Ferromagnetic spin ordering at the dislocations in antiferromagnetic oxide.

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Properties appeared at the localized volume, especially in atomic scale, are in great usage for miniaturizing devices. Utilizing surfaces and interfaces with locally different atomic-scale structures to obtain desired properties are thus becoming a common trend in developing future electronic devices and related materials. Dislocations, one-dimensional lattice defects in any crystals, also possess locally different atomic-scale structures at their cores, and have the potential to exhibit unique properties [1-3] as well as surfaces and interfaces. Moreover, dislocations are buried inside bulk crystals and thus strongly correlated with the surrounding bulk environments. This may provide new functional properties due to the novel one-dimensional nanostructures which are different from the stand-alone nanostructures such as nanotubes and nanowires. However, the fundamental properties of individual dislocations are still elusive. Here, we unveiled unique ferromagnetic properties that individual dislocation inside a crystal possesses. We fabricated NiO thin films with high-density dislocations, and investigated the magnetic properties of individual dislocation one by one using magnetic force microscopy (MFM).

The NiO single crystalline thin films are deposited on $SrTiO_3$ substrate using pulsed laser deposition (PLD) method. The deposited films are annealed in air at 1100℃ for 0.5 h to improve crystallinity. The dislocations are introduced into NiO film due to the large lattice mismatches between $SrTiO_3$ substrates and NiO films. The dislocation lines are parallel to the film growth direction as schematically shown in Fig. 1.

The dislocations form dips at the surface, so they can be observed using atomic force microscope (AFM) as dark or black dots as shown in Fig. 2(a). Fig. 2(b) show MFM phase image simultaneously obtained with the AFM topographic image in Fig. 2(a). In the MFM image, black spots are observed at the positions of dislocations. Spins are ordered in antiferromagnetic manner in the bulk region and the bulk region has no spontaneous magnetizations. Hence the black spots observed in the MFM image are derived from the spontaneous magnetizations at the dislocations [4]. These ferromagnetic dislocations are embedded in the antiferromagnetic bulk crystalline environment. Thus, the ferromagnetic spin ordering at the dislocation cores are formed under the strong correlation with the antiferromagnetic bulk. This strong spin correlation triggered the anomalous magnetic property at the dislocation core. For example, the magnetic coercive force of the ferromagnetic dislocations is over 4 T. The coercive force of usual permanent magnet is less than 1 T, so the coercivity of ferromagnetic dislocations is extremely large. The Curie temperature is also very high: over 250℃. This Curie temperature of ferromagnetic dislocations is almost consistent with the Neel temperature of antiferromagnetic NiO. The coincidence of the Curie temperature at the dislocations and Neel temperature of the bulk should indicate the strong spin correlation between ferromagnetic dislocations and antiferromagnetic bulk. Thus, we unveiled a new way of forming “functional dislocations”, where many new properties may appear through strong correlation between dislocations and bulk.

References

[1] A. Nakamura, *et al*., *Nature Mater.* **2** (2003) 453.
[2] K. Szot, *et al*., *Nature Mater.* **5** (2006) 312.
[3] Y. Ran, *et al*., *Nature Phys.* **5** (2009) 298.

[4] I. Sugiyama, *et al.*, *Nature Nanotechnol.* **8** (2013) 266.

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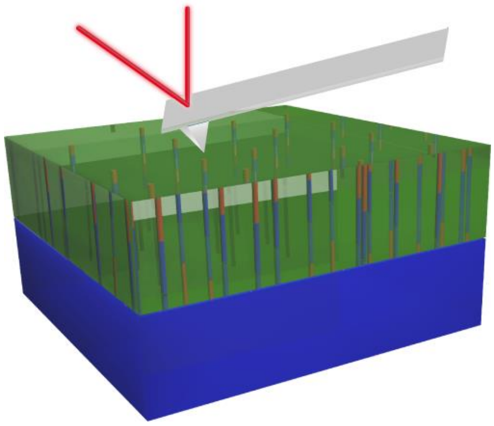

Fig. 1 A schematic of atomic scale ferromagnetic dislocations embedded in antiferromagnetic NiO. The blue block is $SrTiO_3$ substrate and the green block is NiO single crystalline thin film. The red/blue cylinders are magnetic dislocations in NiO film. The AFM and MFM observations are carried out on the surface of film.

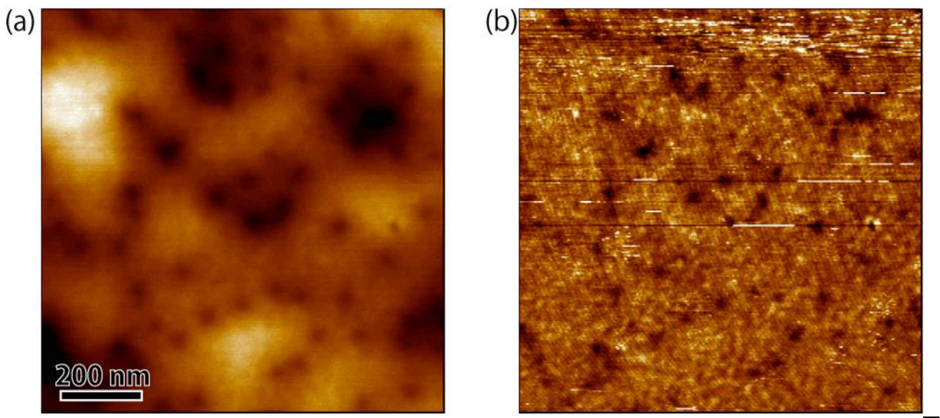

Fig. 2 (a) AFM topographic image and (b) MFM phase image of the NiO thin film. Dark spots in AFM topographic image correspond to the dislocations. MFM image was taken 20 nm above the surface to reduce the effect of atomic force.