe. The resistance decreases more rapidly by varying the field from negative to positive sense, and it shows abrupt jumps at point A ($H_\parallel = 0.8$ kOe) and B ($H_\parallel = 1.1$ kOe). After reaching $H_\parallel = 1.4$ kOe, the field is decreased. The resistance also exhibits steep jumps at the symmetrical point C ($H_\parallel = -0.8$ kOe) and D ($H_\parallel = -1.1$ kOe). The abrupt jumps (A–D) are due to the rapid reversals of the magnetic moment in the wires.[2]

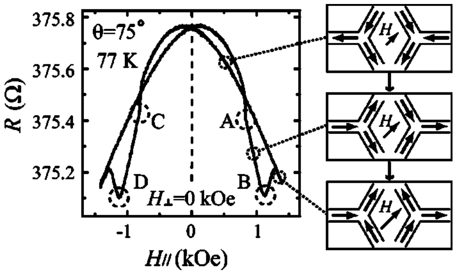

FIG. 3. The magnetoresistance of the honeycomb nano-network at $H_\perp = 0$ kOe at 77 K. The angle between the current direction **J** and the projection of the field $H_\parallel$ on the film plane is 75°. The dotted circles A–D denote the discontinuities in the magnetoresistance. The schematic annotations show the magnetic configurations corresponding to the magnetoresistance.

The magnetoresistance at $H_\perp = 0$ indicates that the ice-rule dominates the magnetization at the magnetization process as well as at the remanent state. There are two distinct jumps observed at A ($H_\parallel = 0.8$ kOe) and B ($H_\parallel = 1.1$ kOe). It indicates that there are two distinct magnetization reversals at $\theta = 75°$. Note that three nonequivalent magnetization flips are expected since the wires of the lattice are classified into three groups, each of which has different angle to the external magnetic field. It can be interpreted by the magnetic ice-rule prohibiting the three-in and three-out configurations. Because of the ice-rule, the number of magnetization reversals is reduced from 3 to 2. The experimental result, therefore, indicates the magnetic energy at the vertex governs the magnetization process in the present system.

Figure 4 shows the magnetoresistance at 90 K as a func-

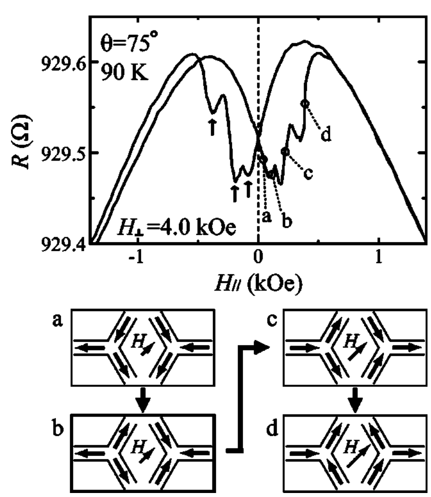

FIG. 4. The magnetoresistances of the honeycomb nano-network measured with the application of a constant perpendicular magnetic field $H_\perp = 4.0$ kOe at 90 K. Arrows indicate jumps in magnetoresistance corresponding to magnetization switching processes. The schematic annotations (A–D) show the magnetic configurations corresponding to the magnetoresistance indicated by letters in the figure.

tion of $H_{\parallel}$ at $\theta = 75°$ with the application of a constant perpendicular magnetic field $H_{\perp} = 4.0$ kOe. Note that three discontinuities are appeared in the magnetoresistance curve, which indicates that there are three nonequivalent magnetization reversals. On the other hand, two magnetization reversals are observed at $H_{\perp} = 0$ because of the ice-rule as shown in Fig. 3. It means that the magnetic ice-rule disappears by the application of the perpendicular magnetic field $H_{\perp}$ which reduces the magnetic energy at the vertices. Therefore, the application of $H_{\perp}$ reduces the energy difference between three-in or three-out magnetic configurations and two-in, one-out or one-in, two-out magnetic configurations, being comparable to the thermal energy.

IV. CONCLUSION

We investigated the remanent magnetic structures and the magnetization processes in a permalloy wire-based honeycomb network system by using MFM and magnetoresistance measurements. The MFM measurement shows that the magnetic configuration at each vertex is governed by the vertex interaction similar to the ice-rule. The magnetic ice-rule also dominates the magnetization process in the network. The application of perpendicular magnetic field $H_{\perp}$ suppresses the magnetic ice-rule and results in the drastic change of the magnetization process of the network.

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