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ARTICLE

Magnetic Property Tunability of Amorphous SmCo Thin Films by Mechanical Strain Supplied by Flexible Substrates

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Abstract: Amorphous SmCo thin films with thickness of 10–150 nm were deposited on the flexible polyethylene terephthalate (PET) substrates. Tensile/compressive strain was generated in the amorphous SmCo thin film when PET substrate was flattened from concave/convex shape after thin film deposition. Results show that both the normalized remanent magnetization and the squareness of hysteresis loops of SmCo/PET can be tuned by the strain. Compared with that induced by compressive strain, the tunable amplitude induced by tensile strain is larger for the amorphous SmCo thin films. Because the amorphous SmCo thin film has negative magnetostrictive property, the magnetic properties of amorphous SmCo thin film can be controlled by the mechanical strain supplied by flexible substrates. When the negative magnetostriction effect occurs, the magnetization process of amorphous SmCo thin films is hindered by the tensile strain, whereas it is promoted by the compressive strain. The amorphous SmCo/PET shows great potential in the field of flexible spintronic devices and flexible micro-nano electronic devices.

Key words: amorphous SmCo thin film; flexible substrates; strain; magnetic properties

Flexible devices on plastic substrates are promising for disposable electronic products, smart cards, light-emitting diodes, wearable electronic devices, and sensors[1–6]. Heterostructures commonly consist of magnetic thin films and flexible substrates[7]. Most studies focus on the soft ferromagnetic and ferrimagnetic materials, such as $Co_{40}Fe_{40}B_{20}$/polyethylene terephthalate (PET) [7], $Fe_{81}Ga_{19}$/PET[8], and CoFeB/polyimide (PI) [9], as magnetic layers of the heterostructures. The hard magnetism materials are rarely researched, although they have higher recording density and signal-to-noise ratio[10].

Amorphous hard SmCo thin films have great potential in the fields of information storage[11–12] and spintronics[13]. The two-state[14] or even multiple-state[15] storage can be realized by the amorphous hard magnetic SmCo/(011)PMN-PT heterostructure because of the magnetostrictive properties of amorphous SmCo thin film and the polarization switching of PMN-PT substrate. The stiff and thick substrate can hardly be deformed. Thus, the strain on the magnetic film is relatively small[14,16]. Besides, the clamping effect caused by the stiff substrate can reduce the induced anisotropy and magnetoelastic coupling in the magnetostrictive thin films[16]. Thus, it is crucial to combine amorphous hard SmCo thin films with flexible substrates.

In this research, the effect of strain on the magnetization properties of amorphous hard SmCo thin films in SmCo/PET heterostructures was investigated. This research is of great importance for the development of flexible spintronic devices and flexible micro-nano electronic devices.

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1 Experiment

Amorphous SmCo thin films with thickness of 10–150 nm were grown on the bent flexible PET substrates (approximately 250 μm) by direct-current magnetron sputtering in the Ar atmosphere. The thick capping layer of Cr (50 nm) was deposited to protect the amorphous SmCo layer from oxidation. All films were fabricated at room temperature without magnetic field. The substrates were anti-sputtered before the film deposition. The Sm-Co target with Sm content of 17at% was used to prepare the film. The average Sm and Co contents in the film were about 23at% and 77at%, respectively, which is roughly consistent with the nominal composition of target $SmCo_5$[12]. The magnetic properties were determined by the Quantum Design superconducting quantum interference devices (SQUID-VSM) at room temperature.

2 Results and Discussion

2.1 Application method of strain

In order to investigate the strain-dependent magnetization properties of amorphous SmCo thin films, several aluminum alloy molds with different curvature radii were used to apply different tensile or compressive strains to the films. As shown in Fig. 1, PET substrates were directly bent by fixing them onto the concave/convex surface of the molds. Although the bent substrates were strained, the deposited amorphous SmCo thin films were stressed until all specimens were flattened. Therefore, the tensile/compressive stress can be produced in the amorphous SmCo thin films when PET substrates change from concave/convex shapes to the flat plane after deposition. The applied strain/stress on the amorphous SmCo thin films can be calculated by Eq.(1–3), as follows[8,17]:

$$\varepsilon_T = t/(2R - t) \quad (1)$$

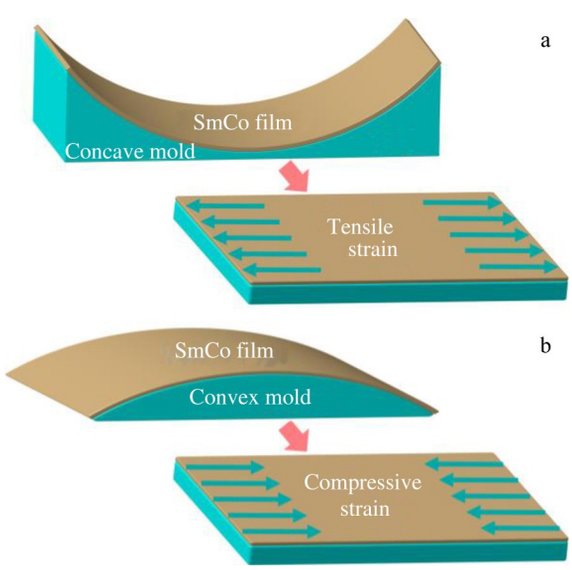

Fig.1 Schematic diagrams of bent substrates before sputtering and strains in amorphous SmCo thin films during substrate flattening process: (a) concave shape to flat plane and (b) convex shape to flat plane

$$\varepsilon_C = t/(2R + t) \quad (2)$$

$$\sigma = \varepsilon E_f/(1 - \nu^2) \quad (3)$$

where ε_T and ε_C are the tensile and compressive strains of the amorphous SmCo thin films after the substrate changes from concave and convex shapes to flat planes, respectively; σ is the stress; R is the curvature radius of molds; t is the specimen thickness including the film thickness; E_f is the Young's modulus of amorphous SmCo thin films of approximately 120 GPa[18]; ν is the Poisson ratio of 0.27[18]. After the substrates change to flat planes, the strains caused by the convex or concave molds of different radii are 0.2%, 0.4%, 0.6%, and 0.8%.

2.2 Tunable magnetic properties of amorphous SmCo thin films under tensile strains

Fig. 2 shows the hysteresis loops of amorphous SmCo thin films with 10 – 150 nm in thickness under different tensile strains. The applied magnetic field is parallel to the direction of the strain in the films. M_r is the remanent magnetization and M_s is the saturation magnetization. As shown in Fig. 2a, when the specimen is subjected to tensile strain, the hysteresis loop changes to a slanted one, and the inclination of the hysteresis loops is increased with increasing the tensile strain. Additionally, the M_r/M_s values are decreased from 0.37 to 0.03 with increasing the tensile strain, as shown in Fig.3a.

According to Fig. 2b–2d, with increasing the film thickness, the tunable amplitude is decreased. $\Delta M_r/M_s$ value refers to the M_r/M_s value under tensile strain of 0.8% minus that under tensile strain of 0.2%. With increasing the thickness of amorphous SmCo thin film, the inclination of hysteresis loop is decreased and the reduction amplitude of M_r/M_s is also decreased (Fig. 3b). Therefore, the magnetization properties of amorphous SmCo thin films can be controlled by the tensile strain supplied by flexible substrates. The magnetization of amorphous SmCo thin films becomes harder under tensile strains and the tunable amplitude is decreased with increasing the film thickness.

2.3 Tunable magnetic properties of amorphous SmCo thin films under compressive strains

Fig. 4 shows the hysteresis loops of amorphous SmCo thin films with 10 – 150 nm in thickness under different compressive strains. During the measurement, the applied magnetic field is parallel to the direction of the strain in the thin films. The hysteresis loop changes to a square one when the specimen is subjected to compressive strain. In addition, the M_r/M_s value is increased from 0.14 to 0.58 with increasing the compressive strain, as shown in Fig.5a.

With increasing the thickness of amorphous SmCo thin films, the squareness of the hysteresis loop caused by compressive strain is decreased, and the reduction amplitude of M_r/M_s value is also decreased (Fig. 4b). Thus, with increasing the film thickness, the tunable amplitude is decreased, as shown in Fig. 5b. Particularly, when the film thickness exceeds 100 nm, there is almost no variation regulations, as shown in Fig. 4b – 4d. Generally, the magnetic properties of amorphous SmCo thin films can be controlled by

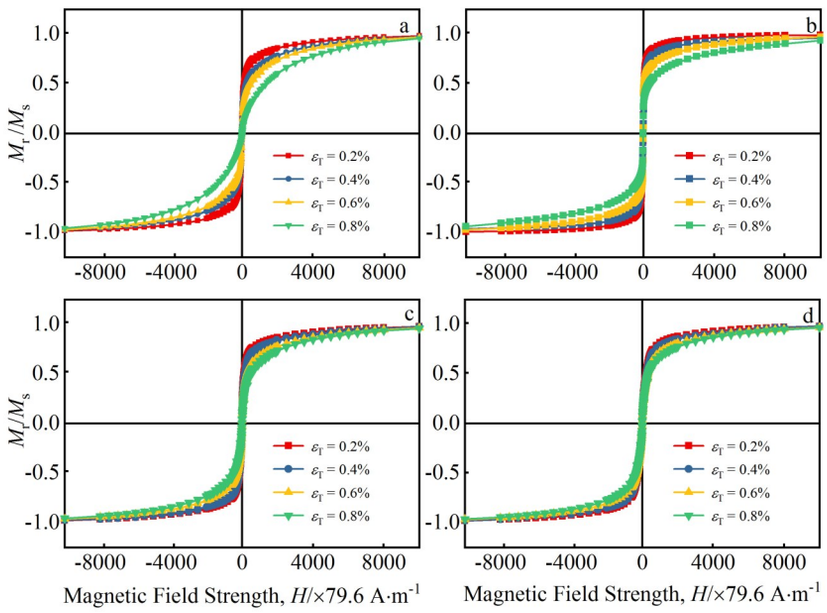

Fig.2 Hysteresis loops of amorphous SmCo/PET with film thickness of 10 nm (a), 50 nm (b), 100 nm (c), and 150 nm (d) under different tensile strains

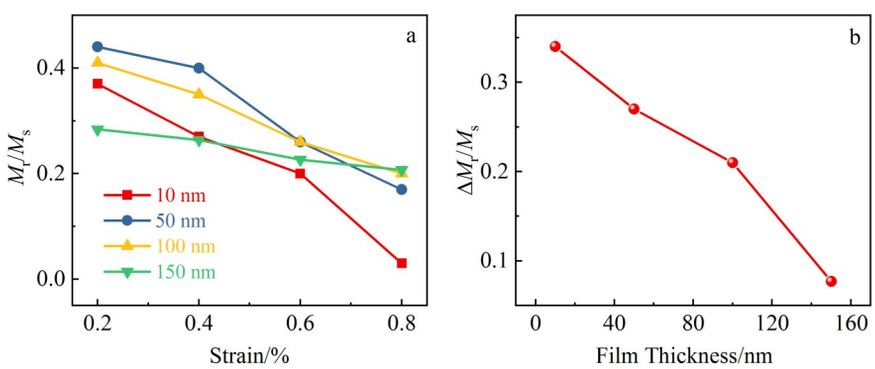

Fig.3 Normalized M_r/M_s values of amorphous SmCo/PET with different film thicknesses under different tensile strains (a); $\Delta M_r/M_s$ values of amorphous SmCo thin film with different thicknesses on PET substrate with tensile strains (b)

both tensile strain and compressive strain supplied by flexible substrates. The magnetization of amorphous SmCo thin films is easier under compressive strains. The tunable amplitude is decreased with increasing the film thickness. Thus, compared with that induced by compressive strain, the tunable amplitude induced by tensile strain is larger for the amorphous SmCo thin films.

These phenomena are all caused by the fact that the amorphous SmCo thin film is a negative magnetostrictive material[14,18]. In amorphous SmCo/PET, under the action of applied strain, the inverse magnetostrictive effect may occur, instead of magnetostrictive effect. When the amorphous SmCo/PET is flattened from the concave mold, the tensile strain appears and hinders the magnetization process of amorphous SmCo thin films. On the contrary, after the PET substrate is flattened from the concave mold, the compressive strain occurs and promotes the magnetization process of amorphous SmCo thin films.

2.4 Strain dependence of magnetization work for amorphous SmCo thin films

The magnetization work[16,19] can be calculated by Eq.(4). as follows:

$$W = \int_0^{M_s} H(M)\,\mathrm{d}M \tag{4}$$

where W is the magnetization work; H is the magnetic field strength; M is the magnetic strength; M_s is the experimental saturation magnetization of the amorphous SmCo thin films. In this research, M_s of amorphous SmCo thin films is about 5.45×10^5 A/m. Fig.6 shows the external strain dependences of magnetization work for amorphous SmCo thin films of different thicknesses (10–150 nm). As shown in Fig. 6a, the magnetization work is increased with increasing the applied tensile strain, which indicates that more and more energy is required for the amorphous SmCo thin films to reach

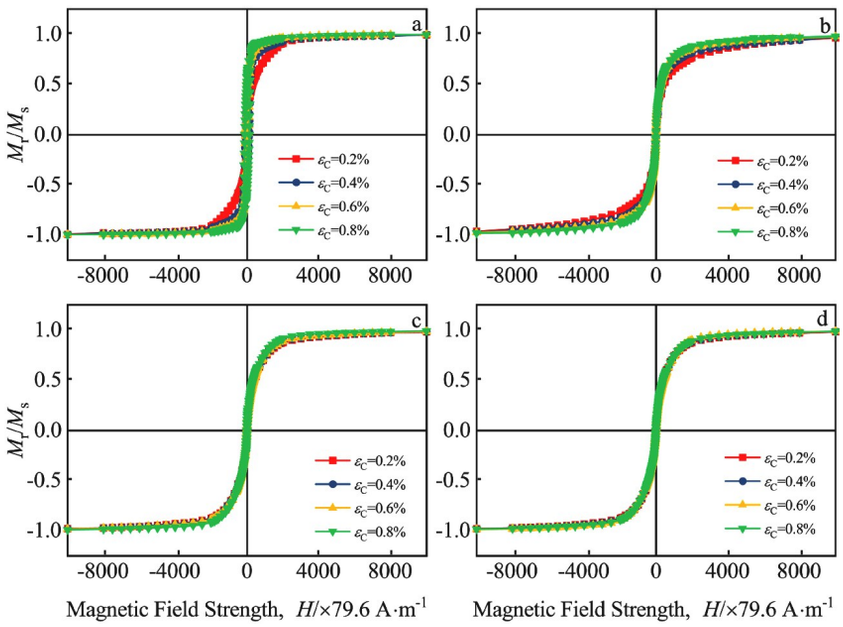

Fig.4 Hysteresis loops of amorphous SmCo/PET with film thickness of 10 nm (a), 50 nm (b), 100 nm (c), and 150 nm (d) under different compressive strains

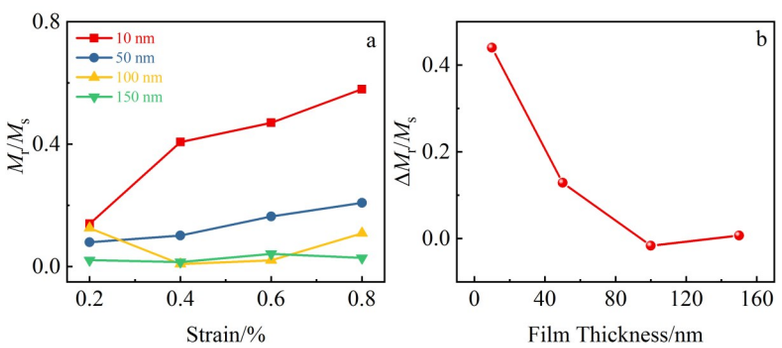

Fig.5 Normalized M_r/M_s values of amorphous SmCo/PET with different film thicknesses under different compressive strains (a); $\Delta M_r/M_s$ values of amorphous SmCo thin film with different thicknesses on PET substrate with compressive strains (b)

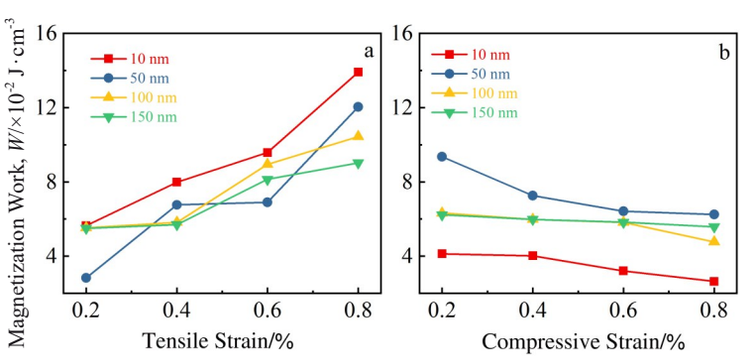

Fig.6 Tensile (a) and compressive (b) strain dependence of magnetization work W for amorphous SmCo thin films on PET substrates with different thicknesses

saturation magnetization. Besides, the magnetization of specimens becomes more and more difficult. Analogously, the specimens can be magnetized more easily with increasing the compressive strain from 0.2% to 0.8%, as shown in Fig.6b. It can be seen that the magnetization of amorphous SmCo thin films has more obvious response to the tensile strain than that to the compressive strain does. This result is consistent with the phenomenon in the CoFeB/PI heterostructures[9]. However,

this mechanism is still obscure and requires further study. In addition, it can be found that the specimens of all film thicknesses exhibit the similar trends on the tunability of magnetization work: the tunability is weakened with increasing the film thickness. This is because the strain transmission from substrate to the thicker amorphous SmCo film is decreased, which is caused by the Young's modulus difference between amorphous SmCo film and PET substrate[7,20].

3 Conclusions

1) The normalized remanent magnetization and squareness of hysteresis loops for SmCo/PET can be tuned by strains. The magnetization process becomes harder with increasing the tensile strain, and it is easier with increasing the compressive strain.

2) The tunable amplitude is decreased with increasing the film thickness.

3) The magnetic behavior of amorphous SmCo thin films based on strains is related to the negative magnetostrictive property of amorphous SmCo thin film. The amorphous SmCo/PET shows great potential in the field of flexible spintronic devices and flexible micro-nano electronic devices.

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柔性衬底提供的机械应变对非晶SmCo薄膜磁性的调控

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摘　要：将非晶SmCo薄膜沉积在弯曲的柔性聚对苯二甲酸乙二醇酯（PET）衬底上，薄膜厚度范围为10~150 nm。薄膜沉积结束后，当PET衬底从凹/凸变平时，非晶SmCo薄膜受到拉伸/压缩应变。结果表明，应变既可以调控SmCo/PET的剩余磁化强度，也可以调控其磁滞回线的方形度。与压缩应变相比，拉伸应变对非晶SmCo磁性的调控幅度更大。非晶SmCo薄膜的磁性之所以能够被柔性衬底提供的机械应变所调控是因为非晶SmCo薄膜具有负磁致伸缩特性。当负磁致伸缩效应发生时，拉伸应变会阻碍非晶SmCo薄膜的磁化过程，而压缩应变则会促进非晶SmCo薄膜的磁化过程。非晶SmCo/PET在开发柔性自旋电子器件和柔性微纳电子器件方面具有巨大潜力。

关键词：非晶SmCo薄膜；柔性衬底；应变；磁性

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