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Submicrometer-sized slotline and coplanar waveguide devices were used for ferromagnetic resonance (FMR) measurement on submicrometer-sized magnetic fine particles. FMR measurements were taken on individual magnetic disks, having diameters ranging from 50 to 1 μm , using either a slotline-coplanar waveguide (CPW) junction device or a coplanar waveguide transmission line junction device. The magnetic samples were etched from a 105 nm thick amorphous $\text{Fe}_{80}\text{B}_{15}\text{Si}_5$ film on a quartz substrate. Absorption modes, which were measured with the submicrometer-sized slotline CPW, followed the Kittel magnetic resonance model for frequencies from 1 to 20 GHz for the 1 μm diam disk. By detecting the second harmonic of the lock-in amplifier's reference signal, we have measured disk samples as small as 1 μm in diameter. We estimated that the sensitivity is of the order of 3×10^9 spins, almost four orders of magnitude better than the sensitivity of a standard electron paramagnetic resonance system. © 1997 American Institute of Physics. [S0021-8979(97)65608-X]

INTRODUCTION

There is growing interest in producing and measuring nanostructured materials due to their unique properties and their potential use as microwave sensors. Standard ferromagnetic resonance (FMR) cavity measurement techniques do not have sufficient sensitivity to measure individual nanometer-sized particles, or even individual micron-sized particles at microwave frequencies. In this paper, we present a measurement technique that allows for the detection of ferromagnetic resonance signals from 0.1 to 20 GHz of very fine magnetic particles with volume as small as 10^{-13} cm^3 .

One standard technique for measuring FMR is to use an electron paramagnetic resonance (EPR) system. An EPR system requires relatively large samples $2 \times 10^{-6} \text{ cm}^3$. In this technique, large microwave magnetic fields are necessary to compensate for the small microwave absorption per unit volume of typical samples, leading to the use of microwave cavities. The sensitivity of a microwave cavity-based FMR measurement, as measured by the number of detectable electron spins, is typically given as $10^{13} \Delta H$ spins, where ΔH is the resonance absorption linewidth, and the input microwave power to microwave cavity is 1 mW. Magnetic particles having micron dimensions will possess 10^9 electron spins or less, making FMR measurements on individual micron-sized particles difficult if standard cavities are to be used for FMR detection.

Microwave cavities have now been replaced with planar microwave transmission devices that have submicrometer-sized junctions in order to measure FMR on submicrometer-sized magnetic samples. The advantage of a planar device is that it is ideally suited to magnetic thin-film samples. Typically, a planar device sends microwave energy down an input slotline transmission line that ends at a shorted discontinuity. A large microwave magnetic-field component parallel

to the device plane exits at the slotline termination, which is used to couple into the magnetic film. The termination of the slotline is separated from a collinearly aligned coplanar waveguide (CPW) transmission line. The separation between the two transmission lines is a metallic strip in the order of 1 μm . The two planar transmission lines are coupled to each other via the magnetic film, when the film is placed on top of the coupling region on the narrow strip. In the case of the frequency of the microwave field coinciding with the internal precession frequency, there is a strong ferromagnetic resonance. The coupling between the two transmission lines is stronger than when the magnetic material is biased at off resonance. This is due to the precession of the magnetization.

In contrast to microwave cavities, the quality factor of these devices is small, and there are few constraints on the sample size or geometry. In addition, these devices show broad frequency bandwidth, such that a single device can be used in taking FMR resonance in the junction region from 1 to 20 GHz. It can be said that the microwave field excitation is nonuniform near the junction region. Neither the slotline nor the CPW transmission line propagates pure transverse electromagnetic (TEM) modes. The dominant slotline propagation mode has large magnetic-field components along the slotline axis, while the dominant propagation mode for the CPW is approximately TEM, with small magnetic-field components along the CPW axis. Overall, the propagation modes for the two transmission lines are roughly orthogonal. This causes strong reflections from the junction region, such that typical devices show an isolation of greater than 20 dB between the input and output ports. However, the axial magnetic-field components do provide a small coupling between transmission lines, which can be modified by adjusting the junction spacing.

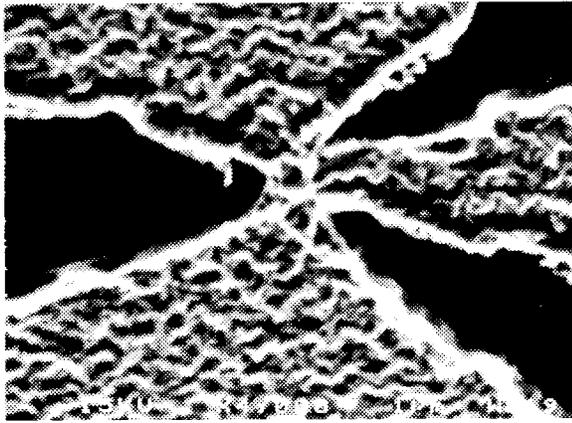


FIG. 1. Electron micrograph of the central slotline-CPW junction region.

Since both the CPW and slotline transmission lines have elliptically polarized magnetic fields, they can be strongly coupled to magnetic media. Placement of a magnetic sample on the junction region changes the coupling of microwave energy across the junction region through the intermediary circularly polarized precession of electron spins in the sample. Thus, the transmitted power depends upon the sample conductivity and magnetic permeability, where the latter can be modified through application of an external magnetic field. For large samples, resonant absorption modes can be directly measured by taking the difference in swept-frequency transmission measurements at two different magnetic fields. To further increase the sensitivity of FMR measurements using planar microwave devices, we have fabricated devices where the transmission line junction area was reduced one-million fold using a tapered slotline and CPW. We believe this change greatly concentrates the microwave magnetic-field intensity in the junction region, allowing microwave absorption measurements of much smaller samples than previous devices.

FABRICATION

The fabrication process was as follows: First, a $1\text{-}\mu\text{m}$ thick copper ground plane was deposited onto an optically polished fused quartz wafer. The wafer was then coated with photoresist and the central junction region was written using a scanning electron microscope with pattern generation software. After removing the exposed resist, the circuit was dry etched by an ion-beam milling system. Figure 1 shows an electron micrograph of the central slotline-CPW junction region, where the lighter region is metallized and the darker areas show the exposed dielectric substrate. Here, the tapered slotline comes in from the left, while the CPW is at the right. The metallized region appears rough because of the photoresist layer, which was hardened during the ion-beam milling process. Figure 2 shows the electron micrograph of the central CPW junction region.

Test samples were fabricated from a 105 nm thick amorphous $\text{Fe}_{80}\text{B}_{15}\text{Si}_5$ film, deposited on optically polished fused quartz by ion-beam sputtering. Ferromagnetic resonance measurements, taken on 5 mm diam disks by an X-band

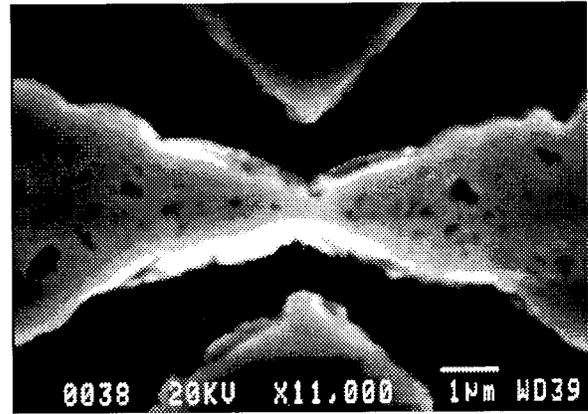


FIG. 2. Electron micrograph of the central CPW junction region.

microwave cavity at 9.51 GHz , gave values for the Lande g factor and effective magnetization ($4\pi M_{\text{eff}}$) and in-plane uniaxial anisotropy field (H_A). $H_A=40\text{ Oe}$, $g=2.05$, and $4\pi M_{\text{eff}}=16\text{ kG}$. The in-plane FMR linewidth (ΔH) was 38 Oe . Another piece cut from the film had disks ranging in diameter from 1 to $50\text{ }\mu\text{m}$, fabricated on it using electron beam-writing and wet-etching procedures.

EXPERIMENTAL SETUP

The slotline-CPW circuit was set up in a standard FMR measurement geometry, with the applied magnetic field being provided in the film plane by a rotatable electromagnet. A continuous wave sweeper source (HP8350) tunable from 100 MHz to 20 GHz was used as the microwave source. Microwaves were sent into the device through the slotline port, with the power transmitted through the junction region and coplanar waveguide. FMR measurements were taken at frequencies from 2 to 20 GHz . Signal sensitivity was enhanced using a 1 kHz modulation field. The FMR signal was then measured using a lock-in amplifier tuned to the second harmonic of the modulating frequency.

FMR measurements were taken on each disk by centering it on the junction region with the assistance of an optical

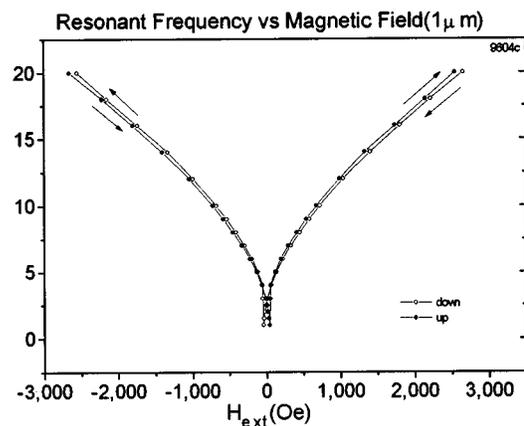


FIG. 3. The measured resonant frequencies vs fields on $1\text{ }\mu\text{m}$ disk.

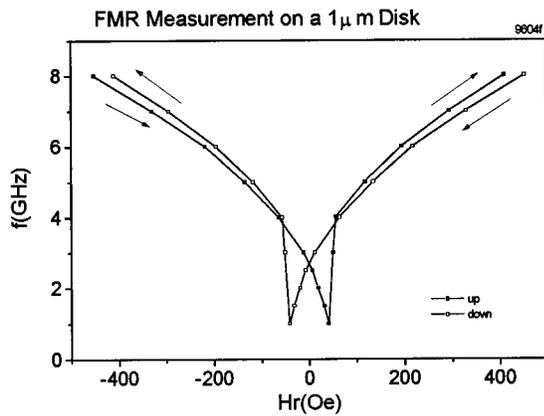


FIG. 4. The low-field region of Fig. 3.

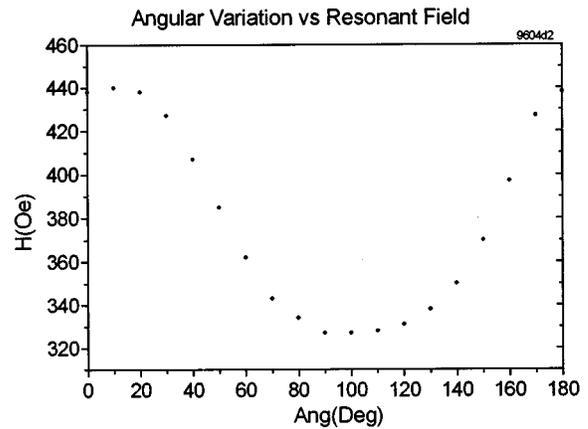


FIG. 5. The measured H field with angular variation.

microscope. The disk was oriented such that the previously determined film easy axis lay transverse to the slotline-CPW axis and collinear with the applied field. Only one disk lay near the transmission lines in this geometry. No FMR signal was obtained unless a disk overlapped the junction region.

These measurements were taken at a sweeper-source power setting of 10 mW, with a 1 kHz modulation field of 20 Oe, and at lock-in amplifier sensitivity and time-constant settings of 1 μ V and 100 ms, respectively. The lock-in amplifier was tuned to 2 kHz (second harmonic, $2F$). Absorption modes were best resolved at frequencies above 6 GHz, where they showed a symmetric line shape and good signal strength.

The expected behavior for this material can be obtained from the Kittel resonance equation

$$\omega = |\gamma| \sqrt{(H_{\text{ext}} + H_A + 4\pi M_{\text{eff}})(H_{\text{ext}} + H_A)}. \quad (1)$$

SECOND-HARMONIC DETECTION METHOD

In the experiment, we detected the first harmonic of the modulation frequency using a lock-in amplifier. We also detect the second harmonic of the modulation frequency using the same lock-in amplifier. With this method, we were able to measure the second-harmonic response of the magnetic film. For our application, 1 kHz was used for modulation and the modulating field was 10 G.

It is clear that the first harmonic closely matches the first derivative with respect to field and the second harmonic closely matches the second order of the derivative with respect to magnetic field. This means that we measure the second derivative of the voltage signal with the second-harmonic response of the measured system.

EXPERIMENTAL RESULTS

If we sweep forward and backward and measure the second derivative at different frequencies we obtained fields with respect to frequency. Figures 3 and 4 show the measured relationship of resonant field and resonant frequency. Figure 5 shows the angular variation of the FMR measurement from 10° to 160° for the 1 μ m sample.

CONCLUSION

In conclusion, slotline-CPW devices or CPW transmission line devices having very small junction regions have been used for FMR measurements of individual disks of amorphous $\text{Fe}_{80}\text{B}_{15}\text{Si}_5$ ranging in diameter down to 4 μ m. The estimated number of spins in this sample was $3 \times 10^9 \Delta H$ spins, at an input power level of approximately 1 mW, which shows a sensitivity for this technique approximately four orders of magnitude better than standard cavity-based FMR measurements. Improved results are foreseen if higher dielectric substrates and better transmission line impedance matching are obtained. Both modifications should yield larger microwave magnetic-field intensities at the junction, further increasing the device sensitivity. Such refinements may make this technique a very good tool for understanding the properties of nanostructured materials, and, perhaps, also for biological samples.

¹H. Dotch, H. J. Schmitt, and J. Müller, *Appl. Phys. Lett.* **23**, 639 (1973).

²Vittoria, *Microwave Properties of Magnetic Films* (World Scientific, Singapore, 1993).