Ferromagnetic resonance of NiFe/Cu multilayered nanowires

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Ferromagnetic resonance (FMR) response of $Ni_{80}Fe_{20}$ single layered and [$Ni_{80}Fe_{20}$(50nm)/Cu(10nm)]xn multilayered nanowires was investigated. FMR studies indicated that the easy axis of magnetization of nanowires is preponderant parallel to the nanowires axis. The magnetocrystalline anisotropy is smaller than other factors such as shape anisotropy and dipolar interactions due to the high aspect ratio of nanowires. The effective anisotropy field (H_{eff}), the giromagnetic ratio, γ, and Landé factor, g, were evaluated to be γ = 2.88 MHz/Oe, H_{eff} = 2.76 kOe and g=2.08 for [NiFe/Cu]xn multilayered nanowires, and γ = 2.94 MHz/Oe, H_{eff} = 3.36 kOe and g=2.1 for NiFe single layered nanowires.

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1. Introduction

The research on magnetic nanostructures led to the exploration of novel physics and material properties at reduced physical dimensions. The nanowires arrays (NWs) are extensively study because of their specific physical properties in such high aspect ratio structures, and to estimate their potential use in applications such as patterned recording media, nano-sensors and nano-devices. The magnetic properties at high frequencies of ferromagnetic nanowires arrays are the primary subject of studies by various techniques, and in particular by ferromagnetic resonance.

The aim of this paper is to present our latest results concerning FMR measurements in $Ni_{80}Fe_{20}$ (permalloy) single layered and [$Ni_{80}Fe_{20}$(50nm)/Cu(10nm)]xn multilayered nanowires.

The study focuses on the determination by FMR of the direction of the anisotropy of these systems. The influence of the non-magnetic Cu layers on the axial magnetic anisotropy in the multilayered nanowire was also investigated.

2. Experimental

Arrays of [$Ni_{80}Fe_{20}$(50nm)/Cu(10nm)] x n multilayered and ($Ni_{80}Fe_{20}$) single layered nanowires were prepared by electrodeposited into the nanopores of aluminium anodized (AAO) templates (Synkera®) with nominal pore diameters, D, of 35 nm, length, L, of 50 μm, interwire distance is about d=110nm and are arranged hexagonally. The density of the nanopores is about 10^9 pores/cm^2 and their porosity (or nanowires packing factor, defined as the product of the pore density per unit surface by the pore surface) is P=0.1. Before the electrodeposition process a thin layer of Au and Cr was deposited by e-beam evaporation on one side of the AAO template, serving as working electrode for subsequent electrodeposition. A three electrode cell with a platinum wire as counter electrode and an Ag/AgCl reference electrode was used to carry out the electrodeposition process. We used a single bath with an aqueous solution of $NiSO_4$ 90g/L, $FeSO_4$ 13.5g/L, $CuSO_4$ 2g/L, and H_3BO_3 25g/L. The pH value of the electrolyte was adjusted at 3 by adding few drops of 0.5M H_2SO_4 solution or 1M NaOH solution.

Multilayered structures were electrodeposited by switching between the deposition potentials of the two constituents (respectively -1.4 V and -0.3 V for NiFe and Cu deposition). The applied voltage was controlled with a HEKA PG 340 bipotentiostat /galvanostat. At least n=700 sequences have been electrodeposited consecutively for [$Ni_{80}Fe_{20}$(50nm)/Cu(10nm)]xn multilayered nanowires. Finally, the whole assembly (AAO template - nanowires) was mechanically polished, using colloidal diamond (particles size – 3 μm) and Syton (particles size – 20nm) in such a way to have the nanowires ending at the template surface.

The existence of permalloy and Cu layers was evidenced by X-ray diffraction (BRUKER D8- Advance) measurements as well as SEM (Scanning Electron Microscope) combined with energy dispersive spectroscopy (EDS). The SEM images were taken with a CrossBeam Neon 40 EsB microscope from Carl Zeiss SMT AG, whereas the EDS analysis was performed.

The coercivity and magnetization of the nanowires were measured using a Vibrating Sample Magnetometer (VSM) with the magnetic field applied parallel (||) and perpendicular ($\perp$) to the nanowire axis.

FMR spectra (microwave power absorbed by sample versus external d.c. magnetic field) were obtained using as port sample a microstripline connected to a vector network

analyzer (VNA-Agilent N5230A) after a proper calibration [2]. The range of frequency of microwave signal was from 50MHz to 25GHz The microstripline was designed to work with a characteristic impedance Z_0=50Ω. The sample with a parallelepiped (2mm^2) shape is placed directly and symmetrically on microstripline as shown in Fig. 1. The static magnetic field, $0 \leq H_{DC} \leq 6$kOe, was applied parallel with the nanowires axis, whereas the microwave magnetic field, H_{ac}, was perpendicular on the nanowires axis and in the plane of the membrane.

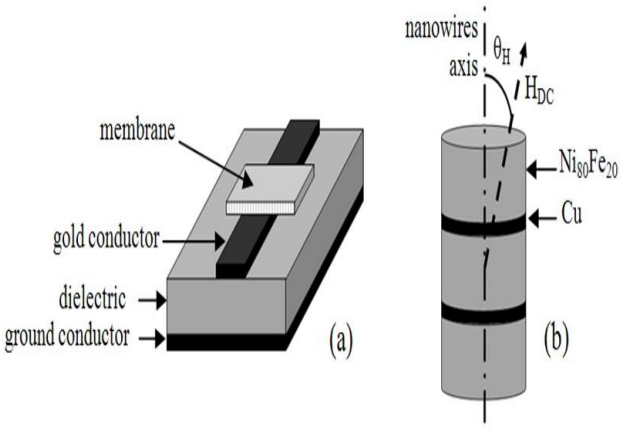

Fig. 1. Schematic of the experimental arrangement with the microstrip line (a) and the geometry of nanowires showing applied magnetic field H_{DC}, nanowires axis and the angle θ_H between them (b).

The angle-dependent FMR measurements (microwave power absorbed by sample versus θ_H - the angle between the orientation of the external bias field with respect to the nanowires axis) were performed using a Bruker ELEXSYS 500 spectrometer working in X-band at the microwave frequency f = 9.3 GHz for a static magnetic field $0 \leq H_{DC} \leq 10$ kOe [3]. The values of θ_H were changed in steps of 10^o between 0^o and 180^o.

All measurements were done at room temperature.

3. Results and discussion

Fig. 2 depicts magnetic hysteresis curves of $Ni_{80}Fe_{20}$ single-layered nanowires, L=50μm. The magnetization curves for both orientations, parallel and perpendicular to the nanowire axis are shown.

From the slope of both hysteresis curves, we can see that the $Ni_{80}Fe_{20}$ single-layered nanowires exhibit a magnetic anisotropy on a direction which is different from parallel and perpendicular directions to the nanowires axis. However, the hysteresis curve on the parallel direction to the nanowire axis indicates that the magnetocrystalline anisotropy is smaller compared with the shape anisotropy.

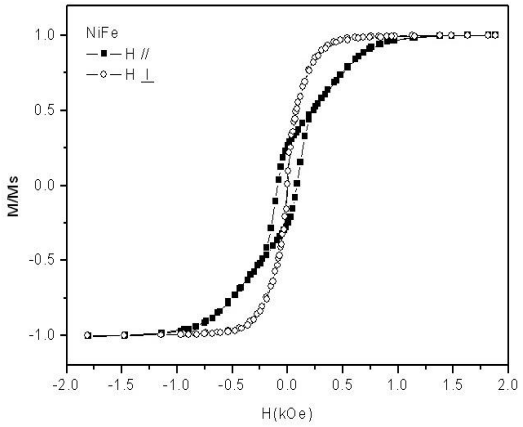

Fig. 2. Magnetic hysteresis curves of $Ni_{80}Fe_{20}$ single layered nanowires.

Fig. 3 depicts magnetic hysteresis curves of $(Ni_{80}Fe_{20}/Cu)xn$ multilayered nanowires, L=50μm. The both magnetization curves parallel and perpendicular to the nanowire axis are shown.

From the hysteresis curves shown in Fig. 3, one can infer that the parallel direction to the $(Ni_{80}Fe_{20}/Cu)xn$ multilayered nanowires axis corresponds to an easy axis.

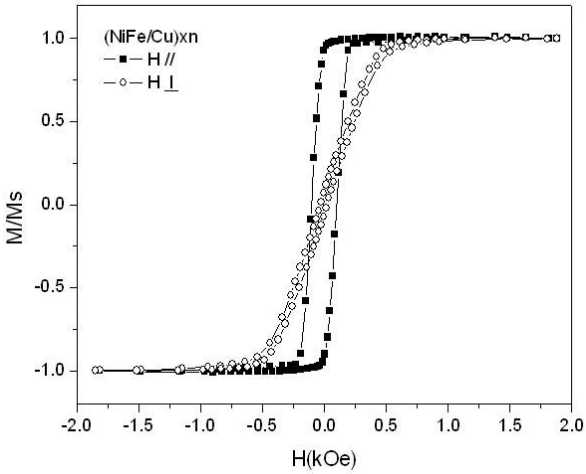

Fig. 3. Magnetic hysteresis curves of $Ni_{80}Fe_{20}$/Cu multilayered nanowires.

The square hysteresis curve on parallel direction with nanowires axis indicates a strong shape anisotropy compared with magnetocrystalline anisotropy on that direction [4, 5].

The magnetization measurements are qualitatively consistent with the more precise FMR results.

Fig. 4 shows the angular dependence of the resonant field for single and multilayered nanowires with length L=50μm. The plots shape indicates systems with uniaxial anisotropy.

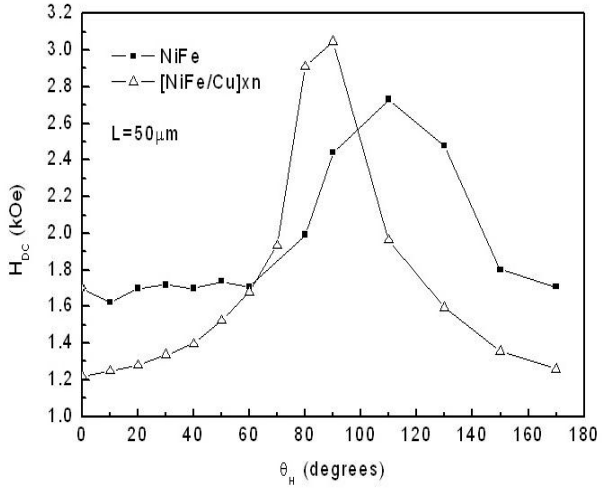

Fig. 4. Angular dependence of the resonant field for single and multilayered nanowires.

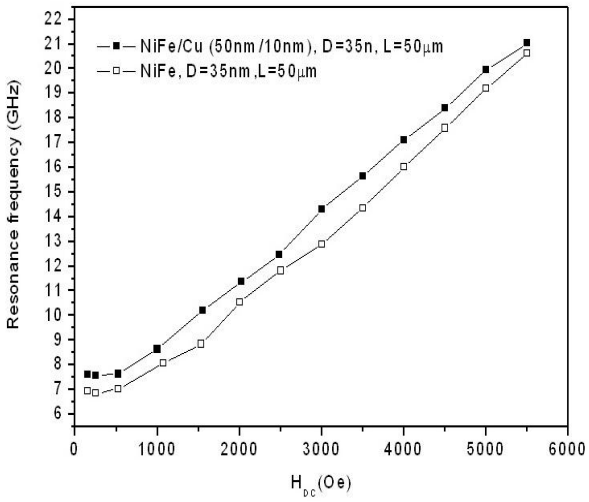

Fig. 5. Resonance frequency (f_R) versus external magnetic field H_{DC} .

Due to high aspect ratio (wire-length/diameter>1) the nanowires can be considered as infinite cylinders . The magnetic anisotropy is strong for both sample as is indicated in Fig.4 by large difference in the resonant field between the direction parallel and perpendicular to the nanowires [11,12]. The amplitude (H^{max}-H^{min}) and the plot shape of the H vs θ_H are directly related to the amplitude and sign of the effective anisotropic field [12], the bell shape of the angular dependence curves indicates a positive effective anisotropic field.

The high aspect ratio of the nanowires with Cu layer thickness t_{Cu}=10nm also implies that the dipole-dipole interaction between adjacent NiFe layers of multilayered NiFe/Cu nanowires arrays tends to align the magnetization of layers along the nanowire axis. The magnetic behavior of the multilayered NiFe/Cu nanowires is almost the same as that corresponding to the single layer NiFe nanowires – which tend to have a strong shape anisotropy ($2\pi M_S > H_K$) due to the elongated shape.

The angular dependence of the resonant field indicates that the easy axis of magnetization of NiFe/Cu multilayered nanowires array is parallel with the nanowires axis confirming the VSM measurements. The small deviation of the direction of the easy axis for NiFe nanowires arrays indicates that the magnetic anisotropy is almost parallel to the longitudinal nanowires axis confirming the VSM measurements.

Fig. 5 shows the dependencies of the resonance frequency (f_R) versus external magnetic field H_{DC} for both nanowires arrays. The plot shape indicates two different regions (i) a linear increase with H_{DC} at high field enough to saturate the samples and (ii) a nearly constant value at low field H_{DC}<1 kOe because the samples was magnetic unsaturated. In both cases, the slope of the linear part (H_{DC}>1 kOe) is about 3MHz/Oe, a typical value for gyromagnetic ratio of *3d*-metals [5, 6]. The corresponding Landé factors (g) are obtained from the slope of the linear parts [7].

The FMR resonant condition of the uniform mode of oscillations of an system with uniaxial anisotropy is given by [2]:

$$\frac{2\pi f_R}{\gamma} = H_{DC} + H_{eff} \qquad (1)$$

where f_R is the resonance frequency, $\gamma = 2\pi\mu_B / h$ is the gyromagnetic ratio, g is the Landé factor, h is Planck's constant, μ_B is the Bohr magneton and H_{eff} is the effective anisotropy field of the system.

The expression of H_{eff} includes contributions from the shape anisotropy ($2\pi M_z$), the interwire magnetostatic interactions ($-6\pi M_z P$) and the uniaxial anisotropy field (H_k) [3]:

$$H_{eff} = 2\pi M_z (1-3P) + H_k \qquad (2)$$

Considering Eq. (1) and the angular dependence of the resonant field, we have determined that the values of the effective anisotropy field H_{eff} (for H_{DC}=0), the uniaxial anisotropy field H_K, the giromagnetic ratio γ, and Landé factor g, are: γ=2.88MHz/Oe , H_{eff} = 2.76 kOe, H_k=1.2 kOe and g=2.08 for [NiFe/Cu]xn multilayered nanowires, and γ=2.94MHz/Oe, H_{eff} =3.36kOe, H_k=1.8kOe and g=2.1 for NiFe single layered nanowires. By using Eq. (2), the shape anisotropy, $2\pi M_z$, is found to be $2\pi M_z$=5.2 kOe, the value which is in accordance with the reported experimental values for NiFe nanowires [10].

Fig. 5 shows that these arrays of NWs exhibit resonance frequencies even at zero-applied DC magnetic field. These zero-field resonance frequencies, range from 6.5GHz up to 20GHz for NiFe NWs and from 7.5GHz up to 21GHz for NiFe/Cu NWs. These zero-field absorption frequencies depend only on the effective anisotropy field of the NWs,which means that they can be tuned by adjusting any of the parameters included in H_{eff}.

4. Conclusion

FMR experiments using the microstripline method and X-band spectrometer where used to investigate the magnetic anisotropy direction in $Ni_{80}Fe_{20}$ (permalloy) single layered and $[Ni_{80}Fe_{20}$(50nm)/Cu(10nm)]xn multilayered nanowires. The broadening of the FMR spectra is related to the presence of the dipole-dipole interaction between adjacent NiFe layers which tends to align the magnetization of layers along the nanowire axis. The plots shape of the FMR spectra, the angular dependence of the resonant field and the magnetic hysteresis curves indicate a system with uniaxial anisotropy and with the easy magnetization axis of the nanowires parallel to the nanowires axis. The presence of non-magnetic Cu layers produces a decrease of the axial magnetic anisotropy in the multilayered nanowire. The bell shape of the angular dependence curves of the resonant field for single and multilayered nanowires indicates a positive effective field.

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