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Ultra-soft magnetic films: micromagnetism and high frequency properties

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Abstract

The wavelength and amplitude of the longitudinal oscillations of the transversal and longitudinal components of magnetization was obtained from the contrast ripple observed by the Lorentz TEM. The micromagnetic ripple is connected with the internal stray field in the film. The theory, based on Landau–Lifshitz equation, is developed, where the internal stray field is taken into account. The theory predicts that the micromagnetic ripple can broaden the ferromagnetic resonance (FMR) to lower range of the frequencies. For a certain range of the internal stray field a second bump at lower frequencies arrives, which shows up in some previously reported spectra.
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Keywords: Soft magnetic film; Micromagnetic ripple; High frequency; Landau–Lifshitz theory

1. Introduction

Nanocrystalline ferromagnetic films with a high saturation magnetization, low conductivity and with a good response in the GHz region are highly requested for high frequency applications, such as planar inductors, integrated passives, electromagnetic noise countermeasure, sensors, etc., in the RF range, especially in the 800 MHz–6 GHz range (see, [1] and references therein). The operating range of the films is limited by the frequency and the width of the ferromagnetic resonance (FMR). Here, we discuss the influence of local inhomogeneity of magnetization on high frequency properties. This inhomogeneity comes from non-complete averaging out the magnetocrystalline anisotropy in nanocrystalline films [2,3]. The residual magnetocrystalline anisotropy causes a local deviation of the easy axis (EA) of magnetization from the average direction, an angular spread of the magnetization and a stray field predominantly oriented along the EA. The local oscillation of the magnetization is observed as a ripple structure in a defocused film image in the Lorentz Transmission Electron Microscopy (LTEM) in the Fresnel mode [4,5]. We have shown that the amplitude of the oscillations can be obtained from an analysis of

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the LTEM ripples [6]. Our approach is based on the Landau–Lifshitz equation where the effective field includes the internal stray field estimated from the LTEM observations.

2. Samples

$(Fe_{99}Zr_1)_{1-x}N_x$, $x \leqslant 0.25$ films with a thickness between 30 and 1000 nm were deposited by DC magnetron reactive sputtering [7]. The films were grown in a nanocrystalline structural state with grain size of 2–30 nm depending on the growth conditions. Glass or silicon substrates with or without polymer or Cu underlayers were used. The $Co_{59}Fe_{26}Ni_{15}$ films were produced by electrodeposition at room temperature in the galvanostatic mode on copper underlayer (300 nm) which was sputtered on Cr-covered (20 nm) oxidized (200 nm) silicon [8]. In both cases, a horizontal magnetic field parallel to the plane was applied in order to introduce in-plane uniaxial anisotropy. The films showed soft magnetic properties with the coercivity in the range of 1–20 Oe and the anisotropy up to 20 Oe.

3. LTEM analysis

TEM and LTEM studies were performed, using JEOL 2010F transmission electron microscope equipped with a post-column energy filter that provides an additional magnification of around 20 at the plane of the CCD camera with respect to the maximal attainable magnification by using a low field objective minilens.

An example of an LTEM image with a ripple structure is depicted in Fig. 1(a). The contrast of the LTEM digital micrograph in the figure was analyzed taking linear scans at various places and in different directions within the image. A linear scan perpendicular to the ripple fringes (T-profiles) shows a quasi-periodic arrangement of the fringes, Fig. 1(a) and (b). This type of fringes corresponds to the wiggling of the magnetization vector perpendicular to the EA, called here the transverse component of magnetization (TCM).

We assume here that xy coordinate plane is parallel to the film surface and the x-axis is parallel to the average direction of the EA. It was noted [4] that, due to exchange interactions, longitudinal oscillations of TCM $M_y(x)$ are energetically more favorable than the transversal oscillations of TCM $M_y(y)$, so we neglect the latter.

Approximating the oscillation of TCM by a single period harmonic function

$$M_y(x) = M\beta_0 \sin(2\pi x/\lambda_x), \tag{1}$$

one can relate [9], using the theory of electron diffraction, the contrast of the LTEM picture, C_x, with the periodicity of the ripples, λ_x, and with the deviation amplitude, β_0, of the local magnetization from the mean direction (wiggling angle)

$$\begin{aligned} C_x &= [I_x(0) - I_x(\lambda_x/2)]/Ix(\lambda_x/4) \\ &= (2\pi M\beta_0 t\lambda_x/\Phi_0)\sin[\Delta z\lambda_0/(2\pi\lambda_x^2)]. \end{aligned} \tag{2}$$

Here, M is the local magnetization, $I_x(0)$, $I_x(\lambda_x/2)$ and $I_x(\lambda_x/4)$ are the image intensities in the maximum, in the minimum and in the middle point of the ripples, respectively, t is the thickness of the film, $\Phi_0 = h/2e$ is the flux quantum, Δz is the defocus distance in the microscope and λ_0 is the electron wavelength (λ_0 = 2.5 pm for the 200 keV-electrons). For maximum contrast one can obtain the relation, which has been used before [11]

$$4\pi M\beta_0 \approx 10.3C/(t\lambda), \tag{3}$$

where $4\pi M$ is in gauss, t and λ are in microns.

With the wavelength $\lambda_x = 0.22 \pm 0.02$ μm and a contrast of $C = 0.5 \pm 0.1$, as obtained from Fig. 1(a) and (b), and with $B = 4\pi Ms = 17$ kG, $t = 0.07$ μm, Eq. (3) gives the amplitude of the wiggling angle $\beta_0 \approx 1.2°$ or the amplitude of the TCM $4\pi M_{y0} = 4\pi M\beta_0 \approx 360$ G.

Additionally, the intensity of the image is rather inhomogeneous along the ripple direction, seen as a dotted contrast in Fig. 1(a), and demonstrated in the longitudinal scan (L-profile) in Fig. 1(a) and (c). This variation cannot be explained by longitudinal oscillations of the TCM, but requires a variation of the magnetization along the main direction, i.e., an oscillation of longitudinal component of magnetization (LCM). The origin of the oscillations of the LCM could be the film topography, as discussed in

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