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Study of the effect of the deposition rate and seed layers on structure and magnetic properties of magnetron sputtered FeNi films

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ABSTRACT

FeNi thin films were prepared by magnetron sputtering. A magnetic field of 250 Oe was applied during sample preparation parallel to the substrate surface in order to induce a uniaxial magnetic anisotropy. The film crystallinity and magnetic properties were studied as a function of the deposition rate and material of seed layer (Cu, Cr, Ta, Ti). Detailed analysis of the X-ray diffraction patterns shows no correlation between rate of deposition and grain size, which was deduced using Scherrer's formula. The Ta and Ti seed layers improve the structural features of FeNi films resulting in larger grain size and the development of a strong texture, both of which are favourable for particular sensor applications. Large grain size increases the angular dispersion of magnetic anisotropy.

1. Introduction

FeNi films are very important soft magnetic materials, that are widely used in magnetic recording media and magnetic sensing devices [1]. It is known that the magnetic properties of the FeNi films are largely determined by the peculiarities of their structure [2]. In turn, the conditions of thin film preparation have a great influence on the formation of the film structure [3]. This problem has been studied for many years specifically in the case of thin films prepared by various deposition processes [4]. Furthermore, the structure of sputtered thin films depends significantly on the material of the seed layers on which a film is deposited [5–8] (Fig. 1a).

Different seed layers, such as Cu, Cr, TiN, Ag, FeNiCr, Ta, Si, MgO, Ru and Ti have been previously used to improve the magnetic and magnetoresistive properties of FeNi films [9–21]. However, these results are often difficult to compare to each other, as the films in different studies were obtained under different conditions. During the last decades, magnetron sputtering has become one of the leading techniques in the microelectronics industry. The continuous progress in the development of sputtering equipment extends the capabilities of this technique [22]. It is especially important for deposition of magnetically soft thin films with controlled features of induced magnetic anisotropy. In the present work, we study the influences of both the FeNi deposition rate and Cr, Cu, Ta and Ti seed layers on the structure and magnetic properties of FeNi films prepared by dc magnetron sputtering in the same conditions. The materials chosen to play the role of seed layers are traditionally used in microelectronic devices, including magnetic sensors.

2. Experimental details

The samples were deposited by magnetron sputtering onto glass substrates at room temperature. Background pressure was 3×10^{-7} mbar and the argon pressure during deposition was 3.8×10^{-3} mbar. Permalloy layers were deposited using a $Fe_{19}Ni_{81}$ target. The deposition rate for permalloy layers was changed by varying the of target–substrate distance at a constant magnetron power of 100 W. The deposition rates and the thicknesses of the multilayers were determined via calibration of the system using

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0042-207X/

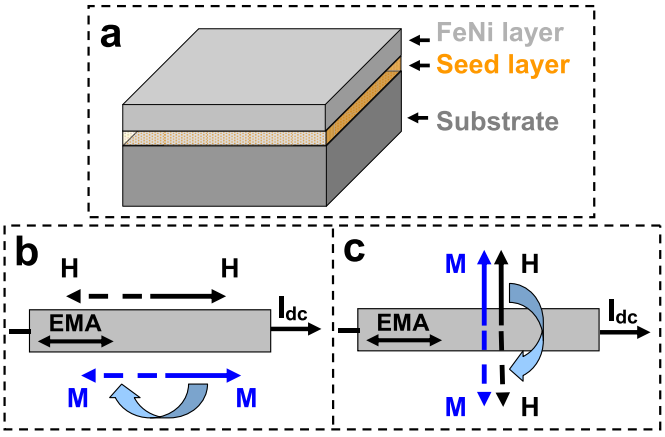

Fig. 1. General scheme of the sample (a). Geometries of the measurements of MR hysteresis loops: when magnetic field was applied parallel (b) or perpendicular (c) to the easy magnetization axis (EMA) and current (I_{dc}) direction. M is the magnetization, H is the external magnetic field applied during measurements of MR.

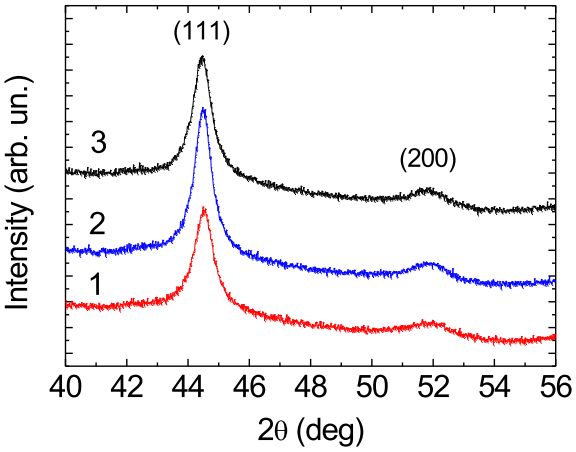

Fig. 2. X-ray diffraction spectra for the FeNi films prepared with different deposition rates: (1) – 10 nm/min, (2) – 18 nm/min, (3) – 28 nm/min.

sharp step samples with a thickness of about 100 nm deposited onto Si wafer and atomic force microscopy. The deposition rates were 25, 12, 7 and 4 nm/min for Cu, Ta, Cr and Ti layers, respectively. The thicknesses of the magnetic FeNi and seed layers were 100 nm and 10 nm, respectively. A magnetic field of 250 Oe was applied during sample preparation parallel to the substrate surface in order to induce a uniaxial magnetic anisotropy in all FeNi films. The microstructure was studied by X-ray diffraction (XRD) using a PHILIPS X'PERT PRO automatic diffractometer with CuK_α radiation. The information from broadened XRD lines was used to estimate the average size of coherent diffraction domains by using the standard Scherrer approach.

The in-plane magnetic hysteresis loops were recorded by means of the magnetooptical Kerr effect (MOKE). Angular dispersion of magnetic anisotropy was estimated using the hysteresis method [23]. These measurements were carried out on samples with dimensions of 1 cm × 1 cm. The dispersion angle α_{90} is defined as the angle for which 90% of the local easy magnetization axes lie with $\pm\alpha$ of the average easy axis direction. The anisotropic magnetoresistance (AMR) was measured following the conventional four-point probe technique in approximately 1.5 mm × 10 mm strips with the easy magnetization axis (EMA) and the current direction along the long side (Fig. 1b–c). The AMR ratio was defined as follow: $\Delta R/R = 100 \times [(R_{\parallel} - R_{\perp})/R_{\parallel}]$, where $R_{\parallel}$ and $R_{\perp}$ are the electrical resistance of the sample magnetized parallel or perpendicular to the current direction, respectively.

3. Results and discussion

Fig. 2 shows XRD spectra for the FeNi films prepared with different deposition rates: 10, 18 and 28 nm/min. The X-ray diffractograms for the FeNi films deposited directly onto glass substrates exhibited a bright (111) peak and a small and wide (200) diffraction peak, that correspond to a face-centered cubic structure. The XRD patterns are similar for all samples and show that in all samples the crystallites are oriented preferentially along the (111) plane, as follows from the ratio of the integral intensity of the (111) to that of the (200) diffraction peaks (Table 1). The average grain sizes for all films were calculated from the broadening of the (111) X-ray peaks using the Scherrer formula: $L = K\lambda/\beta\cos(\theta)$, where L is the crystallite size, K is the Scherrer constant (0.9 in our case), λ is the wavelength of the X-ray, β is the full width at half maximum intensity of the peak and θ is the Bragg angle. The crystallite size was found to be equal for all of the studied samples (~10 nm). The similarity of the crystalline state of the samples is indirectly confirmed by the similarity of their magnetoresistance responses (Table 1). It is known, that magnetoresistance is very sensitive to the structural characteristics of the samples [15]. Thus, no correlation between crystallite size and rate of deposition was noted.Fig. 3 shows the magnetization curves of the samples measured parallel and perpendicular to the easy magnetization axis created during deposition in a magnetic field. The shape of the $M(H)$ loops indicates clear uniaxial induced magnetic anisotropy in the film plane. The presence of the magnetic anisotropy is also confirmed by the magnetoresistive curves (MR) (Fig. 4a). The coercive force varies weakly and does not exhibit dependence on the deposition rate. The anisotropy field value does not change with the deposition rate, but angular dispersion of magnetic anisotropy varies noticeably and non-monotonically (Table 1). Such behaviour of the EMA dispersion is probably caused by the change of thin film deposition conditions.

For FeNi films, effective magnetic anisotropy is the mixture of the M-induced uniaxial anisotropy and a randomly oriented anisotropy which is either crystallographic or strain-induced [24]. The source of M-induced uniaxial anisotropy is the magnetostatic energy of crystallite boundaries. Because of the defects in the grain boundaries (vacancies, impurity atoms, disordered structures) the magnetization saturation of the boundary is lower than the one of the crystallite. The presence of a layer of "magnetic charges" in the interface increases the interface energy. However, if the mobility of defects during film deposition is sufficiently high, they are redistributed inside the boundary so as to reduce its energy [25]. In practice, the occurrence of anisotropy is caused by several sources with very different kinetic characteristics. For example, both the grain boundaries and the boundaries of the clusters can contribute to the anisotropy. Different defects contribute in different measure to the anisotropy. In addition, voids and nonmagnetic inclusions could be a source of angular dispersion of anisotropy. When the magnetization veers around these imperfections the angular dispersion increases [23].

It is worth mentioning that in our work under Ar pressure of 3.8×10^{-3} mbar the mean free path was 3 cm [26] and it was always smaller than the target–substrate distance, which varied from 14 to 8.5 cm. The increase of the target–substrate distance leads to the increase of the number of collisions between the ejected particles and the Ar gas, which in turn results in a lower average energy and a broader angular distribution of the trace directions for the particles arriving to the substrate [26]. The reduced