Effect of the tip–contact interaction on the MFM image of magnetic nanocontact

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MFM images of magnetic nanocontacts fabricated in nano-oxide layers are evaluated with special attention to the tip–contact interaction. We show that a sharp ring or arc signal with a diameter on the order of 100 nm appears while the diameter of the contact is on the order of 1 nm. We also show that the position of the sharp signal is determined by the competition between the forces due to the magnetic anisotropy in the contact and due to the tip–contact interaction. © 2011 American Institute of Physics. [doi:10.1063/1.3565493]

I. INTRODUCTION

Magnetic nanocontacts in a nano-oxide layer sandwiched by two magnetic electrodes have attracted considerable attention because of their potential application to novel spintronics devices.¹ Due to the shape magnetic anisotropy it is expected that magnetic structures such as Bloch and Néel magnetic walls are confined in the contact when the magnetizations of two magnetic electrodes are aligned to be antiparallel to each other.² In 2007, Fuke *et al.* reported a spin-valve with CoFe magnetic nanocontacts showing a magnetoresistance ratio of 7%–10%.³

Very recently, Miyake *et al.* performed magnetic force microscopy (MFM) measurement and observed sharp ring or arc signals on the order of 100 nm diameter.⁴ In general the resolution of MFM images is about 10 nm, and people consider it impossible to observe an image of the contact which is on the order of 1 nm. Therefore, it is intriguing to ask whether the ring or arc signals observed by Miyake *et al.* were related to the magnetic nanocontact. In this paper, we evaluated MFM images with special attention to the tip–contact interaction so as to clarify the origin of the experimentally observed ring or arc signals.

II. FORMULATION

The system we consider is schematically shown in Figs. 1(a) and 1(b). Following the experiments⁴ we consider the parallel magnetization configuration of two ferromagnetic electrodes as shown in Fig. 1(a). We specified that the z axis is the vertical direction as shown in Fig. 1(b). In MFM measurement, the shift of the resonance frequency is measured as the tip is scanned over the surface of the sample. When the tip oscillates in the z direction, the frequency shift is proportional to $\partial F_z / \partial z$ with F_z being the z component of the force acting on the tip by the sample.⁵ In the following, therefore, we shall calculate $\partial F_z / \partial z$ as the MFM signal of the contact. Because there are no MFM signals for a uni-

formly magnetized slab, we assume that the contact is expressed by a dipole moment, m_2 , under an effective magnetic field. Furthermore, we also assume that the tip can be represented by a dipole moment, m_1 .

The origin of the coordinate is taken to be the position of the contact, and the position of the tip is represented by r . The total energy E_{total} is given by

$$E_{\text{total}} = V_{\text{dipole}} + \kappa(m_{2,x}^2 + m_{2,y}^2) - m_2 \cdot B_{\text{eff}}, \quad (1)$$

where

$$V_{\text{dipole}} = \frac{\mu_0}{4\pi r^3} \left[m_1 \cdot m_2 - \frac{3(r \cdot m_1)(r \cdot m_2)}{r^2} \right], \quad (2)$$

is a dipole–dipole interaction between the tip and the contact, κ represents the strength of the shape anisotropy of the contact, and B_{eff} is the effective magnetic field due to the interaction between the contact and the electrodes [See Fig. 1(b)].

Because the V_{dipole} term is dominant over the other terms in the vicinity of the nanocontact, m_2 is affected by the tip stray field. To include such an effect, we determined the direction of m_2 in the presence of the tip's magnetic field so as to minimize E_{total} . Then, we calculated $\partial F_z / \partial z$ using the

FIG. 1. (a) Schematic illustration of the magnetic nanocontact. Even in a parallel configuration of electrode magnetizations, the magnetic moments in the contact have longitudinal components due to shape anisotropy. (b) Models of the MFM-tip and magnetic nanocontact under consideration are shown schematically. Both the nanocontact and the tip are described by dipole moments.

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obtained m_2 . Because the signal depends on the tip height, the force gradient is averaged over that in the tip height corresponding to the oscillation.

The magnitudes of dipole moments are characterized by the product of the saturation magnetization and volume, i.e., $m_1 = M_s V_1$ and $m_2 = M_s V_2$, where V_1 and V_2 are the volume of the tip and the contact, respectively. In this study, we assume $M_s = 1 \times 10^6 \text{ A/m}$, $V_1 = 1 \times 10^5 \text{ nm}^3$, and $V_2 = 1 \text{ nm}^3$. We choose the $m_1 = -m_1 e_z$ and $B_{\text{eff}} = -B_{\text{eff}} e_x$, i.e., the electrode magnetization is proportional to $-e_x$. The force gradient is averaged over $z = 30 - 50 \text{ nm}$. In this case, the stray field is estimated to be $1.6 - 7.4 \text{ kOe}$. The effective magnetic field should be stronger than the interlayer coupling field, which is on the order of 100 Oe .³ Thus, we assume $B_{\text{eff}} = 0.03 \text{ T}$. The strength of the shape anisotropy is taken to be $\kappa = 1 \times 10^{19} - 5 \times 10^{19} \text{ J/A}^2 \text{ m}^4$, which is the same order as that of a cylinder of nanometer-size. For example, for a cylinder with height of 2 nm , $\kappa = 9.1 \times 10^{19} \text{ J/A}^2 \text{ m}^4$ for diameter 1 nm and $\kappa = 2.2 \times 10^{19} \text{ J/A}^2 \text{ m}^4$ for diameter 1.5 nm .

III. RESULTS AND DISCUSSION

Figures 2(a)–2(d) show the calculated MFM images of the magnetic nanocontact with $\kappa = 1.0, 2.0, 3.0$, and $5.0 \times 10^{19} \text{ J/A}^2 \text{ m}^4$, respectively. The shape of the MFM image strongly depends on the value of κ . For $\kappa = 1.0 \times 10^{19} \text{ J/A}^2 \text{ m}^4$, as shown in Fig. 2(a), the MFM signal forms a straight line, the length of which is much greater than the size of the contact. For $\kappa = 2.0 \times 10^{19} \text{ J/A}^2 \text{ m}^4$, we obtain the arc MFM image as shown in Fig. 2(b). The MFM image for $\kappa = 5.0 \times 10^{19} \text{ J/A}^2 \text{ m}^4$ is a right semicircle as shown in Fig. 2(d). For $\kappa > 7 \times 10^{19} \text{ J/A}^2 \text{ m}^4$, sharp signals in the

FIG. 2. MFM image of the magnetic nanocontact. The contact is located at the origin. The electrode magnetization is proportional to $-e_x$. The shape anisotropy of the contact is $\kappa = 1.0 \times 10^{19} \text{ J/A}^2 \text{ m}^4$ for (a), $2.0 \times 10^{19} \text{ J/A}^2 \text{ m}^4$ for (b), $3.0 \times 10^{19} \text{ J/A}^2 \text{ m}^4$ for (c), and $5.0 \times 10^{19} \text{ J/A}^2 \text{ m}^4$ for (d), respectively.

MFM image vanish. In each panel of this figure, we find a sharp circular or arclike signal with its radius of the order of 100 nm . The obtained signals shown in Figs. 2(a) and 2(b) are quite similar to those observed by Miyake *et al.*⁴ It should be noted that we cannot observe such sharp signals without taking into account the tip–contact interaction.

In order to understand the origin of the sharp signal, we analyze how the direction of m_2 depends on the position of the tip. In Figs. 3(a)–3(f) we plot the direction of m_2 in the vicinity of the sharp peak as a function of the tip height by the white solid line. The anisotropy constant is assumed to be $\kappa = 2.0 \times 10^{19} \text{ J/A}^2 \text{ m}^4$. The y-coordinate of the tip is set to be zero and the x-coordinate is varied from -45 nm (a) to -55 nm (f). As shown in Fig. 3(a), at $x = -45 \text{ nm}$, the direction of m_2 continuously follows the oscillation of the tip. The tip–contact interaction decreases as the distance between the tip and the contact increases, and it becomes comparable to the shape anisotropy at a certain value of $x \simeq -50 \text{ nm}$. As shown in Figs. 3(c) and 3(d), the direction of m_2 jumps and shows hysteresis. This discrete change of direction of m_2 leads to a strong derivative of the magnetic force, $\partial F_z / \partial z$, resulting in the sharp signal of the MFM image.

In the vicinity of the hysteresis, the effective magnetic field due to tip–contact interaction becomes parallel to the $x - y$ plane at the position of the contact. This condition is expressed by $z = \sqrt{(x^2 + y^2)/2}$ and is indicated by the arrows in Figs. 3(a)–3(f). When the tip oscillates around this point, the tip dipole field shakes the dipole moment of the contact, m_2 , and its direction switches from upward to downward and *vice versa*. With further increase in the distance,

FIG. 3. The direction of the dipole moment m_2 of the contact is shown by white solid lines in the vicinity of the sharp peak as a function of the tip height for $\kappa = 2.0 \times 10^{19} \text{ J/A}^2 \text{ m}^4$ and $y = 0$. E_{total} is plotted by gray scale and corresponding equi-energy lines are shown by the dotted lines. The arrows indicate the position of the tip when the tip magnetic field at the contact is parallel to the $x - y$ plane, i.e., $z = |x|\sqrt{2}$.

FIG. 4. The ratio b/k along the x axis is plotted for several values of κ . The upper axis represents the corresponding tip height $z = |x|/\sqrt{2}$. Then, the corresponding range of tip oscillation is indicated by the shaded regions. When $|b/k|$ passes the thick horizontal lines, a sharp signal appears.

the shape magnetic anisotropy becomes dominant over the tip–contact interaction. As shown in Figs. 3(e) and 3(f), the direction is nearly independent of the tip height and does not show hysteresis or jumps, resulting in no sharp signals.

To investigate the origin of the hysteresis of the m_2 direction, we shall consider the total energy for $z = |x|/\sqrt{2}$. When a minimum of E_{total} splits into two minima on $z = |x|/\sqrt{2}$, the hysteresis appears. Because the tips magnetic field is parallel to the x axis, the total energy can be expressed as

$$\begin{aligned} E_{\text{total}} &= (B_{\text{tip},x} - B_{\text{eff}})m_2 \sin \theta + \kappa m_2^2 \sin^2 \theta \\ &\equiv b \sin \theta + k \sin^2 \theta, \end{aligned} \quad (3)$$

where $B_{\text{tip},x}$ is the x component of the tips magnetic field. E_{total} has two minima for $|b/k| < 2$, but a single minimum

for $|b/k| > 2$. Therefore, the position of hysteresis on the x axis can be obtained by solving the equation $|b/k| = 2$.

Figure 4 shows the calculated b/k along the x axis. In this figure, the corresponding range of the tip oscillation is indicated by the shaded regions. If the region of the tip oscillation indicated by shaded region in Fig. 4 includes the $|b/k| = 2$ point, i.e., b/k crosses the thick horizontal solid lines, a sharp signal appears on the x axis. This condition indicates that the origin of the signal is the competition between the tip–contact interaction and the anisotropy.

IV. SUMMARY

MFM images of magnetic nanocontacts for parallel configurations of electrode magnetization were evaluated by modeling the tip and contact as dipole moments. We showed that a sharp ring or arc signal with a diameter of about 100 nm was obtained, while the size of contact was of the order of 1 nm. The origin of the ringlike or arclike signal is the jump of the contact dipole moment, which appears when the tip–contact interaction becomes comparable to the shape anisotropy of the contact.

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