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Tunable remanent state resonance frequency in arrays of magnetic nanowires

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The zero-field microwave absorption, or natural ferromagnetic resonance, spectra in arrays of electrodeposited magnetic nanowires is studied as a function of the saturation magnetization of NiCu, NiFe, CoNiFe, and CoFe alloys of several compositions. Measurements show that due to the shape anisotropy, these systems present strong absorption peaks in the absence of an applied magnetic field in the GHz range due to the ferromagnetic resonance. Furthermore, the zero-field resonance frequency is observed to be independent of the wire diameter and density as well as the magnetic history and its value depends only on the material, through the saturation magnetization and the gyromagnetic factor. It is shown that, using different electrolytic solutions and depositing at different electrostatic potentials, the alloy composition can be varied and the remanent state resonance frequency can be tailored quasicontinuously between 4 and 31 GHz. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1507610]

Magnetic nanostructures have motivated a great research effort during past years. The impact they have had in recent technological progress witnesses not only the richness and variety of properties that characterize these materials but also the wealth of perspectives which are currently being investigated.[1] Other than recording media, random access memories, read heads, and field sensors, ferromagnetic nanostructures can provide interesting perspectives for microwave devices. As pointed out by other authors,[2–4] ferromagnetic metals have the attractive quality of having a large saturation magnetization and thus, higher resonance frequencies than typical ferrite materials. Nevertheless, one major drawback of these materials is their large conductivity which limits microwaves to fully penetrate, giving rise to unwanted losses. One solution to overcome this difficulty is to fabricate a composite containing small dispersed ferromagnetic particles in an insulating binder. Full microwave penetration is then assured when at least one of the dimensions of the particles is small compared to the penetration depth.

Recently, it has been shown that arrays of magnetic nanowires embedded in a polycarbonate membrane and due to their small diameter comply with these restrictions and exhibit very interesting microwave properties at GHz frequencies.[5] In these systems, the resonance frequency has been shown to be tunable with the magnetic field and the anisotropy properties. In particular, it has been shown that in systems with negligible magnetocrystalline and/or magnetoelastic anisotropy, the resonance frequency can be tailored over a wide range of values simply by adjusting the dipolar interaction among wires.

Among the different classes of microwave devices where magnetic nanowires could have a significant impact are those requiring nonreciprocal operation such as stopband filters and isolators where there is no alternative to magnetic materials and, in particular, those working at zero or small steady magnetic bias fields.

In this contribution, it is shown that taking advantage of the versatility of electrochemistry to grow different magnetic alloys combined with the size and shape properties of the nanowire arrays, the zero-field resonance frequency can be adjusted over a range of values that spans from 4 up to 31 GHz.

The nanowire arrays have been fabricated by electrodeposition into polycarbonate nanoporous templates. These templates are 22 μm thick lab-made membranes with randomly distributed circular pores which present very little diameter and angular ($<5°$) dispersion with respect to the surface normal. The nanowires are grown in these templates by standard three-electrode electrodeposition at room temperature. The deposition is done at a constant potential using a Pt cathode. For this study, a series of binary alloys based on NiCu, NiFe, NiFeCo, and CoFe have been grown. In order to vary the alloy composition, the deposition potential was varied between -1.0 and -2.0 V.

The microwave transmission coefficient measurements were performed at room temperature for all wire arrays using a microstrip transmission line and by sweeping the frequency through the resonance peak at zero-applied field after being saturated at different applied field directions.[5]

Figure 1 shows the zero-field resonance frequency measured after saturation of the sample at different applied field directions, 0° being the parallel to the wires (90° being perpendicular to the wires), in a series of permalloy ($Ni_{82}Fe_{18}$) and Ni nanowires grown on different templates. The pore diameters vary between 75 and 150 nm and wire surface fraction, or porosity, varies between 1% and 25%, which

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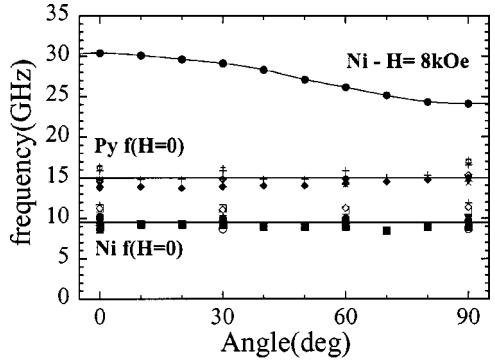

FIG. 1. The zero-field resonance frequency measured after saturation of the sample at different applied field directions in different arrays of Ni and permalloy nanowires. These samples have wire diameters ranging from 66 up to 150 nm, and porosity between 1% and 30%. For comparison, the angular dependence of the resonance frequency is shown at saturation, $H=8$ kOe, measured on an array of Ni nanowires of diameter 112 nm and a porosity of 12% is also shown. Lines are just a guide for the eye.

allows one to have arrays of nanowires with different static remanent states that vary from 0.1 to 0.8 in the direction parallel to the wires. For comparison, the angular resonance frequency measured at saturation, $H=8$ kOe, on an array of Ni nanowires 112 nm and a porosity of 12% is shown. From these results it can be seen that, in contrast to the saturated sample, the zero-field resonance frequency is constant independently of the direction at which the sample was saturated. Furthermore, these results suggest that the value of this frequency is also independent of the template (wire diameter and density).

These properties can be explained in terms of the ferromagnetic resonance (FMR) properties in arrays of nanowires.[5,6] In the case of Ni and permalloy nanowires, the resonance frequency depends only on the shape anisotropy and the dipolar interaction between the wires, and no other anisotropy contributions are present. In this case, the effective field can be written as $H_{\mathrm{EF}}=2\pi M_S(1-3P)$, where M_S is the saturation magnetization and P is the membrane porosity, or surface filling factor. Classical FMR theory predicts that for an ideal system, e.g., single domain, the zero-field resonance frequency, f, is given by[5]

$$f=2\gamma\pi M_S(1-3P), \tag{1}$$

where γ is the gyromagnetic ratio. Nevertheless, as reported previously,[5,6] this expression is only valid in the saturation state. In general, as the field is lowered from saturation down to remanence, the wires split up in domains in order to reduce their stray field, and thus the dipolar interaction. At zero field, the magnetic state of the entire array is such that the dipolar interactions are minimized. The presence of an absorption peak at zero field results from the component of the magnetization in each wire which is forced to align parallel to the wire axis by the shape anisotropy. It follows from Eq. (1) that the zero-field resonance frequency depends only on the shape and the material through the values of M_S and γ and is given by

$$f=2\pi M_S\gamma. \tag{2}$$

These arguments imply that the zero-field resonance frequency is independent of the wire diameter, their density, and the magnetic history, in agreement with the results shown in Fig. 1 and previous static measurements which show that this result is also independent of the value of the remanent magnetization.[5,6]

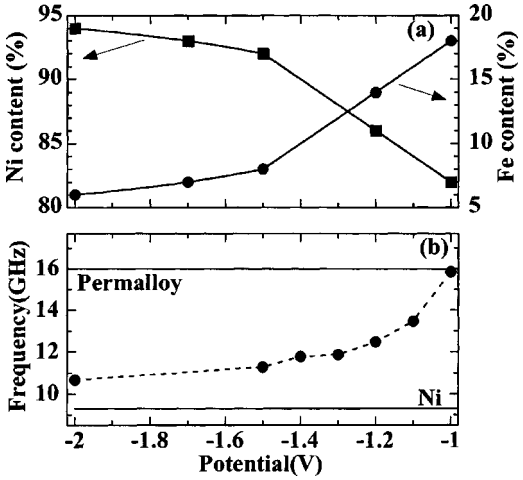

FIG. 2. (a) NiFe alloy composition as a function of the deposition potential, lines are just a guide for the eyes, and (b) zero-field resonance frequency of the corresponding NiFe alloy nanowires (diameter 120 nm and membrane porosity of 12%) measured after saturation with an applied field parallel to the wires. Horizontal lines are the calculated resonance frequencies for Ni ($M_S=485$ emu/cm^3) and permalloy ($M_S=850$ emu/cm^3) given by $f=2\pi M_{S\gamma}$ and $\gamma=3.0$ GHz/kOe. The dotted line is a guide for the eyes.

Electrodeposition of magnetic alloys is a well developed subject, and binary magnetic alloys have been widely studied for the deposition of films.[7] One particular advantage of this deposition technique is that different alloys can be grown from a single solution simply by varying some deposition parameter such as temperature, potential, or current. Figure 2(a) shows the composition of different NiFe alloy nanowires obtained from the same solution after deposition at different potentials.

As the potential is increased from -2.0 to -1.0 V, the iron content increases and the alloy composition varies from $Ni_{94}Fe_6$ to $Ni_{82}Fe_{18}$, respectively. Accordingly, the saturation magnetization and the zero-field resonance frequency should increase with the iron content. Experimentally, this has been confirmed as shown by the results presented in Fig. 2(b), for the zero-field resonance frequency as a function of the electrodeposition potential for a series of nanowires having a diameter of 120 nm. This result confirms that by changing the alloy composition, the value of resonance frequency varies proportionally to the saturation magnetization. The values of the resonance frequency are also in good agreement with the values expected for permalloy ($M_S=850$ emu/cm^3) and nickel ($M_S=485$ emu/cm^3), as indicated by the continuous lines in Fig. 2(b) calculated with Eq. (2) and $\gamma=3.0$ GHz/kOe.

Following the same deposition procedure, other ferromagnetic alloys have been deposited in order to access a large range of values for the saturation magnetization. From the Slater–Pauling plots,[8] NiCu alloys can provide saturation magnetization values lower than Ni, while CoFe alloys can allow one to have very large M_S values. Intermediary values can be obtained from other alloys such as NiFe, NiFeCo, and CoNi. Nevertheless, it should be pointed out that by using different magnetic alloys, other contributions to the effective field, such as a magnetocrystalline or magnetoelastic anisot-

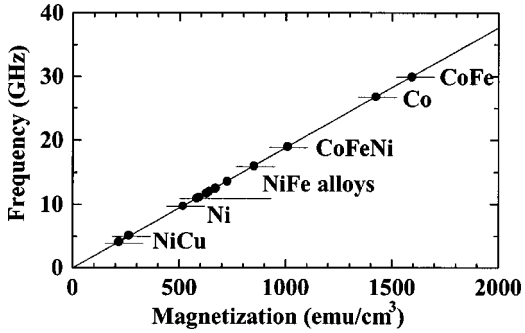

FIG. 3. Measured zero-field resonance frequency vs the extrapolated value of the effective magnetization. The straight line was calculated from Eq. (2) with $\gamma = 3.0$ GHz/kOe.

ropy, might appear and the zero-field resonance frequency will deviate with respect to the value given by Eq. (2). In order to allow such deviations, in the following, we will consider the effective magnetization which corresponds to the numerical value of M_S which satisfies Eq. (2).

Figure 3 shows the zero-field resonance frequency measured in these series of alloys plotted as a function of the extrapolated value of the effective magnetization. In order to simplify, a constant value of $\gamma = 3.0$ GHz/kOe has been used. The straight line corresponds to the frequency calculated from Eq. (2). These results show that the accessible frequency window spans in the range in which it is possible to select the zero-field resonance frequency has a lowest value of 4 GHz for the $Ni_{70}Cu_{30}$ alloy, and a highest frequency of $f = 31$ GHz measured in the $Co_{80}Fe_{20}$ alloy.

It has been shown that using electrodeposition to fabricate a wide range of magnetic alloys, the zero-field resonance frequency in arrays of alloy nanowires can be controlled over a wide range of values by changing the type of magnetic alloy and its composition. When the effective anisotropy of the wires is given only by the shape anisotropy, the zero-field resonance frequency is simply $f = 2\pi M_S \gamma$ and is independent of the wire diameter and density as well as the magnetic history of the system. The frequencies that can be achieved vary from 4 and up to 31 GHz. This property can be interesting for ''on'' or ''off''-resonance microwave devices working at zero or small bias field, such as stopband filters.

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