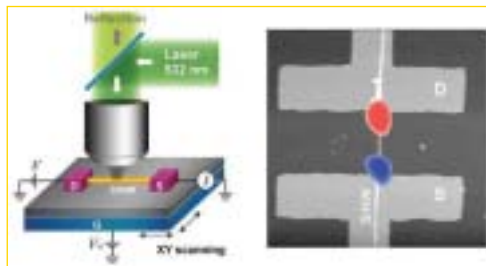


Si nanowires see the light

NANOWIRES



Optical scanning microscope and transport measurement setup (left) and scanning photocurrent image of a Si nanowire (right). (© 2005 American Chemical Society.)

Rowland Institute researchers at Harvard University have shown that individual field-effect transistors made from 20-30 nm thick crystalline Si nanowires (SiNW FETs) can be used as a polarization-sensitive, high-resolution photodetectors for visible light [Ahn *et al.*, *Nano Lett.* (2005), doi: 10.1021/nl050631x]. Like bulk Si, SiNWs' electrical conductance shows good photosensitivity to visible light. Optical scanning measurements show a linear increase in photoconductance of more than two orders of magnitude, with sensitivity similar to InP nanowires and much larger than that of carbon nanotubes. The conductance

polarization anisotropy ratio is a large 0.8. When illuminated by a laser beam near the electrode contacts with no bias applied, the SiNW devices produce a strong photocurrent, owing to electronic band bending. Scanning images of the photocurrent at various gate and drain-source biases reveal the profile of the local electronic band structure within a single SiNW along its axis, and allow measurement of several electronic energy parameters. The technique should therefore provide a new characterization tool for studying photosensitive nanoscale devices. Principal investigator Jiwoong Park says that SiNW photoelectric properties could be applied to fabricate light-sensitive devices such as highly sensitive point photodetectors for high-resolution position sensors, local biosensors for optically active species, and advanced photosensitive scanning probe tips. The researchers are currently working on gigahertz-speed measurements of SiNW photodetectors to explore their use as high-speed components for integrated optoelectronic circuits.

Mark Telford

Controllable, fast rotation

NANOWIRES

For small entities suspended in liquid, a low Reynolds number means that the viscous drag force overwhelms and quickly halts any motion. On applying a counteracting external force, the terminal velocity is reached almost instantly. Controlled rotation is more challenging. For example, magnetic fields have been used to rotate ferromagnetic nanowires, but only at low speed.

Last year, researchers at Johns Hopkins University used an ac electric field from patterned microelectrodes to drive linear motion of nanowires, despite a Reynolds number of 10^{-5} . Now, they have used a rotating field from four phase-shifted electrodes to drive controllable, high-speed rotation of metallic Au, Pt, and Ni nanowires 300 nm in width and 2-30 μm in length [Fan *et al.*, *Phys. Rev. Lett.* (2005) **94**, 247208]. Rotation can be switched on or off instantly with precisely controllable chirality, total angle of rotation, and speed (reaching at least 1800 rpm).

The researchers have also determined the viscous torque resulting from the fluidic drag force on nanowires of different lengths.

A micromotor has been demonstrated where a bent Au nanowire is attached covalently at its apex to a thiolated substrate, and its two arms (each about 16 μm long) drive a dust particle in circular motion. Principal investigator Chia-Ling Chien says that, by extending the method to moving biological entities, applications can include microstirrers, microfluidic devices, and microelectromechanical systems. As well as both magnetic and nonmagnetic nanowires, the method can also rotate multiwalled carbon nanotubes 50 nm wide and 5 μm long.

Mark Telford

SiGe oxide nanowires push Si into the blue

NANOWIRES

Scientists at Taiwan's National Tsing Hua University have synthesized blue-light-emitting $\text{Si}_{1-x}\text{Ge}_x$ oxide nanostructures of various shapes on epitaxial $\text{Si}_{0.8}\text{Ge}_{0.2}$ alloy buffer layers on Si substrates by thermal annealing in N_2 in a quartz tube furnace [He *et al.*, *Appl. Phys. Lett.* (2005) **86**, 263109]. Nucleation in the same regions as a patterned thin film of catalytic Au particles indicates growth via the vapor-liquid-solid mechanism.

Owing to the Ge atoms, the room-temperature photoluminescence spectrum of $(\text{Si}_{0.91}\text{Ge}_{0.09})\text{O}_{0.47}$ nanowires annealed at 1140°C has a shorter-wavelength blue light emission peak at 415 nm, compared with 470 nm for Si oxide nanowires. Strong emission is attributed to the oxygen deficiency. Raising the anneal temperature from 950°C to 1200°C yields a longer peak emission wavelength and greater intensity (correlated to a rise in nanowire density).

The shorter emission wavelength may enable use in high-density optical devices. But, for practical application, nanowire shape, size, patterning, and



Scanning electron micrograph of $\text{Si}_{1-x}\text{Ge}_x$ oxide nanostructures. (© 2005 American Institute of Physics.)

spacing must be precisely controllable, says principal investigator L. J. Chou. The team is therefore growing ordered $\text{Si}_{1-x}\text{Ge}_x$ oxide nanowire arrays on different substrates by several means, including force-assembly, nanosphere lithography, and atomic force microscope-tip induced patterning.

Mark Telford

Au particles for bioimaging

NANOPARTICLES

Using sub-100 fs pulses of 790 nm near-infrared laser light, scientists at Boston College led by John T. Fourkas have observed highly efficient multiphoton absorption induced luminescence (MAIL) of visible light from single Au particles as small as an organic fluorophore molecule (a few nanometers in diameter) [Farrer *et al.*, *Nano Lett.* (2005) **5** (6), 1139]. The most efficient Au nanoparticles could be seen for excitation intensities lower than those typically used for multiphoton imaging of fluorescently labeled biological tissues or cells. Compared to fluorophores, the Au particles have polarized emission, are highly photostable, and do not exhibit significant blinking. The observations suggest that metal nanoparticles are a viable alternative to fluorophores or semiconductor nanoparticles for biological labeling and imaging. The technique paves the way for observing behavior in living tissues at the single-molecule level, says Fourkas. "We can now see single nanoparticles under conditions where people usually look at thousands or millions of stain molecules. This could allow us, for instance, to track a single molecule of a drug in a cell or other biological sample."

Other advantages are that the Au particles can be prepared easily, have very low toxicity, and can readily be attached to molecules of biological interest, says Fourkas. Also, the laser light used is at a wavelength range that causes minimal damage to most biological tissue. Hence, the generation of strong emission in small particles at low excitation energies and in a broad range of environments may enable *in vivo* imaging at the single-particle level, particularly if methods for preparing Au nanoparticles with reproducible asymmetries can be developed.

Mark Telford

Carbon nanotubes boost neural signaling

CARBON NANOTUBES

Scientists at Italy's University of Trieste, University of Ferrara, International School for Advanced Studies, and National Consortium of Materials Science and Technology (INSTM) have grown nerve cells from the brain's hippocampus region on substrates coated with networks of carbon nanotubes, and found a large increase in neural signal transfer between cells [Lovat *et al.*, *Nano Lett.* (2005) **5** (6), 1107]. Since carbon nanotubes are similar in shape and size to nerve cells, they could help to structurally and functionally reconnect injured neurons.

To obtain a pure, homogenous dispersion, the multiwalled carbon nanotubes were functionalized with pyrrolidine groups to enhance their solubility in the organic solvent dimethylformamide. After solvent evaporation, heating at 350°C then defunctionalized them, leaving purified nanotubes on the substrate. Hippocampal neurons grown on nanotubes display a six-fold increase in the frequency of spontaneous postsynaptic currents, evidence of functional synapse formation and a widely accepted index of network efficacy. The data give information on the performance of carbon nanotubes as supportive devices for bridging and integrating functional neuronal networks *in vitro*.

The researchers foresee an impact of carbon nanotubes on novel chronic neural implants.



Scanning electron micrograph of contact between a neuron and a carbon nanotube substrate. (Courtesy of Laura Ballerini.)

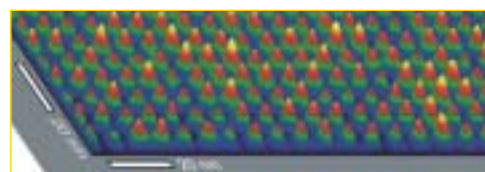
"Investigating nanomaterial interactions with nervous tissue will also favor the design of acceptably small electrodes to provide spinal microstimulation without causing significant neural damage," says Trieste's Laura Ballerini. In the long term, the results will impact on new tissue engineering strategies, where functional reconnection among injured neurons or the improvement in neural signal transfer is the main target. "We need to learn more about the properties of such materials and their physiological interactions with neurons in culture," she adds. "This will provide the groundwork for more exhaustive evaluation in animal models."

Mark Telford

Electron-beam induced deposition nears limit

NANOFABRICATION

Resist-based electron-beam lithography is limited to resolution of ~10 nm, while scanning probe lithography has limited speed. A fast resistless technique with sub-10 nm resolution is electron-beam-induced deposition (EBID). Here, electrons are focused on a surface of adsorbed precursor gas molecules; inelastic collisions generate secondary electrons in the substrate that are re-emitted and dissociate precursor molecules; nonvolatile products adhere to the surface, and a deposit grows. Metal structures created this way are limited to 15-20 nm, it was thought, by the area of secondary electron emission. But Monte Carlo simulations by Delft University of Technology researchers suggest that sub-1 nm dots could be made in a controllable way if exposure time is short. Now, with a coworker at Arizona State University, they have used a scanning transmission electron microscope to fabricate an array of 1 nm dots deposited from



Intensity plot of an annular dark field image of dot array deposited from $W(CO)_6$. (© 2005 American Chemical Society.)

$W(CO)_6$, plus 1.9 nm lines spaced by 3.2 nm [van Dorp *et al.*, *Nano Lett.* (2005), doi: 10.1021/nl050522i]. The objective is to find the resolution limit, unravel the dissociation process, and develop pure, carbon-free metallic deposits. Uses include making contacts to single molecules. But EBID could also yield controlled, fast sub-10 nm lithography for Si chip making. So, the aim is to develop, with Dutch research organization TNO, a system with 100 electron beams in parallel.

Mark Telford

Quantum dots boost solar

NANOPARTICLES

Arthur J. Nozik predicted in 2000 that quantum dots (QDs) could increase efficiency in solar cells through multiple exciton generation (MEG, or impact ionization), rather than the generation of just one exciton (electron-hole pair) per absorbed photon.

Last year, using PbSe QDs, Los Alamos National Laboratory's Richard Schaller and Victor Klimov obtained a quantum yield of 218% (i.e. more than two excitons per absorbed photon) for photons of energy $3.8E_g$ (where E_g is the QD bandgap), and reported a threshold for MEG of $3E_g$.

Now, Nozik's group at the US National Renewable Energy Laboratory and the University of Colorado, together with theorists at the Naval Research Laboratory, has seen quantum yields of 300% for 3.9 nm PbSe QDs (i.e. three excitons per photon) for $4E_g$ photons [Ellingson *et al.*, *Nano Lett.* (2005) **5** (5), 865]. This could double solar cell efficiency to >65%, says Nozik. In addition, the group observed the first MEG in PbS QDs (of size 5.5 nm), at comparable efficiency. Also, they found a threshold of $2E_g$, which makes more of the sun's spectrum usable.

The researchers have suggested a new model for the MEG mechanism, and delineated the unique character of QD electronic structure. This allows for the possibility of the evolution of the quantum state from the initial single exciton to a coherent superposition of multiple exciton states. So, a photon with energy above $3E_g$ directly creates multiexciton states. However, between $2E_g$ and $3E_g$, direct Coulomb interaction couples a symmetric electron-hole pair created by light to an asymmetric pair where the total kinetic energy resides in one carrier and is sufficient to generate a multiparticle electron-hole configuration.

Mark Telford

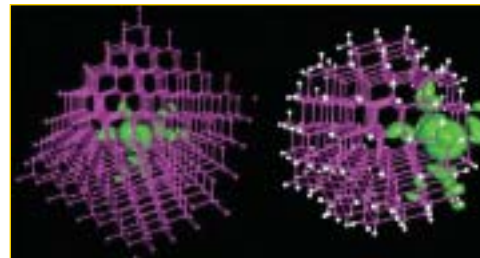
Dielectric constant scaling is a surface effect

NANOPARTICLES

When a semiconducting quantum dot is smaller than the wavefunction of its electrons, the 'squeezing' of the wavefunction (quantum confinement effect) increases the energy band gap between the valence band of energy levels full of atom-bound electrons and the conduction band of unbound electrons.

It was believed that this also explains the decrease in dielectric constant, which is the average of its dielectric response function (the response of charge density to an electric field). But empirical tight-binding calculations made by Delerue *et al.* in 2003 at France's Institut Supérieur d'Electronique du Nord suggested that this is only a surface effect. Now, using *ab initio* calculations on a supercomputer, theorists at the Lawrence Berkeley National Laboratory have performed first-principles studies of the microscopic dielectric function in quantum dots [Cartoixa and Wang, *Phys. Rev. Lett.* (2005) **94 (23), 236804].**

For a 933 atom GaAs quantum dot perturbed by a single electron (e.g. from a dopant atom), they found that the dielectric function is, in fact, bulk-like, and that the change in the dielectric constant is indeed a surface effect. "Averaging makes it appear that the dielectric constant mimics size-dependent changes in the band gaps. But there is no direct relationship,"



Charge response (green) for a single-electron perturbation in GaAs is very similar in (left) bulk and (right) a quantum dot, except near the surface. (Courtesy of Lin-Wang Wang.)

says coauthor Lin-Wang Wang.

"We were able to devise a simple model for calculating the dielectric function on the microscopic scale that gives virtually the same results as *ab initio* calculations and can be used to solve the Poisson equation in a nanosystem," says Wang. "The result suggests a completely different way to model the dielectric function in nanostructures, which is essential to the understanding and calculation of their electronic structures and optical properties." The researchers aim to incorporate their model of the dielectric function into other nanoscience computational tools to calculate, for example, quasiparticle energies and Coulomb blockade effects in a single-electron device.

Mark Telford

Encapsulated quantum dots yield multicolor LEDs

NANOPARTICLES

Efficient light-emitting diodes (LEDs) based on InGaN typically produce blue light, requiring an organic phosphor coating to convert to other wavelengths to yield white light for solid-state lighting. Energy losses occur during light capture, re-emission, and unwanted reabsorption.

Energy can be saved through direct electrical excitation by incorporating in the LED color-selectable chromophores such as quantum dots, which have size-tunable narrow-band emission color, high emission efficiency, chemical flexibility, and excellent photostability. But this has been hindered by the difficulty of making electrical connection to dots.

Now, using GaN substrates from Sandia National Laboratories, Victor I. Klimov's team at Los Alamos National Laboratory has demonstrated the first electroluminescence from all-inorganic, multicolor LEDs based on colloidal quantum dots encapsulated between the *p*- and *n*-doped GaN layers of a *p-n* junction, which provide separate charge injection

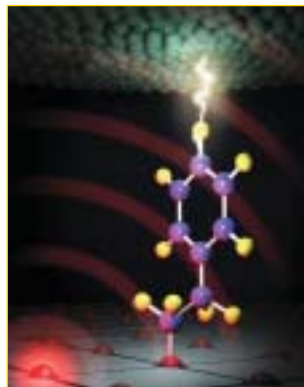
into the dots of holes and electrons, respectively [Mueller *et al.*, *Nano Lett.* (2005) **5** (6), 1039]. After coating a *p*-type GaN layer with a Langmuir-Blodgett monolayer of CdSe/ZnS core/shell dots capped with trioctylphosphine oxide (TOPO)/trioctylphosphine (TOP) ligands, electrical connection is achieved using energetic neutral atom beam lithography/epitaxy (ENABLE), developed by Mark A. Hoffbauer's nanoscale processing team. This allows overgrowth of *n*-type GaN at a low substrate temperature for nitrides (300°C), avoiding degradation of either dot integrity (size or shape) or luminescence.

By encapsulating two layers of dots of different sizes, the researchers have demonstrated LEDs that emit light of two different colors. This is an important step, they say, toward creating devices with multiple layers of differently sized dots for multicolor operation to yield white light LEDs.

Mark Telford

Single charge points to molecular transistor

MOLECULAR ELECTRONICS



Charged atom on a Si surface gates the conduction in a styrene molecule. (Courtesy of Robert Wolkow.)

Researchers at Canada's University of Alberta and National Institute for Nanotechnology, along with colleagues at the University of Liverpool, UK, have shown that a single point charge can regulate conduction through a

nearby molecule [Piva *et al.*, *Nature* (2005) **435**, 658].

Building electronics from single molecules could offer smaller, faster, and cheaper devices than those based on Si. The characterization of molecules held between two electrodes is becoming more reproducible and robust, but making a single-molecule transistor, in which a third terminal switches molecular conductivity on and off, is more difficult. Robert Wolkow

and coworkers now show that the electrostatic field of a point charge can act like a third terminal by exerting control over the response of a molecule in a standard, two-terminal scanning tunnelling microscope (STM) setup. The group investigated styrene molecules on an H-terminated Si surface. The molecules self-organize into lines, starting at a Si dangling bond. Lines and dangling bonds can readily be imaged by the STM at room temperature.

On highly doped, *n*-type Si crystal, the dangling bond is negatively charged. Here, STM images at low bias show a rise in the molecular line's height near the charged dangling bond, as if the molecules nearest the point charge have a built-in offset voltage. At higher imaging voltage, all the molecules appear as tall. In contrast, a dangling bond on a low-doped crystal is not charged and the effect is not seen. The researchers use quantum mechanical modeling to confirm that the charged dangling bond shifts the styrene molecular energy levels, changing the onset of molecular conduction (i.e. the closer the molecule to the point charge, the lower the sample bias needed to see current onset).

Jonathan Wood

DNA lines up to be counted

BIOTECHNOLOGY

Individual DNA molecules have been detected as they move in single file through the confined space of a nanoscale channel. The lipid-based electrophoresis system, developed at Chalmers University of Technology in Sweden and the Institut Curie, France, is able to identify the size of each DNA molecule and probe its conformation [Tokarz *et al.*, *Proc. Natl. Acad. Sci. USA* (2005), **102** (26), 9127].

The starting point for electrophoresis is a liposome filled with a fluorescently labelled DNA solution. Electrodes are brought into contact with the liposome and an electric pulse allows the tips to penetrate the membrane. Withdrawing an electrode draws out a lipid membrane nanotube with a diameter of ~300 nm extending 40 μ m from the much larger, spherical liposome.

Applying a voltage of +100 mV to this electrode causes DNA to be injected from the liposome reservoir and transported along the nanotube toward the electrode. The excitation/detection spot of a confocal microscope is aligned with the nanotube so that peaks in fluorescence intensity are observed as single DNA molecules pass by.

Owe Orwar and colleagues are able to correlate peak intensity, duration, and area with DNA size, showing that the lipid-based system can count and characterize single molecules. The scientists can also probe the conformation of the DNA molecule during transport in the nanotube. Such studies of polymer dynamics could shed light on traffic of confined biopolymers through nanoscale channels *in vivo*. The group suggests that complex networks of lipid nanotubes could route DNA molecules between reaction chambers to perform specific hybridization, sequencing, or modification reactions.

Jonathan Wood

Dendrimers effective in cancer targeting

NANOMEDICINE

A University of Michigan team has demonstrated the potential of using dendrimers for the targeted delivery of anticancer drugs and imaging agents to tumors [Kukowska-Latallo *et al.*, *Cancer Res.* (2005) **65** (12), 5317]. The treatment is ten times more effective in delaying growth of human tumors in mice than free drug alone, extending the life of the mice. There were no toxic effects, suggesting a much higher dose could be used than with the free drug. "Targeting drugs directly to cancer cells reduces the amount that gets to normal cells, increases the drug's anticancer effect, and reduces its toxicity," says principal investigator James R. Baker. "By improving the therapeutic index of cancer drugs, we hope to turn cancer into a chronic, manageable disease." A number of cancers, including breast, ovary, kidney, and lung, overexpress folate receptor protein, which binds and internalizes the vitamin folic acid. Tumors can be selectively targeted by a suitable drug delivery vehicle modified with folic acid. Polyamidoamine (PAMAM) dendrimers have advantages over

antibodies or liposomes for this. The dendrimers are stable, nonimmunogenic and, at <5 nm in diameter, can escape the vasculature and be internalized by tumor cells. Also, they have many reactive groups for conjugation of multiple chemical species.

Acetylated PAMAM dendrimers were conjugated to folic acid (for tumor targeting), the drug methotrexate, and a fluorescent label (for imaging). The nanoparticles were then injected into mice bearing human tumors. The researchers examined the biodistribution of the nanoparticles, imaged the dendrimers within tumor cells, and measured the antitumor efficacy of the conjugates.

"We saw statistically significant tumor growth reduction in all the mice given targeted nanoparticle therapy, as opposed to mice receiving either free methotrexate or the dendrimer alone," says Jolanta Kukowska-Latallo. "All the mice receiving free methotrexate died, either from overgrowth of the tumor or from toxic effects of the drug."

Jonathan Wood