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Letter to the Editor

Scratching-induced large-area and tunable perpendicular anisotropy in flexible metallic glass under ambient conditions

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Abstract

The scratching-induced tunable perpendicular anisotropy in amorphous FeSiB ribbon surface has been directly observed in room temperature and air atmosphere. The magnetic stripe domain width and contrast strength can be easily tuned according to the scratch size, and the magnetic signature is erasable in nano-scale by indentation, which greatly facilitates the direct magnetic patterning. The result presents a simple way of fabricating the large-area magnetic film with controllable perpendicular anisotropy, remarkable intrinsic flexibility and high strength directly from amorphous FeSiB ribbon under ambient conditions, which may simulate much scientific and engineering interest, leading to the novel applications of metallic glasses.

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Magnetic film with artificially controlled perpendicular anisotropy is one of the fundamental building blocks for the rapidly growing fields of ultrahigh magnetic recordings, magnetoelectronics and sensors [1,2]. The use of plastic substrates is also increasing in importance owing to their light weight, flexibility, shock resistance and low cost [3,4], while current magnetic film fabrication is difficult to implement on the intrinsic flexibility and high strength. As a result, alternative magnetic film with tunable perpendicular anisotropy, intrinsic flexibility and high strength should enable new applications in flexible, economical, wearable and disposable electronics. Recently intensive efforts have been carried out to control the magnetic domain structure of the amorphous ribbon by using annealing, laser irradiation, and plastic deformation methods [5–9], which is significant to expand current understanding the fabrication of magnetic anisotropy film. In addition, processing-induced magnetic structures in amorphous ribbon are also important for the considerable power loss and the performance deteriorism of ribbons used in electric power applications [8,9].

The mechanical scratching has been widely used to study the property evolutions of various crystals [10–12], while little work is reported in amorphous materials. In this work, we show the direct evidence of the scratching-induced magnetic stripe domains in amorphous FeSiB ribbon and present a simple way of fabricating magnetic film with tunable perpendicular anisotropy, intrinsic flexibility and high strength under ambient conditions. The ribbon is based on the ordinary iron and can be readily spun into large area (in excess of 20 cm in width) in air atmosphere, which is very compatible with large-scale production technologies. Especially, high homogeneity with neither grain boundaries nor dislocations in amorphous ribbons greatly enhances their elastic limit and reversible range [13], leading to the remarkable intrinsic flexibility (repeatedly bended through 180°) and high strength (the tensile strength >3000 MPa, Vickers hardness ∼10 GPa). Moreover, in view of the power loss in electric power applications it is also of interest to study the

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submicron scratches in amorphous ribbon surface, which have usually been neglected during industrial process.

The $Fe_{77}B_{14}Si_9$ amorphous ribbons with a thickness of 30 μm were used in this experiment. As a pilot study, we selected aluminum oxide particles as the abrasive, the scratches were slowly drawn along the ribbon length direction on the free surface. The magnetic measurements were performed using a PPMS 6000 of Quantum Design Company. The topography and domain structures of the ribbon were studied by using a Digital Instruments NanoScope IIIa D-3000 AFM/MFM.

Fig. 1 shows the typical 10 μm × 10 μm atomic force microscopy (AFM) and magnetic force microscopy (MFM) images of the $Fe_{77}B_{14}Si_9$ ribbon scratched by Al_2O_3 particles with different sizes. There is no direct correlation between the surface morphology and the magnetic domain pattern; the dark and bright areas correspond to the up and down perpendicularly magnetized domains, respectively. For the unscratched ribbon, no magnetic domain is observed on the smooth surface [see Fig. 1(a)], when the ribbon is scratched by the abrasive particles with different sizes, well-aligned scratch grooves are oriented in the ribbon length direction, some irregular spaced grooves are also notable in the AFM images. However, the unexpected magnetic stripe domains are clearly observed in the MFM images as shown in Fig. 1(b)–(d), which are indicative of a perpendicular anisotropy for the film [1,14,15]. According to the statistical results got from a large number of section analyses, the variations of topographic RMS (root mean square), average scratch density, average domain width and magnetic RMS as a function of the Al_2O_3 abrasive particle size are plotted in Fig. 2. With the increase of the abrasive particle size, the average scratch density decreases accordingly; while both the topographic RMS and the average domain width almost linearly increase, and an optimum magnetic RMS is obtained at intermediate scratch size. Through the mean error, it is also worth noting that the domain uniformity enhances with decreasing scratch size. These graphs illustrate the facility in creating controllable perpendicular anisotropy by scratches, which allows us to tune the perpendicular anisotropy artificially.

Fig. 3 presents the magnetic hysteresis loops of the unscratched and scratched FeSiB ribbons at 300 K. The ribbon is very difficult to be saturated in the direction perpendicular to the ribbon plane due to the high aspect ratio (the magnetization curve measured in ribbon length direction also shown for comparison) [16], which indicates that the very strong shape anisotropy of the ribbons has forced magnetic moments lie within the plane. The loops for the scratched and unscratched ribbons are almost the same, strongly indicating that the scratch only affects the top nanometer of the surface and the main part is unaltered.

The magnetic domain evolution under stress is studied by the microindentation, which is capable of creating an indent or a scratch groove with depth control. The ribbon

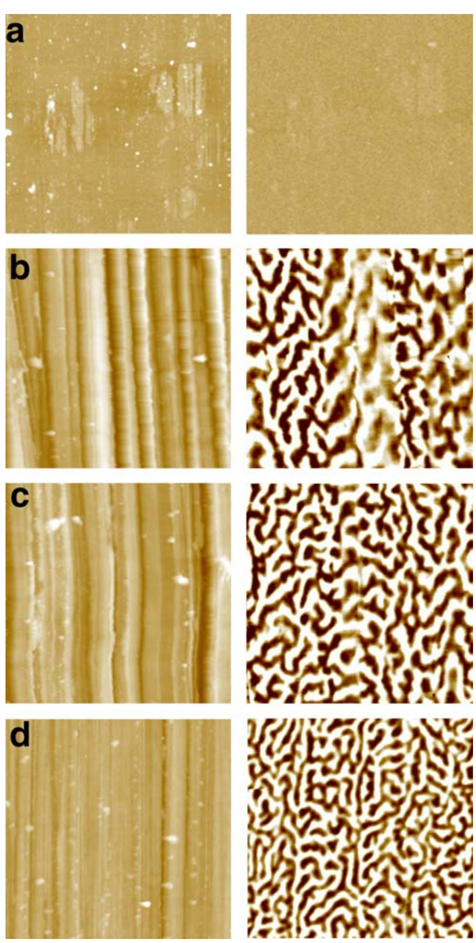

Fig. 1. The 10 μm × 10 μm AFM (left) and MFM (right) images of the $Fe_{77}B_{14}Si_9$ ribbons scratched by the Al_2O_3 abrasive particles with different sizes: (a) unscratched; (b) 10 μm; (c) 7 μm; (d) 5 μm. The images are directly taken in zero-field at room temperature.

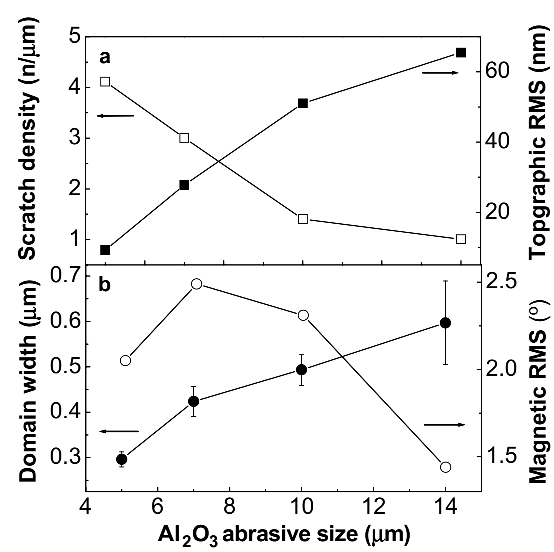

Fig. 2. (a) The average scratch intensity and topographic RMS (root mean square) vs. the Al_2O_3 abrasive particle size. (b) The average domain width and magnetic RMS vs. the Al_2O_3 abrasive particle size.

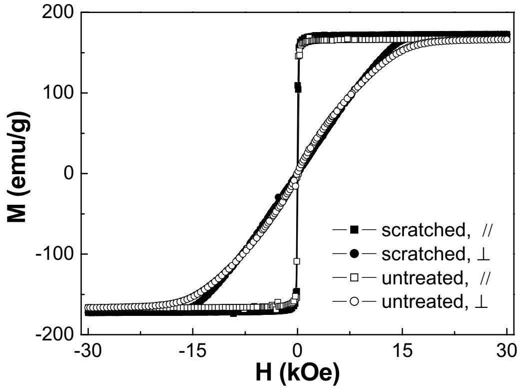

Fig. 3. The magnetic loops for the unscratched and scratched (by the Al_2O_3 abrasive particle with 5 μm size) FeSiB ribbon at 300 K with the external field parallel or perpendicular to the ribbon plane, respectively.

is firstly pre-scratched with 5 μm abrasive particles, and then the indentation is performed by a four-sided pyramid diamond indenter. By overlapping the topography with its magnetic counterpart, the MFM image shows the magnetic structure has been modified significantly: the domain width increases in the four-sided indent region [see Fig. 4(a)], while comparing with Fig. 1(d) the regions around indent show obvious magnetic degradation. For the micro-scratch (see Fig. 4(b)), it can be observed that magnetic stripe domain almost vanishes on the both sides of the groove (marked by *A*), region *C* still retains the magnetic stripe domains, and nearly ordered stripe domains parallel to the micro-scratch direction occur in region *B*. Especially, the modified area coverage also allows to be tuned by the intent load, which greatly benefits the direct magnetic patterning. Therefore, the magnetic stripe domain pattern not only can be easily tuned by the scratch size, but also is erasable in nano-scale by indentation. The flexible FeSiB ribbon with artificially controlled perpendicular anisotropy and high strength has potential applications for magnetoelectrics and sensitive stress detection, and may provide a new route to the basically mechanical data storage developed very recently [17], which has a potential density ten times higher than today's disk drives.

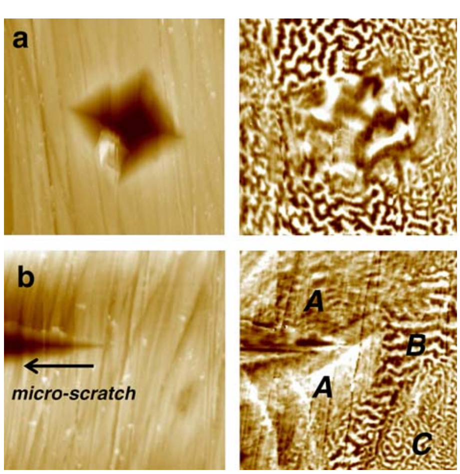

Fig. 4. The AFM topography (left) and the corresponding MFM (right) images around an indent placed in the pre-scratched ribbon (by the Al_2O_3 abrasive particle with 5 μm size): (a) scan size 15 μm × 15 μm; (b) scan size 15 μm × 15 μm, the micro-scratch is drawn perpendicular to the pre-scratching direction.

The known mechanisms capable of producing perpendicular anisotropy in film include magnetocrystalline anisotropy, magnetoelastic anisotropy, and microshape anisotropy [1,9]. The perpendicular anisotropy of the amorphous ribbons surface should be due to the stress anisotropy modulated magnetoelastic effects. The magnetoelastic energy (E_{ME}) can be manifested as [1,8,9]: $E_{\mathrm{ME}} = -\frac{3}{2}\lambda\sum_{i=1}^{3}\sigma_i\gamma_i^2$, where λ is the material-dependent magnetostriction constant, σ_i is the applied stress and the γ_i is the direction cosines of the magnetization (M) with respect to the principal stress axes. For positive λ materials, such as $Fe_{77}B_{14}Si_9$ ribbon ($\lambda_s \sim 27$ ppm), M will align along with the direction of the least negative (or the most positive) stress to minimize the total magnetic energy [8]. In the scratching-treated ribbon surface, compressive in-plane stress (negative) leads to the easy magnetization axis in the surface normal direction (i.e. the direction of the least negative stress), so maze-like stripe domain structures (as shown in Fig. 1) form to lower the total energy of the film by reducing the net magnetization (at the expense of having the domain orientations anti-aligned with the easy axis). The stripe domain width narrows with decreasing the scratch size (see Fig. 2(b)), indicating that higher strain in ribbon surface has made the easy axis stronger and the narrower domains are necessary to provide more demagnetization.

The magnetoelastic effect is further confirmed by the indentation experiments. The magnetic signature shows obvious degradation in the region around the four-sided indent owing to the indent-induced tensile stress in ribbon surface, even almost lost on both sides of the groove. This feather-like magnetic pattern with negligible contrast is typical of a film with an in-plane magnetization [14], which results from the tensile stress (positive) induced the easy magnetization axis in plane (i.e. the direction of the most positive stress). In addition, nearly ordered stripe magnetic domain pattern in the groove head region may be due to the local uniaxial compressive stress imposed by micro-scratch direction [14].

In conclusions, we show the direct evidence of the scratching-induced tunable and erasable perpendicular anisotropy in large-area amorphous FeSiB ribbon under ambient conditions. As a pilot study, it is clear that the ribbon scratched by abrasive particles is not suitable in itself for engineering applications, but the approach developed should in principle apply to ribbon scratched under accurate width and depth control. Therefore, the present approach may provide a novel and economical route to fabricate large-area magnetic film with tunable perpendicular anisotropy, intrinsic flexibility and high strength, and could lead to new applications of metallic glasses.

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