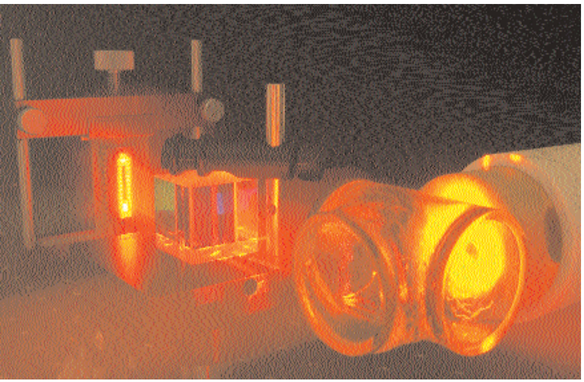
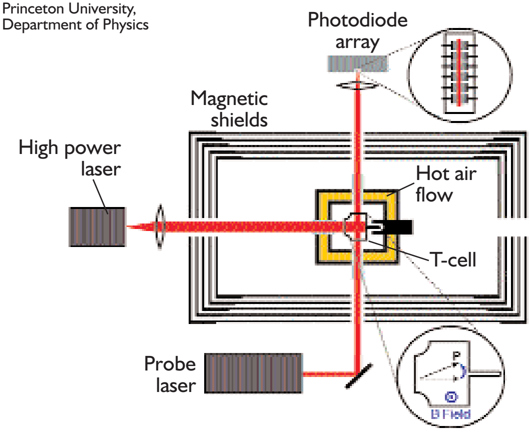
by Eric J. Lerner

A magnetic microscope for the brain

The human brain produces a complex, ever-varying electromagnetic field, generated by the coordinated activity of billions of neurons. Neuroscientists now believe that this oscillating field, created by neuronal processes, also plays a crucial role in the brain's functioning by synchronizing and coordinating the activities that create it.

The limitations of the instruments available to scientists, however, have restricted studies of these fields. Electrodes placed on the scalp, and used for a century, detect electrical components of the field—which are graphically recorded to produce an electroencephalogram. Electrodes, however, cannot reliably detect where inside the brain the fields are generated. Functional magnetic resonance imaging, which detects increases in the metabolism of neurons, has spatial resolution down to 1 mm, but it requires seconds for a response—far longer than the 5- to 100-Hz variation of the brain's fields. Superconducting quantum interference devices (SQUIDs) can measure the brain's magnetic fields rapidly, but they require coil sizes that limit spatial resolution to 1 cm or more. No instrument can simultaneously record the time and spatial variation of the field, which has structure down to 100 μm.


Princeton University, Department of Physics



To measure magnetic fields in the brain, a high-power laser is polarized and absorbed by potassium vapor in a T cell. A single-frequency probe laser detects the orientation of the electron spins as they precess in the magnetic field and this signal is detected by a photodiode array.

A new ultrasensitive magnetometer may overcome that limitation. The atomic magnetometer developed by physicists at Princeton University and the University of Washington provides 2-mm resolution with a sensitivity to magnetic fields twice that of a SQUID (*Nature* 2003, *422*, 596). "With an optimized device, we should be able to achieve 10 times better sensitivity than a SQUID with a resolution of 100 to 200 μm," says team leader M. V. Romalis of Princeton.

Atomic magnetometers measure the precession of atoms in a magnetic field. First, polarized light from a laser aligns the spins of the atoms in a gas (potassium vapor in this device). Then, a small magnetic field at right angles to the spin direction causes it to tilt—the stronger the field, the more the tilt. The plane of polarization of a second laser beam is rotated in proportion to the tilt of the atoms' spins. Thus, measuring this optical polarization shift produces a measure of the magnetic field along the path of the beam. If an external magnetic field is added, the additional rotation it imparts is a measure of that external field.

The main limitation on the sensitivity of atomic magnetometers results from collisions of atoms that cause their spins to flip, which reduces the average polarization of the spins. To minimize such collisions, conventional magnetometers use dilute gases, but that requires large columns of gas, which lowers spatial resolution.

The researchers realized that they could get greater sensitivity and resolution by greatly increasing the density and rate of collisions. "If the time between collisions is much less than the time it takes the spins to rotate in the magnetic field, the atom will just feel the average effect of the collisions, and it won't have time to flip," explains Romalis. With denser gas producing a bigger signal, the team could shrink the magnetometer chamber from about 10 cm on a side to less than 1 cm.

The new magnetometer design improves resolution and cancels out noise by probing the fields at seven different points along a line, which yields 2-mm spatial resolution with a magnetic sensitivity of 0.54 fT (5.4 pg)/Hz$^{1/2}$ at frequencies from 28 to 45 Hz. Using a two-dimensional diode array and scanning the polarizing laser beam in the third dimension produce a three-dimensional map of the field in a cell.

"Our next step is to optimize the magnetometer and demonstrate its use in detecting the brain's magnetic fields," says Romalis. Unlike cryogenic SQUIDs, the atomic magnetometer requires no cooling, and so it will be more capable than SQUIDs and easier to use.

Spin and energy—free?

Most physicists would not expect startling new theoretical conclusions to emerge from electrostatics, whose basic mathematical structure was completed 150 years ago. Yet two researchers at the University of California, Riverside, arrived at conclusions that, if true, would be revolutionary. In a forthcoming paper (*J. Physics A: Math. Gen.* **2003**, *36*, 6495), Anders O. Wistrom and V. M. Khachatourian say they have proven mathematically that electrostatic forces among three charged, perfectly conducting spheres will cause them to start

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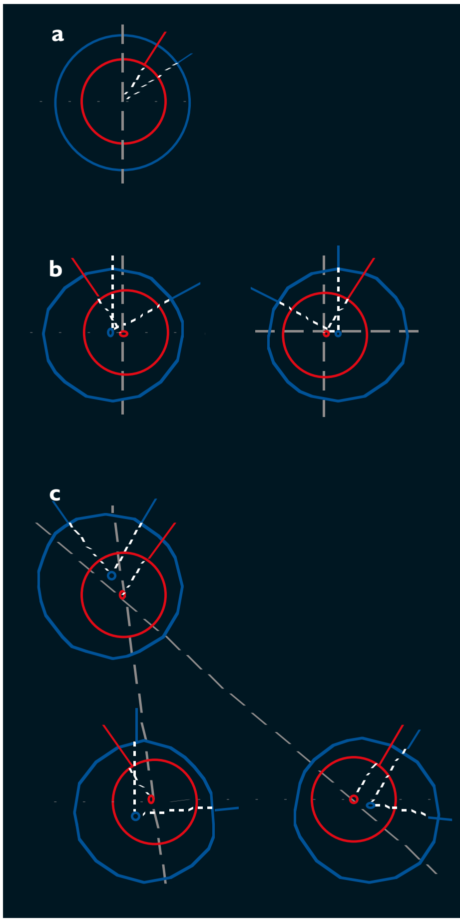


For an isolated spherical shell held at constant potential (voltage), excess charges will repel each other and move apart to maximize the distance between all pairs of charge (a). At equilibrium, charges are uniformly distributed on the shell surface. We can substitute the surface charges (blue) with a fictitious charge Q located at the center of the sphere. The direction of an electric field generated by Q is normal to the constant voltage surface (red).

For a system of two charged spheres, charges move to find new equilibrium positions to maximize the distance between all pairs of charge (b). For the case of two spheres held at the same voltage (red), the static charge distribution (blue) will no longer be uniform. If we now replace the nonuniformly distributed surface charges by a fictitious charge Q, the location of Q will no longer be at the center of the sphere. We also find that the direction of the electric field generated by Q can no longer be perpendicular to the constant-voltage (red) surface. For the two-body case, axial symmetry of surface charges yields zero electrostatic torque.

When a third sphere is added, the surface charge distributions on the conducting shells are generally asymmetric (c). It follows that the direction of the electric field generated by the fictitious charges Q are also asymmetric (blue), which leads to torque for most sphere arrangements.
—Anders O. Wistrom

Department of Chemical and Environmental Engineering, University of California, Riverside

spinning. This conclusion, which the authors have derived from Coulomb's law, contradicts long-held assumptions about how electrical fields behave. Equally striking, it implies that, in theory, an arrangement of three such spheres could transfer unlimited amounts of energy into the spinning spheres—a violation of conservation of energy.

Such remarkable claims would be dismissed quickly as perpetual motion if reviewers for the *Journal of Physics* had not carefully checked the work. In addition, the researchers had earlier performed experiments that they believe show the same phenomenon (*Appl. Phys. Lett.* **2002**, *80*, 2800). However, some large questions remain.

"We started to look at this problem because of our interest in the forces between colloidal particles," says Wistrom, "and this led to our experiments." In these experiments, the researchers charged a fixed metal sphere with up to 5,000 V and measured the effect on two uncharged metal spheres suspended by fine wires. "When the voltage was applied, the free spheres slowly rotated in opposite directions until they were stopped by the torsion in the supporting wires," says Wistrom. "And when the potential was turned off, they went back to their original positions."

The initial experimental paper gave no quantitative data. "We wanted to wait until we had theoretical calculations to compare the data with," says Wistrom. However, he told *The Industrial Physicist* that in one set of experiments, 0.8-kg, 14-cm-radius spheres, which were almost touching, rotated through about 30° in a 10-min period, implying a torque on the order of 0.5 dyn•cm. This torque is small but hundreds of times larger than those routinely calibrated with Cavendish balances, which measure the force of gravity between small spheres. So although the torque could have been measured quite accurately with simple equipment, it appears that Wistrom made only rough observations.

Theoretical calculations of the forces and torques among three spheres had never been done because the problem lacks an axis of symmetry and the mathematics is complex. However, by using new approaches to the problem, Wistrom and Khachatourian solved the problem mathematically for the case in which the spheres are distant relative to their radii. They found torques on each sphere, but they were thousands of times larger than their experiments had indicated. The researchers were unable to mathematically solve for conditions in which the spheres were close to each other.

Their results contradict several basic details of electromagnetic field theory that have stood for more than a century. One is that because the potential is the same all over the surface of a conducting sphere, the field direction must be everywhere perpendicular to that surface, which eliminates any torque. Second, and perhaps more fundamental, a net torque implies no limit on energy transfer to the spinning spheres. When electrostatic forces cause a translational motion of objects, the objects will eventually move far from each other, collide, or remain in a stable orbit. In any of these cases, energy transfer from the field to the object is limited and finite. But if one uses electrostatic forces to apply torque to a perfectly conducting sphere, the object's spin increases, whereas the distribution of charges on its surface remains motionless, continuing to apply the same net torque. In the absence of friction or opposing forces, there would be no limit to the energy transfer.

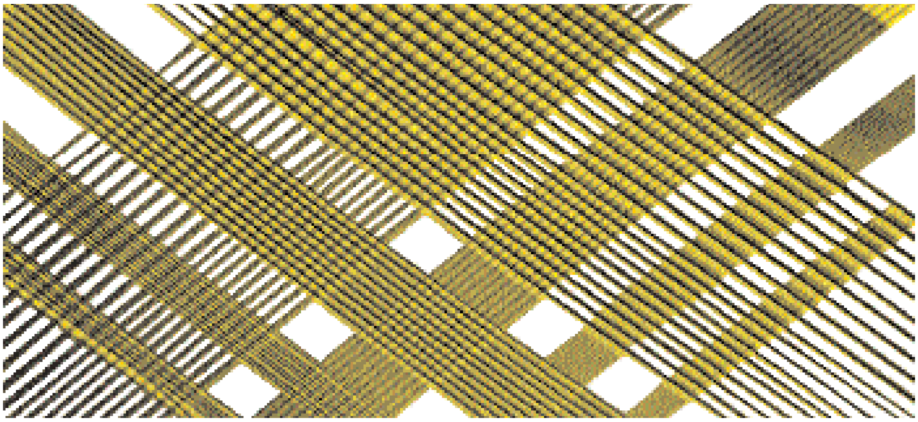
"We know these results sound puzzling, but we don't have the resources to do additional work on this," Wistrom comments. Other researchers could check the claims easily. A computer simulation could certainly determine whether the predicted torques exist in theory. A replication of the Riverside experiment could accurately measure the torques. And because the effect is expected to increase as the square of the applied potential, an experiment at higher voltage—say, 50 to 100 kV—could produce enough torque to overcome bearing friction. That experiment could test whether a spin-up of the spheres really occurred. Until such tests are conducted, the promise of free energy from electrostatic forces will inevitably generate great skepticism.

Finest nanowire arrays

Nearly every month, researchers develop new methods of producing smaller nanocircuit components. Many of these involve creating master patterns with electron beam lithography and then stamping out components, including fine wires, with a die pressed into temporarily molten material (see *The Industrial Physicist*, December 2002/January 2003, p. 9). Such methods are limited by the resolution obtainable with electron beams—currently around 20 nm in diameter for wires.

The latest method, which achieves diameters as small as 8 nm, or about 80 atoms across, avoids this limitation by forgoing electron beam lithography. Developed jointly by researchers at the University of California campuses at Los Angeles and Santa Barbara and Caltech scientists, the method uses molecular-beam epitaxy (MBE) to form wire arrays (*Science* **2003**, *300*, 112).

Alternating 8-nm-thick layers of gallium arsenide and aluminum gallium arsenide are laid down first with MBE. The finished layers are rotated 90° and the aluminum gallium arsenide layers selectively etched out. The template is then rotated another 36° and exposed to a stream of metal ions, which form a thin layer of metal on each exposed gallium arsenide layer to create the wires.



California Nanosystems Institute, University of California, Los Angeles/Caltech

A stream of metal ions is sprayed onto a template created by molecular-beam epitaxy and etching to produce arrays of up to 40 wires 2 to 3 mm long and as small as 8 nm wide.

Next, the superlattice is placed face down onto an adhesive and the gallium arsenide is etched away, leaving the wire array attached to the adhesive. If desired, the adhesive can be removed with oxygen plasma to leave the wires free. The result is an array of up to 40 wires 2 to 3 mm long and as small as 8 nm wide.

The wire arrays have many applications, including as etch masks for producing similar-sized wires out of semiconductors. Two arrays can be laid down at right angles to one another to form crossbar-array circuits with junction densities as high as $10^{11}/cm^2$. In addition, the team showed that suspending the wires across a 750-nm trench formed a micromechanical oscillator with a resonant frequency of 162 MHz. Ω

Solar-cell burnout

When first placed in operation in sunlight, solar cells lose 15 to 20% of their efficiency in a few days. Unfortunately, researchers have not determined why this drop occurs in the thin-film, hydrogenated amorphous-silicon cells in common but limited use for 20 years. At Ames Laboratory, a Department of Energy facility, and Iowa State University's Microelectronics Research Center, Rana Biswas, Bicai Pan, and Yiying Ye have discovered how the efficiency drop occurs and a possible way to stop it (submitted to *MRS Symp. Proc.* **2003**, *762*, A11.4).

In amorphous silicon, which lacks the regular structure of the crystalline form, some bonds between silicon atoms are

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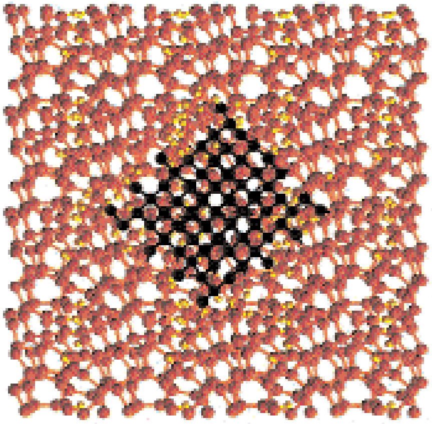
elongated and weak. In earlier work, the Ames team showed that photons need little energy to break these weak bonds and set off a chain of events that leads to lost efficiency. "Using our own simulation models of atomic bonds and molecular dynamics, we showed that the weak bonds broke apart into a dangling bond—a silicon atom with an extra unbonded electron—and a floating bond, a silicon atom bonded to five instead of four other silicon atoms," Biswas explains. The floating bond, essentially an electron orbital that surrounds several silicon atoms, moves swiftly through the material while the dangling bond remains behind. When a photon creates an electron–hole pair near the dangling bond, the dangling silicon atom captures the electron, and it is not available to move toward the electrodes as part of the current, which decreases efficiency.

In recent years, solar-cell researchers had found empirically that mixed-phase silicon, which has tiny nanocrystals embedded in the amorphous structure, suffers less light-induced efficiency loss. The Ames team's new work demonstrates why. "What we found in our models is that at the boundary between the nanocrystals and the amorphous phase, there is a great concentration of very weak and distorted bonds, with bond angles up to 35°, compared with the normal amorphous range of 5° to 15°," says Biswas. These distorted bonds are especially easy to break and would lead to dense arrays of floating and dangling bonds—which would worsen the efficiency problem.


Department of Physics and Ames Laboratory, Iowa State University

Simulation of nanocrystalline hydrogenated silicon, including embedded crystalline silicon atoms (black), amorphous silicon (red), and hydrogen (yellow), used to study the drop in efficiency of solar cells.

However, Biswas's group reasons that with so many broken bonds in a tiny area, the mobile floating bonds will quickly run into dangling bonds and eliminate the defect. Dangling bonds close together in this tiny area can also recombine with each other. Because the photons form the dangling bonds preferentially in the boundary layers, where they will be harmlessly eliminated, fewer dangling bonds are available to soak up electrons.

"With this model, we can now study how the efficiency loss is affected by varying the mix of nanocrystals and amorphous phase," says Biswas. The team's initial models assumed that nanocrystals occupied only 10% of the volume, but later modeling will look at mixtures with only a small proportion of amorphous material and at others in between the two extremes. It is hoped that this modeling will enable the team to determine the optimum mix for maximum efficiency. Ω