Triangular Diode Acts as Asymmetric Energy Barrier to Magnetic Domain Wall Movement

Control of domain wall propagation in magnetic nanostructures is vital to both the understanding of domain wall properties such as wall resistance along with the science required for applications such as novel domain wall logic devices. In the October 4 issue of *Applied Physics Letters* (p. 2848), D.A. Allwood and co-workers from the University of Durham, UK, have reported the synthesis and characterization of a lithographically-patterned magnetic structure that allows control of wall propagation along a single direction. A domain wall diode is constructed by joining planar nanowires (fabricated by focused ion-beam milling of a 3 nm thick thermally evaporated $Ni_{80}Fe_{20}$ permalloy thin film on silicon) with a structure in the form of an isosceles right-angle triangle having a 500-nm base length. Each nanowire is 9 μm in length; one 200-nm width wire is joined at the apex of the triangle along with a 100-nm width wire at the base.

Three different magnetic structures were created containing this diode. Structure I has no additional components, Structure II has a 3 μm × 600 nm "domain wall injection pad" connected to the 200-nm width wire, and Structure III has a 3 μm × 600 nm pad connected to the 100-nm width wire. Analysis on these structures was performed using a high-sensitivity magneto-optical Kerr effect (MOKE) magnetometer with a 27 Hz alternating magnetic field applied along the wire long axis and a 5 μm diameter laser interrogation spot. Hysteresis loops were measured for each structure (Figure 1). For Structure I, nucleation and propagation of a wall is manifested as a sharp transition. However, single 200 nm wires exhibited transitions at the same value of coercivity, indicating that these domain walls may originate in the wire ends of the structure. For Structure II, a wall is injected from the pad into the 200-nm width wire. The geometry of the diode requires the width of the propagating wall to increase, causing minimal pinning before propagation to the 100-nm width wire occurs. For Structure III, a wall is injected into the 100-nm width wire, but is unable to de-pin from this section through to the diode (reversal in the 200-nm width wire is due to nucleation). Calculations of the pinning field suggest the triangular diode can be seen as an asymmetric energy barrier to wall propagation. Overall, said the researchers, these measurements demonstrate that wall propagation occurs in one direction. Hence this is truly a domain wall diode that can be utilized in memory applications requiring intrinsically defined directions of wall propagation, they said.

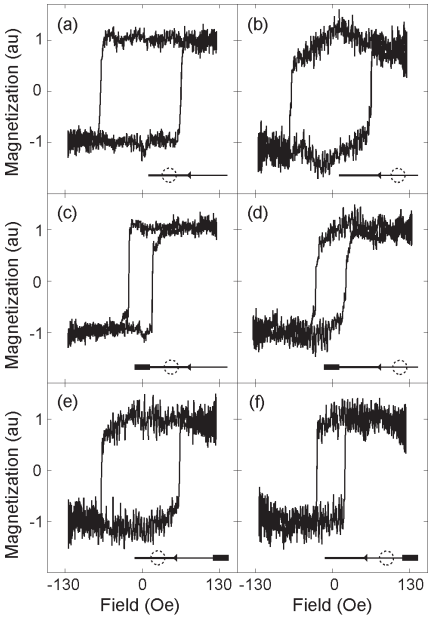

Figure 1. Hysteresis loops measured by magneto-optical Kerr effect for Structure I (a) with the laser beam on the 200 nm wire and (b) with the laser beam on the 100 nm wire; Structure II (c) 200 nm wire and (d) 100 nm wire; and Structure III (e) 200 nm wire and (f) 100 nm wire. Also inset to each plot is a schematic of the relevant structure and MOKE measurement position, indicated by the broken circle. Reprinted with permission from Applied Physics Letters ***85*** *(October 4, 2004). © 2004 AIP.*

ADITI S. RISBUD

New Photochromic Bands Observed in Functionalized Semiconducting SWNTs

Nanosensors are one of the many potential applications for single-walled carbon nanotubes (SWNTs). Previously, it was shown that SWNTs can function as sensors by using chemical doping, high-pressure reforming, or adsorption of atoms or functional groups to modify their electronic properties. Recently, R.F. Khairutdinov of the University of Alaska in Fairbanks and M.E. Itkis and R.C. Haddon of the University of California in Riverside have demonstrated that light can be used as a simple and convenient tool to control the electronic characteristics and, thereby, the conductivity of SWNTs.

As reported in the August issue of *Nano Letters* (p. 1529), the research team

reversibly modified the interband transition (S_{11}) intensities in semiconducting SWNTs—by light-induced refilling and depletion of the valence band—and in spiropyran-functionalized SWNTs (SP-SWNTs) by photoinduced changes in the dye's polarity. It is well-known that spiropyran molecules exhibit photochromic effects under UV-excitation, undergoing a transition to the merocyanine form. In this work, the researchers showed that the S_{11} modulation of SP-SWNTs corresponds to the UV-induced, reversible conversion of spiropyran by a ring-opening reaction to its merocyanine form. However, they also observed an absorption band at 440 nm that they indicate is due to the merocyanine aggregation by the functionalized SWNTs. Absorption-band shifts observed for merocyanine-SWNTs indicated to the researchers that the dye's π-electron system strongly interacts with the SWNT. In addition, the researchers interpreted other spectral features as evidence that spiropyrans/merocyanines are either bonded to the sidewalls or to the ends of the SWNTs. They used atomic force microscopy to show that SP-SWNTs exist in solution both as individual nanotubes and bundles of 2–5 nanotubes with lengths in the range of 0.4–2 μm.

The researchers said that discovering the nature of SWNT-substrate interactions will lead to further advances in SWNT-based chemical sensors. Furthermore, they believe that their work "presents an impetus for an exploration of a new type of chemical sensors based on the interaction of an analyte with a host molecule."

STEVEN TROHALAKI

WS_2 Nanotubes Synthesized for Lithium Storage

The discovery of fullerenes and carbon nanotubes has led to extensive research aimed toward the synthesis of similar one-dimensional nanostructures to carbon nanotubes, but based on different materials. These novel nanomaterials could find applications in diverse fields such as quantum computing, sensing and biomedical devices, and energy needs such as hydrogen storage. An example for such one-dimensional nanomaterials is WS_2 nanotubes discovered by R. Tenne and co-workers in the early 1990s.

In the October issue of *Electrochemical and Solid-State Letters* (p. A321), G.X. Wang, S. Bewlay, J. Yao, H.K. Liu, and S.X. Dou from the University of Wollongong, Australia report a major breakthrough in utilizing such WS_2 nanotubes for storing lithium in Li-ion batteries. Li-ion batteries are the most commonly used type of rechargeable batteries in portable electronic devices. Wang's research team has focused on how lithium is stored in WS_2 nanotubes, which represents an important process in using these materials as electrodes or anodes in rechargeable batteries.

The researchers synthesized WS_2 nanotubes from amorphous WS_3 at high temperature in a hydrogen atmosphere. They report a very high yield of ~80%. Characterization of the material by transmission electron microscopy with field emission indicated that the nanotubes have a length of a few hundred nanometers, have open tips, a diameter between 30 nm and 40 nm, with wall thicknesses of ~15 nm. The hollow core measured roughly 4.6 nm. Electrochemical properties were assessed based on coin cell testing.

Wang and co-workers identified electrochemical properties of the WS_2 nanotubes that differ significantly from WS_2 as a powder material. The WS_2 nanotube electrode

delivered a lithium insertion capacity correlating to 8.6 mol lithium per mol WS_2 nanotube whereas the lithium insertion capacity was 0.6 mol lithium per mol crystalline WS_2. The researchers attribute the nanotube capability to its 1D topology and open structure. They further found that the WS_2 nanotubes show stable cyclability over a wide voltage range (0.1–3.1 V vs. Li/Li^+), so that batteries built with these materials will be tolerant for overcharge and overdischarge. Based on their results, the researchers said that WS_2 nanotubes may be an attractive material for usage in electrochemical applications. In particular, they said, the capacity for storing Li is much enhanced in the nanotube modification of the material than the crystalline powder materials.

MARKUS J. BUEHLER

Fabrication of Suspended Micro- and Nanostructures Accomplished by Direct Drawing of Polymer Fibers

In designing and fabricating micro- and nanostructures, ease of fabrication is an important consideration. S. Harfenist, R.W. Cohn, and co-workers at the ElectroOptics Research Institute and Nanotechnology Center in the University of Louisville have demonstrated a simple and versatile method for creating suspended micro- and nanostructures by direct drawing of fibers from liquid polymers. The novelty of this approach is that it offers control and flexibility of forming and simultaneously patterning polymer fibers as suspended bridges and networks of three-dimensional structures.

As reported in the October 13 issue of *Nano Letters* (p. 1931), the researchers used tips attached to an atomic force microscope (AFM) or a computer-controlled micromill to draw fibers from a drop of poly(methyl methacrylate) (PMMA) electron beam resist placed on a substrate. The tip was dipped into the polymer drop several times until a fiber formed between the tip and the drop. The tip end of the fiber was drawn to a second drop of liquid polymer or adhered to a surface to form a polymer fiber that dries and solidifies into a suspended beam. The fibers produced were circular and uniform in diameter ranging from under 50 nanometers to tens of microns and can be made to span lengths from a few microns to several centimeters. This approach can be modified to produce suspended fibers in parallel and to pattern and orient them into three-dimensional geometries. For example, a bead of liquid polymer applied and allowed to dry momentarily on the edge of a stiff sheet of plastic or a microscope glass slide before being quickly dragged over an array of sharp silicon tips results in fibers suspended along each row of tips (see Figure 1). In a different example, polymer fibers several centimeters long can be drawn by hand on the cleaved end of a glass optical fiber and can be repeatedly manipulated and coiled without breaking. Fibers have been formed at draw rates between 10 μm/s and 100 mm/s, depending upon experimental conditions.

According to the researchers, polymer fibers formed and patterned by this approach may be applied as three-dimensional templates for subsequent processing. Capillaries with different functionality can be produced by coating the

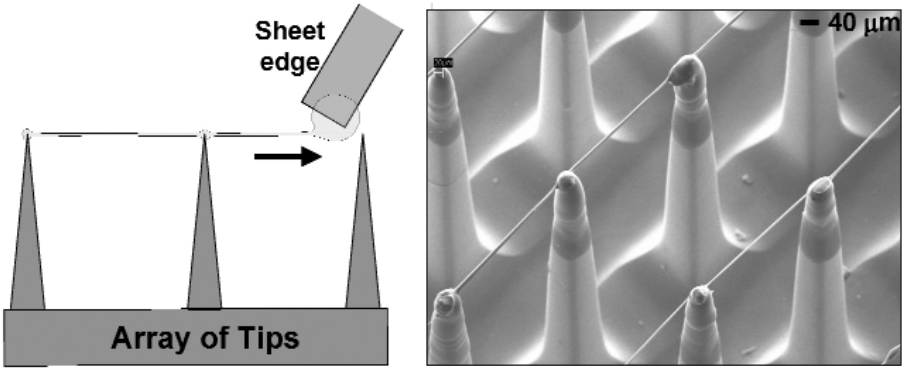

Figure 1. Fabrication of suspended nanostructures by direct drawing of polymer fibers. A drop of polymer is applied at the edge of a sheet and quickly drawn across a tip array creating multiple suspended parallel fibers.

polymer fibers with desired materials using various deposition techniques followed by selective removal of the polymer core. The researchers demonstrated capillaries in chrome, parylene, gold, and glass.

The speed and ease of fabrication by this direct-drawing method compared to conventional multi-step lithography, together with choice of polymer with desirable properties, opens the possibility of applications in the fabrication of microfluidic devices, and optical and sensing elements.

SOMA CHATTOPADHYAY

Use of Centrifuge Force to Fabricate Reticulated Porous Ceramics Results in Uniform Structure

Reticulated porous ceramics (RPCs) are synthesized materials composed of an arrangement of superimposed ceramic lattices. These materials exhibit porosity higher than 70%. Control of the pore structure is key for application of RPCs. A common method for manufacturing RPCs consists in immersing a polyurethane sponge in prepared ceramic slurry, removing the excess slurry by roll pressing and then sintering. However, the roll-press method does not effectively remove the excess slurry accumulated in the joints of the lattice. An alternative process to remove the excess slurry from the preform by utilizing centrifugal force has been presented by X. Pu, X. Liu, F. Qiu,

and L. Huang from the Shanghai Institute of Ceramics of the Chinese Academy of Sciences. Their technique ensures a uniform structure on the ceramic reticule.

As reported in the July issue of the *Journal of the American Ceramic Society* (p. 1392), the researchers prepared a slurry from silicon nitride powders mixed with 7 wt% alumina added as a sintering additive, 23 wt% silica sol as a binder, 1.5 wt% carboxymethylcellulose as a thickening agent, and 0.2 wt% of Nopco 267-A as an antifoaming agent. The slurry was ball milled using silicon nitride balls. A polyurethane sponge was submerged in slurry and compressed there to achieve the most adsorption possible, then centrifuged at high speed. In this manner, the lattice was uniformly covered with a thin film. The preform thus obtained was dried and recoated in slurry, this time using vacuum to ensure coverage. This process was repeated using slurries of different viscosities.

The measured weight gain of the sample after the first coating in slurry slightly increased with increasing slurry viscosity, and became constant for high-viscosity slurries. However, for the second coating, the measured weight gain was double that of the first coating for low-viscosity slurries, and increased dramatically with slurry viscosity. This is an effect of the enhanced adsorption created by the first thin film deposited on the lattice, said the researchers.

Measurements of the diameters in the lattice struts were fairly uniform and almost identical to the joint diameters. The strut diameter increased with increasing slurry viscosity, as expected, since the weight gain was higher at higher viscosity in the second coating. Through this process, the researchers demonstrated the ability to obtain a highly uniform and robust reticule structure, even starting with any irregularly shaped sample. The combination of high-speed centrifuging after each coating and the use of high-viscosity slurry for the second coating improved mechanical properties of RPCs, the researchers reported. The only difficulty they noted was the need for completing the second coating before drying the sample to prevent it from absorbing water and crashing.

SIARI SOSA

Circuit Quantum Electrodynamics Used to Couple Photon with Qubit

One of the goals in quantum physics is to develop a quantum computer in which the transistors that form logic gates to manipulate bits in a classical computer are replaced with quantum logic gates that can store and process information quantum mechanically. The fundamental units of information manipulated in a quantum computer are called quantum bits or "qubits," but implementations of the quantum logic gates are sometimes also referred to as qubits. R. Schoelkopf and the theory group of S. Girvin, both at Yale University, have conducted an experiment in which a single photon was coherently coupled to a single superconducting qubit or artificial atom consisting of about 10 billion aluminum atoms acting in concert like a single atom (see Figure 1). One way to connect qubits in a quantum computer is to make a "quantum bus" to carry information back and forth by using single photons. The work of Schoelkopf, Girvin, postdoctoral associate A. Wallraff, and graduate student D. Schuster introduces a paradigm in which quantum optics experiments can be performed in a microchip electrical circuit using microwaves instead of visible photons and lasers.

As reported in the September 9 issue of *Nature* (p. 162), the researchers constructed a miniaturized superconducting cavity based upon a coplanar waveguide structure of niobium on a silicon substrate in which to trap the microwave photon and force it to collide about 12 million times per second with the qubit implementation based upon a Cooper pair box. The Cooper pair box consisted of a long, thin superconducting island (several microns

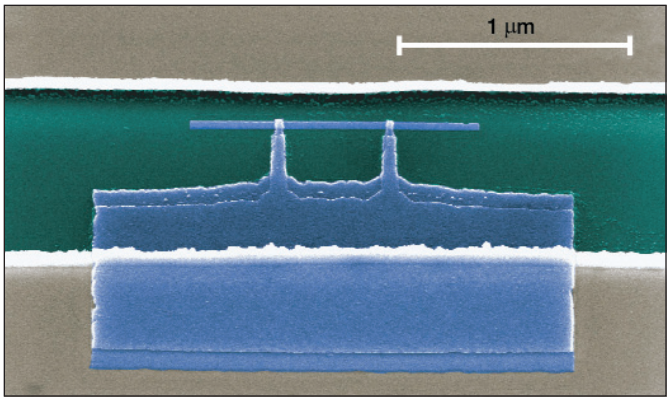

Figure 1. Integrated circuit for cavity quantum electrodynamics: false color electron micrograph of a Cooper pair box (blue) fabricated onto the Si substrate (green) into the gap between the center conductor (top) and the ground plane (bottom) of a resonator (beige) using electron beam lithography and double angle evaporation of aluminum. The Josephson tunnel junctions are formed at the overlap between the long thin island parallel to the center conductor and the fingers extending from the much larger reservoir coupled to the ground plane. Reprinted with permission from Nature ***431*** *(September 9, 2004) p. 163. ©2004 Nature Publishing Group.*

long and <1 μm wide) fabricated in the gap between the center conductor of the coplanar waveguide structure and the ground plane. The Cooper pair box was coupled by two submicron Josephson junctions to a larger superconducting reservoir, which was coupled to the ground plane. Under the rules of quantum mechanics, the state of the system becomes a coherent superposition of two simultaneous possibilities: The energy is either an excitation of the atom or it is a photon. It is this superposition that was observed in the Yale experiment.

The researchers said, "The very strong coupling of the microwaves to the qubit… makes it possible to use probe photons sent through the cavity to quickly and accurately determine whether the artificial atom is in its ground state or excited state without changing that state." This type of measurement is important in developing a quantum computer. The researchers said, "Such a device [quantum computer] consists of quantum bits that, unlike ordinary bits, can be in coherent superpositions of 0 (ground state) or 1 (excited state) at the same time."

In order to isolate one photon, the researchers operated the circuit at a temperature of 0.02 kelvin. They said, "This also allowed us to build the circuit with superconducting wires that have no resistance, so we could make a cavity where the single photon could be stored for a relatively long time."

Miniature Fuel Cell Fabricated Using Microelectronic Techniques Displayed a Porous Si Layer as a Catalyst Support Layer

Several types of miniature fuel cells are in development, with a primary goal of utilizing current microfabrication technology to achieve power generation for portable electronic devices. Many of these miniature fuel cells use catalyst layers containing Pt/Ru on activated carbon, which is incompatible with the silicon-batch fabrication process. In order to better implement Si microfabrication techniques to assemble miniature fuel cells, M. Hayase, T. Kawase, and T. Hatsuzawa from the Tokyo Institute of Technology in Japan developed an alternative process to forming a catalyst layer, which these researchers described in the August issue of *Electrochemical and Solid-State Letters* (p. A231).

First, the investigators patterned fuel channels of 80–90 μm depth by photolithography and wet etching a highly doped Si wafer. An *n*-type Si wafer was chosen because of its higher wet-etching rate with low resistivity to ensure it worked as a current collector. A 100 nm copper layer was sputtered on the Si wafer to supply current from a potentiostat. On the opposite side, anodization of the Si wafer in a 46% HF-ethanol solution using a current density of 100 mA/cm^2 resulted in a porous Si layer that grew up to the base of the fuel channels at a rate of 45 nm/s. These were the optimal conditions found for formation of a uniform porous Si layer. Anodizing typically lasted for 5–6 min, as observed experimentally. A catalyst layer was later deposited on the porous Si layer by using a plating bath of 1.0 M H_2SO_4 + 10 mM H_2PtCl_6 + 5 mM K_2RuCl_5 + 50 mM HF at 293 K. The hydrofluoric acid added to the bath removed any silica present at any stage and resulted in electroless deposition of Ru and Pt. Thus, combining the HF addition to the bath with the use of a pulse plating technique assured the deposition of catalyst metal ions inside the pores of the catalyst layer. Otherwise, it was not possible to obtain coverage inside the pores since the catalyst metal ions were not able to reach the pores by electrodeposition means exclusively. The pulse plating technique utilized consisted of applying a current of 5 mA/cm^2 at a frequency of 1 Hz for 0.2 s followed by a halt of 0.8 s. This cycle was repeated for 5 min, obtaining coverage toward the porous Si layer to a depth of 10 μm. The Si wafer was then immersed in a 40% $FeCl_2$ solution at 313 K for 3–5 min to remove the copper layer. Two Si wafers thus processed were hot pressed with their catalyst sides facing top and bottom of a Nafion 112 piece, which worked as a polymer electrolyte membrane, using Nafion 5% solution as an adhesive. Hot pressing was accomplished at 0.05 MPa and 443 K for 30 min. The total thickness of the miniature fuel cell thus assembled was 250 μm.

Testing the full assembly with hydrogen gas gave a peak power of 1.5 mW/cm^2 at 353 K, and the porous Si layer indeed functioned as a current collector, reported the researchers. They said that the parabolic shape of the polarization curves show that the controlling mechanism is the catalyst performance. Power-generation capabilities of this miniature fuel cell are better than those of similar structure not using activated carbon as a catalyst layer, they said.

SIARI SOSA

Electrochemical Polishing Technique Yields Apparatus for Manipulation of Micro- to Nanometer-Sized Magnetic Beads

To date, the application of miniature electromagnets for molecular and cellular manipulation has been limited by weak magnetic field gradients and resultant weak magnetic forces that are produced by these devices. A further complication is resistive heating of the electromagnet that may damage living cells and lead to expansion of the material used for the electromagnet core. This thermally induced expansion diminishes the ability to control the level of applied force. For example, precisely controlled forces in excess of 100 pN are required to produce nanometer-range displacements of a 4.5-μm diameter magnetic microbead and the adhesion receptor on a living cell. B.D. Matthews of Harvard Medical School, D.A. LaVan of Yale University, and their colleagues have fabricated a temperature-controlled electromagnetic microneedle (EMN) capable of forces >50 nN with minimal heating.

As described in the October 4 issue of *Applied Physics Letters* (p. 2968), Matthews and co-workers have developed a novel electropolishing technique to create micromagnetic pole tips for controlled manipulation, probing, and positioning of magnetic particles. Their apparatus consists of multiple loops of insulated electromagnetic wire coiled around a permalloy magnetic core (1 mm diameter). Copper wire (50 μm diameter, 44 gauge) was wound around the magnetic core. Typical electromagnets in this study had 2000 turns of wire, a resistance of 16 Ohms, an inductance of 1.4 mH, and a capacitance of less than 2 pF. The core and electromagnet wires were housed within a temperature-regulated water flow chamber. Two 1-mm diameter plastic shields were fitted over the ends of the core, with an exposed section of the wire between them. The exposed end of the rod was initially electropolished in an 8:7:5 phosphoric acid, sulfuric acid, and water solution with an applied potential of 6 V. After the core diameter was reduced by 50%, the plastic shield was removed from the distal end of the rod and electropolishing continued at a 4 V applied potential until the distal end broke off. The final tip geometry was determined by the initial surface area exposed between the two plastic sleeves. Optical micrographs show that the technique is reproducible.

The researchers concluded that the magnitude of the magnetic field gradient generated by the EMN is primarily a function of the needle tip. EMNs with large tip radii (20 μm) are capable of interacting with multiple beads, they said. Electropolishing to smaller radii (0.1–6 μm) allows selective capturing of single magnetic beads. The researchers demonstrated removal of a single 4.5 μm superparamagnetic bead from a group of similar ones, less than 10 μm from each other. It is then possible, they said, to relocate the bead by moving the needle and simply shutting off the current. The researchers demonstrated that 50 nN forces could be applied to 4.5 μm diameter beads using an EMN with a pole tip radius of 20 μm, while more than 1 nN could be applied to 250 nm diameter beads using an EMN with a pole tip radius of 100 nm.

JEREMIAH T. ABIADE

Bacteria Use "Molecular Lasso" to Cop Copper

The bacteria that destroy about one-third of the potent greenhouse gas methane before it can reach the atmosphere produce a small organic compound and release it into the surrounding environment, where it "lassos" atoms of copper. The bacteria then reabsorb the compound and use the copper as a weapon against methane, from which they extract energy. The crystal structure of the compound, called methanobactin, is reported in the September 10 issue of *Science* (p. 1612). The research was led by H.J. Kim, who did much of the work as a graduate student at the University of Kansas and is now a postdoctoral associate at the University of Minnesota College of Biological Sciences. Methanobactin may have antibacterial properties, and its ability to absorb copper may find application in the semiconductor industry, which needs copper-free water.

The methanobactin molecule is a tiny, pyramid-shaped compound with a cleft that holds a single atom of copper in place. The researchers identified the components as a tetrapeptide, a tripeptide, and several moieties, including two 4-thionyl-5-hydroxy-imidazole chromophores that coordinate the copper, a pyrrolidine that confers a bend in the overall chain, and an amino-terminal isopropylester group. The copper coordination environment, found at the base of the pyramid structure, includes a dual N- and S-donating system derived from the thionyl imidazolate moieties.

The bacteria that make methanobactin are common. "These bacteria are often found in rice paddies and wetlands," said Kim. "Methane is produced in the bottom muck and diffuses into the water, where these bacteria live. The bacteria sequester the methane and turn it into methyl alcohol."

The bacteria churn out methanobactin molecules in large numbers and send them into the environment to fetch copper. When the compound returns with copper, it is thought that the copper is incorporated into molecules of a key enzyme that converts methane to methyl alcohol. Due to its high reactivity, copper would be an appropriate atom to metabolize methane. Their reactivity also makes copper atoms toxic to the bacteria. Thus, methanobactin serves to keep copper under control and protect the bacterial cells from it, said the researchers.

One piece of the story still to be learned is how the methanobactin is retrieved by bacterial cells, Kim said. The cells apparently latch onto copper-bearing methanobactin molecules, but what happens next is unknown. Methanobactin has no tether to its mother cell. Therefore, when bacterial cells release their methanobactin molecules, they probably never see them again; instead, they take delivery of copper from methanobactin released by other cells of the same species, the researchers said

"Synthesized compounds analogous to some parts of the methanobactin molecule have been shown to be antibacterial," said Kim.

SnO_2 Nanoribbons Channel Light at the Nanoscale

In photonics technology, the use of electrons moving through semiconductors as information carriers is replaced with the movement of photons. For the promise of photonics to be delivered, however, scientists need to manipulate and route photons with the same dexterity as they do electrons. Peidong Yang's research team at Lawrence Berkeley National Laboratory and the University of California at Berkeley have demonstrated that semiconductor nanoribbons can serve as waveguides for channeling and directing the movement of light through circuitry.

"Not only have we shown that semiconductor nanoribbons can be used as low-loss and highly flexible, optical waveguides, we've also shown that they have the potential to be integrated within other active optical components to make photonic circuits," said Yang.

"Chemically synthesized nanowires and nanoribbons have several features that make them good photonic building blocks," Yang said. "They offer inherent one-dimensionality, a diversity of optical and electrical properties, good size control, low surface roughness, and, in principle, the ability to operate above and below light diffraction limits."

As reported in the August 27 issue of *Science* (p. 1269), Yang and his colleagues synthesized their nanoribbon waveguides from tin oxide. The single-crystalline nanoribbons measured ~1500 μm in length and featured a variety of widths and thicknesses. Yang said ribbons measuring 100–400 nm in width and thickness proved to be ideal for guiding visible and ultraviolet light.

"To steer visible and ultraviolet light within dielectric waveguides such as the tin oxide crystals we were synthesizing, we needed to make sure that a sufficient portion of the light's electromagnetic field was confined within the nanostructures so there would be minimal optical transmission loss," Yang said. "Considering the dielectric constant of the tin oxide, it follows that the diameter of 100 to 400 nanometers would be ideal for waveguiding light that measures from 300 to 800 nanometers in wavelengths." In their tests, Yang and his colleagues attached nanowire light sources and optical detectors to opposite ends of their tin oxide nanoribbons, then demonstrated that light could be propagated and modulated through subwavelength optical cavities within the nanoribbons. The nanoribbons were long and strong enough to be pushed, bent, and shaped with the use of a commercial micromanipulator under an optical microscope. Freestanding ribbons were also extremely flexible and could be curved through tight S-turns and twisted into a variety of shapes, which Yang said is "remarkable for a crystal that is brittle in its bulk form."

According to the researchers, while the nanoribbon waveguides can be coupled together to create optical networks that could serve as the basis of miniaturized photonic circuitry, the ribbons need to be in close proximity, preferably in direct physical contact, to enable an efficient transfer of light between them (see Figure 1).

Yang said, "We tested various coupling geometries and found that a staggered side-by-side arrangement, in which two ribbons interact over a distance of several micrometers, outperforms direct end-to-end coupling."

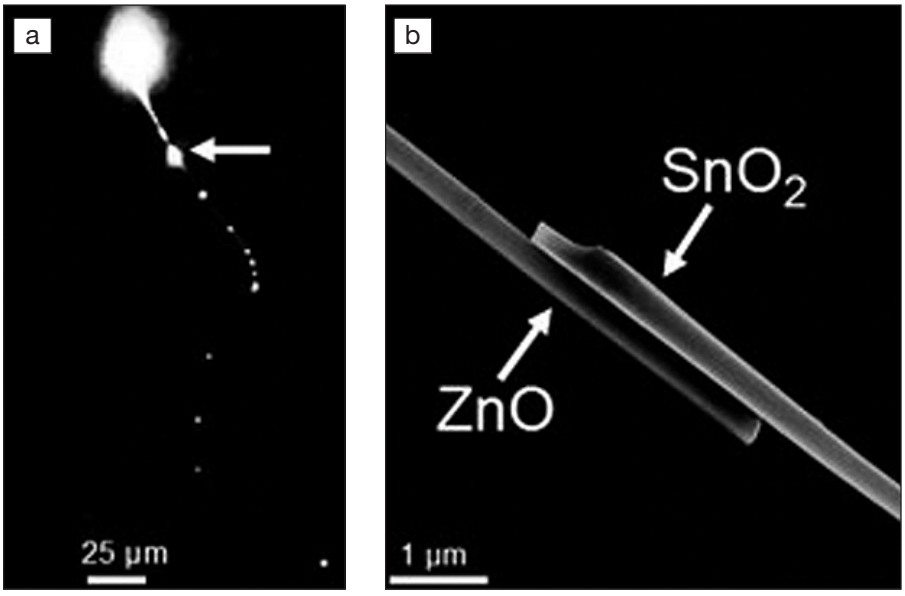

Figure 1. (a) A zinc-oxide nanowire laser is pumped with light, which is channeled into a tin-oxide nanoribbon at a junction between the two materials and guided through the rest of the ribbon's length; (b) an electron microscope image of the junction between wire and ribbon.