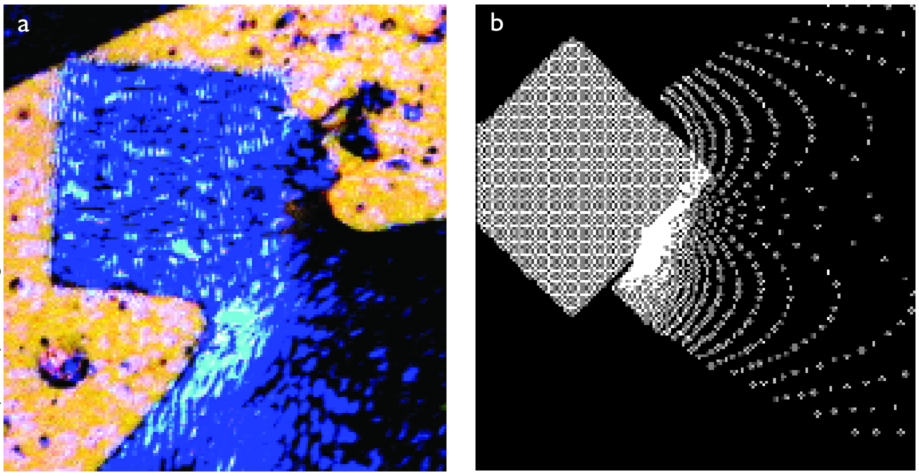
 by Eric J. Lerner

Plasmon microscopy

Microscopy has moved well beyond the diffraction limitations of the wavelength of light by using near-field scanning—putting a small hole within a wavelength of the object being scanned. But such near-field scans have disadvantages; for one thing, they tend to be slow. A new technique developed at the University of Maryland (College Park) and Queen's University (Belfast, Northern Ireland) allows far-field optical microscopy with resolutions well below the wavelength of light by using surface plasmons (http://arXiv.org/abs/cond-mat/?0405098 and http://arXiv.org/abs/cond-mat/?0403276).

Surface plasmons are waves of electron density that move along the interface between a conductor and a dielectric. They can be excited by photons, and they can excite photons in turn. When the frequency of the exciting radiation is close to the plasma frequency in the metal, the wavelength of the plasmons becomes much shorter than that of the exciting light. This phenomenon has allowed the use of plasmons in various techniques that overcome diffraction limits, such as in creating narrow beams.

In the new microscope, samples are placed over a gold film (the conductor) and are immersed in a droplet of water or glycerin (the dielectric). Argon laser light at 502 nm excites the plasmons at the gold–glycerin interface, which produces surface plasmons with a wavelength of 69.8 nm. The result is an immersion microscope with an effective refractive index of 7.14, far higher than the refractive index of any liquid.



Department of Electrical and Computer Engineering, University of Maryland, College Park

A nanohole array with 150-nm-diam holes at 500-nm spacing is illuminated by 502-nm-wavelength laser light in a plasmon microscope (a), and the image is reconstructed via ray tracing (b), indicating a resolution of at least 100 nm.

Small holes scratched into the gold foil's surface form sources for the plasmons. The emitted plasmons are focused in the metal plane by the nearly parabolic edge of the droplet, thus creating a greatly magnified image of the holes in the central part of the droplet. When the plasmons encounter irregularities on the metal–dielectric interface, caused by the sample roughness, they couple to photons, which are then emitted normal to the surface. A conventional far-field optical microscope can then view the magnified image.

Experiments performed by Igor Smolyaninov of the University of Maryland's department of electrical and computer engineering used an array of nanoholes as a test pattern, and demonstrated a resolution of 60 nm—comparable to the plasmons' wavelength and only one-eighth the wavelength of the illuminating laser. "Theoretically, such microscopes can reach down to the few-nanometer resolution level," Smolyaninov comments. This would allow optical imaging of individual viruses or DNA molecules.

"Optical imaging in an aqueous medium means that the samples are not destroyed, as they are with electron microscopy, which is a big advantage," says Smolyaninov. Equally important, the process, when used in reverse, can reduce lithographic patterns.

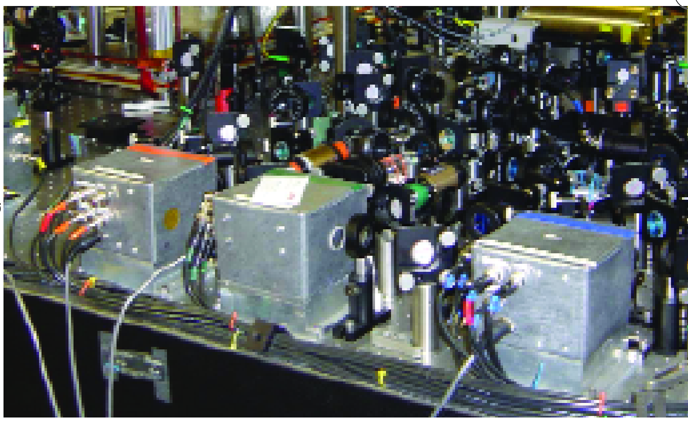
Immersion lithography is already in advanced development to reduce feature sizes by 30%. A reduction in size of seven- or eightfold could greatly ease the transition to the next generation of lithographic tools and possibly compete with X-ray or extreme-ultraviolet-based approaches. The necessity for a conducting underlayer, however, may prove a limitation for lithography.

Quantum measurement

Quantum-mechanics textbooks have mystified several generations of physics students with the idea that the act of measuring a quantum-mechanical system produces a result that is inherently random, unpredictable, and without cause, even though the average result of many identical measurements is precisely predictable. Writers have spilled much ink in interpreting this mysterious behavior of nature.

Now an experimental group at Caltech has demonstrated a way to measure a quantum system that results in a predictable, not a random outcome (*Science* **2004**, *304*, 270). They achieved this by using a feedback loop during the process of measurement, which guided the quantum system into the desired state. The technique sheds light on long-simmering controversies over the interpretation of quantum mechanics and could make possible ultrasensitive measurements of magnetic fields.

Until relatively recently, the measurement of a quantum system was considered an essentially instantaneous operation. When not observed, a quantum system evolves deterministically, as described by the Schrödinger wave equations. These equations describe probability waves that determine the likelihood that, for example, a particle occupies a specific position or has a spin oriented in a specific direction. A mea-



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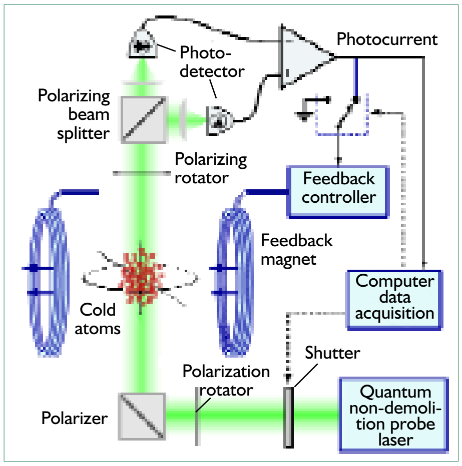


Schematic of a quantum feedback control experiment (left) and a partial view of the diode lasers (silver cases in front) and optics used to perform atom trapping and cooling as well as quantum measurement (above).

surement causes the collapse of the wavefunction so that the particle or quantum system instantly becomes located at a specific position or orientation that the measurement instrument detects. Schrödinger's equations can predict the results of many identical measurements, but not that of a single measurement.

This situation has led to endless arguments by theoreticians and philosophers about what constitutes a measurement, whether a conscious observer is required, and how such essentially acausal randomness can be fit into a deterministic universe. But over the past decade, experimenters have taken a different approach to the problem of measurement by attempting to study and control it in the laboratory.

In the Caltech experiments, carried out by JM Geremia, John K. Stockton, and Hideo Mabuchi of the department of physics and control and dynamical systems, the quantum system consisted of a cloud of 100 billion cesium atoms cooled to 1 μK. At that temperature, the quantum wavefunctions of individual atoms overlapped in the 0.1-cm^3 cloud so that they became a single quantum system with a single spin orientation.

The experimenters extended the measurement process so that far from being instantaneous, the collapse of the wavefunction lasted more than 100 μs. They stretched out the process by using a weak laser beam for measuring the spin orientation. The photons interacted with the atoms in the cloud and became polarized, and the measurement of the photons' polarization indicated the z component of the cloud's spin orientation. However, because of the weakness of the laser beam, polarization measurements fluctuated, and an accurate measurement of the magnitude of the spin's z component could be obtained only by averaging over about 100 μs, which accounted for the measurement time.

"As the laser beam interacts with the cloud, the quantum state of the atoms becomes entangled with that of the light. As the probe laser polarization is detected, the atoms settle into a state with a more definite spin z component," explains Geremia. Only the z component is measured because under the quantum uncertainty principle, as the z component becomes more definite, the x and y components become less so, a process known as spin squeezing.

Normally, spin squeezing would lead to a random measurement of the z component—many measurements would average to 0 but each would be unpredictable. However, the Caltech technique uses the fluctuating polarization signal during the 100-μs-long measurement as a feedback signal to a magnetic coil. When the polarization changes, the magnetic field does too. The magnet field, in turn, changes the direction of the cloud's spin. This gradually moves the z component to 0 for each measurement. "With quantum measurement and classical feedback, we can determine not just the average result of many measurements, but the actual result of each measurement," Geremia emphasizes.

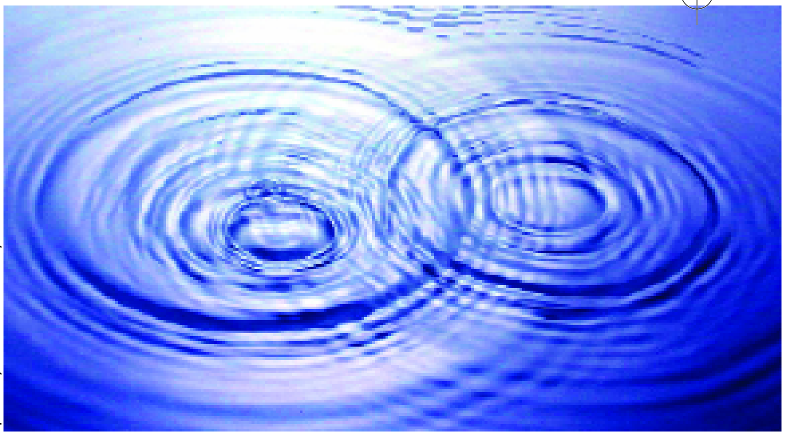
Practically, the technique could be applied to the measurement of ultrasmall magnetic fields. The amount of current needed to return the z component of the spin to 0 can be used as a measurement of the change in the z component of the ambient magnetic field. From a theoretical standpoint, the ability to control quantum measurement to obtain a deterministic result takes a good deal of the mystery out of the process. With such control, there would be no doubt about the fate of Schrödinger's cat. ■

Quantum entanglement

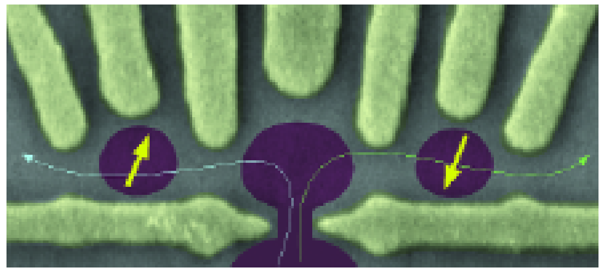
The potential for quantum computing (QC) rests on the process of quantum entanglement. Entangled states occur when two or more particles or quantum systems share a single quantum state, and what happens to one system is linked to what happens to the other. For example, if one electron's spin is up, the other entangled electron's spin is down. With photons, much effort has focused on producing entangled states, but once made, sending entangled photons to distant locations is relatively easy because the photons are always in motion. But several QC schemes in the solid state require entangled electrons as well, and that has necessitated putting them in close proximity to each other so that their quantum wavefunctions overlap. This has made the design of practical QC devices difficult.

A Harvard University–University of California, Santa Barbara, collaboration led by Harvard's Charles M. Marcus has demonstrated a way to convey electron quantum entanglement over distances in microcircuits (*Science* **2004**, *304*, 565). The researchers used an interaction between the spins of electrons with the unwieldy name of Ruderman-Kittel-Kasuya-Yoshida (RKKY), which is based on the Pauli exclusion principle. That principle prohibits electrons with the same spin orientation from occupying the same position in space.

The new device uses quantum dots, which contain only a few free electrons. Two conventional quantum dots are placed to the left and right of a central, larger



Department of Physics, Harvard University, photo by Andrew Davidhazy



Electron quantum entanglement (represented at left) has been demonstrated over distances in microcircuits by a device illustrated above with a scanning electron micrograph, in which the schematic ovals indicate the location of three quantum dots.

quantum dot and connected through it. The central dot's electrons freely interact with a large conductor, which creates a sea of electrons.

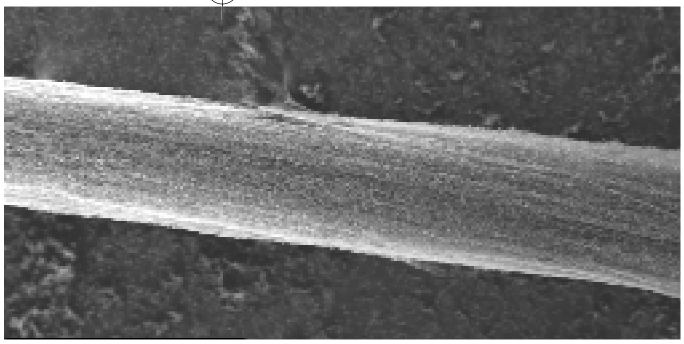
When the left quantum dot contains an odd number of electrons, an unbalanced spin (say, directed upward) results. This upward spin repels similarly aligned electrons in the central dot's electron sea, creating a region with opposite-directed (downward) spin. This spin, in turn, affects neighboring electrons, so a standing wave of up and down spin spreads across the central dot. If the right dot also has an odd number of electrons, the spin wave puts the right dot into a spin state determined by the left-hand dot's spin and the distance between them. "The spin states can thus be readily entangled, even when separated," explains Marcus.

To measure the coherent spin-state between the two quantum dots, and to link it to conventional circuitry, the device uses a second spin-related quantum phenomenon called the Kondo effect. In an isolated quantum dot, conductance through the dot is low because the energy level inside it is not matched to the energy level of the conduction electrons outside. However, once the spin of the dot's electrons link to the spin of those in the sea of electrons, a new resonance appears, which allows a measurable change in conduction.

This resonance condition occurs only if the spins of the electrons are not otherwise entangled, as, for instance, with another localized spin. So, if the left-hand quantum dot has a zero spin—an even number of electrons—then the right-hand dot's spin is free to entangle with the sea of electrons, and the conductance is high. However, if the left-hand quantum dot has an odd number of electrons and, thus, a spin of 1/2, then the spin wave locks the right-hand dot's spin in place, which destroys the resonance and reduces the conductance. By measuring the conductance of one dot, the spin of the other can be determined, a necessary condition for quantum computation.

Smoke spun into fiber

Rumplestiltskin may have been able to spin straw into gold thread, but even in fairy tales no one spun thread from



University of Cambridge, Department of Materials Science and Metallurgy

A fiber of carbon nanotubes spun directly from an elastic smoke cloud in the reaction zone where the nanotubes were formed.

smoke. This feat has now been accomplished in a laboratory at the University of Cambridge in England, where a research team has spun an elastic smoke cloud into nanotube fibers, which these days may be more valuable technically than gold (*Science* 2004, *304*, 276).

Nanotube fibers have previously been formed from a polymer-based solution (see *The Industrial Physicist*, October/November 2003, pp. 21–22). But the resulting fibers, although exceedingly strong, were a mix of nanotubes and polymer glue. For many applications, especially those exploiting nanotubes' unique electrical properties, pure nanotube fibers would provide more benefit. The Cambridge team succeeded in producing such fibers for the first time, forming them in the furnace that generated the nanotubes.

Alan H. Windle and his colleagues fed a solution of ethanol and a few percent ferrocene and thiophene into a furnace at a temperature between 1,050 and 1,200 °C. They injected the solution at 0.08 to 0.25 mL/min into a stream of hydrogen gas flowing at 400 to 800 mL/min. The oxygen in the feed had the effect of burning away the non-nanotube soot particles, and the iron particles from the ferrocene acted as nucleation sites to form the nanotubes. "There had to be a fine balance in the hydrogen and solution flow rates so that only nanotubes formed, but no other carbon particles," said Windle, whose team included Ya-Li Li and Ian A. Kinloch.

The nanotubes rapidly linked together as they formed into a diaphanous web or aerogel, which had the appearance of an elastic smoke cloud a few centimeters in diameter. The aerogel had a density of only tens of micrograms per cubic centimeter but enough strength that it could be wound into a filament. The team used two methods to spin fibers. Inserting a rotating rod at an angle into the cloud produced a twisted fiber, and winding the cloud onto a spindle perpendicular to the gas flow produced either a fiber or an aligned nanotube film. The iron particles, concentrated on the outside of the fibers, were cleared off with hydrochloric acid.

The resulting 30-μm-diameter fibers, depending on the rate of hydrogen flow, consisted of single-walled or multiwalled nanotubes. Individual nanotubes within the fiber, each one a few nanometers across, extended up to 10s of μm in length. Windle believes that better process control and postprocessing treatment will improve the fibers' mechanical properties. "We're working to increase the stability of the conditions in the furnace," he explains.