

Viewpoint

Silicon Nanowires Feel the Force of Magnetic Resonance

John Mamin and Daniel Rugar

IBM Research Division, Almaden Research Center, San Jose, CA 94024, USA

Published February 13, 2012

Silicon nanowire sensors offer a route to improving the sensitivity and spatial resolution of magnetic resonance force microscopy.

Subject Areas: **Magnetism, Nanophysics**

A Viewpoint on:

Nanomechanical detection of nuclear magnetic resonance using a silicon nanowire oscillator

John M. Nichol, Eric R. Hemesath, Lincoln J. Lauhon, and Raffi Budakian

Phys. Rev. B **85**, 054414 (2012) – Published February 13, 2012

The technique of magnetic resonance force microscopy (MRFM) was conceived as a way to combine the 3D capabilities of magnetic resonance imaging (MRI) with the angstrom-scale resolution of scanning probe techniques, with the ultimate goal of imaging individual biological molecules in three dimensions [1]. The technique makes use of a sensitive mechanical oscillator to detect the minute magnetic forces associated with a small number of magnetic moments, or spins. Compared to conventional magnetic resonance detection methods that use inductive coils to sense nuclear spins, MRFM is about 100 million times more sensitive [2]. With such a dramatic improvement, it is now possible to image virus particles in 3D with 10 nanometer (nm) resolution, far beyond the millimeter resolution of medical MRI. Still, reaching the ultimate goal of single-molecule imaging will require innovations that radically enhance the technique's sensitivity.

The basic idea behind MRFM is to sense the nuclear spins in a sample by measuring the force that a magnetic field gradient exerts on these moments. Usually, this is accomplished by having the magnetic force drive a small mechanical oscillator, such as a microfabricated cantilever. In one scheme, the sample is attached directly to the cantilever, and the incorporated spins, typically hydrogen nuclei, feel the force from a nearby gradient source. For nanoscale samples, the force can be as small as a few attonewtons (1 attonewton = 10^{-18} newtons). The key to extending the sensitivity and resolution of MRFM is finding better force transducers to detect these small forces. In an experimental *tour de force*, John Nichol at the University of Illinois, Urbana-Champaign, and his colleagues report in *Physical Review B* a significant step in this direction. They have created an oscillator made from a silicon nanowire and used it to detect the magnetic forces on a nanoscale sample of spins [3].

The trick to making a sensitive, low-noise force trans-

ducer is to design an oscillator with low stiffness, high resonance frequency, and minimal damping. These requirements inexorably imply low mass, which naturally points to nanometer-scale mechanical devices. The field of nanomechanics has seen explosive growth, with innovative new techniques for creating oscillators from nanotubes, nanowires, and graphene sheets [4]. Nichol *et al.* have taken advantage of such “bottom-up” fabrication methods to make a high-quality oscillator from a silicon nanowire that is 15 micrometers long and tapers down to a tip with a diameter of less than 50 nm.

In their demonstration experiment, they coat the tip of the nanowire with hydrogen-rich polystyrene (Fig. 1). The nanowire dangles vertically from a substrate and acts as a cantilever that vibrates in response to oscillating forces applied perpendicular to its length. Since the magnetic forces acting on the hydrogen nuclear spins are so small, the amplitude of the nanowire vibration is only in the angstrom range. Detecting this motion is a major challenge, since the nanowire is so tiny. Nichol *et al.* have therefore built a special optical interferometer with light polarized along the nanowire axis for enhanced reflectivity. This allows them to achieve the necessary detection sensitivity with minimal heating of the nanowire [3, 5]. To generate the magnetic force, they bring the coated tip close to a source of magnetic field gradient, which in their case is produced by running current through a tiny electromagnet consisting of a microfabricated metallic wire. In addition to generating a controllable field gradient, the wire also serves to generate a radio-frequency magnetic field to stimulate magnetic resonance of the hydrogen nuclei.

Achieving attonewton force sensitivity requires the silicon cantilever to have a high mechanical quality factor, Q . One of the fundamental challenges to force detection, and a significant impediment to further progress in MRFM, is that the Q factor of a cantilever invariably decreases when its tip is brought close to a surface. This

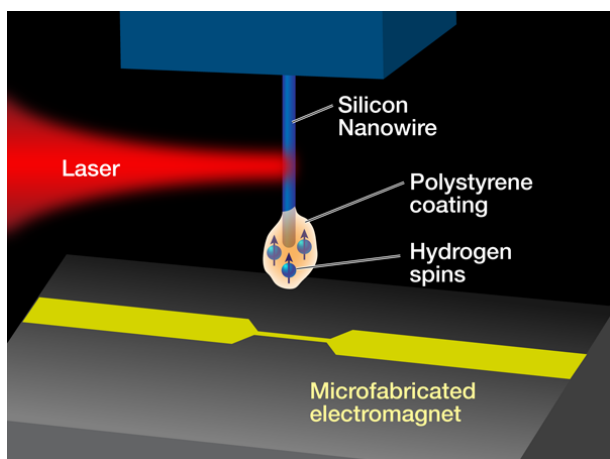


FIG. 1: A silicon nanowire is used as an ultrasensitive cantilever in order to detect nuclear spins via magnetic resonance. A thin layer of polystyrene, containing weakly magnetic hydrogen nuclei, coats the end of the nanowire. A microfabricated wire serves as an electromagnet to produce a magnetic field gradient and thereby exert a force on the spins. Through a suitable modulation of the current in the wire, the interaction between the spins and the field gradient drives the silicon nanowire at its resonance frequency. The motion is then sensed with a laser. The hope is that the improved sensitivity afforded by this technique will eventually allow nanomagnetic resonance on the molecular scale. (APS/Alan Stonebraker)

effect is often referred to as “noncontact friction,” and is ubiquitous in near-surface force measurements, though the magnitude of the effect can vary [6–8]. One of the remarkable aspects of Nichol *et al.*’s nanowire is that it experiences a much lower noncontact friction than is typical for conventional silicon cantilevers. Partly, this is a geometric effect: the small diameter of the nanowire at the tip presents a very small cross section to the surface, giving less potential for interaction. The nanowire also operates at 780 kilohertz (kHz), which is a much higher frequency than the lithographically fabricated cantilevers that have been used previously in MRFM. It may be that the forces from the surface that normally contribute to dissipation primarily fluctuate at lower frequencies, and therefore do not couple as efficiently to a high-frequency oscillator. Either way, the resulting total dissipation is a factor of 250 times lower for the nanowire than for microfabricated cantilevers, leading to a remarkable enhancement in force sensitivity.

In order to actually use these high-frequency oscillators to detect magnetic resonance, the team had to develop an entirely new spin-detection protocol. MRFM

typically relies on periodically flipping the nuclear spins of the sample at the cantilever resonance frequency to drive the cantilever vibration. This technique works well as long as the spins’ orientation can be controlled coherently, which is the case when the flipping is performed at a rate of roughly 10 kHz or less. Rather than attempt to manipulate the spins at the much higher cantilever resonant frequency of 780 kHz, Nichol *et al.* instead create a signal by modulating the magnetic field gradient. By modulating the gradient a few hundred Hz off resonance, and flipping the spins at a few hundred Hz, the force, which is given by the product of the gradient and the spin, has a frequency component right at the cantilever resonance, generating a distinct and unambiguous signal.

With the exceptional level of sensitivity afforded by the nanowire, Nichols *et al.* are able to detect a spin signal of 2.4 attonewton (rms) with excellent signal-to-noise ratio. This force is more than a million times smaller than typically detected by conventional atomic force microscopy.

It is the inherently nanomechanical nature of the nanowire resonator, along with its remarkably low non-contact friction, that made these results possible. This marriage of nanomechanics and magnetic resonance represents one possible route to continued progress toward the ultimate goal of extending the resolving power of force-detected magnetic resonance imaging to the molecular level. It also provides a compelling demonstration that nanostructures, such as nanowires, which are based on “bottom-up” fabrication techniques, can indeed become useful transducers to enable new measurement capabilities.

References

- [1] J. A. Sidles, J. L. Garbini, K. J. Bruland, D. Rugar, O. Zueger, S. Hoen, and C. S. Yannoni, *Rev. Mod. Phys.* **67**, 249 (1995).
- [2] C. L. Degen, M. Poggio, H. J. Mamin, C. T. Rettner, and D. Rugar, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 1313 (2009).
- [3] J. M. Nichol, E. R. Hemesath, L. J. Lauhon, and R. Budakian, *Phys. Rev. B* **85**, 054414 (2012).
- [4] See references contained in Ref. 3 for examples of this “bottom-up” approach.
- [5] J. M. Nichol, E. R. Hemesath, L. J. Lauhon, and R. Budakian, *Appl. Phys. Lett.* **93**, 193110 (2008).
- [6] B. C. Stipe, H. J. Mamin, T. D. Stowe, T. W. Kenny, and D. Rugar, *Phys. Rev. Lett.* **87**, 096801 (2001).
- [7] S. Kuehn, R. F. Loring, and J. A. Marohn, *Phys. Rev. Lett.* **96**, 156103 (2006).
- [8] A. I. Volokitin and B. N. J. Persson, *Phys. Rev. Lett.* **95**, 086104 (2005).

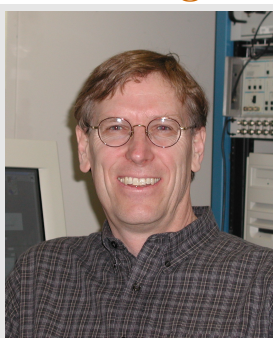
About the Authors

John Mamin



John Mamin has been a Research Staff Member at the IBM Almaden Research Center since 1987. After receiving his B.S. in physics at Stanford University, he did his graduate and postdoctoral studies in physics at the University of California, Berkeley, working in superconductivity and the then-emerging field of scanning probe microscopy. His research interests at IBM have included magnetic force microscopy, probe-based data storage, micromechanics, and pushing the limits of force detection. He is a Fellow of the American Physical Society, and co-recipient of the 2011 Günther Laukien Prize for work in nanoscale magnetic resonance.

Daniel Rugar



Daniel Rugar is Manager of Nanoscale Studies at the IBM Almaden Research Center, and a Consulting Professor of Applied Physics at Stanford University. He received his B.A. degree in physics from Pomona College and his Ph.D. in applied physics from Stanford University. He joined IBM in 1984 and has made numerous contributions to the field of scanning probe microscopy, especially for atomic force microscopy, magnetic force microscopy, and nanoscale magnetic resonance imaging. He recently shared the Günther Laukien Prize for the development of magnetic resonance force microscopy. He is a fellow of the American Physical Society.