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Influence of various substrate materials on the structure and magnetic properties of Fe–N thin films deposited by DC magnetron sputtering

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Abstract

The Fe–N films were synthesized on glass, single crystal Si (100), and NaCl (100) substrate, respectively, by DC magnetron sputtering, and the substrate temperature was optimized to obtain the single-phase γ′-Fe_4N magnetic film. The structure and morphology of the samples were characterized using X-ray diffraction (XRD) and atomic force microscopy (AFM). The magnetic properties of the thin films prepared on different substrates were investigated by superconducting quantum interference device (SQUID). The results showed that substrate materials had a significant influence on the magnetic properties of single-phase γ′-Fe_4N. The saturation magnetization of films on three different substrate materials had almost the same value, but the coercive force of the films was higher on single-crystal substrates than that of on the amorphous glass substrate. It was also found that the deposition temperature for obtaining single-phase γ′-Fe_4N films on NaCl (100) substrate is the lowest. Furthermore, with decreasing of γ′-Fe_4N grain size, the coercive force of thin films also decreased. However, the surface roughness had not resulted in much more differences in coercive force for the single-phase γ′-Fe_4N thin films with the same thickness.

Keywords: γ′-Fe_4N single-phase; Substrate materials; Magnetic properties

1. Introduction

Iron nitride films have received many attentions because of their excellent magnetic properties [1–11] and their ability to improve surface hardness and wear resistance [12] for application in magnetic devices. It is well known that some iron nitrides, such as α-Fe (N), ε-$Fe_{2-3}N$ (hcp), γ′-Fe_4N (fcc), and α″-$Fe_{16}N_2$ (bct) are magnetic phases [13–16]. Among different phases of iron nitrides, the γ′-Fe_4N phase has the face-centered cubic iron lattice with a nitrogen atom positioned at the body-center site. Compared to the phase α″-$Fe_{16}N_2$, the Fe_4N phase has better thermal stability and chemical stability. Hence, Fe_4N has been considered to be a potential candidate for a high-density recording material [17–20]. Using molecular beam epitaxy (MBE) technique, Costa-Kra et al. [21] have obtained γ′-Fe_4N magnetic epitaxy on MgO (001) substrate. Yamaguchi et al. [22] also synthesized single γ′-Fe_4N phase by nitrifying iron thin film in ammonia-hydrogen gas. However, so far, there are few reports that the single-phase γ′-Fe_4N magnetic films are synthesized by magnetron sputtering.

While analyzing Fe–N thin films deposited by magnetron sputtering, the influence of experimental parameters such as nitrogen partial pressure, substrate temperature, and distance between the substrate holder and the target on the structures and properties of Fe–N films has been studied in detail by our previous work [23–25]. The substrate material is known as a very important parameter for determining the film structure and properties. The proper choice of substrate materials can stabilize not only certain crystal structures, but also improve adhesion and properties of the deposited coatings. However, to our best knowledge, the influence of substrate material on the magnetic properties of single phase γ′-Fe_4N thin film is rarely reported, although there have been lots of efforts to find the influence of the grain size, internal and external stresses, surface roughness, induced anisotropy, and composition on the coercive force of the films. In this work, the influence of substrate material on the structure and magnetic properties of Fe–N thin films is explored.

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2. Experimental

Iron nitride films were deposited on glass, single-crystal Si (100), and NaCl (100) substrate at different substrate temperatures in a mixed Ar/N_2 discharge using DC magnetron sputtering. The distance between the substrate holder and the high purity (99.99%) α-iron (60 mm in diameter) target is 6.5 cm. The base pressure was 8×10^{-5} Pa. Prior to deposition, the substrates were cleaned ultrasonically in acetone and alcohol consecutively. During sputtering, the DC power was kept constant at 110 W, The pure argon (99.999) and nitrogen (99.999) gases were inlet into the chamber, controlled by two independent mass-flow controllers. The nitrogen fractions in whole gas flow were 10%, and the total pressure was fixed at 2.0 Pa. The sputtering time was controlled at 40 min, and the deposition rate is about 0.1 nm/s. The deposition temperature for the films on glass and single-crystal Si (100) substrate is fixed at room temperature, 150, 250, and 350 °C, respectively, whereas that for the films on single-crystal NaCl (100) substrate is at room temperature, 100, 150, and 250 °C, respectively.

The structures of the films were analyzed by X-ray diffraction (XRD) with Cu Kα radiation using a current of 150 mA and voltage of 40 kV (Rigaku, D/MAX-rA). The surface morphology of the films was characterized by atomic force microscopy (AFM) (Park Scientific Instruments Autoprobe CP with multitask system configurations). Magnetic properties of the films were measured by SQUIDS magnetometer (MPMS-5S, Quantum Design, San Diego, CA, USA), and the mass of the samples was obtained using electronic balance (AG249) for evaluating the saturation magnetization.

3. Results and discussion

3.1. Film structure

Fig. 1(a) shows the XRD patterns for Fe–N films deposited on glass substrate at different temperatures (room temperature, 150, 250, and 350 °C, respectively). When substrate temperature is lower than 150 °C, only one peak at $2\theta=42.7°$ can be found, which is due to the mixture phases of ε-Fe_3N and ζ-Fe_2N. As this peak is low and wide, we believe that the film is composed of random small crystal grains because of the low ability for surface atoms to diffuse at low substrate temperature. With increasing substrate temperature to 250 °C, the strong XRD peak at 41.2° from γ′-Fe_4N (111) and other two small peaks from γ′-Fe_4N (200) and γ′-Fe_4N (311) appear. When substrate temperature is 350 °C, the peak of ε-Fe_3N (111) appears besides four peaks of the γ′-Fe_4N. This means a mixture of both phases appears at this temperature.

Fig. 1(b) shows the XRD patterns for Fe–N films deposited on single-crystal Si (100) substrate at different temperatures (room temperature, 150, 250, and 350 °C, respectively). The peaks at $2\theta=33.01°$ and $2\theta=69.24°$ result from Si substrate. When the deposition temperature is RT and 150 °C, no obvious peaks are found because the film is very thin. With increasing substrate temperature to 250 °C, the strong XRD peak at about 41.65° from γ′-Fe_4N (111) and the other small peaks at 47.9° from γ′-Fe_4N (200) appear. When substrate temperature is 350 °C, the peak of α-Fe (110) appears besides the peaks of the γ′-Fe_4N.

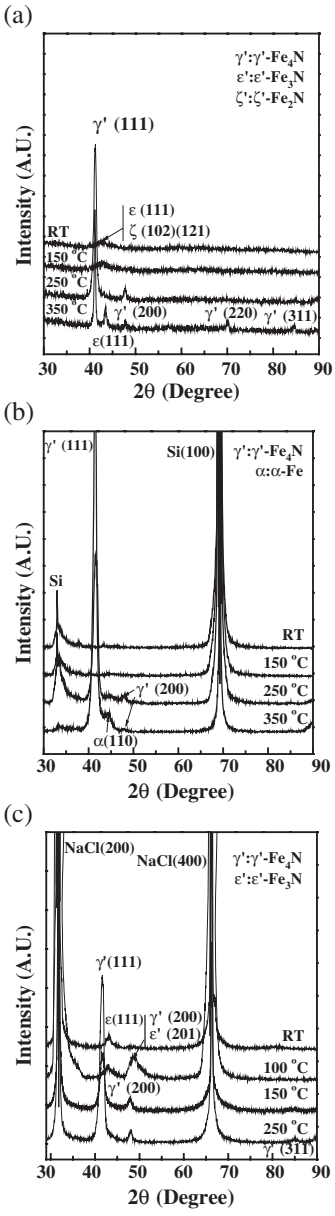

Fig. 1. XRD patterns for Fe–N films deposited at different temperatures on the various substrates of (a) glass, (b) single-crystal Si(100), and (c) single-crystal NaCl(100) substrate, respectively.

Fig. 1(c) shows the XRD patterns of Fe–N films deposited on single-crystal NaCl (100) substrate at different temperatures (room temperature, 100, 150, and 250 °C, respectively). The peaks at $2\theta=31.76°$ and $2\theta=66.37°$ result from NaCl (100) substrate. When substrate temperature is at room temperature, only one peak at $2\theta=43.1°$ can be seen, which is due to ε-Fe_3N (111). With increasing substrate temperature up to 100 °C, only three peaks from ε-Fe_3N (111), ε-Fe_3N (201), and γ′-Fe_4N (200) appear, which means that a mixture of phases containing both ε-Fe_3N and γ′-Fe_4N is obtained in the film. However, as substrate temperature increases up to