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High-sensitivity ferromagnetic resonance measurements on micrometer-sized samples

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Ferromagnetic resonance measurements were taken on a 4 μm diam disk using a planar microwave transmission line device. The absorption modes of a sample placed on this device can be measured by monitoring the microwave power transmitted across the device while a swept magnetic field varies the sample absorption through resonance. Results for the disk, which was etched from a 105 nm thick amorphous $\text{Fe}_{80}\text{B}_{15}\text{Si}_5$ film, followed the Kittel model over the frequency range from 2 to 20 GHz, in agreement with parameters measured on 5 mm diam disks by a microwave cavity. These results indicate the device has a sensitivity of $3 \times 10^9 \cdot \Delta H$ spins, almost two orders of magnitude better than microwave cavity measurements. © 1997 American Institute of Physics. [S0003-6951(97)00820-6]

There is growing interest in producing and measuring submicron magnetic particles in order to examine their unique properties and to appraise their usefulness for various applications. Unfortunately, many standard measurement techniques do not have sufficient sensitivity to measure individual micrometer-sized particles. These techniques must measure particle ensembles, where otherwise interesting results might be masked through volume averaging of the signal from each particle. One measurement technique that requires relatively large samples is ferromagnetic resonance (FMR). The sensitivity of typical microwave cavity-based FMR measurements, as measured by the minimum number of detectable electron spins, is typically given as $10^{11} \cdot \Delta H$ spins, where ΔH is the FMR absorption linewidth and the system power is 100 mW.¹ Unfortunately, magnetic particles having micrometer dimensions will possess 10^{10} electron spins or less, showing the difficulties that cavity-based FMR measuring techniques have for individual magnetic particles.

FMR measurements have also been taken using planar microwave transmission line devices as a replacement for the microwave cavity.^{2,3} These transmission lines are fabricated by selectively removing metal strips from metal-coated low-loss dielectric substrates. Microwave propagation then occurs along the strips in an otherwise continuous metal conductor. In this letter, we describe a method for performing high-sensitivity FMR measurements on individual micrometer-sized magnetic disks using a planar microwave transmission line device. Here, we first discuss the planar microwave transmission line device geometry and device fabrication, and then the FMR measurements on 4 μm diam sample disks.

Planar FMR devices are designed such that a slot line is the input transmission line, with a coplanar waveguide (CPW) being the output transmission line. These collinearly aligned transmission lines are shorted in a junction region, which appears in the center of the two schematics shown in Fig. 1. The top schematic [Fig. 1(a)] also shows the slot line

and CPW geometries, and the microwave magnetic-field (\mathbf{h}) patterns of their propagating modes. The slot line consists of a single strip, or slot, where the metal overlayer is removed from the dielectric. Since a voltage difference exists between the two metallic slot sides, the electric-field lines also span the slot. Slot-line magnetic-field lines extend vertically from the slot into both the dielectric and air, and have roughly elliptical field patterns spaced a half-wavelength apart. The coplanar waveguide consists of a pair of slots that separate a central strip conductor from the surrounding pair of ground electrodes. At low frequencies, the CPW magnetic-field pattern is that of a pure transverse electromagnetic mode, with the microwave magnetic-field pattern forming an ellipse about the central strip conductor. It is important to note that the low-frequency CPW mode is approximately orthogonal to the slot-line propagating mode. These orthogonal propagation modes mean the CPW effectively appears as a short to the input slot line, and causes the device to have an isolation of 30 dB or more between input and output ports.

The geometry of the junction region is the most important parameter for device performance. The microwave magnetic field at the shorted end of a slot line is predicted to have a large component normal to the device plane because of the large electrical currents that round the slot-line terminus.⁴ For a single shorted slot line in an otherwise continuous

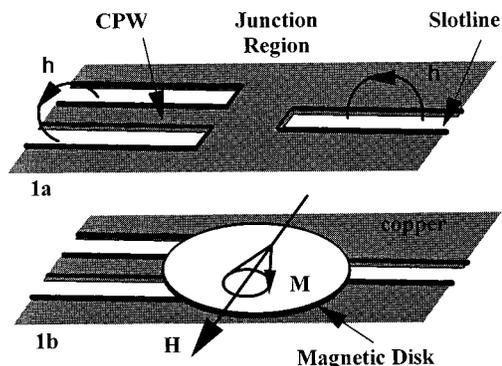


FIG. 1. These two schematics show the geometry of the slot line and CPW in the junction region (top) and the sample placement for FMR measurements (bottom).

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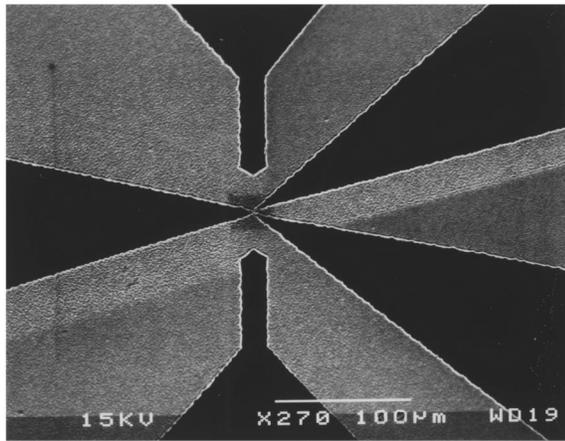


FIG. 2. An electron micrograph showing the junction region where a sample would be placed for testing. The dark slots show the geometry of the tapered slot line (left) and CPW (right).

metal plane, this normal-oriented microwave magnetic-field pattern is distributed over a large area around the slot-line terminus since the effective electrical length of the slot line extends a fraction of a wavelength into the metal. Placing the CPW close to the slot-line terminus effectively maintains the short, yet can greatly enhance the intensity of the normal-oriented microwave magnetic field since the electrical currents are now constricted within the junction region. Thus, it is expected that the shorter the junction region, i.e., the slot-line-to-CPW-terminus spacing, the higher the intensity of the normal-oriented microwave magnetic field in that region.

In order to perform FMR measurements on micrometer-diameter magnetic disks, it was found necessary to fabricate devices having junction regions of approximately $1 \mu\text{m}$ length. These devices were fabricated on copper metallized fused quartz wafers using a two-step process. First, a $1 \times 1 \text{ mm}$ area centered about the junction area was patterned using electron-beam lithography techniques, and then the metallization over the slots was dry etched by ion beam milling. This pattern was then matched to a larger mask, which was used in patterning the remainder of the $4 \times 2 \text{ cm}$ circuit using standard photolithography and wet-etching techniques. A micrograph of the junction region for one of these devices is shown in Fig. 2. Here, the dark areas are the exposed dielectric in the slots while the lighter, roughened areas are hardened photoresist that overcoat the copper metallization. The slot line enters from the left, while the CPW appears on the right. In order to meet the very small junction region dimension requirements, it was necessary to taper the slot line and CPW slots down to a point at their terminuses. Also appearing in Fig. 2 are additional etched areas above and below the junction region, which are employed to further constrict the electrical currents in the junction region.

The presence of intense microwave magnetic fields oriented normal to the device plane in the junction region are essential for FMR measurements. Figure 1(b) shows the placement of a magnetic disk over the junction region, where it overlaps both transmission line terminuses. In this geometry, it is expected that much of the microwave energy transmitted across the junction region is coupled through the sample, and thus, the device transmission is highly depen-

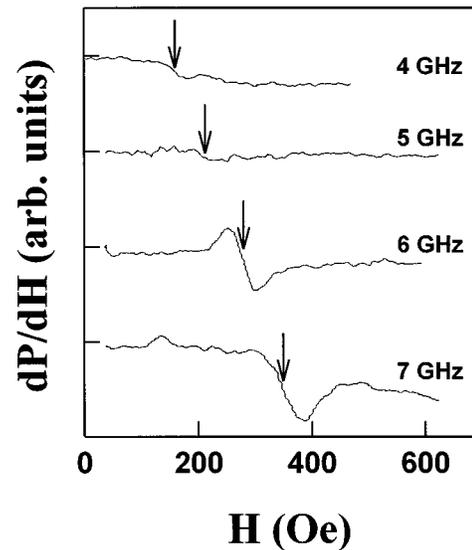


FIG. 3. FMR data are shown for the $4 \mu\text{m}$ disk. The arrows show the choices of H_r for each absorption mode.

dent on the sample microwave absorption. Resonant absorption modes are then generated by placing a magnetic field in the device plane. This was done experimentally by mounting the device in the gap of a rotatable electromagnet.³ The microwave source was a continuous-wave sweeper source, with measurements being taken at set frequencies from 2 to 20 GHz. The microwave power transmitted across the device was passed through a microwave amplifier before being rectified by a diode detector. Following standard FMR practice, a modulating magnetic field was superimposed on the static magnetic field to increase the signal sensitivity using phase-loop lock detection techniques. The resulting FMR signal was then collected from the lock-in amplifier.

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. X-band FMR measurements on 5 mm diam disks gave values for the Landé g factor, effective magnetization ($4\pi M_{\text{eff}}$) and in-plane uniaxial anisotropy field (H_k) of $g=2.05$, $4\pi M_{\text{eff}}=16.1 \text{ kG}$, and $H_k=25 \text{ Oe}$, respectively. The in-plane FMR linewidth (ΔH) was 38 Oe. Another piece cut from the film had 12 disks, ranging in diameter from 1 to $50 \mu\text{m}$, fabricated on it using electron-beam writing and wet-etching procedures.

FMR measurements were taken on each disk by centering it on the junction region, such that the previously determined film in-plane easy axis lay transverse to the slot-line/CPW axis and collinear with the applied field. No FMR signal was obtained unless a disk overlapped the junction region, nor was a signal obtained for the $1 \mu\text{m}$ disk. Figure 3 shows differential power transmission (dP/dH) data taken on a $4 \mu\text{m}$ diam disk at integral frequencies between 4 and 7 GHz. These measurements were taken at a sweeper-source power setting of 60 mW and a 100 Hz modulation field value of 30 Oe. The transmitted power was strongly frequency dependent, ranging from 0.01 to 0.1 mW before amplification. The absorption mode strength was strongest near 6 GHz, with the signal strength being especially low for measurements above 8 GHz. Asymmetric line shapes are com-

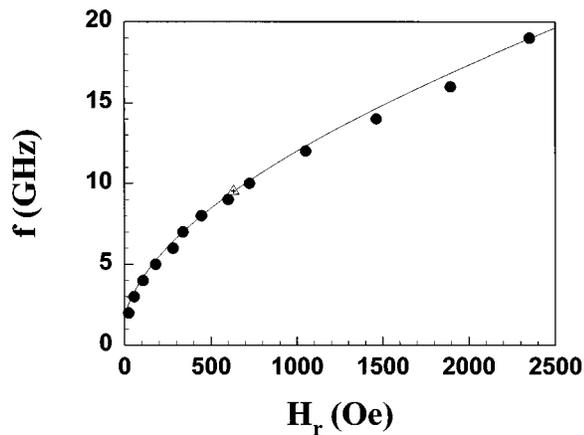


FIG. 4. The frequency dependence of the $4 \mu\text{m}$ disk resonant absorption field is shown. The triangle shows the microwave cavity result, while the line is the calculated dependence from cavity results.

monly observed for the planar FMR device, and can be attributed to inhomogeneous microwave field distributions in the sample disk.

Figure 4 shows the frequency (f) dependence of the resonant magnetic field (H_r) for the same $4 \mu\text{m}$ diam disk. The value of H_r was chosen from the data zero crossing before reaching the absorption mode minimum. Examples for the selection of H_r are shown by the arrows for each FMR spectra in Fig. 3. For high-frequency measurements, H_r was selected after repetitive signal averaging. The solid line shows the expected behavior for this material from the Kittel resonance condition

$$\omega = |\gamma| \sqrt{(H_r + 4\pi M_{\text{eff}} + H_k)(H_r + H_k)}, \quad (1)$$

where $\omega = 2\pi f$, γ is the gyromagnetic constant, and g , H_k , and $4\pi M_{\text{eff}}$ were the measured cavity results. Although the calculated curve lies above the data, the value of $4\pi M_{\text{eff}}$ should be reduced between 5%–8% compared to the 5 mm disk value because of the increased thickness/diameter aspect ratio of these tiny disks.

In conclusion, planar FMR devices have been used to measure the resonant absorption mode of a $4 \mu\text{m}$ disk of amorphous $\text{Fe}_{80}\text{B}_{15}\text{Si}_5$. This sample is estimated to contain $3 \times 10^9 \cdot \Delta H$ spins, indicating that this technique has a sensitivity almost two orders of magnitude better than standard cavity-based FMR measurements. Further improvements should be possible by using substrates having higher dielectric constants, and by better transmission line impedance matching in the tapered slots. Both modifications should yield larger microwave magnetic-field intensities in the junction region. Such refinements may make this technique a valuable analytical tool for understanding the properties of submicron magnetic particles, and perhaps also for biological samples.

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¹See, for example, J. A. Weil, J. R. Bolton, and J. E. Wertz, *Electron Paramagnetic Resonance* (Wiley, New York, 1994), p. 500.

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