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Improving the quality of AMR of permalloy films by N^{2+} ion irradiation

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ABSTRACT

To systematically investigate the influence on physical properties of magnetic materials irradiated by energetic ion, permalloy films were irradiated by 80 keV N^{2+} ions to a range of fluences. A post-processing approach by ion irradiation was found to improve the quality of AMR of permalloy films in the case of no significant influence on the crystal structure, the static and dynamic magnetic properties. Ion irradiation decreases Hc, $\Delta H0$ and $R0$, and increases ΔR at the highest fluence. We infer that the main factor affecting the physical properties of the films irradiated by N^{2+} ions is ion-beam-induced annealing effect.

1. Introduction

Ion irradiation is a unique and effectual tool to modify the physical properties of materials [1]. Great efforts have been made on the effects of ion radiation of ferromagnetic nanostructures during the last two decades [2–6]. In general, ion irradiation modifies the structure [7,8], chemical ordering of alloys [9–12], interface of multilayers [13,14], and consequently affects their physical properties. Moreover, it has been shown that ion irradiation can modify a material locally by causing chemical reactions [15]. Therefore, it is crucial to understand the mechanism of ion irradiation for adjusting or optimizing magnetic properties of materials. But critical factors involving radiation-induced defects (interstitials and vacancies) and heat are difficult to observe experimentally [16]. It is known that the physical properties of magnetic materials are sensitive to the microscopic intrinsic parameters of the material. So we hope to find out the potential irradiation mechanism by investigating changes in physical properties of ferromagnetic materials after ion irradiation.

Permalloy as a typical soft magnetic Fe–Ni alloy has high magnetic permeability, small magnetostriction, and significant anisotropic magnetoresistance (AMR). With technological importance in magneto-electronic devices such as magnetic shielding, transformer, magnetic recording heads and flux concentrators, permalloy films are often used to investigate the effects of ion irradiation or implantation [17–19]. In this paper, experiments of permalloy films with a thickness of 80 nm irradiated by 80 keV N^{2+} ions were designed to investigate the effects of ion irradiation. Influences on the structure, the static and dynamic magnetic properties and the electrical transportation properties were systematically investigated. An effective way to improve the quality of AMR of permalloy films was introduced by utilizing ion irradiation.

2. Experimental

Permalloy ($Fe_{19}Ni_{81}$) films with a thickness of 80 nm were prepared by dc magnetron sputtering onto glass substrates with a background pressure of less than 5×10^{-5} Pa. One type of sample is square (5 mm × 5 mm), while the others are micro-strips (2 mm × 20 μm) patterned by using the laser exposure and lift-off method. The square samples were used to measure the static magnetic and structural properties. The micro-strip samples were used to measure the dynamics and magnetoresistance properties by using the spin rectification effect (SRE) [20], which is a nonlinear coupling between conducting electrons with local spins that results in a dc electrical detection of the ferromagnetic resonance (FMR) and perpendicular standing spin waves (PSSW) [21,22].

The square and micro-strip samples were irradiated by 80 keV N^{2+} ions to fluences in a range from 1×10^{13} to 1×10^{17} ions/cm^2. The ion irradiation was performed at room temperature and normal incidence with a beamflux of 5.3 μA, respectively. According to SRIM software simulations [23], the mean projected range of the 80 keV N^{2+} was $R_p = 158.7$ nm with a straggling of 68.1 nm. The experimental work was carried out at 320 kV platform for multi-discipline research with highly charged ions at the Institute of Modern Physics, Chinese Academy of Sciences.

The structural characterization of all the samples was performed by grazing incidence X-ray diffraction (GIXRD, X'Pert pro Panalytical with Cu K_α radiation). The X-ray patterns were recorded by step scanning with a step of 0.01° at 6 s per step. Static magnetic properties were

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studied using a vibrating sample magnetometer (VSM, microsense EV7 system). To study the dynamic properties, the stripe was inserted into a ground-signal-ground coplanar waveguide (CPW) deposited on the glass substrate. By feeding the CPW with 20 dBm microwaves using a microwave power generator (E8257D Agilent), a radio frequency (*rf*) magnetic field acting perpendicularly to the device plane pushes the magnetization of the strip into precession. When applying an in-plane magnetic field, dc voltage can be detected when FMR and PSSW occur.

3. Results and discussion

Fig. 1(a) shows the depth profile of projected ions and the predicted damage distribution created by 80 keV N^{2+} ions to a fluence of 1×10^{17} ions/cm^2. These results were obtained from Monte Carlo simulations using the SRIM-2008.04 full-cascade mode [23], in which the calculations were carried out under the assumptions of a sample density of 8.699 g/cm^3 and threshold displacement energies of 40 eV for Ni and Fe. The results of Fig. 1(a) indicate that the maximum concentration of N (N/Fe & Ni atomic ratio) and the ion-beam-induced damage is approximately 0.71% and 32.5 dpa at the highest fluence. Fig. 1(b) shows the average N concentration and average damage as a function of ion fluence. It can be found that the average N concentration introduced by ion irradiation is quite low among the full range of irradiation fluences, where it is only approximately 0.56% at the highest ion irradiation fluence (1×10^{17} ions/cm^2). The N concentration is very low, and therefore the effects of impurity atoms on the structural analysis are negligible after the irradiation of 80 keV N^{2+} ions with 1×10^{17} ions/cm^2. In addition, the average damage dose in the film is about 27 displacements per atoms (dpa) at the highest ion irradiation fluence. It indicates that irradiation can produce large amounts of displacement of lattice atoms at the highest fluence. In addition, the thickness of sputtering loss induced by irradiation is approximately 5.4 nm at the highest fluence by using SRIM. Fig. 1(a) shows SRIM predicted energy loss values. E_{ele} and E_{nucl} are the electronic and nuclear energy loss over the 80 nm film thickness for $Fe_{19}Ni_{81}$ thin films, respectively. The average values of E_{ele} and E_{nucl} are 694 and 172 eV/nm respectively. It can be found that the electronic energy loss is much greater than the nuclear energy loss. Because most of the energy transferred to electrons is dissipated in the form of heat, electronic excitation effects can significantly influence the damage recovery. Therefore, it is inferred that an annealing effect induced by ion irradiation improve the uniformity of the material.

Fig. 2(a) shows the GIXRD patterns of the $Fe_{19}Ni_8$ thin films after irradiated by 80 keV N^{2+} ions to a fluence of 1×10^{17} ions/cm^2. It shows that all the samples are well-crystallized with face-centred cubic structure. Additionally, the mean grain size of all the samples calculated by Scherrer's formula is about 9 nm, and neither NiN nor FeN phases were observed in the XRD data. The lattice parameter (Fig. 2(b)) of as-deposited thin film is 3.522 Å, which is close to that of bulk permalloy [24]. The lattice parameters of the irradiated samples are in the range of 3.522–3.537 Å with only a small expansion compared to the as-deposited film, and show little variation with increasing irradiation fluence.

The in-plane magnetic hysteresis loops ($M-H$) are shown in Fig. 2(c). It is found that the coercivity (H_c) decreases after high fluence irradiation. The coercivity of the as-deposited samples is 8.5 Oe and is reduced to 5.9 Oe at a radiation fluence of 1×10^{16} ions/cm^2. The decrease in H_c after high fluence irradiation may result from the increase of unifromity or the release of internal strain of the films. This result suggests that the quality of permalloy films is optimized. The saturation magnetization (M_s) are revealed in Fig. 2(d). Taking into account the volume measurement error, the saturation magnetization (M_s) almost remains unchanged with increasing irradiation fluence. The M_s of the as-deposited samples is 688.9 emu/cc. The results reveal that ion irradiation does not affect the static magnetism in the range of radiation fluence, which agrees well with to XRD results.

To further investigate the underlying influence of irradiation on permalloy's magnetic properties, the SRE method [25,26] was used to study the dynamics of the samples. Fig. 3(a) shows a typical spectrum of an as-deposited sample at 9 GHz microwave frequency, wherein the dc voltage was measured as a function of an applied magnetic field. Two peaks can be observed: one is FMR at $H = 1.111$ kOe, and the other is PSSW at $H = 0.604$ kOe. Based on the lineshape fitting of the SRE [21,25,26], we can separate the two peaks and obtain the position and line width of each peak. We focus on FMR. Fig. 3(b) shows the linewidth (ΔH) of the FMR as a function of the microwave frequency. The FMR linewidth increases with the microwave frequency and roughly follows a linear relationship, $\Delta H = \Delta H_0 + \frac{\alpha\omega}{\gamma}$, [25] where α is the intrinsic Gilbert damping, ω is the angular frequency, $\gamma = 17.7$ GHz/kOe is the gyromagnetic ratio, and ΔH_0 is the non-intrinsic linewidth, which

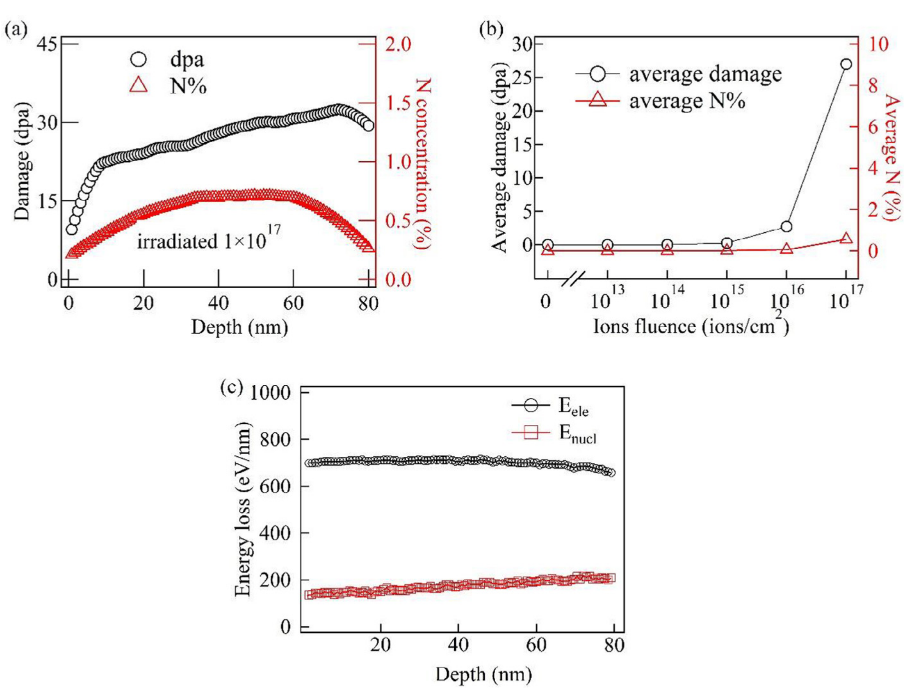

Fig. 1. (a) Damage profile in displacement per atom (left axis) and N profile predicted by SRIM (right axis) with 80 keV N^{2+} irradiation at a fluence 1×10^{17} ions/cm^2. (b) The average N concentration and the average damage in displacement per atom in films as a function of ion fluence, which were predicted by using SRIM simulations. (c) SRIM predicted energy loss values. E_{ele} and E_{nucl} are the electronic and nuclear energy loss over the 80 nm film thickness for $Fe_{19}Ni_{81}$ thin films, respectively.