Ferromagnetic resonance measurements on Co nanowires

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Abstract. Co nanowires grown by electrodeposition technique in polycarbonate membrane have been analysed. The nanowires have 25 μm length and 60 nm diameter and are oriented perpendicular to the sample plane. The study focuses on the ferromagnetic resonance (FMR) measurements in Q band (34 GHz), study which allow the identification of the anisotropy effects in Co nanowires.

1. Introduction

Magnetic nanowires are an interesting physical system, with many potential applications, such as high density magnetic recording and sensors [1]. This systems offer the opportunity for the studies of static and dynamic magnetic properties due to controllable and reproducible characteristics and properties.

For such nanostructured materials it is possible to study both, a large ensemble of wires as well as isolated single wires. Although studies on single wires are important to understand the mechanism of magnetization reversing in a single wire, it is also of importance for possible device applications to quantify the distribution of the internal fields for wire arrays. The internal fields include the domain-wall nucleation field and the depinning field (the magnetization reversal by domain wall propagation) as well as the anisotropy field.

The anisotropies fields of nanowires arrays can be investigated by various techniques [2]. One of these techniques is the ferromagnetic resonance spectroscopy (FMR) due to the fact that the resonance field depends directly on the anisotropy. The measurements had been performed on Co nanowire arrays with diameter of 60 nm which are embedded in a polycarbonate membrane. The room temperature FMR experiments were done in Q band, frequency f = 34.4 GHz. The FMR technique has still the advantage of yielding well-defined spectra from which a quantitative analysis of the angular dependence of the resonance field could be performed.

2. Experiment

The Co nanowires arrays were fabricated by an electrodeposition method using polycarbonate membrane with a diameter of 5 mm and the pore sizes of 60 nm. This method consists in the deposition of a metal inside the membrane pores under the current action [3]. Prior to deposition, a metallic layer of 1 μm Au serving as the cathode is deposited by evaporation on one face of the membrane. Then, the membrane is introduce inside an electrolytic bath (pH = 5) witch contains the
metals ions and a Pt anode. The solution pH must be kept constant since his variation may induces changes in the magnetic behaviour of the nanowires. The pH of the electrolytic bath can be adjusted by adding H_2SO_4 or NaOH [4].

A current is applied between the cathode and the anode. During the deposition the current variation between the cathode and the anode is measured. This variation must be constant and when it increases the membrane pores are filled.

The room temperature FMR experiments were carried out in Q band, frequency f = 34.4 GHz. In the experiments presented here, the microwave pumping field h had a frequency f = 34.4 GHz (Q band) and was always oriented perpendicular to the applied bias field H_0 and to the wire axes as shown in figure 1.

The angle \( \theta \) of the applied bias field was then changed in zero field such that the orientation of \( H_0 \) varied between parallel to the wire axes (\( \theta = 0^\circ \)) and perpendicular to that axes (\( \theta = 90^\circ \)).

### 3. Results and discussions

The experimental FMR spectra measured at different angles \( \theta \) are shown in figure 2. It can be clearly observed a change in the line width of FMR spectra with the angle variation. By increasing the value of angle \( \theta \), the resonance spectra change from a relatively narrow line, \( \Delta H = 1760 \) kOe for \( \theta = 0^\circ \) to a broader one, \( \Delta H = 2300 \) kOe for \( \theta = 90^\circ \).

For the resonance field, \( H_R \), a sinusoidal dependence with the angle \( \theta \) was found. This dependence is presented in figure 3. The minimum field of \( 5 \) kOe corresponds to the angles \( 0^\circ \) and \( 180^\circ \) while the maximum field (\( \sim 14 \) kOe) to the angle \( 90^\circ \).

![Figure 1](image1.png)

**Figure 1.** A schematic picture showing the orientation of the applied bias field, \( H_0 \), and the microwave pumping field, h.

![Figure 2](image2.png)

**Figure 2.** FMR spectra for a 60 nm Co-wire array at 34.4 GHz.
In order to explain the angular dependence of resonance field, a theoretical model has been used [5]. This model starts from the total energy of an infinite cylinder and considers that the resonance field could be obtained from the dispersion relation:

\[
\left( \frac{\omega}{\gamma} \right)^2 = \left[ H_{\text{eff}} \cos 2\theta_0 + H_0 \cos(\theta_0 - \theta) \right] \times \left[ H_{\text{eff}} \cos^2 \theta_0 + H_0 \cos(\theta_0 - \theta) \right] \tag{1}
\]

where \( \gamma \) is the giromagnetic ratio \( \gamma = g\mu_B / h \), \( \theta_0 \) is the equilibrium angle of the magnetization \( M \) and \( \theta \) is the applied field \( H_0 \) direction angle. \( H_{\text{eff}} \) is the effective uniaxial field along the wire axis.

![Figure 3](image)

**Figure 3.** The experimental angular variation of the resonance field \( H_R \) for Co nanowires at 34.4 GHz (full squares) and the calculated angular variation of the resonance field (full line).

The \( \theta_0 \) is obtained from equilibrium conditions for the static magnetization by using the first derivative of the total energy of the sample [5].

The best fit of the experimental data with the equation (1) is shown in figure 3, and was obtained for \( H_{\text{eff}} = 4.7 \text{kOe} \). The effective field contains three components: the shape anisotropy field, \( H_{\text{shape}} \), the dipolar interaction field, \( H_{\text{dip}} \), and an additional second order uniaxial anisotropy contribution, \( H_u \). His expression is the following:

\[
H_{\text{eff}} = H_{\text{shape}} - H_{\text{dip}} \pm H_u \tag{2}
\]

In this equation the sign of the uniaxial anisotropy contribution is given by the orientation of the anisotropy field towards the wire axis, a positive sign for a parallel orientation and a negative one for a perpendicular orientation.

For the Co nanowires the shape anisotropy field is given by the equation: \( H_{\text{shape}} = 2\pi M_s = 8.8 \text{kOe} \), where \( M_s \) is the saturation magnetization.

The second term in the equation (2) is the dipolar field described by the expression: \( H_{\text{dip}} = 6\pi M_s f \), where \( f \) is the filing factor. This expression was obtained considering two components: \( 4\pi M_s \) due to the magnetic charges situated on the wires end, and \( 2\pi M_s \) from the charges situated on the wires length. The calculated value for dipolar field corresponding to the Co nanowires is 800 Oe.
Considering all this arguments we obtained for the second order anisotropy contribution \( H_a \) an average value of 3.3 kOe. Therefore, the magnetic anisotropy appears to be uniaxial with the easy axis almost perpendicular to the wire axis.

4. Conclusions

For an array of Co nanowires, the angular dependence of the resonance field was investigated by FMR. The fit of the resonance field position \( H_R \) vs the bias field angle \( \theta \) yields an effective anisotropy filed of \( H_{\text{eff}} = 4.7 \text{kOe} \). This value is smaller than the sum between the anisotropy shape field and the dipolar field. Therefore, a small additional second order uniaxial anisotropy could exist in the nanowires, the easy axis being oriented almost perpendicular to the wire axis.

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