Effects of sample size and field orientation on pseudo-Hall voltage in micronscale nickel thin-film squares

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Pseudo-Hall effect (PHE) in Ni thin-film squares of 1–5 μm size is measured with a constant current through two leads along one diagonal of the square and the voltage output from leads along the other diagonal. The PHE voltage in response to an in-plane magnetic field depends on the square size and field orientation. The minimum PHE voltage at low field is close to zero only with the 2 μm square containing four symmetrical closure domains leading to a 600% relative change in PHE voltage. The PHE signal is found the largest when the field direction is along the square side while the smallest when along the square diagonal. © *1997 American Institute of Physics.* [S0021-8979(97)63408-8]

Size effects in micronscale magnetoresistive (MR) elements are important for both basic understanding of micromagnetics and high-density magnetic storage technology. Previous studies have observed size effects on the magnetization behavior of micronscale thin-film MR elements. For example, the domain structure of 1–5 μm Ni squares of 35 nm thickness has been characterized by magnetic force microscopy (MFM)[1] showing that the magnetization changes from a single domain at 1 μm width (with the magnetization direction along a diagonal of the square) to a symmetrical multi-domain at 2 μm (with four closure domains) and then to chaos multi-domain at 4 μm or larger. It is then interesting to study how the MR behavior of the micronscale Ni squares may depend on the size. In this article, we report on the pseudo-Hall effect (PHE)[2] in micronscale Ni squares. The PHE is due to the well-known anisotropic MR effect where the electrical field and the current are in different directions. It is useful for reducing thermal drift of MR sensor output.[3] We observe the PHE voltage as a function of the square size and the field orientation with respect to the sample. Our experimental results reveal that a well-defined domain structure may give an excellent MR behavior.

Micronscale Ni thin-film squares with one lead at each corner were fabricated using *e*-beam lithography and a lift-off technique.[4] In the fabrication, a polymethylmethacrylate (PMMA) resist was first spun onto a SiO_2 substrate. Patterns of squares were exposed in the PMMA using a high resolution *e*-beam lithography system. The exposed PMMA was removed during development to form a resist template on the substrate. A Ni film of 35 nm thickness was evaporated onto the entire sample using electron evaporator. Finally, the resist was dissolved in acetone, lifting off the Ni film on top of the resist. The Ni squares have side width varying from 1 to 5 μm. Current and voltage leads are arranged on the corner of the square as shown in Fig. 1.

Pseudo-Hall measurements were performed as follows: A constant current (I) is driven across one diagonal direction in the square and the voltage drop (V) across the other diagonal direction is measured as a function of an in-plane magnetic field. We use V/I as the PHE signal since V is actually proportional to I. Figures 2(a), 2(b), and 2(c) show the room temperature PHE response curves of Ni squares of side width at 1, 2, and 4 μm, in sequence, with the field direction along the square side.

The PHE response curve shows a minimum at low field. The minimum value depends on the square size as shown in Fig. 3. The 2 μm square gives the minimum closer to zero than other squares, therefore a larger relative change in the PHE voltage (over 600% for the 2 μm square). The absolute value of the PHE output change is about 50 mV/A when the field direction is along the square side.

Hysteresis effect in the PHE response is indicated by the arrows in Fig. 2. The PHE minimum occurs after the field reverses in direction and the corresponding field position is around 70, 40, and 20 Oe for the square side width of 1, 2, and 4 μm, in sequence, as the field direction is along the square side. We attribute the minimum occurrence to the magnetization reversal in the square. Thus the results show

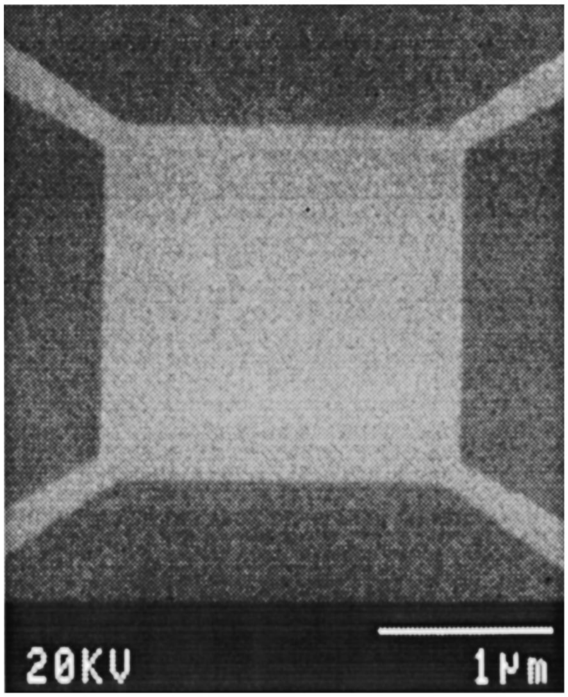

FIG. 1. A SEM picture of the 2 μm Ni square sample.

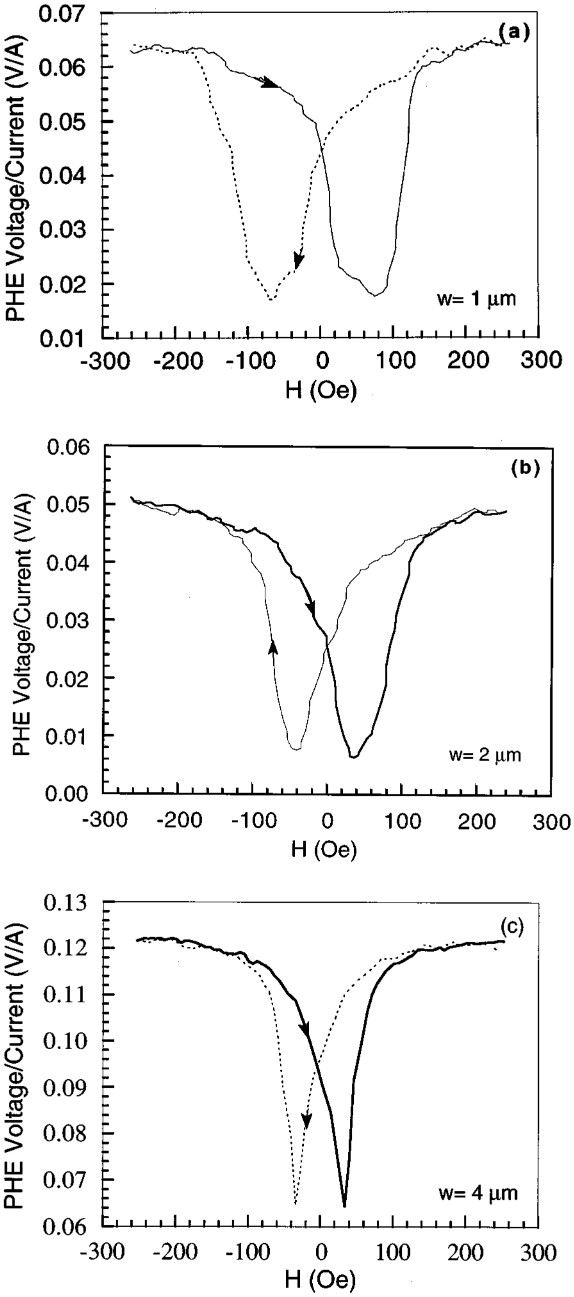

FIG. 2. PHE response curves of Ni squares of width at (a) 1 μm, (b) 2 μm, and (c) 4 μm. The field direction is along the square side.

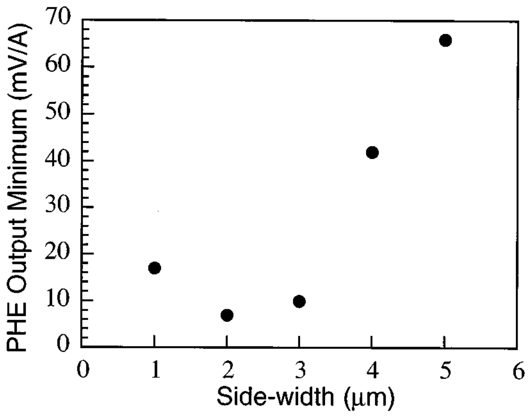

FIG. 3. The PHE voltage minimum as a function of the Ni square side width.

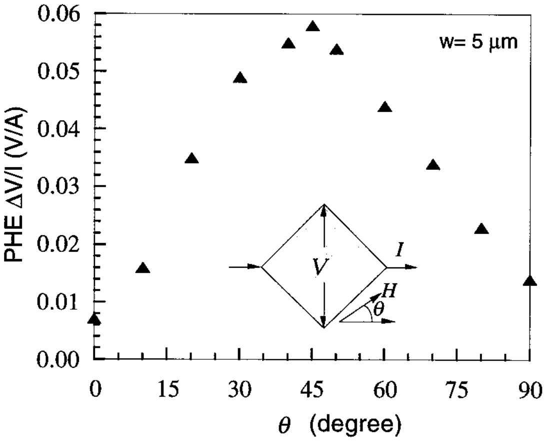

FIG. 4. The PHE voltage change as a function of the angle between the field direction and current direction.

that the smaller the Ni square, the larger the switching field. Also seen in Fig. 2 is that the smaller the square, the larger the PHE saturation field. This can be explained due to the demagnetizing field which increases with reducing the square size.

The PHE signal varies with the magnetic field orientation. During our measurements, the field direction was rotated in the plane of the square and the PHE voltage change (ΔV) from the minimum at low field to the maximum at saturation field was obtained as a function of the field orientation. As shown in Fig. 4, ΔV reaches a maximum when the field direction is along the square side but decreases as the field direction turns towards the square diagonal. This can be understood since the PHE signal is proportional to $\sin\theta\cos\theta$, where θ is the angle between current and magnetization directions.[2] When the field is along the side of the square, the angle θ turns to 45° giving the largest PHE output.

A recent paper by Prados *et al.*[5] reported a large MR change in Co/Ni multilayer disks by using a current-across-voltage configuration. Actually, they were measuring the PHE voltage change but the explanation in Ref. 5 was using a Wheatstone bridge model. Following their analysis, if a Ni

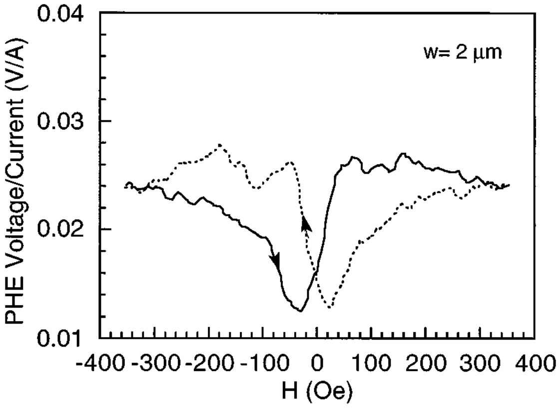

FIG. 5. The PHE response curve for the field direction along the square diagonal.

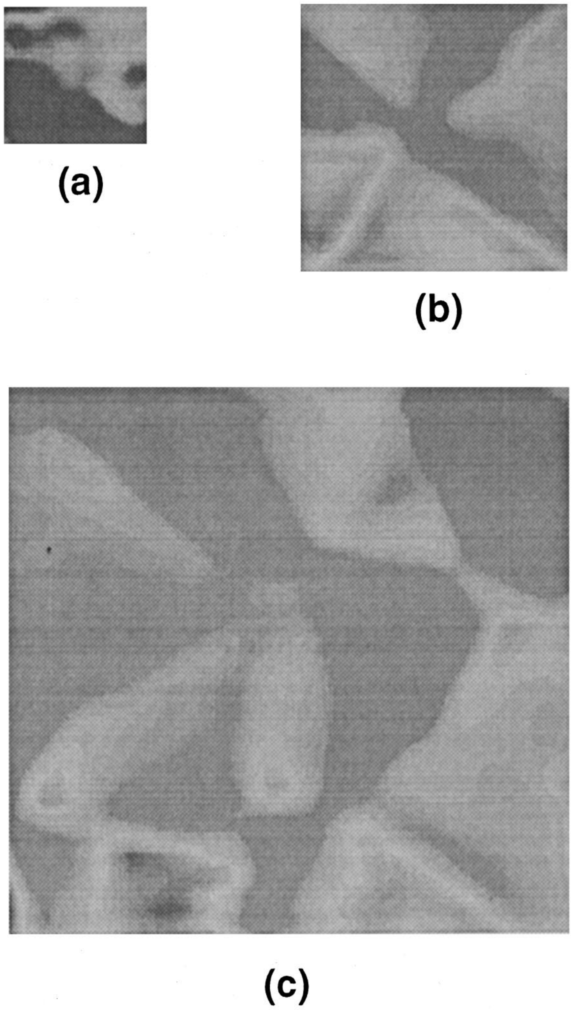

FIG. 6. MFM images of Ni squares of side width at (a) 1 μm, (b) 2 μm, and (c) 4 μm.

square can be modeled by a Wheatstone bridge, the PHE signal in the current-across-voltage configuration should be

$$V/I=(R_\parallel-R_\perp)/2 \tag{1}$$

for the field direction along the square side where $R_\parallel$ represents the resistance of the arm to which the field is parallel and $R_\perp$, that of the arm to which the field is perpendicular. Noting that $R_\parallel$ increases with the field while $R_\perp$ decreases,[6] one may explain the PHE response for the field direction along the square side. For the field direction along the square diagonal, i.e., 45° between the field and each of the bridge arms, however, the resistance of each arm varies in the same way as that of the others so that the bridge stays in balance and gives a flat output. Figure 5 shows our experimental observation of the PHE response for the field direction along the square diagonal, which is obviously in disagreement with the Wheatstone bridge model nor the model in Ref. 2. Besides, we note that the PHE response curves of 2 μm or larger squares show repeatable fine structures when the field direction is along the diagonal while those of the 1 μm square have no such fine structure. These observations suggest that the transport behavior in patterned magnetic nanostructures cannot be explained by lump circuit model and requires micromagnetics study.

The magnetic domain structures of our samples have been studied by using MFM. Figure 6 presents the MFM images of the Ni squares of 1, 2, and 4 μm side width. It is found that the 2 μm square consists of four symmetrical closure domains. For an ideal symmetry with the four closure domains of identical shape and four 90° domain walls, theoretical analysis gives zero PHE voltage,[7] which explains well the PHE minimum being close to zero for the 2 μm square. The fine structure in the PHE response curves should correspond to domain flipping. Because there are a few domains in our Ni squares, each domain flipping should cause a sudden change in the local resistivity of the domain region.

In summary, we have studied PHE in micronscale Ni thin-film squares with different domain structure at different size. The PHE voltage tends to zero when the square has four symmetrical closure domains. The PHE signal varies with the field orientation and the amplitude of PHE voltage change is largest with field direction along the side of the square. We believe that the PHE in micronscale ferromagnetic thin-film structures can be used to study domain effect on magneto-transport and also will be useful for MR sensor design.

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[7] The PHE voltage in our case can be calculated as $V=(\rho_\parallel-\rho_\perp)\int j_x \sin\theta\cos\theta\, dy$, where the x axis is along the current leads and then y along the voltage leads. j_x is the current density component along the x direction. The symmetry of the four closure domains with identical shape and 90° domain walls requires $V=0$ from the above equation.