



## Report Title

Final Report: Single Spin Readout for the Silicon-Based Quantum Computer

### ABSTRACT

This report presents research funded under ARO grant DAAD19-02-1-0310 and conducted during the time period of 07/15/2002 - 07/14/2006. In the course of this research we have made major advancements in the development of Magnetic Resonance Force Microscopy (MRFM) on the way towards its application as a single spin readout for the silicon-based quantum computer. The main achievement of this work is the demonstration of electron spin resonance (ESR) signal detection using MRFM with a sensitivity of better than ten fully polarized electron spins. This exceptional sensitivity was enabled by several advances in ultra sensitive MRFM detection: detection of ESR signal with with sensitivity of less than ten fully polarized electron spins, detection of the ESR signal of phosphorus donors in doped Si, demonstration of high magnetic field gradients from rare-earth nanomagnetic probe tips, fabrication of ultrasensitive MRFM force sensing cantilevers, development of light-free cantilever displacement-detection techniques, theoretical understanding of cantilever induced spin relaxation and of the MRFM probe-sample interaction, construction of novel MRFM equipment, and preparation of patterned samples for detection of phosphorus ESR in Si.

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### List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

#### (a) Papers published in peer-reviewed journals (N/A for none)

P. Chris Hammel. Seeing single spins. *Nature*, 430:300, July 2004.

D. Mozysky, I. Martin, D. Pelekhov, and P. C. Hammel. "Theory of spin relaxation in magnetic resonance force microscopy." *Applied Physics Letters*, 82(8):1278{1280, 2003.

Denis V. Pelekhov, Camelia Selcu, Palash Banerjee, Kin Chung Fong, P. Chris Hammel, Harish Bhaskaran, and Keith Schwab. "Light-free magnetic resonance force microscopy for studies of electron spin polarized systems." *J. Magn. Magn. Matls.*, 286:324, 2005.

A. Suter, D. V. Pelekhov, M. L. Roukes, and P. C. Hammel. "Probe-sample coupling in the magnetic resonance force microscope." *J. Mag. Reson.*, 154:210, 2002.

G.P. Berman, F. Borgonovi, G. Chapline, S.A. Gurvitz, P.C. Hammel, D.V. Pelekhov, A. Suter, and V.I. Tsifrinovich. "Application of magnetic resonance force microscopy cyclic adiabatic inversion for a single-spin measurement." *J. Phys. A*, 36:4417, 2003.

G. P. Berman, G. D. Doolen, P. C. Hammel, and V. I. Tsifrinovich. "Static stern-gerlach effect in magnetic force microscopy." *Physical Review A (Atomic, Molecular, and Optical Physics)*, 65(3):032311, 2002.

**Number of Papers published in peer-reviewed journals:** 6.00

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#### (b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

D. V. Pelekhov, I. Martin, A. Suter, D. W. Reagor, and P. C. Hammel. "Magnetic resonance force microscopy and the solid state quantum computer." *Proceedings of the SPIE - The International Society for Optical Engineering*, 4656:1-9, 2002.

**Number of Papers published in non peer-reviewed journals:** 1.00

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#### (c) Presentations

"Force-Detected Scanned Probe Magnetic Resonance Microscopy," presented at the March meeting of the American Physical Society, Montreal, Canada, March 26, 2004

"The Silicon-Based Quantum Computer," presented at the 3rd Annual Conference of the Southwest Quantum Information and Technology Network, NIST, Boulder, CO, March 8-10, 2002.

**Number of Presentations:** 2.00

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#### Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

0

**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

0

**(d) Manuscripts**

Number of Manuscripts: 0.00

Number of Inventions:

**Graduate Students**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	
Kin Chung Fong	1.00	No
Inhee Lee	1.00	No
<b>FTE Equivalent:</b>	<b>2.00</b>	
<b>Total Number:</b>	<b>2</b>	

**Names of Post Doctorates**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	
Palash Banerjee	1.00	No
<b>FTE Equivalent:</b>	<b>1.00</b>	
<b>Total Number:</b>	<b>1</b>	

**Names of Faculty Supported**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
P. Chris Hammel		No
<b>FTE Equivalent:</b>		
<b>Total Number:</b>	<b>1</b>	

**Names of Under Graduate students supported**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	
Ross Steward	1.00	No
GINGRICH, ERIC CHRIS	1.00	No
ANGELINI, JOSHUA DYL	1.00	No
Kelty II, Stephen M.	1.00	No
<b>FTE Equivalent:</b>	<b>4.00</b>	
<b>Total Number:</b>	<b>4</b>	

**Names of Personnel receiving masters degrees**

<u>NAME</u>
<b>Total Number:</b>

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**Names of personnel receiving PHDs**

NAME

**Total Number:**

---

**Names of other research staff**

NAME

PERCENT SUPPORTED

Denis Pelekhov, Senior Research Sci 0.40 No

**FTE Equivalent: 0.40**

**Total Number: 1**

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**Sub Contractors (DD882)**

**Inventions (DD882)**

# Final Report: Single Spin Readout for the Silicon-Based Quantum Computer

P. Chris Hammel

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(Dated: January 3, 2007)

This report presents research funded under ARO grant DAAD19-02-1-0310 and conducted during the time period of 07/15/2002 - 07/14/2006. In the course of this research we have made major advancements in the development of Magnetic Resonance Force Microscopy (MRFM) on the way towards its application as a single spin readout for the silicon-based quantum computer. The main achievement of this work is the demonstration of electron spin resonance (ESR) signal detection using MRFM with a sensitivity of *better than ten* fully polarized electron spins. This exceptional sensitivity was enabled by several advances in ultra sensitive MRFM detection: detection of ESR signal with with sensitivity of *less than ten* fully polarized electron spins, detection of the ESR signal of phosphorus donors in doped Si, demonstration of high magnetic field gradients from rare-earth nanomagnetic probe tips, fabrication of ultrasensitive MRFM force sensing cantilevers, development of light-free cantilever displacement-detection techniques, theoretical understanding of cantilever induced spin relaxation and of the MRFM probe-sample interaction, construction of novel MRFM equipment, and preparation of patterned samples for detection of phosphorus ESR in Si.

## PERSONNEL

### Ohio State University

In addition to the PI, the following personnel were employed on this project:

Denis Pelekhov	Senior Research Scientist
Palash Banerjee	Postdoc
Iouri Oboukhov	Postdoc
Kin Chung Fong	Graduate Res. Asst.
Evan Frodermann	Graduate Res. Asst.
Yulu Che	Graduate Res. Asst.
Inhee Lee	Graduate Res. Asst.

### Collaborators

Collaborations with the following contributed to various aspects of the work.

M.L. Roukes	Caltech
K. Schwab	Cornell University
R. Movshovich	LANL
Ivar Martin	LANL
D. Mozysky	LANL
G. Berman	LANL
S. Lyon	Princeton University

## ULTRA-HIGH SENSITIVITY ESR MRFM SIGNAL DETECTION

The overriding goal of this project, ultrasensitive mechanical detection of electron spin resonance (ESR) was achieved: MRFM detection of ESR signals with excellent sensitivity of *better than ten* fully polarized electron spins was demonstrated. The experiment, performed at

$T = 4$  K on a  $\gamma$ -irradiated  $\text{SiO}_2$  sample having a paramagnetic defect density of  $2.0 \times 10^{18} \text{ cm}^{-3}$  employed a commercially available  $\text{Si}_3\text{N}_4$  cantilever [1] (spring constant  $k \approx 0.01$  N/m to which we attached a  $\text{SmCo}_5$  micromagnetic probe tip. Magnetic field gradients as large as 2.2 Gauss/nm were generated by this probe.

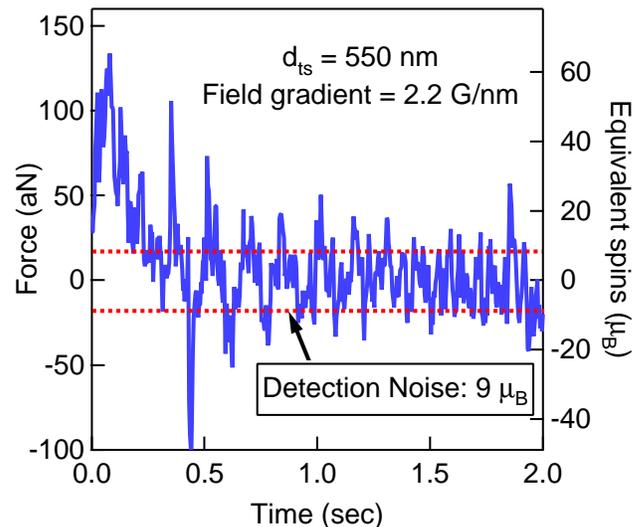


FIG. 1: ESR MRFM signal obtained using OSCAR spin manipulation technique using a high-gradient (2.2 Gauss/nm) probe magnet. The decay of the signal caused by electron spin relaxation can be seen. The *rms* noise floor of the measurement is  $9 \mu_B$ .

Such a high gradient enabled electron spin manipulation using the Oscillating Cantilever Adiabatic Reversals (OSCAR) technique [2] in which the electron spin orientation is cyclically inverted using cyclic adiabatic inversion; this relies on the modulation of the effective magnetic field seen by the spins in the sample that results

from the motion of the the high gradient tip as the cantilever oscillates. The 20 nm oscillation amplitude of the cantilever produced a magnetic field modulation depth of  $\approx 44$  Gauss. In the presence of RF radiation, this field modulation causes inversion of the direction of the effective field during each half cycle of cantilever oscillations. The modulation rate, equal to the mechanical resonant frequency of the cantilever, is slow enough for electron magnetic moments to follow the changing direction of the effective magnetic field as it rotates. As a result, the sample magnetization is continuously inverted in phase with the position of the end of oscillating cantilever. In turn, the interaction of the probe magnet on the cantilever with cyclically inverted electron spins generates as oscillatory force on the cantilever that shifts its mechanical resonant frequency. This shift is detected during an MRFM experiment using a specially developed DSP frequency detection system.

Fig.1 shows an example of such a signal. The signal was obtained with a probe magnet positioned within 500 nm from the sample resulting in 2.2 Gauss/nm probe field gradient. The frequency of the cantilever was continuously monitored during the modulation sequence. The peak frequency shift corresponds to a probe-sample interaction force from  $65 \mu_B$ . The signal decays with time due to electron spin relaxation. The *rms* noise floor of the measurement is  $9 \mu_B$ .

## SI ESR DETECTION USING MRFM

A second goal, detection of the ESR signal stemming from phosphorus donors in Si sample (See Fig. 2), was also demonstrated. A fragment of  $^{28}\text{Si}$  enriched membrane  $\approx (100 \mu\text{m})^2$  and  $\approx 9 \mu\text{m}$  thick was attached to the cantilever.  $^{28}\text{Si}$  enrichment was expected to result in decreased electron spin relaxation arising from nuclear spin  $1/2$   $^{29}\text{Si}$  isotopes. However, the ESR signal observed in the experiment was detected at low (4–10 K) temperature by means of cyclic saturation indicating that a spin relaxation time shorter than the cantilever period ( $\sim 100 \mu\text{s}$ ). The typical electron spin relaxation time  $T_1$  observed in phosphorus doped  $^{28}\text{Si}$  in conventional ESR experiments at similar temperatures is longer than 1 s. One explanations for the increased electron spin relaxation observed in our experiment light-induced relaxation due to the optical fiber interferometer used for cantilever displacement detection. Even weak irradiation with sub Si bandgap light (1550 nm) used in our interferometer can significantly reduce the electron relaxation time. This finding propelled our effort to develop light-free cantilever displacement detection for MRFM experiments.

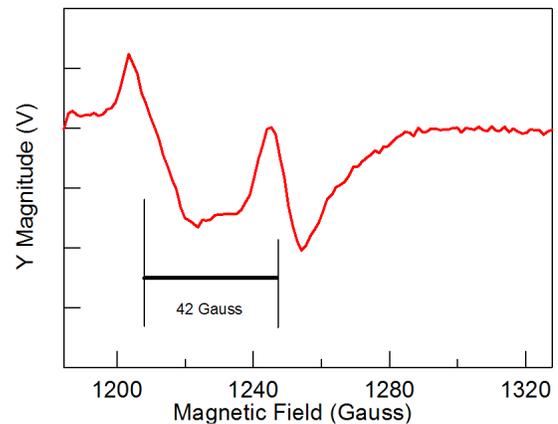


FIG. 2: ESR signal phosphorus spins in a phosphorus doped Si sample. The well-known doublet split by 42 G due to the hyperfine coupling to the nuclear spin is evident.

## HIGH GRADIENT MICROMAGNETIC PROBE TIPS

The micromagnetic probe on the MRFM cantilever provides the large field gradient needed to couple the sample spins to the cantilever and defines the region sample volume selected for study or manipulation. The high field gradient increases the force per electron spin and therefore improves sensitivity. The micromagnetic probe must also have high magnetic coercivity to minimize fluctuations of the tip that can contribute to unwanted sample spin relaxation, reduces damping of the cantilever in an applied magnetic field, and preserves magnetic properties of the probe magnet as the externally applied magnetic field is varied in the course of ESR measurements. Very high quality factor  $Q$  cantilevers are required in order to sensitively detect the tiny forces associated with individual electronic spins so minimal damping is essential.

Unfortunately, high coercivity magnetic materials such as, for example, NdFeB and  $\text{Sm}_2\text{Co}_{17}$  cannot be easily deposited on a cantilever unlike softer magnetic materials such as Co and NiFe. Therefore fabrication of high coercivity magnets are different from the techniques for fabrication of soft probe magnets. Each approach has advantages and disadvantages, so we developed both approaches.

*Hard magnetic materials* A particle of  $\text{Sm}_2\text{Co}_{17}$  or NdFeB is manually glued onto a commercial cantilever (Fig. 3a), a sharp point resulting in a high field gradient is formed by focused ion beam (FIB) micromachining (Various stages of FIB magnet preparation are shown in Fig. 3a and Fig. 4a). This approach is labor intensive and not suitable for batch fabrication. However the advantageous physical properties of the resulting probe magnet outweigh the ease of fabrication of probe magnets using

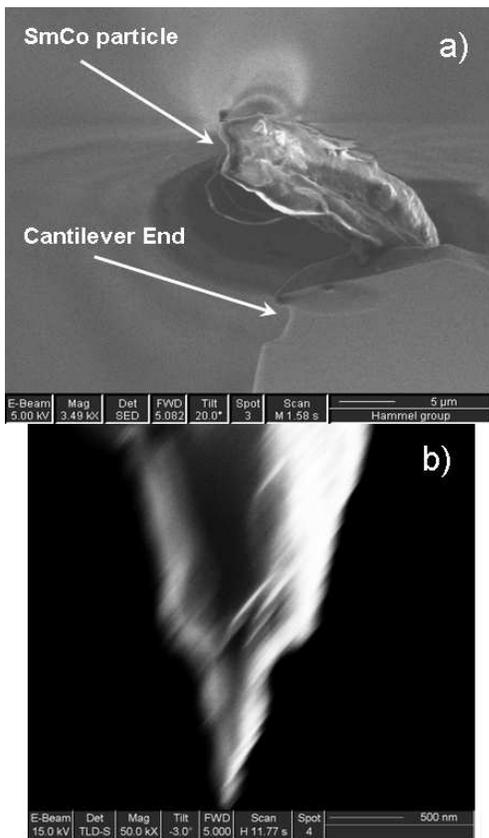


FIG. 3: Probe micromagnet fabrication. a) SmCo particle manually glued at the end of a commercial cantilever prior to focused ion beam (FIB) machining b) High-gradient probe micromagnet with tip diameter 50-100 nm fabricated via FIB machining.

soft magnetic materials. We have also explored use of spherical particles magnetic particles of the same hard magnetic rare earth materials (Fig.4b). This approach does not require FIB shaping, however, the dimensions of these micromagnetic probe tips are limited to commercially available particle sizes (typically a few  $\mu\text{m}$ ). Finally, the probe magnet is polarized in an eight Tesla magnetic field.

It has proven essential to develop sophisticated and sensitive techniques for studying the magnetic properties of these tiny moment micromagnets as a prerequisite to their successful development. We have developed a sensitive cantilever-based magnetometry technique for characterizing the micromagnetic probes at various stages of their fabrication as shown in Fig. 5a. We find that the probe magnets used for MRFM have a stable magnetic moment of the expected magnitude with coercive fields approaching 2 Tesla).

MRFM probe magnets with characteristic tip diameters as small 50-100 nm as shown in Fig.3b that generate magnetic field gradients as high as 2.5 Gauss/nm can be

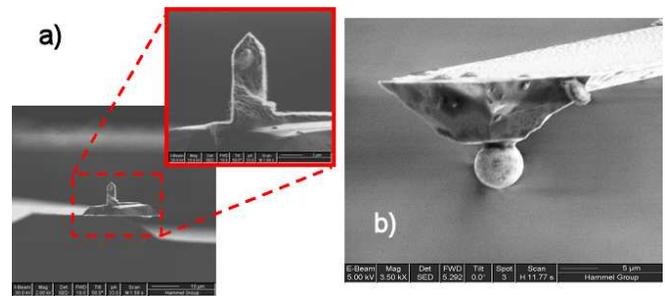


FIG. 4: Hard magnetic rare earth micromagnetic probe tips. a)  $\text{Sm}_2\text{Co}_{17}$  probe magnet shaped by FIB machining. b) Nd-FeB microsphere.

fabricated on a routine basis. On a soft micromechanical cantilever, this field gradient is sufficient for single electron spin detection.

*Soft magnetic materials* Micromagnetic probe tips composed of NiFe were electrodeposited on MRFM cantilevers by the group of M.L. Roukes at Caltech as shown in Fig. 5b. Suitable for soft magnetic materials, this approach allows parallel deposition of a large number of probe tips.

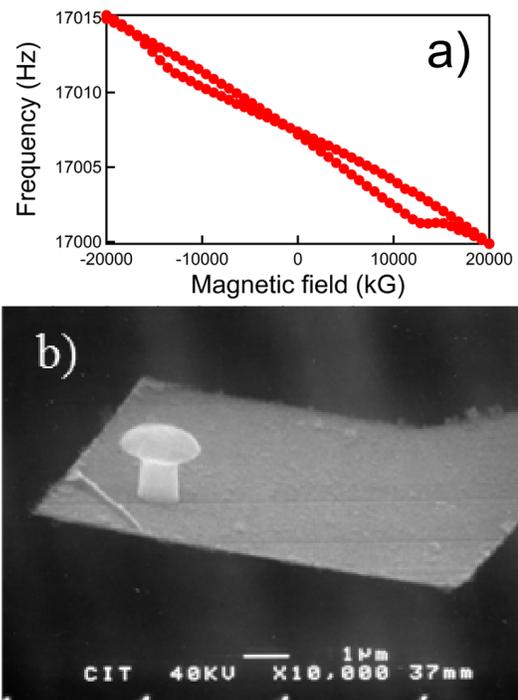


FIG. 5: Probe micromagnets. a) Vibrating cantilever magnetometry data obtained from a FIB fabricated  $\text{Sm}_2\text{Co}_{17}$  magnet at  $T = 4$  K. The constant slope of the frequency curve is indication of high coercivity. Measured magnetic moment of the particle is  $m = 3.5 \times 10^{-11}$  J/T. b) Electrodeposited NiFe micromagnet (Caltech)

## MRFM CANTILEVER DEVELOPMENT

Ultra sensitive MRFM signal detection requires specially designed cantilevers optimized to minimize thermal force noise  $F_n$ :

$$F_n = \sqrt{\frac{4kk_B T \Delta\nu}{\omega_0 Q}}.$$

Here  $k$  is the cantilever force constant,  $k_B$  Boltzmann's constant,  $T$  temperature,  $\Delta\nu$  the measurement bandwidth,  $\omega_0$  the resonant frequency of the cantilever and  $Q$  the cantilever quality factor.

Thermal noise will be minimized for a soft cantilever with a high resonant frequency. Since  $\omega = \sqrt{k/m_{\text{eff}}}$  extremely low mass cantilevers are needed.

One of the most serious barriers to ultrahigh mechanical detection of ESR arises because the micromagnetic tip needed for detection can cause the spins to relax prematurely. This is a very serious problem because it necessitates increasing one's detector bandwidth and hence increasing noise. We discovered [3] the detailed mechanism and solutions to the problem that were subsequently found to be successful in eliminating the excess relaxation. We found that thermally induced vibrations of the cantilever, and hence the ultrahigh gradient tip cause magnetic field fluctuations that the target electron spin to relax. We showed this problem can be solved by fabricating a cantilever loaded by a mass at its tip. This mass loading selectively suppresses the vibration of the problematic higher order modes of the cantilever thus reducing electron spin relaxation rate.

In the course of our work we have been pursuing fabrication of cantilevers optimized for high sensitivity MRFM experiments, *i.e.*, low mass cantilevers with a mass loaded tips. These custom cantilevers are fabricated by our collaborators in the group of M. L. Roukes at Caltech and in the group of K. Schwab now at Cornell University, formerly LPS.

Fig. 6 shows some examples of these cantilevers: Fig. 6a) shows a triangular cantilever fabricated at LPS ( $f_0 = 43.0$  kHz) and b) shows a mass loaded cantilever fabricated at Caltech ( $f_0 = 29.6$  kHz).

*Low spring constant cantilevers* Reducing their spring constant  $k$  improves sensitivity of MRFM detection cantilevers. Also since the cantilever frequency shift is inversely proportional to  $k$  it will be larger and so easier to detect for a soft cantilever.

The demonstration of nine electron spin detection sensitivity was achieved with a commercially available  $\text{Si}_3\text{N}_4$  cantilever with a spring constant of 0.01 N/m. Cantilevers with  $k$  0.001 N/m will increase detection sensitivity by a factor of ten thus allowing single spin MRFM sensitivity; such cantilevers are not currently available commercially.

To address this issue, we have custom fabricated such a cantilever in collaboration with the group of K. Schwab from The Laboratory for Physical Sciences of University of Maryland. The result of this collaboration is shown on Fig.7.

A series of Si chips (cantilever carriers) optimized to simplify cleaving the chips out of the wafer were batch fabricated. Each carrier contains four cantilevers 125–200  $\mu\text{m}$  long and 20  $\mu\text{m}$  wide; their estimated spring constants will vary between 1 and 5 mN/m. The actual spring constant of the cantilever will depend on the final thickness of the cantilever defined by the tolerance of the fabrication process ( $\sim 100$ –150 nm).

## LIGHT-FREE CAPACITIVE DISPLACEMENT DETECTION

At present optical interferometry is universally used for force detection of magnetic resonance force signals. This approach is undesirable for readout and characterization of a silicon quantum computer because the scattered light from the interferometer laser can reduce the electron spin decoherence time  $T_1$ . Irradiation of a sample even with low intensities of sub-bandgap light (sub-bandgap light is capable of ionizing shallow phosphorus donors) can re-

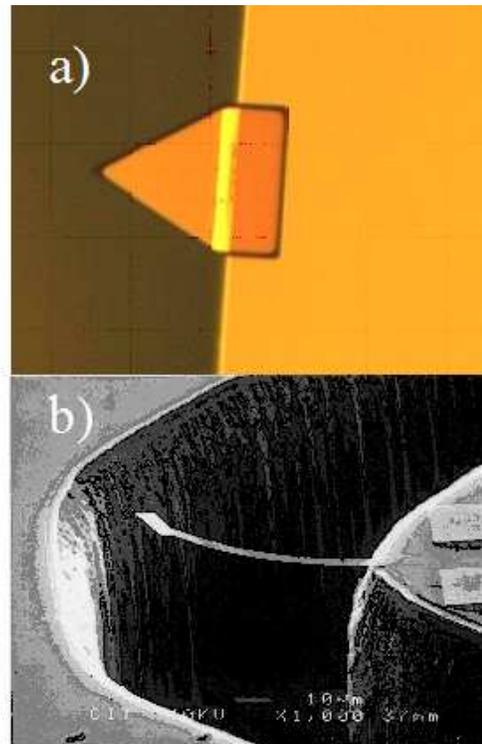


FIG. 6: Low mass MRFM cantilevers. a) Triangular cantilever fabricated at LPS  $f_0 = 43.0$  kHz b) Mass loaded cantilever fabricated at Caltech  $f_0 = 29.6$  kHz

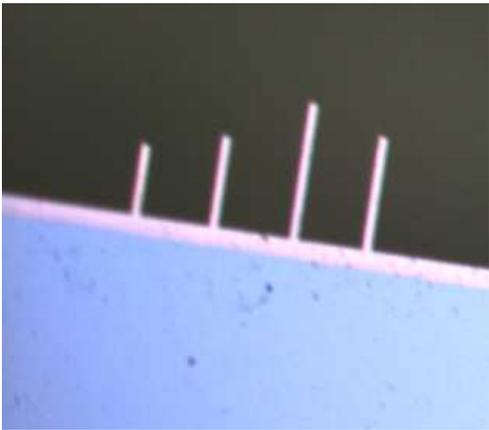


FIG. 7: Custom fabricated Si cantilevers with estimated spring constants of 1–5 mN/m. Each chip contains four cantilevers from 125 to 200  $\mu\text{m}$  long and 20  $\mu\text{m}$  wide.

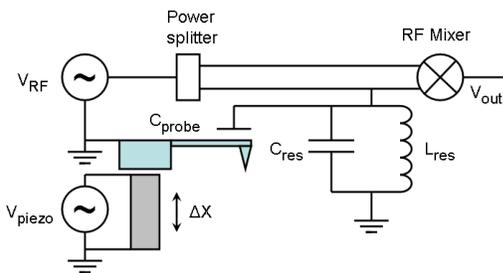


FIG. 8: Schematic diagram of a capacitively detected cantilever. A microstrip resonator operating at its resonant frequency of 2.5 GHz (represented here by a lumped LC circuit) is capacitively coupled to a micromechanical cantilever via a capacitive gap  $d$ . The cantilever is coated with 100  $\text{\AA}$  of gold for improved conductivity and is grounded. Motion induced changes in  $C$  shift the resonant frequency of the microwave resonator and hence the phase of the transmitted microwave signal relative to the carrier; this is detected by means of an rf mixer and a lock-in amplifier.

duce the electron relaxation time by orders of magnitude. In practice, it is difficult to completely shield the sample from the stray laser light, so it is important to develop an alternative detection scheme that doesn't employ optical radiation.

We have implemented MRFM displacement detection based on detecting the change in capacitance between a detection electrode and the MRFM probe separated by a gap  $d$  that changes with probe motion. For a  $\sim 100 \mu\text{m}$  long cantilever, the capacitance is  $C \sim 10^{-13}$  pf for a gap  $d = 1 \mu\text{m}$ . To match the excellent displacement detection sensitivity of optical interferometry ( $\sim 0.001 \text{\AA}$  displacements) we must detect of capacitance changes of the order of  $C \frac{\Delta d}{d} \simeq 10^{-20}$  pf.

*Microwave capacitance detection* Zeptofarad ( $10^{-21}$  F) detection sensitivity has been reported [4] by detecting

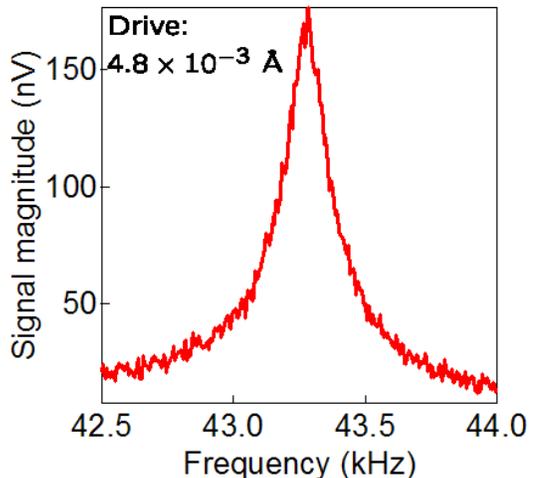


FIG. 9: Response of a triangular cantilever fabricated at the Laboratory for Physical Sciences to a piezo excitation detected via capacitive displacement detection. The demonstrated detector noise floor is  $5.0 \times 10^{-12} \text{m}/\sqrt{\text{Hz}}$ ; this corresponds to a force sensitivity of 80 aN/ $\sqrt{\text{Hz}}$ . The signal was acquired at  $T = 300$  K in vacuum.

the frequency shift of a microwave microstrip resonator that incorporates the capacitor. We demonstrated capacitive displacement detection to the MRFM by capacitively coupling a microwave resonator to the cantilever as shown schematically in Fig. 8. A 2.5 GHz microwave resonator is capacitively coupled to the micromechanical cantilever whose displacement changes the coupling capacitance and thus the resonant frequency of the resonator. This change is detected using standard microwave phase detection techniques. We estimate displacement detection sensitivity to be  $10^{-13} \text{m}/\sqrt{\text{Hz}}$ . Room temperature capacitive displacement detection of the displacement of the low mass cantilevers LPS triangular cantilevers (shown in Fig. 7) is shown in Fig. (9). The demonstrated detector noise floor is  $5.0 \times 10^{-12} \text{m}/\sqrt{\text{Hz}}$ , corresponding to a force sensitivity of 80 aN/ $\sqrt{\text{Hz}}$ . The signal was acquired at  $T = 300$  K in vacuum. We further demonstrated the first non-optical detection of MRFM signals at low temperature. Fig. 10 using this capacitive detection system installed in the  $^3\text{He}$  cryostat. This ESR signal was obtained from a DPPH sample at  $T = 4$  K.

*FET based detection* We have explored another possible approach to capacitive displacement detection employing an on-chip FET integrated with the cantilever. The work was done in collaboration with K. Schwab. The capacitance between the cantilever and the reference electrode (Fig. 11a) is detected through its modification of the channel conductance in the integrated on-chip with the micromechanical cantilever. The current sensitivity is  $\approx 100 \times 10^{-12} \text{m}/\sqrt{\text{Hz}}$  at 4 K.

## PROBE-SAMPLE INTERACTION

The interaction between the micromagnetic probe and the spin magnetization of the sample depends on several factors including the spatial variation of the magnetic field gradient of the probe, the shape of the sensitive slice (surface of constant magnetic field magnitude), the magnetic resonance approach used to introduce a time dependence to the spins located in the sensitive slice (e.g., field modulation, modulation of the frequency or the amplitude of the transverse microwave field) and the dynamics of the spins. We have calculated this interaction in detail using both analytical and numerical techniques [5] to provide essential inputs into MRFM image data deconvolution and interpretation.

Our key results include

- The probe produces a dipolar field that either augments or opposes the applied field depending on location of the target spin relative to the tip
- Within the sensitive slice the field gradient can change sign leading to cancellation of forces produced by spin magnetization residing at different points in the slice. The MRFM spectrum (dependence of the time-dependent spin force on the cantilever) has several distinctive features as a consequence:
  - The existence of a “zero-probe-field resonance” (ZPFR where  $B_{\text{applied}} = \omega_{\text{rf}}/\gamma$ ) due to all those spins far enough from the micromagnetic probe that the probe field is less than the intrinsic magnetic resonance linewidth. Because this describes a large number of spins, this produces a very strong signal in spite of the fact that the probe field gradient and hence the force exerted per spin is small.
  - Zeroes and changes in sign of the spectrum where

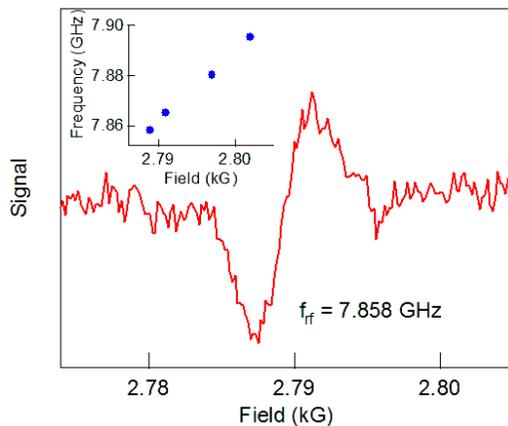


FIG. 10: ESR MRFM signal detected via capacitive displacement detection. The signal is detected from a DPPH sample at 4K. The insert shows the linear (as expected) field dependence of the ESR resonant frequency.

forces cancel and

- the presence of signal at applied fields greater than the ZPFR.
- These features underscore the importance of a new concept for force detected magnetic resonance imaging, the “force slice” related to but distinct from the better known “sensitive slice.”

The detailed understanding gained in this study is essential to analysis and interpretation of MRFM data. One particular application of this analysis is the development of a technique for precise measurement of the field of a micromagnet on sub-micrometer length scales.

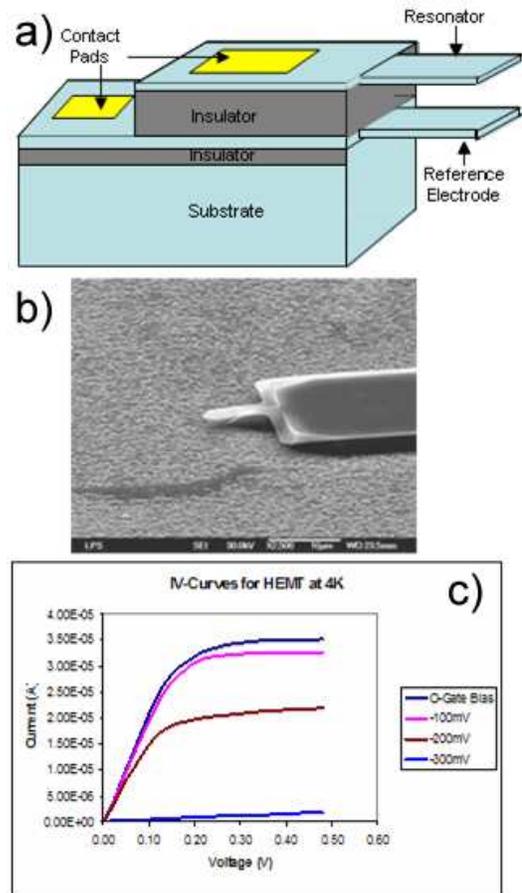


FIG. 11: a) Schematic diagram of the capacitively detected MRFM cantilever detection chip with integrated on-chip FET. b) Scanning electron micrograph showing a  $10 \mu\text{m}$  long,  $30 \text{ nm}$ -thick cantilever suspended over the substrate. c)  $I$ - $V$  curves for the FET fabricated on the chip; taken at  $T = 4.2 \text{ K}$

## SPIN RELAXATION DUE TO CANTILEVER FLUCTUATIONS

Single spin detection by Magnetic Resonance Force Microscopy requires close control over the electron spin dynamics so that they coherently drive the cantilever for period of time sufficiently long to provide a detectable signal.

For slowly relaxing samples, the cantilever is driven by rotating the sample magnetization at the cantilever resonant frequency. A drive force from the coherent spin magnetization must persist for length of time comparable to the inverse noise bandwidth—about one second for present cantilevers. It was thus very worrisome that we and others were finding spin relaxation times decreasing rapidly as the cantilever was brought close to the spins being measured (in order to increase the tip field gradient at the spin). The origin of this extra relaxation process was not understood and was the subject of intense study.

We realized that the mechanism for this relaxation originated in thermal fluctuations of the cantilever, and we devised a successful strategy for solving this problem [3]. Spin relaxation occurs as a consequence of magnetic fields  $B_{\perp}$  oriented perpendicular to the applied field that fluctuate at the resonance frequency  $\omega_{\text{eff}}$  of the spin in the local effective magnetic field:

$$\frac{1}{T_{1\rho}} = \frac{\gamma^2}{2} \int dt \langle B_{\perp}(0)B_{\perp}(t) \rangle e^{i\omega_{\text{eff}}t}$$

Because of the large field gradient  $\nabla B_{\text{tip}}$  of the micro-magnetic probe tip mounted on the on the cantilever, fluctuations of the cantilever position  $\delta z$  [characterized by their power spectral density  $S_z(\omega_{\text{eff}})$ ] produce magnetic field fluctuations  $\delta B$  in the sample that relax spins at a rate  $1/T_{1\rho}$ :

$$\begin{aligned} \frac{1}{T_{1\rho}} &= \frac{\gamma^2}{2} \sin^2\theta \int dt \langle \delta B(0)\delta B(t) \rangle e^{i\omega_{\text{eff}}t} \\ &= \frac{\gamma^2}{2} (\nabla_z B_{\text{tip}})^2 \sin^2\theta \int dt \langle \delta z(0)\delta z(t) \rangle e^{i\omega_{\text{eff}}t} \\ &= \frac{\gamma^2}{2} (\nabla_z B_{\text{tip}})^2 \sin^2\theta S_z(\omega_{\text{eff}}) \end{aligned}$$

Here  $\gamma$  is the gyromagnetic ratio and  $\theta$  is the orientation of the effective field relative to the applied field. Our calculations of the relaxation rate from this model compare very well with measured values.

It turns out that it is not thermally driven fluctuations of the fundamental mode that are the responsible for this relaxation, but higher harmonics of the fundamental. Fortunately, it is possible to suppress these higher harmonics while minimally altering the desired properties of the fundamental mode. This can be achieved by loading the tip of the cantilever with a mass approximately 1/10th of the cantilever mass. We calculated this would

increase the spin relaxation time substantially while reducing the fundamental mode frequency by only 10%. This suggestion has recently been employed by Dan Rugar et al. resulting in an increase in the spin relaxation time by almost three orders of magnitude that enabled  $\sim 10$  spin sensitivity.

## LAB CONSTRUCTION

This project moved from Los Alamos National Laboratory to the Ohio State University in July of 2002. The move involved building up the new laboratory in a space left by retirement from the Physics Department; this involved demolition, construction of pits and provision of clean power and reliable signal grounds.

The central apparatus for this research is a  $^3\text{He}$  refrigerated UHV MRFM that enables very low temperature ( $\sim 0.3$  K) experiments on samples with clean surfaces. The necessary vibrationally isolated and magnetically clean pits compatible with the cryogenic MRFM were put in place and a sophisticated cryostat support structure incorporating acoustic damping and active vibration damping was installed.

## DEVELOPMENT OF MRFM EQUIPMENT

In order to accelerate our progress toward a few spin MRFM experiment, we pursued a multi pronged parallel approach to equipment development. We have constructed three experimental cryostats:

- Ultra High Vacuum  $^3\text{He}$  cryostat
- Rapid-turn-around 4 K cryostat
- Dedicated room temperature apparatus for 3D MRFM imaging

### Ultra High Vacuum $^3\text{He}$ cryostat

The state-of-the-art Ultra High Vacuum (UHV)  $^3\text{He}$  cryostat is the major component of the program. This cryostat is capable of achieving temperatures as low as 300 mK. One of the unique features of this cryostat is its considerable cooling power of 10 mW at 500 mK. This feature is essential for flexibility in applying microwave radiation needed for electron spin manipulation in an MRFM experiment. The MRFM scan head installed in the cryostat has provisions for both vertical coarse approach and fine lateral and vertical scanning. This cryostat was used in the experiment where we have demonstrated ESR MRFM signal detection with sensitivity of *less than ten* fully polarized electron spins.

This  $^3\text{He}$  cryostat is optimized to meet the experimental requirements of the high sensitivity MRFM experi-

ment. However, the inevitable drawback of such a sophisticated apparatus is a fairly long turnaround time. To mitigate this problem we are also constructing two supplemental experimental setups: a simplified 4K cryostat and a room temperature apparatus.

### Rapid-turn-around 4 K cryostat

The most attractive feature of the 4K cryostat is the fast turn around time and low helium consumption rate. It has been constructed to accelerate the Si ESR measurements on Si:P samples. This top loading cryostat is equipped with a 5 kGauss solenoid. This system will allow high bandwidth, high sensitivity detection of MRFM signals. It has been used for high sensitivity (as opposed to ultra-high sensitivity) ESR experiments in phosphorus doped Si. This allowed us to develop the entire protocol of electron spin manipulation and MRFM signal detection in a fraction of the time it would have taken in the  $^3\text{He}$  cryostat. The room temperature apparatus has also been used to perform auxiliary tasks such as characterizing newly fabricated cantilevers, testing signal detection and analysis packages, etc.

### Dedicated room temperature apparatus for 3D MRFM imaging

A room temperature MRFM apparatus dedicated solely to development of 3D MRFM imaging has been constructed and tested. This apparatus is a standard “sample-on-cantilever” MRFM design for detection of electron spin resonance (ESR) signals. We use a 10-20  $\mu\text{m}$  particle of DPPH mounted on a  $\text{Si}_3\text{N}_4$  cantilever with a characteristic spring constant of 0.01 N/m. The high magnetic field gradient needed for MRFM is produced by a spherical NdFeB particle brought close to the sample. The scanning range needed for 3D MRFM imaging depends on the size of the probe magnet used in the experiment. The probe magnet is placed on an XYZ positioning stage combining both fine and coarse motion capabilities. The fine positioning stage is based on high-voltage piezo stack design. It is capable of moving the magnet in 3D with nominal displacement of 100  $\mu\text{m}$  along each of the spatial directions. This fairly large fine motion range combined with the commercial coarse approach (“picomotor” by New Focus) based coarse 3D positioning capability provides the scan range necessary for 3D MRFM imaging. The apparatus has been successfully tested using a spherical probe magnet with diameter of 50  $\mu\text{m}$ . The spatial resolution of the method is determined by the thickness of the sensitive slice. The sensitive slice is the spatial region where the magnetic resonance condition is satisfied and thus allowing electron spins to be manipulated by applied microwave field. A

probe magnet with dimensions of 50  $\mu\text{m}$  generates probe field gradient of as high as 70 Gauss/ $\mu\text{m}$  with a resulting sensitive slice thickness of 50 nm (for 3.5 Gauss line width of DPPH signal).

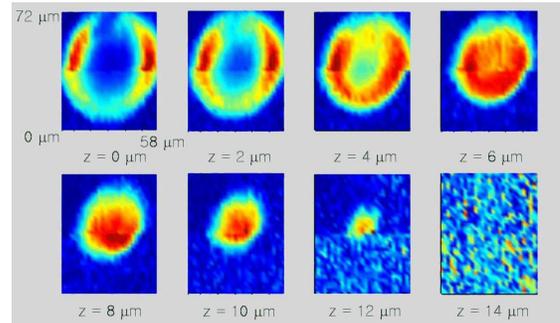


FIG. 12: Evolution of ESR MRFM signal as the probe magnet is moved away from the sample (along the  $z$  direction) in 2  $\mu\text{m}$  steps. Each panel presents a 2D scan of 72  $\mu\text{m}$  by 52  $\mu\text{m}$  in the plane perpendicular to the  $z$  direction. It can be clearly seen how the signature of the sample reduces in diameter as the sensitive slice pulls back and thus intersects the sample in a region where the cross-sectional diameter is smaller.

During an MRFM experiment the intensity of the applied microwave radiation is modulated at a constant rate close to the resonant frequency of the micromechanical cantilever. Simultaneously, the probe magnet is scanned in spatial raster pattern in a plane located at a fixed distance from the sample. This motion of the magnet changes the magnetic field at the sample. When this magnetic field satisfies the magnetic resonance condition, i.e. when  $B_{\text{tip}} = B_{\text{res}} = \omega_{\text{rf}}/\gamma$ , electron spins in the sample respond to amplitude modulation of microwave radiation, in turn generating a time varying force on the cantilever. The cantilever response is dynamically amplified by the quality factor  $Q$ , typically of the order of  $1-5 \times 10^4$ , allowing detection of forces as small as  $10^{-15}$ - $10^{-16}$  N at room temperature. The cantilever oscillation amplitude of cantilever oscillations is continuously recorded as a 3D array corresponding to a 3D set of spatial coordinates with a given step along each of spatial directions  $x$ ,  $y$  and  $z$ , with  $z$  being the distance between the sample and the probe magnet.

Typical 3D MRFM data is shown in Fig. 12 demonstrating a sequence of 2D scans at various probe magnet-sample distances. The ring-like shape of the signal agrees well with the theoretically calculated point response function of a spherical probe magnet. The diameter of this ring decreases as the probe magnet is moved further from the sample, finally converging to a point. This behavior reflects the bowl-like shape of the sensitive slice, which is the volume where the magnetic resonance condition is satisfied. This data, combined with the known point response function, was used for 3D MRFM image reconstruction.

## DEVELOPMENT OF OPTIMIZED MRFM SAMPLES

3D MRFM imaging calls for a special sample with 3D features of known geometry and containing a known number of electron spins. MRFM signal detection and deconvolution can be compared with the known spin density distribution in the sample to validate and optimize imaging protocols as they are developed. Sensitivity calibration using volumes containing small numbers of spins enables MRFM instrument calibration and assists signal interpretation.

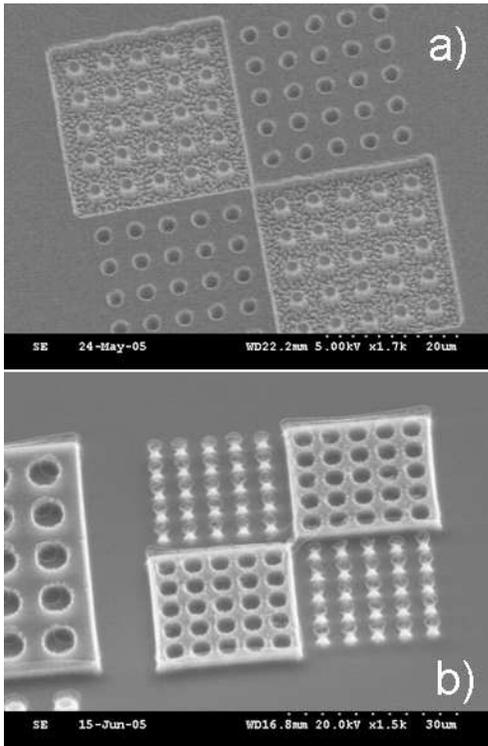


FIG. 13: Patterned arrays of Si micro holes and micro pillars with characteristic dimensions of  $\approx 2\text{--}3\ \mu\text{m}$  fabricated using a Ni and  $\text{SiO}_2$  mask for  $\text{SF}_6$  Reactive Ion Etching (RIE). The Ni mask process results in a rough Si background surface visible in panel (a) that is due to Ni redeposition during etching. This problem was resolved by use of a  $\text{SiO}_2$  mask as shown in panel (b).

The samples were patterned in silicon on insulator (SOI) wafers, with a  $^{28}\text{Si}$  enriched device layer to reduce relaxation of phosphorus donor spins due to hyperfine coupling to  $^{29}\text{Si}$  nuclear spins. The typical thickness of  $^{28}\text{Si}$  layer is  $10\ \mu\text{m}$ .

We have investigated patterning of Si surface via  $\text{SF}_6$  Reactive Ion Etching (RIE) using Ni and  $\text{SiO}_2$  as mask material. The results are presented in Fig.13. It turns out that Ni mask process produces rough background surface Fig.13a due to Ni redeposition during etching. This problem was resolved by use of  $\text{SiO}_2$  masks Fig.13b. However  $\text{SiO}_2$  mask process led to Si undercut beyond desired levels; this problem will be addressed by controlling etching parameters such as etching rate and the type of gas used for RIE processing.

## PUBLICATIONS

Publications are listed below as References 3, 5–8.

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