A Ferromagnetic Resonance Measurement System for Small Volume Magnetic Nanowires

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***Abstract*—This work presents a ferromagnetic resonance (FMR) characterization system for magnetic nanowires on short-circuited coplanar waveguide (CPW) structure. The FMR frequency of cobalt (Co) nanowire chips, with three different volumes-small, medium and large, were measured and compared with Kittel equation. The FMR response of the large chip agrees well with Kittel equation with the mean difference of 0.865GHz. The small and medium chips have higher mean difference values of 1.855GHz and 2.205GHz, respectively. From the FMR response, the signal to noise ratio is reduced as the material volume decreased and resulted in less accurate FMR frequency extraction. Since the lowest detectable signal strength of VNA (Anritsu 37369D) is 0.0002, to detect FMR response accurately for this system, the volume of Co should be greater than 2.2×10^{-4}mm3 and the magnetization should be larger than 317μemu. This paper provides a framework for building identification systems such as nanolabels for low volume biosensing application.**

Keywords*— *Magnetic nanowire array; coplanar waveguide; ferromagnetic resonance; vector network analyzer.

I. Introduction

In the past decade, the detection and identification of different biological entities, like cells, virus and biomolecules, has become an important factor in biomedical applications. Magnetic nanowires, one type of nanolabel, show great potential for use in biosensing application. Its high aspect ratio property due to nanowire's cylindrical shape provides a wide range of magnetic behavior and surface functionalization. Also, this feature leads to large remanent moment that provides some unique AC properties, like ferromagnetic resonance (FMR) that can be detected in the RF frequency range without applying DC magnetic field [1].

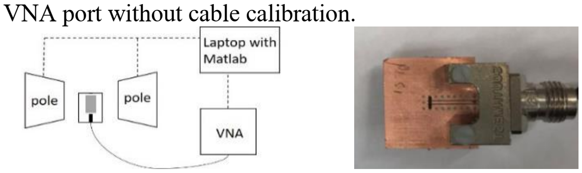
FMR is the absorption frequency observed in magnetic material at specific combination of AC magnetic field and DC magnetic field. This technique has been used to characterize specific types of magnetic nanowires array (MNA) [2]. More recently, researchers showed a biolabeling system based on FMR characterization technique to distinguish two or more types of MNA [3]. In cellular nanolabeling system, however, the small volume and the limitation of measurement system effects are less clear for measurements of magnetic nanowires.

Herein, we built a short-circuited CPW structure to characterize the MNA chip with small volume. The experimental results were compared with the Kittel equation. Three magnetic nanowire chips with different volumes were measured to determine the effect on FMR absorption and frequency extraction. Based on the detection limitation of the vector network analyzer (VNA), the requirements of material volume and the magnetization are presented.

II. Measurement System Setup

The FMR measurement system in Fig. 1a contains a CPW test circuit, MNA sample chips, two poles from an electromagnet, and a VNA. The cobalt (Co) nanowires were grown in an aluminum oxide (AAO) template with 9% porosity and 40nm diameter pores using the electrodeposition process in [3]. The pH value of precursor solution is 2. Herein, Co114 is used with a nanowire length of 0.534μm and a chip width of 1875μm. Three chips are formed - large, medium and small, with chip lengths of a) 3mm, b) 481μm and c) 220μm, respectively. The large, medium and small chip volumes are $\mathbf{3 \times 10^{-3}}$ mm3, $\mathbf{4.8 \times 10^{-4}}$ mm3 and $\mathbf{2.2 \times 10^{-4}}$ mm3, respectively. A short-circuited CPW test circuit, shown in Fig. 1b, was designed on 0.254mm Duroid 5880LZ ($\varepsilon_r = 2$) to have signal line width of 391μm, gap width of 150μm and trace length of 8mm. The CPW test circuit with MNA chip on top was 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 reflection coefficient (S_{11}). FMR absorptions were measured in DC field domain that used a fixed AC field frequency in fast continuous wave (CW) mode with a DC field that was swept from +1.5T to -1.5T at a rate of 0.025T/s. The AC frequency was incremented in the range of 1-40GHz by the interval of 1GHz.

To reduce the interference from other magnetic material, a nonmagnetic cable (Cinch Connectivity Solutions) and connector (Southwest Microwave) were used for measurement. However, the fast CW mode doesn't support the calibration process. Thus, the FMR measurements were referenced to the VNA port without cable calibration.



(a) (b)

Fig. 1. (a) System diagram; (b) short-circuited CPW test circuit with Co114 (1875μm x 487μm)

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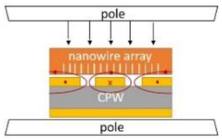


Fig. 2. A cross-section schematic of the CPW test circuit with MNA chip inside two poles to show field distribution in OP direction. The black solid line is the DC field direction, the red solid line is the AC field direction and the white line is nanowire axis.

FMR absorptions were measured in the Out-of-plane (OP) orientation, which means DC field is out of the plane of nanowire chip and along the nanowire axis. The AC field and DC field distributions of OP orientation are shown in the Fig. 2.

III. FMR Results and Analysis

The theoretical relationship of FMR frequency and DC field is expressed by Kittel equation (1), for magnetic nanowire in OP direction [2]:

$$\frac{f_R}{\gamma} = H + 2\pi M_s - 6\pi M_s P \qquad (1)$$

In (1), f_R is the FMR frequency, γ is gyromagnetic ratio with the value of 3.003MHz/Oe for Co, H is the external DC field, P is porosity of the chip with the value of 9% and M_s is saturation magnetization with the value of 1440 emu/cm3, which is obtained from the hysteresis loop measurement.

In Fig. 3, the comparison of experimental FMR response for different volumes chips and Kittel equation are shown. Herein, we use the mean difference to determine the average differences between the experimental data and Kittel equation to quantify how experimental data follows Kittel equation. The large chip FMR response has a mean difference of 0.865GHz and agrees well with the Kittel equation. The medium and small chips FMRs diverge more from the Kittel equation and have mean differences of 1.855GHz and 2.205GHz, respectively, more than twice of the large chip's value. This can be explained by the results shown in Fig. 4.

Fig. 4a shows that as the volume of material decreases, the FMR response possesses lower S_{11} magnitude related to the lower absorption. Fig. 4b shows the data after smoothing. In Fig. 4b, the FMR frequency points, based on the minimum value of the curve, vary for different volume chips. This is due to the fact that VNA noise power is a constant. Hence, as chip volume is reduced, the signal to noise (SNR) ratio decreases which introduces higher error for extracting the FMR frequency value.

Since the lowest detectable signal strength (S_{11} or S_{21}) of VNA is 0.0002, the small chip's signal strength, around 0.00017, has already reached the detection limit. Thus, the FMR error is expected to be high and is confirmed with the mean difference calculations. To detect FMR response accurately for this VNA system, the Co volume should be greater than 2.2×10^{-4} mm3 and magnetization should be larger than 317μemu.

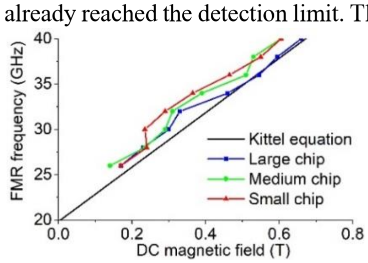
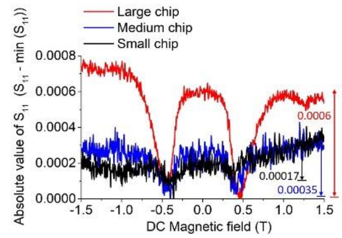
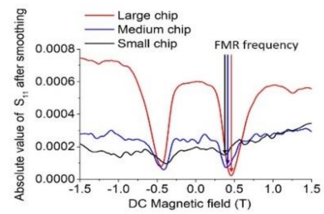


Fig. 3. The comparison of experimental FMR response and Kittel equation (P = 9%) in the OP orientation



(a) The absolute value of S_{11}



(b) The absolute value of S_{11} with smoothing span value of 0.07

Fig. 4. The FMR response for three volumes of Co114 at 34GHz in the OP orientation.

IV. Conclusion

This paper shows a FMR characterization system for small volume MNA chips on short-circuited CPW circuit. The FMR results of Co114 chip with large volume agrees well with Kittel equation with difference mean of 0.865GHz. The lower volume measurement chips diverge more from FMR response to Kittel equation. With lower volume of material, the lower SNR of FMR response introduces more error for extracting the FMR frequency. To detect the FMR response, the volume of Co should be greater than 2.2×10^{-4}mm3 and the magnetization should be larger than 317μemu. A sensitive nanolabeling system for low volume biosensing applications can be built based on this FMR characterization technique.

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