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Journal of Magnetism and Magnetic Materials 272–276 (2004) 1652–1653

Journal of magnetism and magnetic materials

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# FMR characterization of hexagonal arrays of Ni nanowires

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**Abstract**

We report FMR experiments in hexagonal arrays of Ni nanowires ($\sim 35$ nm diameter separated $\sim 105$ nm) performed at 9.4 GHz. The spectra show a main line associated with a uniform mode. The angular variation of this line is characteristic of an easy axis along the wire length. The magnitude of the effective anisotropy field of 1.9–2.3 kOe is consistent with the structural data.


*PACS:* 76.50.+g; 73.22.Lp; 75.30.Gw; 75.75.+a

*Keywords:* Nanowires; FMR; Ni wires; Anisotropy

Magnetic nanowires (NW) have lately attracted the attention of researchers driven by its potential as a high-density recording material as well as by its novel basic properties [1]. It has recently been demonstrated the possibility of creating highly ordered NW by electro-deposition of ferromagnetic materials into self-ordered porous anodic alumina [2]. A theory that focuses on the excitation of spin-wave modes characterized by intra-wire exchange and inter-wire dipolar coupling has been developed [3]. Recently, Brillouin light scattering has confirmed the appearance of quantized spin-wave in these Ni NW arrays [4]. Ebels et al. [5] reported ferromagnetic resonance (FMR) of Ni NW of various diameters grown on polycarbonate membranes. These results show that the wire-shape, its crystalline structure (if textured), and strain may contribute to the total anisotropy. In the case of NW grown on polycarbonate membranes the wires can be created with densities of $\sim 10^8$–$10^9$/cm$^2$, thus they can be thought as roughly independent of each other, as these values correspond to filling factors $f < 0.01$. This is no longer the case in dense NW where the inter-wire distance is comparable to its diameter.

In this work we report FMR measurements performed at 9.4 GHz in three samples of Ni MNW with lengths 2.8, 1.1 and 0.75 μm, all of them having $\sim 35$ nm diameter and $\sim 105$ nm inter-wire distance. The samples were prepared by the method described previously [2].

The FMR experiments were performed in a Bruker EMX300 spectrometer. Fig. 1 shows the FMR spectra of the three samples under study. We identified the uniform mode as the most intense line in the spectra and determined its position performing a fit using a Lorentzian line shape (plus a background) in the region of interest. The additional structure observed may be due to spin-wave excitations [3,4]. The resonance condition for uniaxial ferromagnet is given by

$$(\omega/\gamma)^2 = [H_r \cos\varphi + H_a \cos^2(\varphi - \varphi_a)] \times [H_r \cos\varphi + H_a \cos^2(\varphi - \varphi_a)], \quad (1)$$

where $\omega = 2\pi v$, $v = 9.4\,\mathrm{GHz}$, $\gamma = g\mu_B/\hbar$ is the giromagnetic ratio, $H_r$ is the resonance field, $H_a$ is an effective anisotropy field, $\varphi$ is the equilibrium angle between the **H** and the magnetization, **M**, and $\varphi_a$ is the angle

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0304-8853/$ - see front matter 
doi:10.1016/j.jmmm.2003.12.233

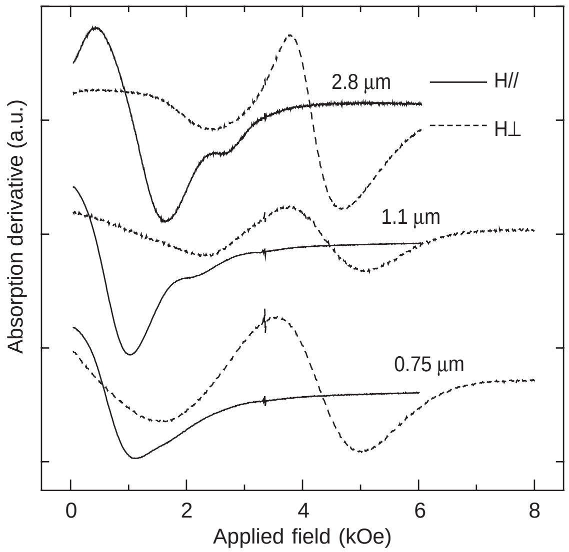


Fig. 1. FMR signal at 9.4 GHz for $H_{\parallel}$ and $H_{\perp}$ to the wire axis for the three samples studied. The spectra were shifted for clarity.

between **H** and the anisotropy axis (along wire axis). In Fig. 2 we show the angular variation observed and the best fit to Eq. (1). The parameters obtained from the fits are the following: $g = 2.17 \pm 0.09$, $2.26 \pm 0.06$, and $2.28 \pm 0.04$, $H_a = 1.99 \pm 0.15$ kOe, $2.32 \pm 0.07$ kOe, and $2.21 \pm 0.04$ kOe for the 2.8, 1.1 and 0.75 μm wire lengths, respectively. The $g$-value is close to the one observed in Ni thin films, $g = 2.24 \pm 0.06$ [6]. The small discrepancies may be due to the uncertainty in determining the line position, in part due to the line structure that is not accounted for by Eq. (1).

The value of the anisotropy field for an isolated Ni NW is given by $2\pi M_s = 3.05$ kOe, much more than observed in our case, yet less than observed in Ref. [5]. The main difference with Ref [5] is the density of the array, which in our case is estimated to give a filling factor of $f = 0.101$ from structural information and geometrical consideration. Note that for large $f$ we expect a change from easy axis (along the wire) to easy plane (perpendicular to the wires). In a mean-field approximation [7] the inter-wire dipolar interaction

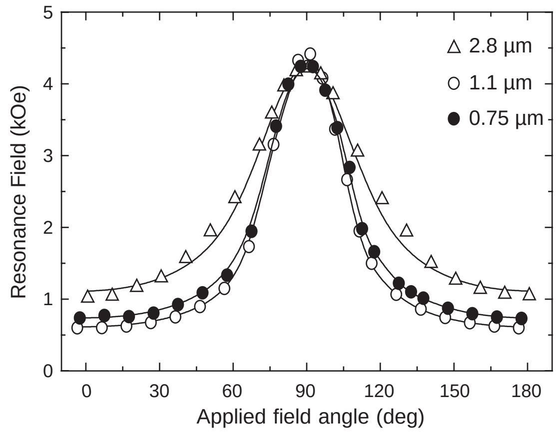


Fig. 2. Observed angular variation of the FMR signal and best fit (full line) using Eq. (1).

correction to $H_a$ is given by $H_a = 2\pi M_s(1-3f)$. This leads to $H_a = 2.15$ kOe, which is in good agreement with the observed values. The crystalline anisotropy should average to zero in a polycrystalline material, therefore contributing only to the linewidth. The variations of $H_a$ observed may be related to slightly different filling factors as no direct correlation of $H_a$ with the wire lengths is observed. We conclude that FMR experiments in magnetic NW yields direct information about the anisotropy, which may be related to the array structure.

Supported by a CSIC(Spain)-CONICET(Argentina) international cooperation grant and MCyT, (Spain) no. MAT2002-00824.

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