

Detecting a single spin

A team at IBM's Almaden Research Center (San Jose, CA) has combined magnetic resonance imaging (MRI) and atomic force microscopy (AFM) to detect a single

of the electron and the 2.96-GHz field. This resonance causes the electron spin to flip direction. The flip in the spin reverses the tiny force between the electron spin

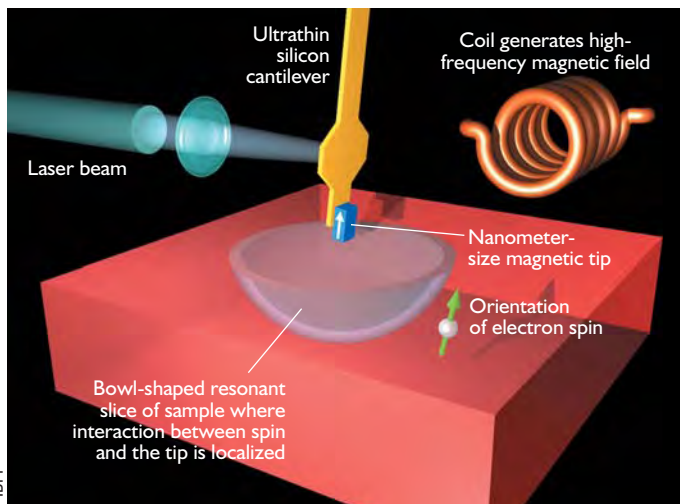
Developing a practical device that can detect the presence of a spin and its direction will require reducing the signal-averaging time to about 1 s. This could be accomplished by increasing the field gradient produced by the magnetic tip from the current 2 G/nm to around 30 G/nm, because the averaging time falls as the inverse fourth power of the field gradient. Mapping individual molecules with MRI will require still greater improvement as nearly 1 million points will be needed per molecule, and nuclear spins require 1,000 times the sensitivity of electron spins. However, such mapping would provide an enormous breakthrough. At the present time, it often takes years to devise a way to crystallize a molecule to determine its structure by X-ray diffraction.

"We do not have a clear path to molecular mapping, but we do have ideas," says Dan Rugar, who leads the IBM team. With nuclear spins, higher magnetic fields are possible and, thus, higher field gradients, which will reduce scanning times. In addition, iron can serve as the magnetic tip, and iron has a greater magnetic moment than samarium-cobalt and, thus, a higher force. Moreover, using the cantilever itself to produce the oscillating magnetic field would eliminate heating from the microwave generator, which would allow lower operating temperatures and less noise.

Long before reaching this goal, the new MRI-AFM approach could join other methods of detecting and modifying electron spins in quantum-computing schemes. In addition, the higher resolution could find applications for MRI microscopy short of the molecular scale. "We've broken the log-jam of MRI resolution limits," says Rugar. "And that should open up a lot of uses." [Q](#)

Handheld chem lab

The ideal chemical-analysis tool would instantly describe the elemental and molecular makeup of a sample, yet it would fit in one hand. That is not reality yet, but a new X-ray fluorescence analyzer developed by researchers at the National Aeronautics and Space Administration's (NASA) Mar-



The magnetic force between the electron and the magnetic tip alternates between attraction and repulsion every time the electron spin flips its orientation, causing the cantilever frequency to change slightly.

electron spin (*Nature* 2004, 430, 329). Although it is not the only way to detect single spins, the MRI approach marks a major step toward realizing an ambitious goal: making three-dimensional images of individual molecules, which potentially could speed the analysis of molecular structures. The improvement in spatial resolution also could open up other nanoscale microscopy applications for MRI.

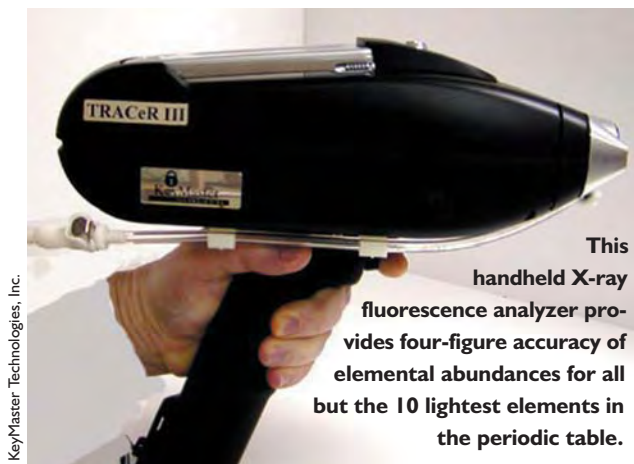
Until now, MRI resolutions have been limited to about 1 μm , with 10 million electron spins or 1 trillion nuclear spins needed to produce a detectable signal. But the IBM approach increases spatial resolution to 25 nm and decreases the minimum number of electron spins to 1. To detect the spin, the device uses an atomic force cantilever with a 150-nm-wide samarium-cobalt magnet at the tip. The spins are contained in a sample of amorphous silica, which has been irradiated with gamma rays to produce unpaired electron spins.

The sample is exposed to a magnetic field oscillating at 2.96 GHz from a microwave coil. When a given electron spin is the right distance from the magnetic cantilever tip, and therefore exposed to the right steady magnetic field, a resonance occurs between the intrinsic gyrofrequency

and the magnetic tip. The device detects the change in force by tracking the cantilever oscillations with an interferometer.

However, the extremely tiny force, a few attonewtons, is only 1 millionth as large as that usually detected by standard atomic force microscopes. To make detection possible, the team reduced the random thermal noise that vibrates the cantilever by doing the experiment at 1.6 K. In addition, they used a protocol that amplified the tiny influence of the spin on the cantilever.

Because the electron spin flips every time the cantilever oscillates, which changes the force on the cantilever, the apparent stiffness of the cantilever changes and, thus, the frequency of oscillation. Whether the frequency increases or decreases depends on the relative phase of the spin flips. That is, the spins can either push the cantilever slightly faster with each oscillation, or slightly slower. By turning off the microwave oscillator every 64 cycles of cantilever oscillation, the device keeps switching the spin from in-phase to out-of-phase, thus creating an oscillation in the cantilever frequency. Although the oscillation is only a few millihertz of 5.5-kHz frequency, the signal builds up to a strongly detectable level over a 13-h period.



KeyMaster Technologies, Inc.

This handheld X-ray fluorescence analyzer provides four-figure accuracy of elemental abundances for all but the 10 lightest elements in the periodic table.

shall Space Flight Center (Huntsville, AL) and KeyMaster Technologies (Kennewick, WA) comes close for many analytical jobs. The handheld device provides four-figure accuracy of elemental abundances for all but the 10 lightest elements in the periodic table, including aluminum alloys. NASA will use the device to inspect alloys in the Space Shuttle, and it should find other applications ranging from automotive-alloy quality control to geologic exploration.

X-ray fluorescence works by irradiating a sample with 15–40-keV X-rays, which knock inner-shell electrons out of atoms. When outer electrons drop down to fill the inner shells, they emit an X-ray photon with an energy characteristic of a particular element. By analyzing these photons with an X-ray spectrometer, the X-ray fluorescence device can determine, after some calculation, the exact quantity of the elements emitting the X-rays.

Because X-ray-generating tubes and X-ray spectrometers can be made compact, handheld X-ray fluorescence analyzers are already on the market. But they can only detect elements higher than titanium in the periodic table, that is, those with an atomic number of more than 22. The problem is that lighter elements produce less-energetic X-rays, which cannot penetrate the windows of these X-ray spectrometers.

“With titanium, you get 4.5-keV X-ray photons, but with sodium, which has an atomic number of 11, you only get 1.1 keV, and that is much harder to detect, because the photon has much less energy to reach the detector,” explains Steve Price of KeyMaster. The thickness that an X-ray penetrates decreases roughly as the cube of the X-ray energy, and that energy, in turn, decreases as the square of the atomic number (Z). So to cut the minimum Z from 22

to 11 is not trivial. On the other hand, such an improvement allows the analysis of some important elements, including magnesium, aluminum, silicon, phosphorus, sulfur, and calcium. These elements are both constituents and contaminants

of important alloys, and they make up a large fraction of common minerals. The key to developing the new analyzer was the window of the vacuum chamber that contains the X-ray spectrometer. “The window could only be a few micrometers thick, and for that thickness, beryllium, the conventional window material, would be too brittle,” says Price. Instead, KeyMaster developed a proprietary polymer window thin enough to allow even 1-keV X-rays through but tough enough to withstand the jolts to a handheld device.

The first analyzers shipped in May. Other than NASA’s Space Shuttle application, the most immediate market is the aerospace industry, which uses the instrument for quality control of aluminum alloys, Price reports. But future markets will include on-the-spot quality inspection of industrial parts and products, and field analysis of minerals by geologists. [Q](#)

Superprisms

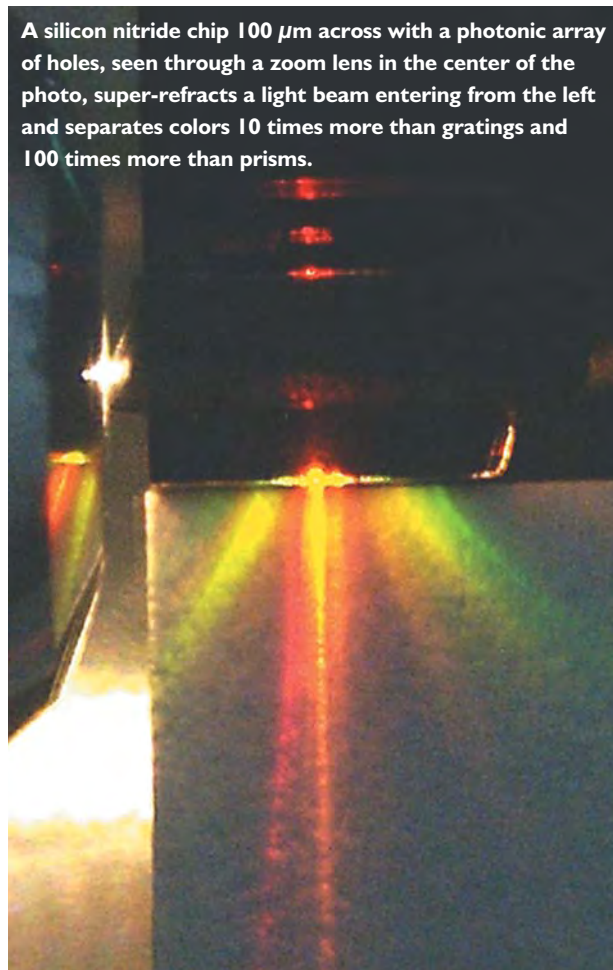
Photonic crystals, waveguides with regular arrays of holes, have a variety of useful optical properties. The latest property demonstrated is the ability to form superprisms—devices that bend light 10 times more than gratings and 100 times more than ordinary glass prisms (*Appl. Phys. Lett.* 2004, 85, 354). Researchers at the School of Physics and Astronomy,

University of Southampton (Southampton, England), and Mesophotonics Ltd. (Chilworth Science Park, England) demonstrated the phenomenon.

The team made the photonic devices using a standard silicon microfabrication process, which generated an array of holes in a silicon nitride layer. The holes, each 160 nm in diameter, were spaced 310 nm in one direction and 465 nm in the other. As in any photonic array, the holes create bandgaps, that is, certain wavelengths of light will not propagate through the array. For wavelengths close to the bandgap, the index of refraction varies extremely rapidly with wavelength and direction, creating the superprism effect.


The researchers measured the deflection of light as it passed through the 186- μm -long photonic crystal. They found that the deflection angle changed by more than

A silicon nitride chip 100 μm across with a photonic array of holes, seen through a zoom lens in the center of the photo, super-refracts a light beam entering from the left and separates colors 10 times more than gratings and 100 times more than prisms.



University of Southampton, England

1 °/nm of wavelength change, 10 times more than with a conventional grating. Tilting the array away from the direction of light propagation enhanced the effect.

The ability to sharply separate nearby wavelengths in a very short distance would be useful in optical microcircuit chips. Such chips would enable sending multiple signals on neighboring wavelengths, combining them for transmission to another chip, and then using a superprism on the receiving chip to separate them again for further processing. 

Growing nanotrees

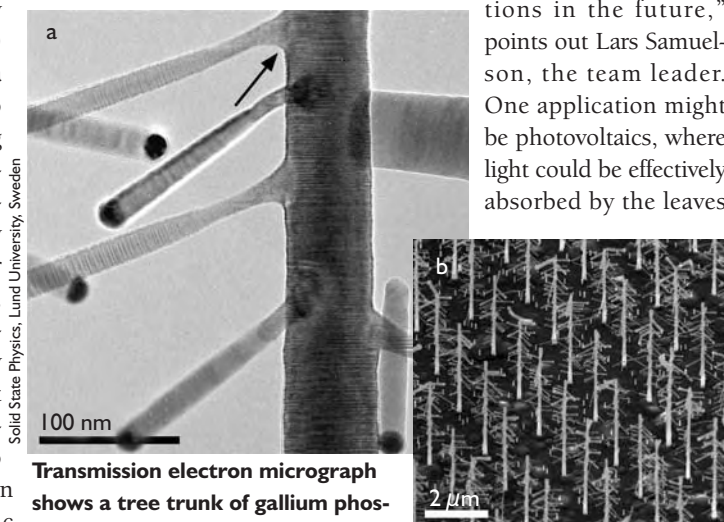
Now that researchers have produced a menagerie of individual electronic devices at nanometer scales, the next step is to shrink two- and three-dimensional arrays in size. Physicists and chemists at Lund University (Lund, Sweden) have developed a novel way to do this—by growing forests of tiny, multichemical nanotrees in a highly controlled manner (*Nat. Mater.* 2004, 3, 380). The nanotree arrays may find use as light emitters or to convert light into usable energy in photovoltaic devices.

The tree-growth process starts by using gold aerosol particles as the seeds. These particles are condensed from gold vapor, electrically charged, and separated by size. An electrostatic field then deposits the 40–70-nm-diameter seeds on a substrate. On each gold seed, a tree trunk of gallium phosphide is grown by a technique called vapor-liquid-solid growth, using a chamber for metal-organic vapor-phase epitaxy. To form the branches, a second dusting of gold seeds, this time 10–40 nm in diameter, is applied and sticks to the trunks. Branches form with threefold or sixfold symmetry, depending on the density of the gold seeds. Finally, using still smaller gold aerosol particles enables the growth of leaves on the branches.

The team can accurately control all the dimensions of the trees by changing the process parameters. The diameter of trunk, branches, and leaves is controlled by the size of the seed particles; branch and leaf length depend on growth time, temperature, and reagent concentrations. Using different chemicals to deposit the different stages yields trunks, branches, and leaves of different materials.

In most of the experiments, the trees grew with random spacing because of their seeding with the aerosol. However, the research team also demonstrated the ability to produce regular arrays of gold seeds with electron-beam lithography, which led to a regular nanotree array.

“These nanotree arrays, or nanoforests, are very interesting for their large surface areas, which may create important applications in the future,” points out Lars Samuelson, the team leader. One application might be photovoltaics, where light could be effectively absorbed by the leaves



Transmission electron micrograph shows a tree trunk of gallium phosphide grown on a gold seed, with branches grown from smaller gold particles (a). Scanning electron micrograph shows an ordered array of nanotrees viewed at 45° from the normal (b).

and branches. Charge carriers—electrons and holes—would then move efficiently through the nanowire trunks to a wafer at the roots of the trees and to the gold seeds at the ends of the branches, which would act as the extraction points, leading to collector circuits.

Alternatively, each of the branches or leaves could be made as a nanoscale light-emitting diode, with each of the gold particles contacted via a conducting and transparent polymer. The Swedish team has already demonstrated efficient emission for double heterostructures composed of gallium arsenide phosphide segments placed within the branches of the nanotrees. 