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Magnetization in permalloy thin films

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Abstract. Thin films of permalloy ($Ni_{80}Fe_{20}$) were prepared using an Ar+N_2 mixture with magnetron sputtering technique at ambient temperature. The film prepared with only Ar gas shows reflections corresponding to the permalloy phase in X-ray diffraction (XRD) pattern. The addition of nitrogen during sputtering results in broadening of the peaks in XRD pattern, which finally leads to an amorphous phase. The M–H loop for the sample prepared with only Ar gas is matching well with the values obtained for the permalloy. For the samples prepared with increased nitrogen partial pressure the magnetic moment decreased rapidly and the values of coercivity increased. The polarized neutron reflectivity measurements (PNR) were performed in the sample prepared with only Ar gas and with nitrogen partial pressure of 5 and 10%. It was found that the spin-up and spin-down reflectivities show exactly similar reflectivity for the sample prepared with Ar gas alone, while PNR measurements on 5 and 10% sample show splitting in the spin-up and spin-down reflectivity.

Keywords. Permalloy; NiFe thin films; NiFe nitrides; polarized neutron reflectometry.

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1. Introduction

Recent years have seen a rapidly growing interest in the field of mass storage technology, sensor development and magnetoelectronics [1–4]. Physical phenomena such as magnetic anisotropy or giant magnetoresistance (GMR), which allow the control of electronic spin currents through magnetically doped nanometer structures by an external magnetic field are also of great technological interest [5,6]. Among the materials playing a role in these nanostructures, permalloys (high-permeability alloys of Ni and Fe) take an important place. NiFe alloy with a composition of $Ni_{80}Fe_{20}$ is a well-known soft magnetic alloy and is known as a permalloy. It forms a face-centred-cubic structure of the type Ni_3Fe. Reactive sputtering is one of the convenient techniques for the incorporation of nitrogen into growing film in order to modify its structural, magnetic and electric properties [7]. Recently, NiFe nitrides were deposited using an rf sputtering technique for a nitrogen flow in the range of 5–30% [8]. A decrease in saturation magnetization is reported as the nitrogen flow during sputtering is increased. However a detailed investigation on how magnetization is decreased with an increase in nitrogen content has not been performed. With reactive nitrogen sputtering NiFe is known to undergo structural and magnetic changes. As nitrogen partial pressure is increased, NiFe forms a disordered structure. Recently we measured various physical and magnetic properties of NiFeN thin films [9] and in this study our aim is to understand the magnetism in NiFe alloy thin films prepared with different amount of nitrogen during sputtering using the polarized neutron reflectivity technique.

2. Experimental

The NiFe thin films were prepared by sputtering an $Ni_{80}Fe_{20}$ target using $Ar+N_2$ gas by DC magnetron sputtering operating at 50 W. The substrates were mounted below the targets and oscillated with respect to the central position of the target for better uniformity of the deposited samples. All the samples were deposited at room temperature (∼298 K, without intentional heating) on Si(1 0 0) substrates. A base pressure of 1×10^{-6} mbar was achieved prior to the deposition. Three different samples with partial pressure of N_2 = 0, 5 and 10% (defined as nitrogen pressure/total pressure) were studied in this work. The typical thickness of the layers was about 100 nm. The structure of the samples was studied using grazing incidence X-ray diffraction (XRD) and the magnetic structure was studied using DC-extraction magnetometer in a physical property measurement system (PPMS). The polarized neutron reflectivity measurements were performed at a time-of-flight reflectometer AMOR at SINQ/PSI, Switzerland. The angle of incidence during the measurements was 0.5° and the polarization of the incoming neutron beam was changed to measure spin-up or spin-down reflectivities. A magnetic field of about 400 G was applied in the direction parallel to the surface of the sample.

3. Results and discussion

Figure 1 shows the XRD pattern of the samples prepared using different nitrogen partial pressures during sputtering. The film prepared with Ar gas (0% N_2) shows reflections corresponding to permalloy. As the nitrogen partial pressure is increased, the broadening of reflection and shift toward lower angle is observed. The linewidth of the diffracted pattern can be used to calculate the grain size of the diffracting specimen using the Scherrer formula [10] $t = 0.9\lambda/b\cos\theta$, where t is the grain size, b is an angular width in terms of 2θ and θ is the Bragg angle, and λ is the wavelength of the radiation used. For the film prepared with Ar gas alone, the average grain size was 7±1 nm, while in the presence of 5% and 10% nitrogen partial pressure during sputtering it decreases to 3.5±1 nm, about half of the value found without any nitrogen. This suggests that even a small amount of nitrogen during sputtering affects the long-range order of the permalloy.

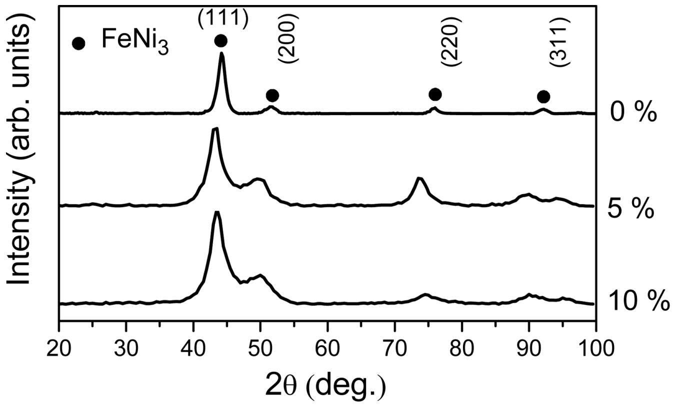

Figure 1. X-ray diffraction pattern of NiFe samples prepared with different amounts of reactive nitrogen during sputtering.

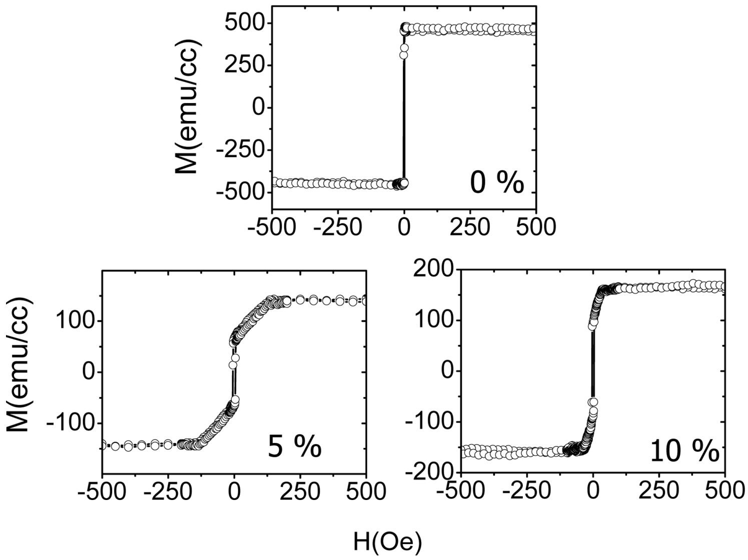

Figure 2. Magnetization measurements of NiFe samples prepared with different amounts of reactive nitrogen during sputtering.

The magnetization measurements were carried out in NiFe films as a function of nitrogen partial pressure during sputtering and are shown in figure 2. The M–H loop for the sample prepared with Ar gas alone is matching well with the values obtained for permalloy [11]. The magnetic moment calculated from the magnetization data is approximately 0.59 μ_B per formula unit, which is close to the value reported in literature [12]. It may be interesting to note how the shape of the M–H loop changes as the nitrogen content in the film is increased. The magnetic moment decreases and a step-like shape is observed due to formation of nitride phases for the samples prepared with 5% and 10% nitrogen during sputtering. As

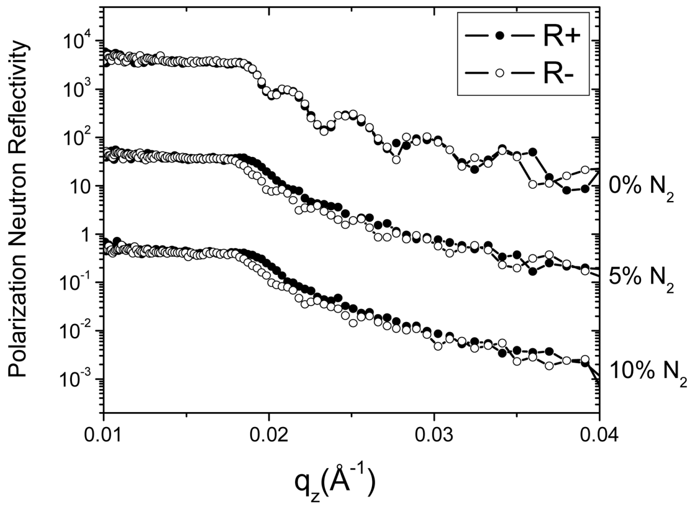

Figure 3. Polarized neutron reflectivity measurements of NiFe samples prepared with different amounts of reactive nitrogen during sputtering. Note that the intensity at the y-axis has been multiplied by a factor of 100 for clarity.

NiFe is sputtered with nitrogen, it incorporates the interstitial positions in fcc NiFe and restricts the magnetic ordering of the permalloy. This causes a reduction in the magnetic moment as observed in figure 2. The step-like shape observed with 5 and 10% nitrogen is due to a mixture of phases formed at this composition and is also evident from the XRD data shown in figure 1.

The PNR measurements of NiFe thin films prepared using different amounts of nitrogen during sputtering are shown in figure 3. The measurements were performed at 0.5° incidence angle at time-of-fight reflectometer AMOR at SINQ/PSI in the presence of 400 G magnetic field at the sample. It is surprising to note that the spin-up and spin-down reflectivities appear together for the sample prepared without any nitrogen, i.e. pure NiFe thin film. However, with the addition of 5 and 10% nitrogen during sputtering the spin-up and spin-down reflectivities are separated. Further, with 5 and 10% nitrogen samples the total thickness oscillations, well resolved in the 0% nitrogen sample, could not be observed. This may be due to increased roughness when sputtered with nitrogen.

As could be seen from the magnetization measurements the sample prepared without any nitrogen is ferromagnetic and shows an M–H loop which is typically found in literature. Also XRD measurements confirmed the structure of permalloy film. Apparently, the magnetization and PNR measurements do not agree in the case of NiFe thin film sample. The reason for this behaviour is not clear. However, in an earlier study we found that the PNR and magnetization measurements give an excellent agreement for Fe and FeN thin films [9]. In the present case also, the samples with 5 and 10% nitrogen give a good agreement between the PNR and magnetization measurements. The situation with pure NiFe thin films remains ambiguous. A way to understand such behaviour could be the differences in the magnetic structure probed by PNR and magnetization measurements. In magnetization measurement macroscopic information about the average magnetic moment is obtained, while the information obtained in PNR is microscopic. In case due to the presence of both ferromagnetic components (Fe and Ni) the net magnetization remains zero due to competition between Fe and Ni to a length scale seen in neutron measurements while in the case of magnetization measurement since the averaging is done over a large volume, the magnetic component is nonzero. However this argument needs to be clarified further with preparation of films under different conditions and PNR measurement under different magnetic fields.

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