Signal Enhancement for Ferromagnetic Resonance Measurement of Magnetic Nanowire array

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***Abstract*—In this paper, a ferromagnetic resonance (FMR) measurement technique to enhance signal detection of magnetic nanowire in array form (MNA) is presented. Two signal enhancement methods were developed for characterizing the MNA sample. The samples were placed on top of a coplanar waveguide (CPW) test circuit and exposed to both AC and DC magnetic fields. The first method indicates that FMR response is stronger for MNA on the slots due to stronger AC field around slots. The second method indicates that the FMR response of MNA with a copper (Cu) back layer is seven times stronger. Thus, to enhance the signal strength of FMR response, the MNA sample should be placed on the slot and/or include a Cu back layer. These methods are useful for identification methods, such as nanolabels used in biosensing applications that use small volume and size samples.**

Keywords—Magnetic nanowire array; coplanar waveguide; ferromagnetic resonance; signal enhancement.

I. Introduction

Magnetic nanoparticles and nanowires are being studied in biomedical applications for MRI contrast [1], drug delivery [2] and cell detection [3]. Recently, nanowires have been widely explored for use as biolabels in cell detection. Compared to magnetic nanoparticles with spherical shape, the high aspect ratio of cylindrical shape magnetic nanowires offers a wider range of magnetic properties and surface functionalization.

To detect the magnetic nanowires, a variety of identification methods exist. Giant magneto-resistive (GMR) sensor provides the resistance information related to the magnetic nanowires with external DC field. First order reversal curves (FORC) offers the interaction and coercivity differences of various types of magnetic nanowires. Ferromagnetic resonance (FMR) technique, however, can provide the resonant frequency information for a magnetic nanowire at specific combination of AC and DC field. Compared to GMR sensor, which requires extra nonmagnetic layers, FMR technique is more straightforward. Compared to FORC technique, FMR technique is more sensitive and less time consuming. Moreover, FMR has also been shown to offer the capability of detecting and identifying two or more types of magnetic nanowire materials [4]. While type can be determined by FMR technique, there remains a need to determine and enhance the signal sensitivity based on a single measurement.

This paper determines the FMR signal strength and investigates methods to enhance signal absorption observed by FMR of magnetic nanowire array (MNA) samples used on coplanar waveguide (CPW) circuits. Two signal enhancement methods were developed. One method is based on sample position on CPW test circuit and the other one is based on conduction effect of copper (Cu) back layer on MNA sample.

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II. Magnetic Nanowire Sample Description and Measurement System Setup

A 50μm aluminum oxide (AAO) template was used to grow cobalt (Co) nanowires with 12% porosity and 40nm diameter pores. The pH value of precursor solution is 2. A 7nm Ti and 300nm thick Cu were sputtered on one side of AAO as electrode for the MNA electrodeposition process [4]. The Cu layer here is also the Cu back layer used in signal enhancement method. Two nanowire samples were used: Co72 and Co80. Nanowire lengths for Co72 and Co80 are 15.5μm and 28.2μm, respectively. The chips dimensions (l=length and w=width) for Co72 (l=2.8 and w=1.9) and Co80 (l=3.698 and w=0.423) are in millimeters. The CPW circuit was designed on 0.254mm Duroid 5880LZ ($\varepsilon_r = 2$) and has z-shaped trace length of 6.8cm [4]. The CPW test circuit with nanowire sample on top were placed in a DC magnetic field provided by two electromagnet poles. A VNA (Anritsu 37369D) was connected to the CPW circuit to provide an AC magnetic field and detect the FMR absorption by transmission coefficient (S_{21}). The AC field frequency was fixed in the range of 1-40GHz and the DC field was swept from +1.5T to -1.5T at a rate of 0.025T/s.

A pair of nonmagnetic cables (Cinch Connectivity Solutions) and connectors (Southwest Microwave) were used to reduce the interference from other magnetic material for measurement. However, the flexible nonmagnetic cables are sensitive to the bending and can make errors in the calibration process. Thus, the FMR measurements were referenced to the VNA port without cable calibration.

(a) IP direction (b) OP direction

Fig. 1. A cross-section schematic of the CPW test circuit with sample to show field distribution in IP and OP direction. The black circle and black dashed line are the DC field direction, the red solid line is the AC field direction and the white line is nanowire axis. All cross sections are from the middle of the CPW circuit.

Typical FMR absorption are sensitive to orientation and were measured in the In-plane (IP) and Out-of-plane (OP) orientation as shown in Fig. 1. For IP orientation, DC field is in the plane of nanowire sample; whereas for OP orientation, DC field is out of the plane of nanowire sample and along the direction of nanowire axis.

III. FMR Results and Analysis

A. Method 1: Signal enhancement based on MNA sample position placememt on the CPW test circuit

The Co80 sample was put either on the slot or on the signal line of CPW circuit to measure FMR response as shown in Fig. 2. The Co80 sample chip size is 3698µm x 423µm. In Fig. 3, the FMR results on the slot and on the signal line at 15GHz in IP orientation are shown. In IP orientation, AC fields above slot and signal line are both orthogonal to magnetization of the nanowire. The FMR absorption for the sample when placed on the slot is stronger than when placed on the signal line. This is due to the stronger AC field around the CPW slot. Thus, to enhance FMR response, the sample chip should be placed on the slot.

B. Method 2: Signal enhancement based on conduction effect of Cu back layer on MNA sample

The Co72 was measured across the CPW test circuit, which includes the slot and the signal line, with and without Cu back layer (300nm thick). In Fig. 4, the FMR results of the nanowire sample with and without Cu back layer are shown in OP orientation. The sample with Cu layer creates almost seven times stronger FMR signal compared to the sample without Cu back layer. The similar enhancement effect also shows up in IP orientation. This can be explained by the HFSS simulation results shown in Fig. 5.

Without Cu layer, the AC fields are concentrated inside the slots; whereas with Cu layer, the AC fields are concentrated above the signal line due to the transfer of electric field attraction from the CPW grounds to sample Cu layer. The Cu layer acts like a floating ground, and is closer to the signal line above the sample. Thus, by including a Cu back layer to the MNA sample, the FMR response is further enhanced.

Fig. 2. Top view of CPW board

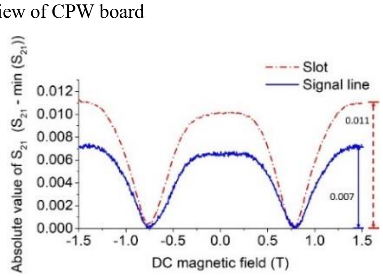

Fig. 3. The comparison between the Co80 sample on the slot and on the signal line at 15GHz in IP orientation.

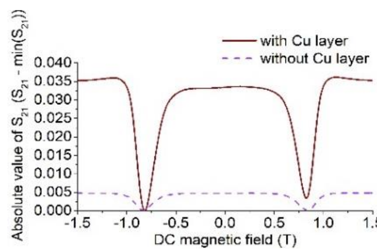

Fig. 4. The comparison between the Co72 sample chip with and without Cu back layer at 40GHz in OP orientation.

(a) Cross section of sample on CPW

(b) Cross section of sample on CPW with Cu back layer

Fig. 5. The HFSS simulation for sample without and with Cu back layer. Red and green arrows represent the AC field strength of 316A/m and 190A/m, respectively

IV. Conclusion

This paper shows two FMR signal enhancement methods. The first shows the FMR results comparison between sample on the slot and on the signal line. The sample on the slot shows stronger FMR response due to stronger AC field strength around CPW slot. The second one shows the comparison between sample with and without Cu back layer. The sample with Cu layer shows seven times larger FMR response compared to the sample without Cu layer, which is due to the transfer of electric field attraction. Thus, placing the nanowire sample on the slot and/or attaching the Cu back layer to the sample are two methods to enhance the signal strength of FMR response. These methods will enhance the detection and identification of magnetic nanowires when used in small size and volume biosensing application.

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