Journal of Magnetism and Magnetic Materials 372 (2014) 12–15

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

The structural and magnetic properties of MnBi and exchange coupled MnBi/Fe films

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ARTICLE INFO

Article history:
Received 13 April 2014
Received in revised form
1 July 2014
Available online 24 July 2014

Keywords:
Magnetic film and multilayer
Anisotropy
Magnetic measurement

ABSTRACT

The structural and magnetic properties of MnBi and MnBi/Fe films prepared by magnetron sputtering and *in situ* vacuum annealing are investigated. MnBi film is highly *c*-axis textured with perpendicular anisotropy. The out-of-plane coercivity increases with temperature, which reaches to 15 kOe and 21 kOe at 300 K and 400 K, respectively. For exchange coupled MnBi/Fe films, when the thickness of Fe layer is thin, the hysteresis loops show single-phase-like reversal behavior due to the effective interfacial exchange coupling. In comparison with MnBi film, the remanent magnetization enhances. The maximum energy product also improves from 7.6 MGOe to 8.0 MGOe at 300 K, and from 5.7 MGOe to 6.1 MGOe at 400 K. As the thickness of Fe layer exceeds the critical dimension, the two-step reversal behavior is observed, indicating the decoupling of soft Fe layer and neighboring hard MnBi layer.

1. Introduction

The low temperature phase (LTP) of MnBi is a ferromagnetic intermetallic compound which crystallizes in the NiAs-type hexagonal crystal structure [1–3]. LTP MnBi has attracted much attention due to the unusual magnetic properties, for example, a magnetocrystalline anisotropy (H_A) of 9.0 T and a coercivity (H_C) of 1.8 T have been achieved for melt-spun ribbons at 550 K [4], which is much larger than Nd–Fe–B magnet under the same conditions. Hence, LTP MnBi has an exciting prospect as a non-rare-earth permanent magnet material for high temperature applications [5]. So far, the reported maximum energy product $(BH)_{max}$ of MnBi magnet is 7.7 MGOe at room temperature, quite far from the theoretical value of 16 MGOe [6–8]. It is noticed that the relatively low saturation magnetization (M_S) of MnBi restricts the promotion of $(BH)_{max}$ [9,10].

It is well known that a high $(BH)_{max}$ can be obtained by combining high M_S of a soft magnetic phase and high H_A of a hard magnetic phase in the nanocomposite structure [11–13]. In this work, the structural and magnetic properties of anisotropic MnBi and MnBi/Fe films are investigated. Single MnBi film shows a perpendicular anisotropy at room temperature. In addition, its H_C increases with increasing temperature. At 300 K and 400 K, out-of-plane H_C reaches to 15 kOe and 21 kOe, respectively. Because of the effective exchange coupling between soft Fe layer and hard MnBi layer, both remanent magnetization (M_R) and $(BH)_{max}$ are improved in nanocomposite MnBi/Fe films.

2. Experiment

Samples with nominal thickness of MnBi (50 nm)/Fe (0–10 nm) were prepared by dc magnetron sputtering. A 10-nm-thick Ta layer was used as cover layer to prevent the oxidation. The growth of the films was carried out in a high-vacuum chamber equipped with multisputtering guns. At first, Bi and Mn layers were sequentially deposited on clean glass substrates at room temperature, which is followed by *in situ* vacuum annealing at 673 K for 1 h for alloying. After annealing, the samples were slowly cooled to room temperature, then Fe layer and Ta cover layer were deposited. The base pressure of the chamber was better than 3×10^{-7} Torr. During sputtering, only Ar gas was introduced into the chamber and the pressure was kept at 4×10^{-3} Torr. Commercial Bi, Mn, Fe, Ta targets with 99.99% purity were used. The structures of samples were characterized by an X-ray diffraction (XRD) analysis with Cu $K\alpha$ radiation and an X-ray photoelectron spectroscopy (XPS) with Al $K\alpha$ radiation. The composition analysis of the samples was done by energy dispersive X-ray spectroscopy (EDS). Magnetic measurements were measured on a superconducting quantum interference device (SQUID).

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http://dx.doi.org/10.1016/j.jmmm.2014.07.027
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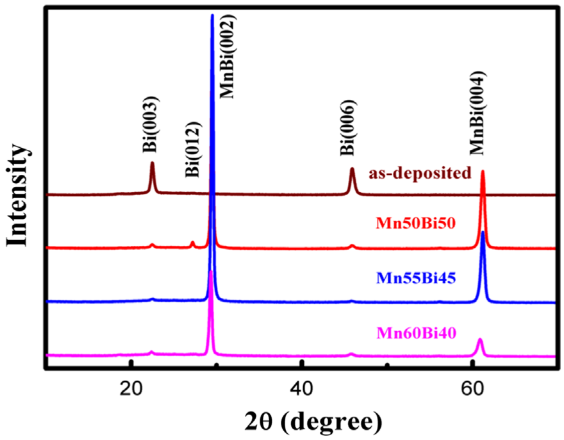

Fig. 1. XRD patterns of the as-deposited film and the annealed films with Mn/Bi atomic ratio of 50/50, 55/45 and 60/40.

3. Results and discussion

Fig. 1 shows the XRD patterns of the as-deposited film and the annealed films with Mn/Bi atomic ratio of 50/50, 55/45 and 60/40. The nominal thicknesses of Mn and Bi layers are 37 nm/13 nm, 35 nm/15 nm and 33 nm/17 nm, respectively. For the as-deposited film, both Bi (0 0 3) and (0 0 6) peaks are clearly observed, but no Mn peak is found. This indicates that the Bi layer is crystallized with *c*-axis textured, while the Mn layer is amorphous. After annealing, strong MnBi (0 0 2) and (0 0 4) peaks appear, implying the formation of LTP MnBi phase with highly *c*-axis textured perpendicular to the film plane. It is also found that small Bi (0 0 3) peak remains, indicating that a few Bi atoms did not participate in alloying process. The sample with Mn/Bi atomic ratio of 55/45 exhibits the strongest intensity of MnBi (0 0 2) and (0 0 4) peaks. Thus, the annealed film with Mn/Bi atomic ratio of 55/45 was measured magnetically and exchanged coupled with soft Fe layer.

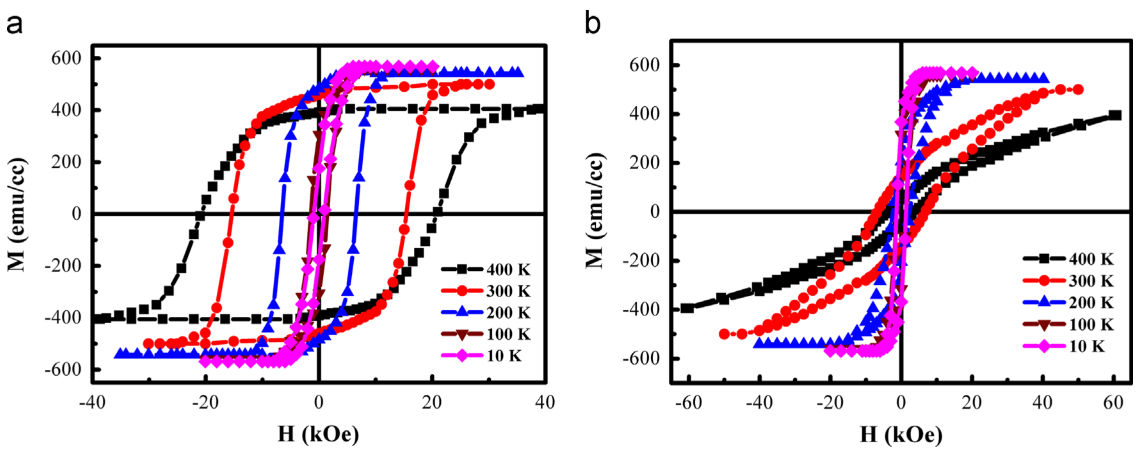

Fig. 2. (a) Out-of-plane and (b) in-plane hysteresis loops for MnBi film from 10 K to 400 K.

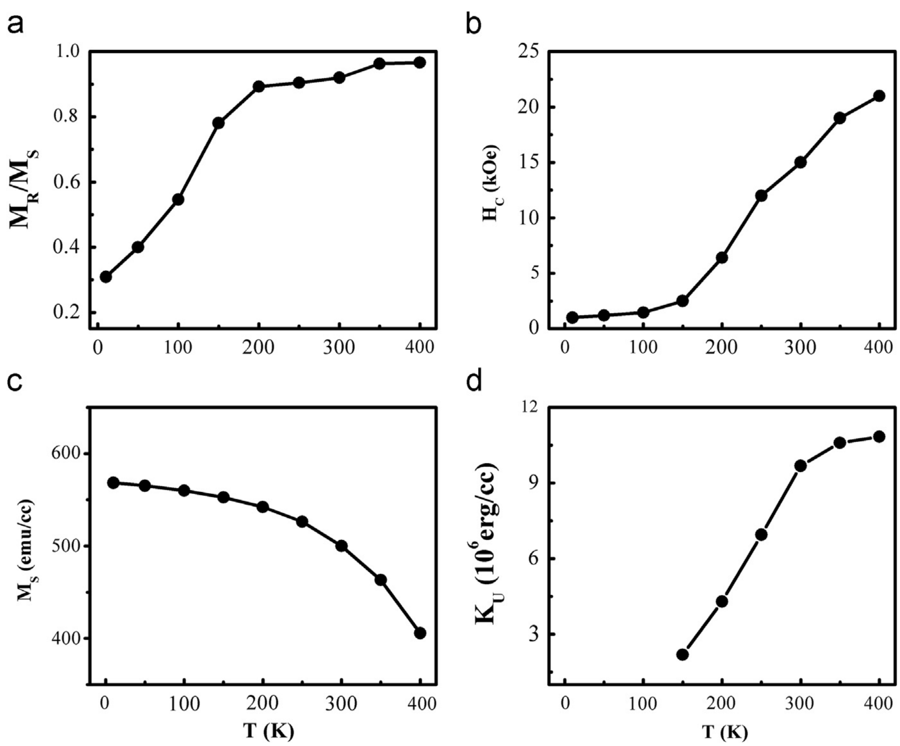

Fig. 3. Temperature dependences of (a) M_R/M_S, (b) H_C, (c) M_S, (d) K_U for MnBi film in out-of-plane direction.