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Author(s): B.J. Suh
P.C. Hammel
Z. Zhang
M.M. Midzor
J.r. Childress

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Ferromagnetic Resonance Imaging of Co Films using Magnetic Resonance Force Microscopy

B. J. Suh, P. C. Hammel, and Z. Zhang

Condensed Matter and Thermal Physics, Los Alamos National Laboratory, Los Alamos, NM

87545

M. M. Midzor, and M. L. Roukes

Condensed Matter Physics, California Institute of Technology, Pasadena, CA 91125

J. R. Childress

University of Florida, Gainesville, FL 32611

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Abstract

Magnetic resonance force microscope (MRFM) technique has been applied to the study of spatial imaging in thin Co ferromagnetic film. A novel approach is proposed to improve spatial resolution in MRFM, which is limited by the broad width of Co ferromagnetic resonance (FMR) line. We introduce a selective local field with a small YIG grain. We have performed MRFM detected FMR on a sample consisting of two sections of Co films laterally separated by $\sim 20 \mu\text{m}$. The experimental results demonstrate the scanning imaging capabilities of MRFM. The results can be understood qualitatively by means of the calculated magnetic field and field gradient profiles generated by the YIG sphere.

I. INTRODUCTION

It is getting more important to develop a proper tool for characterizing magnetic materials as the demand of the industrial applications of magnetic multilayer systems such as for recording heads and/or media increases. Developing a microscopic imaging technique in magnetically layered systems is one of the subjects with decreasing the size of the recording devices. FMR has a potential for the purpose with the advantage of strong signals and sensitivity to magnitude of interlayer exchange coupling. Nevertheless, microscopic FMR cannot be performed using conventional techniques because conventional FMR is performed in a uniform magnetic field so there is no means to identify the spatial origin of a particular contribution to the FMR signal.

Magnetic resonance imaging as presently practiced relies on the fact that the resonance frequency is an entirely local function of applied field, that is, $\omega(\vec{r}) = f[H(\vec{r})]$. Because of strong dipole couplings to neighboring spins in a ferromagnet, the resonance frequency at a particular spatial location is non-local, rather it is determined by magnetization of neighboring regions in addition to the value of the field applied at that point. Thus, imaging by means of an applied field gradient is not as straightforward as in the case of non-interacting spins.

We have recently demonstrated that microscopic FMR in yttrium iron garnet (YIG) films is achievable [1] if the FMR signal is detected with the highly sensitive magnetic resonance force microscope (MRFM) [2,3]. The MRFM mechanically detects the resonance signal by sensitively detecting the oscillatory response of a micro-mechanical resonator [4,5]. As in magnetic resonance imaging, the MRFM experiment is performed in a strong field gradient; this allows the MRFM to confine the excitation of spin precession to a well defined surface of constant magnetic field (i.e., a "sensitive slice") in which the resonance condition is met. However, we found that the FMR lines of YIG remained sharp (< 1 Gauss) in spite of the presence of an applied field gradient [1] which is inadequate to obtain imaging. In fact, Wago *et al.* [6] found that imaging in YIG by standard means involving an applied field

gradient was not successful. This is contrasted with the successful demonstrations of the microscopic imaging capability of the MRFM technique by means of electron spin resonance (ESR) [7] and of nuclear magnetic resonance (NMR) [3,8]. Therefore, it is still challenging to obtain high spatial resolution using FMR in magnetic materials, in particular, in metallic ferromagnets such as Co or Fe films because typical magnetic devices involve thin films composed of transition metals such as Co and Fe.

In this work we explore whether an applied field gradient can cause various portions of a thick Co film to resonate at distinct frequencies. We explore also alternative approaches of the MRFM technique to imaging using a spatially localized magnetic field source such as is used in magnetic force microscopy (MFM) [9]. Although this will not provide high resolution, probably no better than is presently achieved in MFM [9], it could enable microscopic determination of quantities such as the interlayer exchange coupling, quantities not obtainable through MFM measurements.

In principle, the spatial resolution Δz of magnetic resonance imaging (MRI) determined by intrinsic resonance line width ΔH_{lw} and applied field gradient $\partial H_{\text{applied}}/\partial z$:

$$\Delta z \simeq \frac{\Delta H_{lw}}{\partial H_{\text{applied}}/\partial z},$$

however sensitivity must be sufficient to observe signal from resolved volume. We have recently succeeded at observing Co FMR signals with the linewidth of the order of 100 Gauss using MRFM [10]. This is the case of non-interacting spins in which the resonance frequency is a local function of applied field. Thus we could identify a particular spatial location by means of an applied field gradient although the imaging in this Co film will require substantially larger field gradients due to the larger intrinsic FMR linewidth. Here we explore the requirements for spatial imaging of magnetic properties of Co films using magnetic resonance force microscopy. We present a scanning FMR image in thin Co film, achieved by introducing a *selective local field* with a small YIG grain.

II. EXPERIMENTALS

A. Sample

A sample consisting of two sections of Co films laterally separated, was prepared by sputtering method. The sample is deposited directly onto the Si cantilever which is commercially available for atomic force microscope (AFM) [1,11]. The two sections were obtained using a mask consisting of two $70 \pm 5 \mu\text{m}$ wide slits separated by $20 \pm 5 \mu\text{m}$. However, using an optical microscope it is found that one of the sections is deposited on the edge of the cantilever. The estimated sample profile is approximately $[20 \mu\text{m}(\text{Co})/20 \mu\text{m}(\text{separation})/70 \mu\text{m}(\text{Co})]$. Each section of Co film is $\approx 600 \text{ \AA}$ thick and is protected by depositing Ag layer on both side as described as $[\text{Si}(\text{cantilever})/\text{Ag}(35 \text{ \AA})/\text{Co}(600 \text{ \AA})/\text{Ag}(70 \text{ \AA})]$.

B. Measurements

FMR experiments in the above sample have been performed using, so called, the *perpendicular MRFM* set up [10] in which the oscillatory cantilever displacement is perpendicular to the axis of the bar magnet, in contrast to the conventional MRFM geometry where they are parallel [1,3,8,7]. This has advantage to lead smaller saturation and therefore, resonance fields, of order of hundres gauss by applying the magnetic field in the film plane [10]. This also makes it easy to sweep the field along the lateral direction of the film deposited on the cantilever. The simple diagram of the set up is also shown in Fig. 1.

Tunning and matching of FMR frequency, $f_0 \simeq 7.9 \text{ GHz}$, was achieved using microstrip resonator [10,12]. The cantilever frequency was $f_c \simeq 12 \text{ kHz}$ and the Q value was $\sim 10^4$ at 70 mTorr and at room temperature.

The sample position with respect to the bar magnet is fixed at $z \simeq 6 \text{ mm}$ (horizontal position of the sample from the bar magnet) at $x \simeq 1 \text{ mm}$ (vertical position from the cylindrical axis of the bar magnet) as described in Fig. 1. The size of the bar magnet is 6.35

mm ($\frac{1}{4}$ inch) long and 6.35 mm ($\frac{1}{4}$ inch) in diameter. The scanning field is obtained using a solenoid magnet with the scan range, $-300\text{G} \sim 300\text{G}$.

An approximately spherical shape of YIG grain with an estimated diameter, $d \sim 30 \mu\text{m}$, is mounted onto another cantilever and placed close to the sample as shown in Fig. 1. The vertical distance of the center of the YIG sphere from the sample is fixed at $\Delta x \sim 30 \mu\text{m}$. The relative position of the YIG grain along the sample cantilever (z -axis) is denoted by Δz_{YIG} with respect to a certain reference as illustrated in Fig. 1.

Measurements were performed either by scanning solenoid field at each position of the YIG sphere (Δz_{YIG}) or by moving the YIG position (Δz_{YIG}) horizontally at fixed value of solenoid field.

III. RESULTS AND DISCUSSION

A. Calculation of magnetic field and field gradient

Figure 1 shows the simple diagram of the experimental set up and the calculated magnetic field and field gradient. From the expression for the magnetic force: $\vec{F} = (\vec{m} \cdot \nabla) \vec{B}$, we obtain:

$$F_x = m_x \frac{\partial B_x}{\partial x} + m_z \frac{\partial B_x}{\partial z}, \quad (1)$$

where \vec{m} is magnetic moment and \vec{B} is the total applied field. Since the applied field is almost parallel to the film plane, the m_z is dominant. Therefore, the first term in Eq. (1) can be neglected. The calculated results in Fig. 1 are only for B_z and $\partial B_x / \partial z$.

Note that the small grain of YIG is used to generate a selective local field since it has a small saturation magnetization value, $4\pi M_s = 1.6 \text{ kGauss}$. The small value of M_s is easily saturated at small field and therefore, is not affected by the change of the external field with moving the YIG grain with respect to the bar magnet.

As shown in the inset of Fig. 1, the YIG sphere lowers the field locally $\sim 100 \text{ G}$. Therefore, it is expected that the resonance spectrum from the region affected by the local field generated by the YIG sphere appears at higher solenoid field. Of interesting, it is found

that the magnitude of the field gradient increases and its sign changes in the region near the YIG sphere. This will give rise to the change of the phase of the additional spectrum by 180° compared to the spectrum from the other region.

B. FMR spectra and scanning image

Figure 2 shows representative in-phase FMR/MRFM signals obtained at several positions of YIG sphere (Δz_{YIG}) by scanning the solenoid field. Single FMR signal with the resonance linewidth $\cong 60$ G was observed when YIG sphere is positioned far away from the sample region. This indicates that the field gradient generated by the bar magnet is not sufficient enough to resolve the spectra from the two regions laterally separated by $\sim 20 \mu\text{m}$. In fact, the magnetic field gradient $\partial B_x/\partial z$ due to the bar magnet at the sample is ~ 0.2 G/ μm . For our ~ 100 long Co film, this corresponds to a 20 Gauss field difference across the sample (see Fig. 1) which is smaller than the observed resonance linewidth ($\cong 60$ Gauss).

By moving YIG sphere toward the sample region, an additional signal at higher field starts to appear as expected. The maximum shift of the additional signal with respect to the original one is $\cong 170$ G. This is a little larger than the value of the depth of the selective local field which is ~ 100 G (see the inset of Fig. 1). The considerable error in the calculation is ascribed to the lack of the information on the exact size and shape of the YIG grain as well as on the vertical distance of the YIG from the sample (Δx). The additional signal, however, are suppressed around $\Delta z_{\text{YIG}} = 70 \pm 10 \mu\text{m}$, indicating the YIG sphere is in the middle of two regions. The intensity of the additional signal recovers when YIG sphere is moving further to the other sample region, as expected.

Main characters of the additional signals shown in Fig. 2 are: (i) It is out of phase (π shift) with respect to the original signal. This is due to the change of the sign of the field gradient as seen from the calculation shown in Fig. 1. (ii) The signal amplitude is a little larger than that of the original. This is also explained as the effect of the local field gradient whose value is the larger in the region around the YIG sphere. In addition, the shift of the

additional signal with respect to the original one (see the open circle in Fig. 2) is observed to vary by moving the YIG sphere, discussed later.

MRFM signal intensity was monitored as a function of the position of YIG sphere (Δz_{YIG}) at a fixed value of the solenoid field $B = 90$ G (the average value of the various peak positions of the additional signal marked as dotted line in Fig. 2). The results are shown as a dotted curve in Fig. 3. The amplitude of the additional signal is considered to reflect the area of the Co film affected by the selective local field generated by the YIG sphere. Therefore, the amplitude can represent the sample profile.

As seen in Fig. 3, two regions are clearly distinguished: one is ~ 20 μm wide and the other is ~ 60 μm wide separated by ~ 15 μm , comparable to the estimated sample profile, [20 μm /20 μm /70 μm]. The amplitude of the first region is observed to be small compared to the second one. This is ascribed to the misreading of the signal amplitude due to the change of the peak position. In fact, a direct reading of the maximum value of the signal amplitude marked as solid circles in Fig. 2 reveals that the amplitude of the first region is comparable to that of the second one as shown in Fig. 3. This supports that the smaller amplitude of the first region obtained by scanning is a misreading due to the fluctuation of the peak positions as discussed above.

Now we discuss what gives rise to the change of the peak position of the additional signal (open circle in Fig. 2). Assuming that the YIG sphere, i.e. the selective local field, are placed in the middle of two regions, each region is affected only by the shoulder of the selective local field (see the inset of Fig. 1), giving rise to the smaller shift of the additional signal as observed. Therefore, the value of the shift can also represent the sample profile. However, since the magnitude of the local field is quite sensitive to the vertical distance of the YIG sphere from the sample due to its small size, a considerable error can also come from the instability of the vertical distance of the YIG sphere (the variation of Δx) when it is moving along the sample cantilever. From the value of the shift as a function of Δz_{YIG} , we could obtain a sample profile (the lower part of Fig. 3) less comparable to the known situation. This is ascribed to the instability of the vertical distance of the YIG sphere.

IV. SUMMARY

we present the FMR data which demonstrate the scanning imaging capabilities of MRFM technique. By scanning a selective local field generated by a small YIG sphere, we could construct the sample profile, $[20 \mu\text{m}/15 \mu\text{m}/60 \mu\text{m}]$. Considering the diffusive area of the sample expected for the sputtering and/or mask method, the obtained result describes well the sample with the estimated profile, $[20 \mu\text{m}/20 \mu\text{m}/70 \mu\text{m}]$.

The resolution of this method is limited by the size of the magnetic material which generates the selective local field. Improvement of the resolution by using a smaller YIG grain or a nanoscale magnet under developing as well as of the spatial stability of the scanning technique, will open up a new field of application of MRFM technique such as the study of the spatial characteristics of the in-plane magnetic recording materials and the domain properties of the magnetic materials. Note that the improvement of the spatial resolution may be achieved simply using a larger field gradient by reducing the diameter of the bar magnet in the conventional scanning MRFM [10]. However, the present method has the advantage to get a direct spatial information in view that the scanning small magnet can be used as a probe of the spatial coordinates.

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- [10] Z. Zhang *et al.*, preprint (1998).
- [11] Digital Instruments, 520 E. Montecito St, Santa Barbara, CA. The experiments reported here use type ESP cantilevers which are 450 μm long, 30-40 μm wide and 1-3 μm thick.
- [12] Reference to conventional microstrip design.

FIGURES

FIG. 1. Simple diagram of the set up and the calculation of the magnetic field and field gradient.

FIG. 2. Representative signals as a function of solenoid field at several positions of the YIG sphere: (\bullet) and (\circ) denote the position of the maximum amplitude and the center of the additional signal, respectively. The dotted line is the mark for the solenoid field where the scanning image is obtained by moving the YIG sphere as shown in Fig. 3.

FIG. 3. *Upper:* Dotted curve is a plot of the signal amplitude as a function of the position of the YIG sphere, Δz_{YIG} , at a fixed value of solenoid field $B = 90$ G. The curve with solid circles is a plot of the maximum amplitude of the additional signal. *Lower:* The curve with open circles is a plot of the shift of the additional signal with respect to the original one. The estimated sample profile is illustrated in the middle of the figure to be compared with the obtained scanning image.

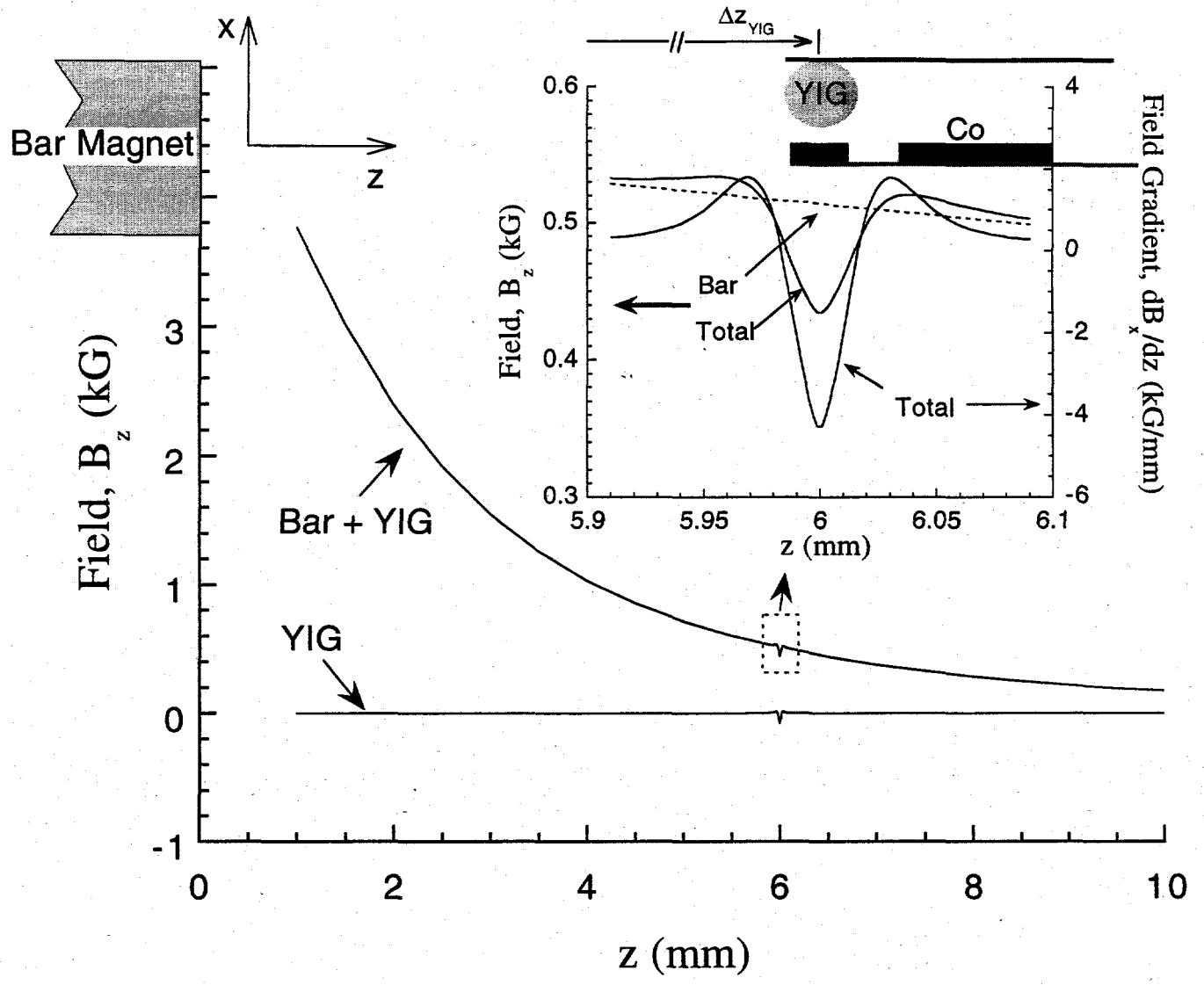


Fig. 1/3 (B. J. Suh et al.)

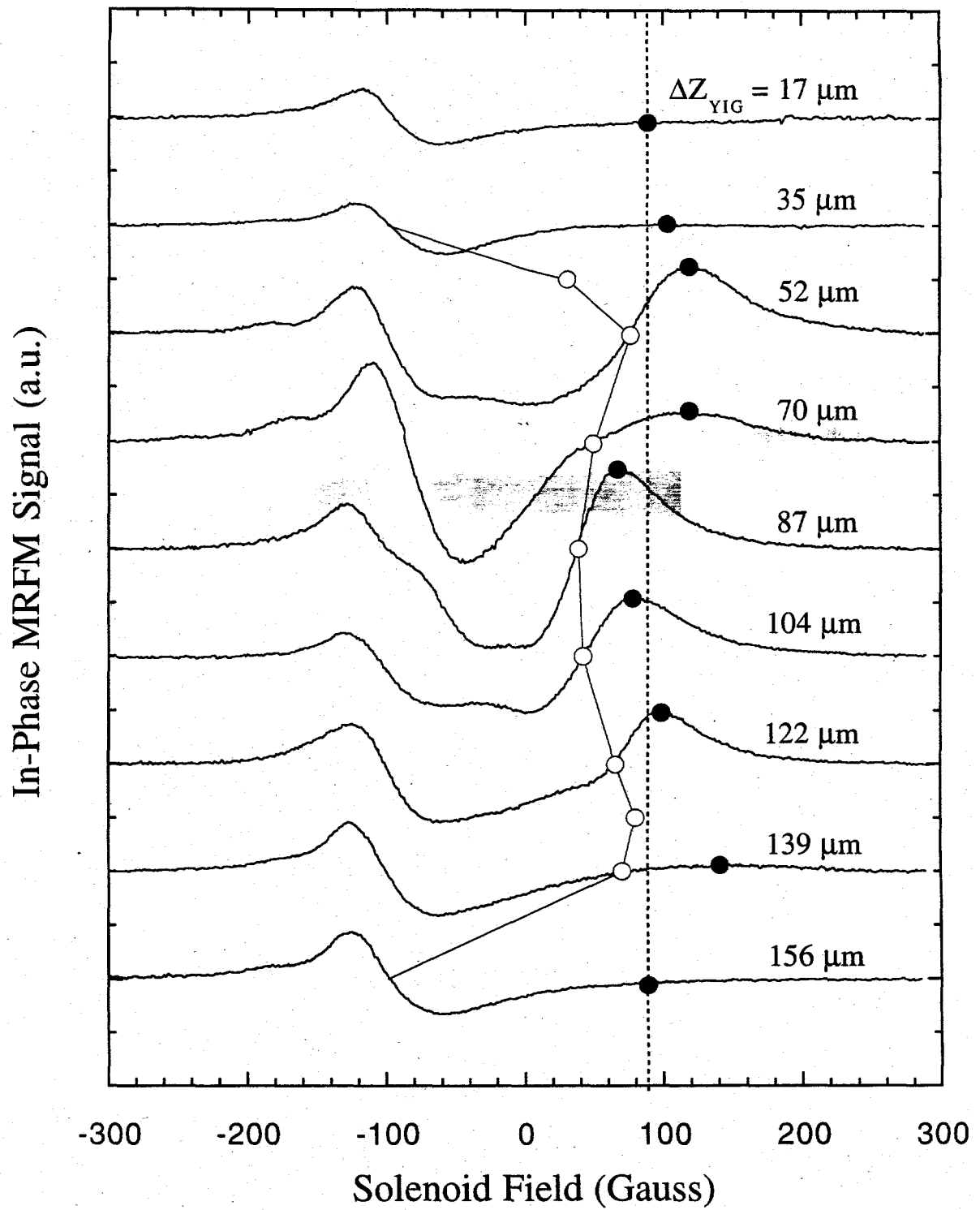


Fig. 2/3 (B. J. Suh et al.)

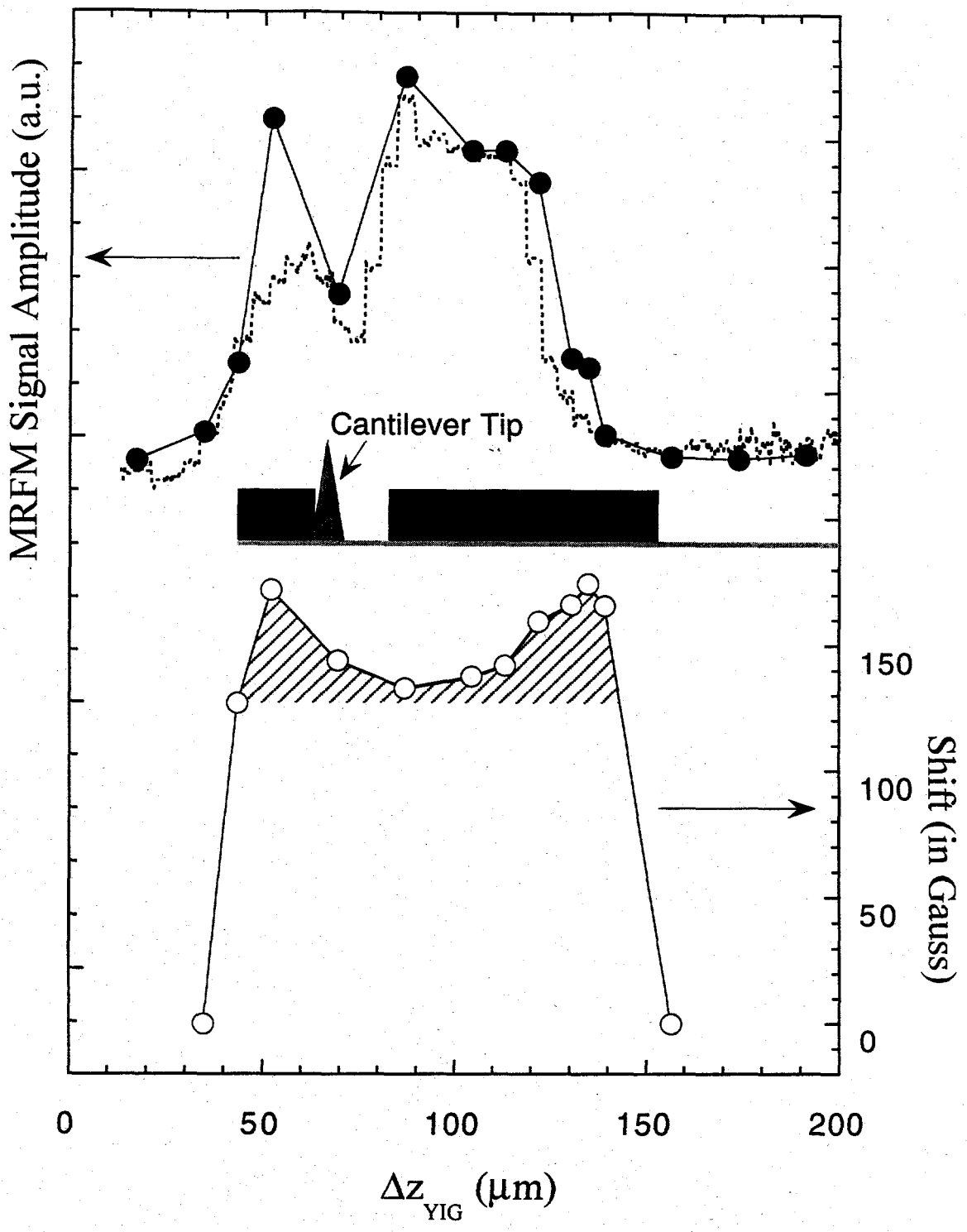


Fig. 3/3 (B. J. Suh et al.)