Passive high-frequency devices based on superlattice ferromagnetic nanowires

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Abstract

In this paper we propose to tailor the bandwidth of a microwave filter by exploitation of shape anisotropy of nanowires. In order to achieve this control of shape anisotropy, we considered superlattice wires containing varying-sized ferromagnetic regions separated by nonferromagnetic regions. Superlattice wires of Ni and Au with a nominal diameter of 200 nm were grown using standard electrodeposition techniques. The microwave properties were probed using X-band (9.8 GHz) ferromagnetic resonance (FMR) experiments performed at room temperature. In order to investigate the effectiveness of the shape anisotropy on the superlattice nanowire based filter the FMR spectrum of superlattice structure is compared to the FMR spectra of nanowires samples with constant length.

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1. Introduction

Recently, the use of magnetic nanostructured materials in passive device design has aroused considerable interest. One important example is the use of magnetic nanowires as possible filters in the GHz frequency range. At these frequencies the nanowire’s diameter is smaller than the skin depth and the absorption of electromagnetic waves is very efficient. The dynamic properties of nanowire assemblies are usually probed by ferromagnetic resonance (FMR) experiments using either a micro-strip transmission line [1] or conventional FMR spectrometers [2,3]. Magnetic nanowires of constant length and embedded in the dielectric template are subjected to a microwave pumping magnetic field and a bias DC magnetic field reciprocally perpendicular. It was shown that the dynamic behavior of magnetic nanowires is dominated by the shape anisotropy and the wires can be considered as models for infinite long cylinder [2]. Thus, the nanowire structure acts as a stopband filter whose electromagnetic wave absorption is determined by gyromagnetic resonance, which, due to the shape anisotropy, occurs even in the absence of the DC magnetic field. One way to control the bandwidth of such a filter is to use materials of different magnetic properties whose zero-field resonance frequency can be adjusted over a large frequency range [4]. Applying a DC magnetic field oriented along different directions with respect to the wire’s axis can further increase the tunability of the nanowire-based filter. In this case, as the orientation of DC field changes, the nanowire’s demagnetizing factors change, shifting its resonance frequency. Following the same idea, it would be possible to tune the FMR phenomenon in nanowires by changing directly the shape anisotropy using nanowires of different aspect ratios. The same idea of using the shape anisotropy to tune the frequency response of microwave filters was used previously in the case of
microstrip filters [5]. Nanowires of constant length and for which the filter’s absorption band was rather shifted (by the choice of the material or use of a DC magnetic field) than adjusted, were used in all previous FMR studies of nanowire networks. In this paper we propose to tailor the bandwidth of a microwave filter by the exploitation of shape anisotropy of nanowires. In order to achieve this control of shape anisotropy, we considered superlattice wires containing in the same structure varying-sized ferromagnetic regions separated by non-ferromagnetic regions. This approach is very attractive, but as it will be shown later, designing a microwave filter based on superlattice nanowire assembly requires good control of dipolar interactions between wires.

2. Experiment

Ni nanowire arrays with a nominal radius of 100 nm and different lengths were prepared by standard electrochemical deposition at room temperature using commercial alumina membranes as templates. The length of the wires between 150 and 1200 nm was controlled by using different deposition times. The obtained samples consist of almost cylindrical and parallel sets of ferromagnetic Ni nanowires embedded in the alumina membrane with an average interwire distance (center to center) of 240 nm. The superlattice nanowires were prepared by alternating Ni regions with Au regions within the same channel. The major hysteresis loops were measured along different directions with respect to the wire’s axis using a vectorial vibrating sample magnetometer. A typical example of FMR spectra is displayed in Fig. 1. One observes that except for the sample with the nominal length of 600 nm where a doublet is observed, all spectra present a single absorption line. This kind of behavior was previously observed in Ni nanowire arrays [2] and was explained using a exchange/dipole spin wave modes theory [6]. Also, for wires of different lengths the FMR spectra are ranging in a wide window of resonant fields in almost monotonically increasing fashion. This confirms that the sample’s effective demagnetizing factor can be tuned by varying the wire’s aspect ratio.

3. Discussions

For the field applied perpendicular to the wire’s axis the resonant field values (see Fig. 2) are smaller than those corresponding to the parallel orientation. This kind of behavior was observed previously in nanowire samples grown in high porosity membranes [7–9]. The dipolar interactions are significant in this case and they overcome the shape anisotropy creating an easy axis perpendicular to the wires [7]. Designing a stopband filter using a superlattice nanowire grown in similar membranes is a very difficult task. One of the reasons is that the effect of shape anisotropy may be cancelled out by the dipolar coupling so at the end the effective demagnetizing field could not provide the desired tuning over the filter bandwidth. Recently, we studied the effects of dipolar interactions in nanowire networks [9]. By calculating the interaction field along and perpendicular to the wire’s direction, the dependence of the total demagnetizing field of nanowire samples as a function of both aspect ratio and average distance between wires was determined (see Fig. 2 in Ref. [9]). From this study it clearly appears that only for nanowire assemblies with strong and very weak dipolar interactions the effective demagnetizing field varies efficiently as a function of aspect ratio. Thus, for weakly interacting wires the demagnetizing factor increases as the aspect ratio (length of the wires) increases while for strongly interacting wires the demagnetizing factor

Fig. 1. FMR derivative spectra for a series of samples of different lengths ranging from 300 to 1200 nm; the DC field is parallel to the wire’s axis.

Fig. 2. FMR derivative spectra for a series of samples of different lengths ranging from 300 to 1200 nm; the DC field is perpendicular to the wire’s axis.
decreases. For intermediate values of dipolar interaction field the total demagnetizing factor is not very sensitive to the aspect ratio. The porosity of the membranes we used to synthesize our nanowire samples is large enough so a significant variation of the resonance field can be achieved for samples with different aspect ratios.

Two different superlattice nanowire samples were prepared. One sample contains three segments of Ni having the same length (300 nm) separated by 300 nm Au segments (Au/Ni/Au/Ni/Au/Ni/Au). The second sample contains segments of Ni of different sizes with the structure Au(150)/Ni(150)/Au(300)/Ni(300)/Au(600)/Ni(600)/Au(1200)/Ni(1200)/Au(2400)/Ni(2400) where the numbers in parentheses represent the length of the metal segments in nanometers. The FMR spectra for parallel and perpendicular orientations for samples one and two are shown in Fig. 3 and Fig. 4, respectively. Comparing the FMR spectra for both samples one observes that absorption bandwidth for the second sample is larger than for the one corresponding to first sample. Thus, in parallel geometry ($\theta = 0^\circ$) the line widths are $\Delta H_1 = 2103$ Oe and $\Delta H_2 = 3006$ Oe, while for transverse geometry ($\theta = 90^\circ$) they are $\Delta H_1 = 1268$ Oe and $\Delta H_2 = 2598$ Oe. The negative demagnetizing factor observed in the simple wire samples is preserved in the case of the superlattice nanowire samples. The strong dipolar coupling between nanowires makes possible that in the superlattice nanowire sample with segments of different lengths the absorption bandwidth is enhanced. One interesting issue in the case of superlattice nanowires concerns the length of the non-magnetic segments. Studies on the role of this component are currently underway and will be in a future publication.

4. Conclusions

The design of passive high-frequency filters based on magnetic nanowires is discussed. The dipolar coupling between wires can assist the tuning of the filter bandwidth only for very large or very small values of dipolar coupling strength. Superlattice nanowires containing magnetic segments of varying lengths separated by non-magnetic regions are used to enhance the bandwidth of the filter.

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References