In the past several years, researchers have employed force-detected nuclear magnetic resonance to extend the resolution of magnetic resonance imaging (MRI) into the nanometer-scale [1]. In 2009, using a technique known as magnetic resonance force microscopy (MRFM), researchers made 3D images of individual tobacco mosaic virus with a resolution better than 10 nm [2]. The sensitivity of MRFM now surpasses the sensitivity of conventional, inductively-detected magnetic resonance by 8 orders of magnitude, allowing for the detection of small spin ensembles containing less than $10^4$ nuclear moments. This increased sensitivity has opened the door for MRI of structures that, until now, had been inaccessible to conventional techniques, e.g. individual virus particles, thin films [3], and – potentially – quantum dots (QDs).

The most recent implementations achieving the highest sensitivity [2–6] have utilized a sample-on-cantilever configuration with the sample affixed to the end of an ultra-sensitive Si cantilever having a spring constant typically on the order of $100 \mu N/m$. The sample is positioned within 100 nm of a FeCo magnetic tip in a “pendulum” geometry so as to avoid snap in to contact [7]. The magnetic tip is patterned on top of an RF microwire which acts as an RF magnetic field source.

One important limitation to the spin sensitivity is mechanical dissipation experienced by the cantilever in a static magnetic field. As MRFM experiments are carried out at elevated magnetic fields in order to saturate the magnetic tips, magnetic dissipation in the cantilever oscillator can significantly reduce the spin sensitivity of a measurement. For mechanical oscillators containing magnetic materials, dissipation that depends on magnetic field is expected and has been observed [8, 9]. Magnetic dissipation should not affect oscillators containing no magnetic material. Recently, however, it has been reported that the application of a magnetic field can cause significant mechanical dissipation in micro-mechanical cantilevers made of nominally non-magnetic Si [8, 10–12]. As shown in Fig. 1(b), this kind of dissipation has also been observed as a loss in mechanical quality factor $Q$ in some bare ultra-sensitive Si cantilevers used for recent MRFM. Its origin is likely the unintentional presence of impurities or defects with magnetic anisotropy, probably introduced during processing.

One way to eliminate this type of dissipation without having to eliminate the presence of magnetic impurities is to ensure that as the cantilever oscillates, it does not change its angle with respect to the applied magnetic field $B_0 = B_0 \hat{z}$, as seen in Fig. 1. We therefore show MRFM measurements of the statistical polarization of $^1$H in a polystyrene particle where we apply $B_0$ along the cantilever’s angular rotation vector. As shown in Fig. 2, the

![Fig. 1](image1.png)  
**FIG. 1:** A nominally non-magnetic $120 \, \mu m \times 4 \, \mu m \times 0.1 \, \mu m$ Si cantilever [14]. Quality factor $Q$ plotted as a function of magnetic field pointing perpendicular (i) and parallel (ii) to the lever’s angular rotation vector at $T = 4.2 \, K$.

![Fig. 2](image2.png)  
**FIG. 2:** (a) Experimental apparatus. Current flows in the microwire (red) along $\hat{z}$, while the lever displacement is along $\hat{y}$. Inset (b) shows an SEM image of an Si cantilever with a polystyrene sample and (c) shows a SEM of a microwire RF source with an integrated FeCo tip.
force detection apparatus is similar to the conventional apparatus described in [4] with the important exception of the orientation of \( B_0 \). A similar geometry for MRFM was first proposed by Marohn et al. in 1998 [13] in order to avoid magnetic spring effects and magnetic dissipation. Our apparatus, however, has the additional advantage of being compatible with the microwire RF sources and patterned magnetic tips designed for nanoscale MRFM.

The cantilever used in this experiment is 150 \( \mu \text{m} \) long, 4 \( \mu \text{m} \) wide, and 0.1 \( \mu \text{m} \) thick and includes a 1-\( \mu \text{m} \) thick mass on its end [14]. A droplet of polystyrene solution is affixed and cured onto the end of the cantilever resulting in a 2-\( \mu \text{m} \) sized particle [15]. The sample-loaded cantilever has a mechanical resonance frequency \( \omega_m = 2\pi \times 2.6 \text{ kHz} \) and an intrinsic quality factor \( Q = 5.0 \times 10^4 \) at \( T = 500 \text{ mK} \). Through measurements of the cantilever’s thermal motion, we determine its effective spring constant to be \( k = 120 \mu \text{N} / \mu \text{m} \). The microwire RF source and nano-sized magnetic tip are fabricated in a process similar to that described in reference [4]. The Au wire is 2.6-\( \mu \text{m} \) long, 1.0-\( \mu \text{m} \) wide, and 0.2-\( \mu \text{m} \) thick and is patterned atop a Si substrate. The FeCo tip deposited atop the microwire is 250 nm tall in the shape of a truncated cone with a diameter at the top and bottom being 270 nm and 510 nm respectively. The MRFM apparatus is isolated from vibrations and mounted in a vacuum chamber with a pressure below \( 10^{-6} \) mbar at the bottom of a continuous flow \( ^3\text{He} \) cryostat. The motion of the lever is detected using 100 nW of 1550 nm laser light focused onto a 10-\( \mu \text{m} \) wide paddle and reflected back into an optical fiber interferometer [16]. We damp the cantilever to a quality factor of \( Q \approx 400 \) in order to increase the bandwidth of our force detection without sacrificing force sensitivity [17]. The damping is realized using an optimal-control feedback algorithm implemented on a National Instruments FPGA board [18].

We measure the statistical polarization of \(^1\text{H}\) at \( T = 500 \text{ mK} \) in the polystyrene particle using the adiabatic rapid passage technique described in reference [4, 15]. Experiments are performed with \( B_0 > 2.5 \text{ T} \) such that the FeCo tip is fully magnetized along \( \hat{z} \). At these fields, the cantilever experiences no magnetic dissipation and maintains its intrinsic quality \( Q \) of \( 5.0 \times 10^4 \) far from the microwire surface. During the measurement, the sample at the end of the cantilever is positioned within 200 nm of the FeCo tip. Upon such close approach to the FeCo tip and microwire, interactions between the sample and the microwire surface begin to dominate the mechanical dissipation [19]; these effects reduce the cantilever \( Q \) to \( 1.5 \times 10^5 \). While this kind of dissipation can be minimized by using the appropriate coating on the end of the cantilever tip, it remains an important limit on MRFM sensitivity.

Magnetic resonance measurements performed with the sample positioned 150 nm above the FeCo tip are shown in Fig. 3(a). The lineshape of the magnetic resonance signal as a function of RF carrier frequency is seen to change as the sample is moved from being directly above the FeCo tip along \( \hat{z} \) in steps of 240 nm. A similar experiment, in which the sample is positioned to one side of the FeCo tip, such that its surface is about 80 nm from the closest point on the FeCo tip, is shown in Fig. 3(b). Here the magnetic resonance lineshape changes as the sample is moved away from the FeCo tip along \( \hat{z} \) in steps of 60 nm. The data, shown as points, demonstrate a narrowing of resonance line-shapes as the sample moves away from the FeCo tip indicating gradients exceeding \( 10^5 \) T/m within a 100 nm spacing [20].

In order to extract more detailed information from these resonances, a simple theory is constructed from a magneto-static model of the FeCo tip and an effective field model for adiabatic rapid passage in the manner of the appendix in reference [2]. The model’s input parameters include the geometry of the FeCo tip and sample taken from scanning electron microscope (SEM) images, the mechanical characteristics of the cantilever, and the form of the adiabatic sweep waveforms [15]. Using realistic parameters, we see a good agreement between our model and the data, especially considering our approximate knowledge of the morphology of the sample. The drop-like sample is modeled as a sphere with a radius of 625 nm, close to the radius of curvature observed by SEM. This agreement allows us to plot the likely field distribution around the FeCo tip in Fig. 4. In this figure, we show the surfaces of constant field around the FeCo tip for a saturating field \( B_0 \) pointing along \( \hat{z} \). In MRFM, these regions are also known as “resonant slices” since they describe the region in space occupied by the spins resonant with a particular carrier frequency \( \omega_{RF} \). \( \omega_{RF} / \gamma = B_{total} = |B_0 + B_{tip}| \), where \( \gamma \) is the gyromag-
The problem of snap in, which is typically due to electrostatic and van der Waals forces, is avoided here because while the cantilever is extremely soft along \( \hat{y} \), it is stiff along \( \hat{z} \), and extremely stiff along \( \hat{x} \).

The accessibility of the different resonant slice regions depicted in Fig. 4 allows for additional flexibility in future nano-MRI imaging experiments. The shape of the resonant slices and the distribution of the magnetic field gradients determines the point-spread function for imaging and therefore the resolution of the technique in each spatial direction. In region (a), for instance, strong gradients in \( \hat{x} \) provide high spatial resolution along this direction, while smaller gradients in the \( yz \)-plane reduce the resolution in those directions. Region (b), on the other hand, offers large gradients and high resolution in \( \hat{z} \) and reduced gradients and resolution in the \( xy \)-plane. The most recent high resolution imaging experiments have positioned the sample directly above the FeCo tip, achieving high spatial resolution in one direction and reduced resolution in the remaining two. By using the additional region next to the FeCo tip, the high spatial resolution could also be achieved in one more direction, allowing for a more complete high resolution image.

In order to measure the magnitude of \( B_1 \) we apply the spin nutation waveform described in reference [4, 15] to our microwire source. Pulses of variable length are inserted in the adiabatic sweep waveform every 500 cantilever cycles (190 ms), resulting in the spin nutation signal shown in Fig. 5. By fitting the data to a decaying sinusoid, we can infer that the rotating RF magnetic field \( B_1 \) exceeds 12 mT (510 kHz for \( ^1H \)) within 200 nm of the magnetic tip for \( T < 500 \) mK. The correlation time \( \tau_m \) of the spin signal was estimated from the signal bandwidth and found to be on the order of 500 ns. This value is significantly longer than the \( \sim 20 \) ms observed for \( ^1H \) in previous experiments on organic material [2], possibly due to the 3 times larger \( B_1 \) applied here [4]. Such a long \( \tau_m \) allows for the use of pulse protocols that can improve the signal-to-noise ratio and therefore the imaging resolution of nanoscale MRFM [5]. The generation of large \( B_1 \) fields is also an important technical achievement, since MRFM protocols utilizing adiabatic rapid passage must...
satisfy the adiabatic limit \((\gamma B_1)^2 \gg \omega_m \Omega_{RF}\) in order to produce a signal. Here \(\Omega_{RF}\) is the frequency modulation amplitude of the adiabatic sweep waveform. Nuclear species with low \(\gamma\) therefore require a large \(B_1\) in order to be observable by MRFM. In addition, nuclear resonances broadened by strain or other effects require large \(\Omega_{RF}\). Therefore this large measured \(B_1\) amplitude indicates that nuclear MRFM on previously inaccessible samples such as In or As nuclei in single self-assembled InAs quantum dots, could be possible.

Assuming a magnetic field gradient of greater than \(10^6\) T/m within 50 nm of our FeCo tip, and the low temperature force noise of our cantilever near the surface of less than \(10\) aN/√Hz, we estimate that our technique has a minimum detectable moment of \(1.0 \times 10^{-23} J T^{-1} Hz^{-1/2}\) at this distance. For In moments in InAs self-assembled QDs, for example, this value represents a sensitivity to the statistical polarization of an ensemble of \(1.6 \times 10^4\) In moments in a typical integration time of one minute [2]. Given that there are between \(10^4\) and \(10^5\) In nuclei in a typical self-assembled QD, these parameters promise that imaging of single QDs by MRFM should be possible.

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