Journal of Magnetism and Magnetic Materials 342 (2013) 1–3

Contents lists available at SciVerse ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Detection of domain wall distribution and nucleation in ferromagnetic nanocontact structures by magnetic force microscopy

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ARTICLE INFO

Article history:
Received 21 August 2012
Received in revised form
13 March 2013
Available online 23 April 2013

Keywords:
Domain wall
Ferromagnetic nanocontact structure
Magnetic force microscopy

ABSTRACT

Ferromagnetic nanocontact structures have attracted broad interest due to their potential applications in nanodevices as well as in the fundamental studies of domain wall location and controllable pinning, which are key factors to understand the physics of nanodevices based on these structures. In this paper, we investigated the distribution of domain wall in permalloy nanocontacts before and after magnetic field utilizing by Magnetic Force Microscopy (MFM). We find that the domain wall located in the vicinity of the nanocontact, which is not the exact contact position as supposed when a field of 5 kOe was applied. The mechanism behind such observation may mainly due to the energy equilibrium inside the sample. Moreover, mismatched nanocontact structures were designed and fabricated with domain wall pinned in the exact contact position, which suggests that the mismatched contact structures maybe an idea structure to investigate the interplay between the spin polarized current and the domain wall.

1. Introduction

In ferromagnetic metals the interaction between electrons and a domain wall can give rise to domain wall motion due to the s-d exchange torque exerted by the current carrying electrons on the domain wall magnetic configuration [1–4]. Current induced discontinuous resistance changes, has been observed experimentally and is attributed to the domain wall scattering in ferromagnetic nanocontact structures when the contact width is less than a critical value [5–8]. Simulation results show a domain wall is pinned at the contact position and can be pushed away by the spin polarized current. However, whether the domain wall is defined exactly at the contact position has not been directly confirmed experimentally.

In this study, ferromagnetic nanocontact structures with different widths were fabricated utilizing electron beam lithography and lift-off process; the domain wall distribution of these structures at the demagnetization and remanent state were investigated by MFM. Due to the magnetic shape anisotropy, it is supposed that magnetic domain walls are confined in the contact position when the magnetizations of two parts magnetic nanowire are aligned to be antiparallel to each other [9]. However, the domain wall has not been trapped in the contact position from our direct observation by MFM technique. In order to ascertain that the distribution of domain wall around the contact region, we fabricated mismatched nanocontact structure The results could provide insight for in-depth understanding of micro-magnetic structure respond to geometrical constraints in nanometer scale and to the applied magnetic fields.

2. Experimental details

The samples were fabricated by electron beam lithography and lift-off processes based on SiO_2/Si substrates. The process started with spin-coating the substrate with 495PMMA and pre-baked at 180 °C for 60 s on a hotplate; then e-beam lithography was carried out using the Raith150 system with electron energy of 10 keV. The samples after exposure were developed in MIBK: IPA (1:3) at 22 °C for 40 s and rinsed in IPA about 30 s, and then blown dry with pure nitrogen gas. After exposure and development, the patterns with a length of 100 μm and width of 1 μm were defined, which have nanocontact structures at the halfway. Permalloy ($Ni_{80}Fe_{20}$) film about 30 nm thick was deposited by a thermal evaporation system; then an Au capping layer about 2 nm thick was deposited on top of the permalloy layer to prevent it from oxidation. After the ultrasonic assisted lift-off process in acetone, the permalloy nanocontact structures with different widths were obtained.

Using MFM system together with atomic force microscopy (AFM), the permalloy contact structures were observed in both their demagnetized (as grown) and remanent states at room temperature with a vertically magnetized tip. The commercial Si probe with CoCr coating was used and the distance between the probe and sample was set as 5 nm for the AFM tapping mode and about 60 nm for MFM measurements.

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http://dx.doi.org/10.1016/j.jmmm.2013.04.042

3. Results and discussion

For a soft magnetic nanowire that is less than 100 nm wide, the orientation of the magnetization is restricted along the wire due to the shape anisotropy, which means that the magnetization of a nanowire will be a single domain. However, the magnetization for the constriction structure altered by the shape, which will display a new distribution. Fig. 1 shows the domain wall distribution for the 55 nm wide nanocontact structure (as-grown) in the demagnetizing state. The light and dark contrast corresponds to the strength of the stray-field gradient on the sample surface. The lighter color represents the frequency shift in the MFM tip when the magnetization of the sample and that of the MFM tip are repulsive. Similarly, the dark region represents the magnetization of the sample and that of the MFM tip is attractive. The Fig. 1a, shows that the magnetization of the contact is vertical downward, so there is no domain wall pinned in the contact position. Two domain walls were located in the gradually narrowed region as shown in Fig. 1b. The two domain walls are asymmetrically around the contact due to the magnetization confined in the narrow region is divergent and convergent, respectively.

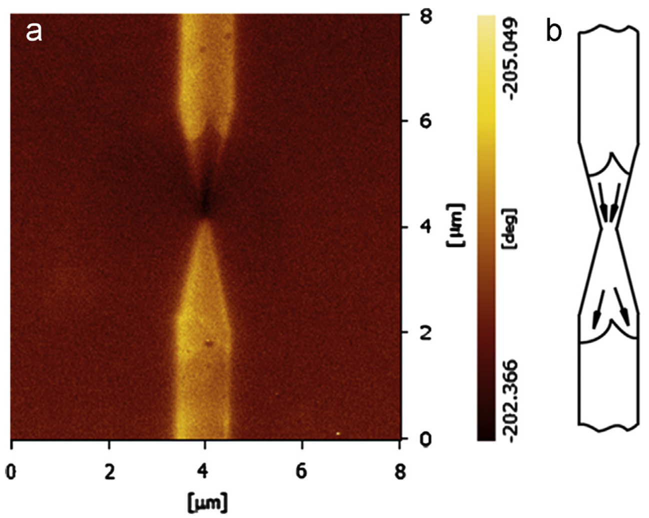

Fig. 1. (a) The MFM image of a contact with width of 55 nm; (b) the schematic diagram of domain wall distribution.

Then we studied the domain wall distribution in contact structure after a magnetic field of 5000 Oe was applied. Fig. 2a and b show the MFM images of contact with a contact width of 120 nm before and after applying a magnetic field, respectively. The white arrows indicate the positions of domain walls. After the magnetic field was applied, the MFM images were taken in a saturation remanent state and the domain walls distributed slightly different, which is shown in Fig. 2b and d. A new domain wall occurred around the original position of domain wall. The occurrence of a new domain wall suggested that the demagnetizing energy becomes larger after applying a magnetic field so that the formation of more domain walls would decrease the demagnetizing energy. Finally, the energy system inside the sample will approach equilibrium due to introducing more domain wall energy. As discussed above, it turned to be that no domain wall observed in the exact contact position, a case that the contact width is below the critical value of about 300 nm for permalloy. Then we tried to investigate the domain wall distribution for contact structures with contact widths that are over 300 nm. Fig. 3 shows the MFM images of contact with a contact width of 570 nm before and after a magnetic field was applied, respectively. Similarly, a new domain wall was observed which again was not located in the exact contact position.

Although there is no domain wall observed in the contact position by MFM till now, the discontinuous resistance changes [5]

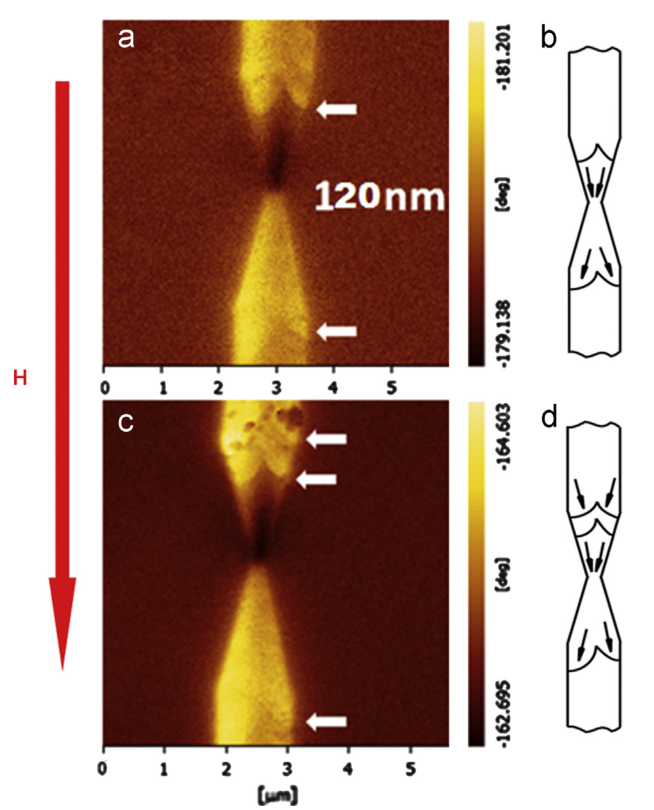

Fig. 2. The MFM images in of a Permalloy nanocontact with a constriction size of 120 nm (a) before and (c) after applying a magnetic field of 5000 Oe. (b) and (d) The schematic diagrams of the corresponding to MFM, respectively.

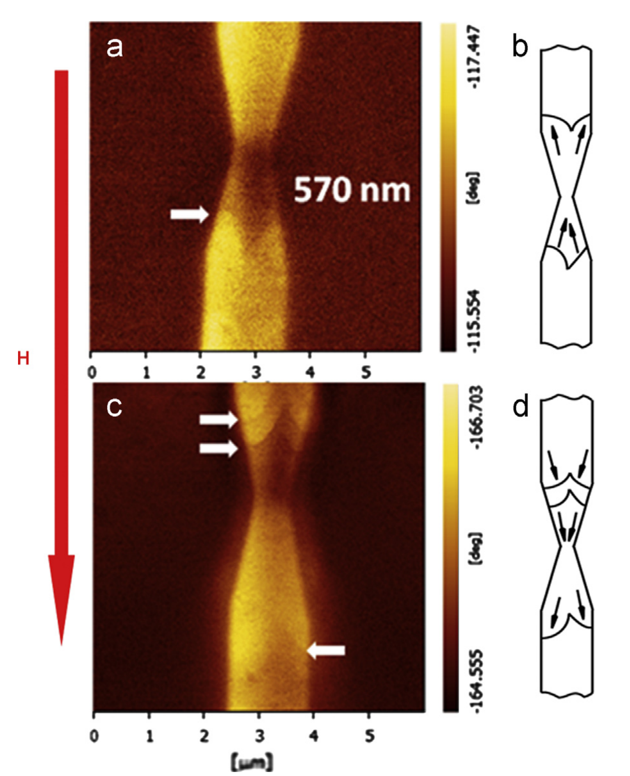

Fig. 3. The MFM images in of a permalloy nanocontact with a constriction size of 570 nm (a) before and (c) after applying a magnetic field of 5000 Oe. (b) and (d) The schematic diagrams of the corresponding MFM.

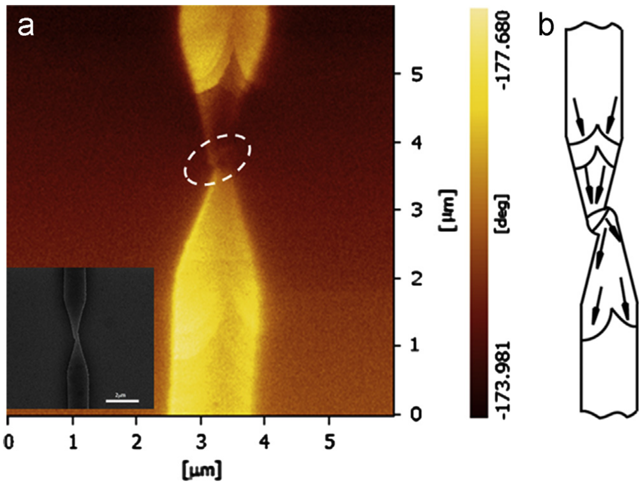

Fig. 4. (a) The MFM image of a mismatched contact structure; (b) the schematic diagram of domain wall distribution of the mismatched contact. The inset is the SEM image of the mismatched contact.

for the nanocontact structures maybe induced by the motion of the domain walls distributed in the gradually narrow part. In order to confirm whether the domain wall can nucleate in the contact region, we fabricated mismatched contact structures to investigate the domain wall distribution in such type of structures. The mismatched contacts we called here have the feature that two half parts of a nanowire displaced a distance in the horizontal direction, as shown in Fig. 4. The contact width of the mismatched sample is about 270 nm, which is two times of that of the normal contact sample. The inset is an SEM image of the mismatched contact topography. Fig. 4a shows the MFM image for this mismatched contact structure in demagnetization state. The domain wall distribution is more complex than that of normal contact, which is shown in Fig. 4b. It is obvious that a domain wall just located in the position of the displacement. These results suggest that the mismatched contact structures maybe useful for domain-wall resistance investigation.

4. Conclusion

Permalloy nanocontact structures were fabricated and characterized by magnetic force microscopy in both demagnetized and remanent states. Two domain walls are observed in the position around the narrow parts along the axis direction of nanowire, which is due to spontaneous magnetization related with the constriction structure. After applying a magnetic field in the longitudinal direction of the nanocontact plane, a new domain wall occurred near the original pinning position. This indicates that the remanent magnetization in the samples can change the domain wall distribution. Moreover, the geometrical structure can affect the domain wall nucleation by comparing normal contacts with mismatched contacts structure. Our results may provide insight for in-depth understanding of micromagnetic structure respond to geometrical constraints in nanometer scale and to explore the effect of the magnetic fields.

Acknowledgments

This work was supported by National Natural Science Foundation of China (Grants nos. 50825206, 1083401, 60871045, 91023041 , 11174362) and The Knowledge Innovation Program of CAS (KJCX2-EW-W02).

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