challenges associated with using the cobalt complex," he adds.

The recombination of the positive and negative charges produced when the dye absorbs light is much faster with the cobalt complex. The recombination needs to be slow enough to allow the mediator time to collect the positive charge before the charges recombine and produce heat.

One way to increase efficiency of DSCs is to slow down the rate of recombination. DSCs could not take advantage of this strategy in the past because they could achieve charge-carrier-collection efficiency of 100% — the mediator collected 100% of the positive charges created by the dye.

"Now there actually is a recombination problem," McGehee says. Techniques that introduce a recombination barrier into the solar cells, such as the use of atomic-layer deposition to coat the titanium dioxide, can now be applied to DSCs, McGehee says. "I think there's going to be a flurry of efficiency improvements coming in the next couple of years as people do these things."

Grätzel and his colleagues are aiming for 15% efficiency as the next target. "This is something that is now very much in reach," Grätzel says. The team is tweaking the zinc porphyrin dye and also experimenting with dye mixtures and custom-made new cobalt complexes to reach the efficiency goal.

## NANOTECHNOLOGY

### Airbrushed Carbon Nanotubes Form Electronic Skin

Touch-sensitive skin for prosthetic and robotic limbs, stretchable wiring for future electronic displays, and smart bandages are just a few of the potential applications that Stanford Univ. engineers envision for their transparent, super-stretchy sensor.

The sensor is made of two layers of silicone, coated with parallel lines of carbon nanotubes (CNTs), and glued together to form a conductive grid. Each junction point of the grid (*i.e.*, where the CNT lines of one layer overlap with those of the second layer) forms a parallel-plate capacitor, enabling the device to sense pressure at multiple locations.

"This sensor can register pressure ranging from a firm pinch between your thumb and forefinger to twice the pressure exerted by an elephant standing on one foot," says Darren Lipomi, a postdoctoral researcher in chemical engineering at Stanford.

One of the challenges with making a stretchable pressure sensor is that most conductive materials lose their conductivity when deformed. This CNT-based film, however, can be stretched up to 2.5 times its original length without a loss in conductivity — allowing the skin-like material to retain its electronic properties even when it is pulled or tugged.

"To our knowledge, this nanotube film in the stretched state is the most conductive stretchable material that's been reported," Lipomi says. "At 150% strain, most stretchable conductors reported in the literature lose a lot of conductivity, but these don't," he adds.

The Stanford engineers spray-paint a dispersion of single-walled carbon nanotubes onto a silicone substrate, which deposits bundles of randomly oriented CNTs. The coated film is then stretched, which causes some of the nanotubes to straighten out in one direction, and then returned to its original length. Instead of going back to the random orientation, the nanotubes buckle into wave-like structures. The engineers found that the resistance of the film decreases during the initial stretch, but subsequent stretching does not decrease the film's resistance any further.

▲ Lines of carbon nanotubes intersect to form a grid of tiny parallel-plate capacitors. Because the capacitance of a parallel-plate capacitor is inversely proportional to the distance between the plates, when the grid is compressed, its capacitance increases. Image courtesy of Steve Fyffe, Stanford News Service.

▲ The transparent, stretchable pressure sensor maintains its conductivity when stretched up to 2.5 times its original length. Image courtesy of Steve Fyffe, Stanford News Service.

"That allows us to program the resistance by stretching the film to a certain level, and then that film becomes reversibly stretchable within that range without changing the resistance significantly," Lipomi says.

The CNT-coated films are then glued together with a silicone elastomer, which forms the compressible dielectric layer.

So far, the engineers have made a 16-cm$^2$ device 1 mm in thickness with 64 tiny capacitors — formed by the intersection of eight lines of CNT ink spray-painted on each of the two silicone layers. The sensitivity (*i.e.*, the smallest change in capacitance distinguishable from noise) of the device is 50 kPa.

The next step will be to increase the sensitivity of the device, Lipomi says. The team plans to integrate its findings from previous work in which they created a rigid sensor with a microstructured dielectric layer that was sensitive enough to detect the

pressure exerted by a fly carcass.

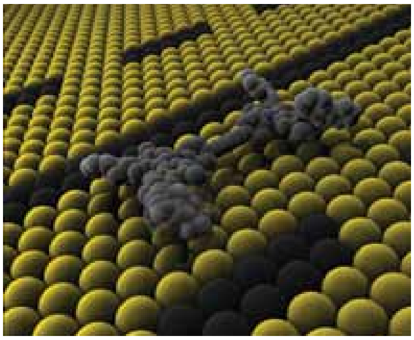
"We did not spend very much time trying to optimize the sensitivity aspect on this sensor," says Zhenan Bao, an associate professor of chemical engineering at Stanford. "But the previous concept can be applied here; we just need to make some modifications to the surface of the electrode so that we can have that same sensitivity."

Meanwhile, pressure sensitivity is not the only human feeling that the engineers envision for their stretchy material. "In the future, it should be possible to use these materials and principles to design organic, skin-like devices with other human — and superhuman — characteristics, such as the ability to sense moisture, temperature, light, or chemical and biological species," the engineers say.

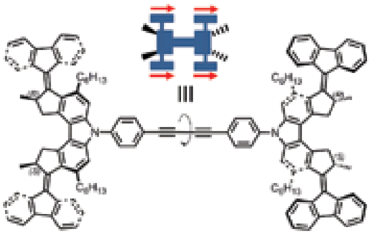
## Tiniest Four-Wheeled Molecule Drives Forward

Synthetic molecular machines hold promise for nanorobotics, improved drug delivery systems, and chemical synthesis. Now, researchers have taken a step toward creating these nano-machines by building a four-wheeled molecule — dubbed a nanocar — that can convert electrical energy into forward motion.

The nanocar is a synthetic organic molecule made of four molecular motors. When placed on a conductive substrate and electrically stimulated, the so-called wheels rotate and propel the molecule forward.



▲ The 3D geometry of the four-wheeler is essential to its forward motion. Image courtesy of Randy Wind and Martin Roelfs.



▲ The nanocar consists of four chiral units that act like molecular motors. For the molecule to move forward, all four wheels must move in the same direction. Of all the possible isomers that the molecule could assume, this requirement is met only by the meso-(R, S-R, S) isomer. The direction of the motors is represented by the red arrows. Image courtesy of *Nature*.

This is not the first example of synthetic molecular movement.

"There have been previous examples of molecules that could move on surfaces," says lead researcher Tibor Kudernac, a postdoctoral student at the Univ. of Twente in the Netherlands. "But although controlled movement of single molecules along a surface has been reported, the molecules in those examples act as passive elements that either diffuse along a preferential direction with equal probability for forward and backward movement or are dragged by an STM [scanning tunneling microscope] tip," Kudernac says.

The nanocar transforms electrical energy into mechanical motion and therefore could be used to perform tasks at the nanoscale, such as carrying atoms or molecules from one location to another.

The proof-of-principle research demonstrates that a synthetic molecule can be designed and made to perform mechanical tasks, Kudernac says. "This particular molecule will probably never find any application, but the demonstration that we can do something like that probably will lead to further designs and other molecules that can do something more complex, more application-related."

The nanocar makes use of molecular wheels — chiral units that undergo geometric changes and rotate in one direction as a result of electrical or vibrational energy input.

For the car to move forward, all four wheels must move in the same direction. The researchers met this requirement by identifying and then designing the molecule to have a specific configuration: the meso-(R, S–R, S) isomer of the molecule. They placed the meso-isomer on a copper surface and used an STM to both fuel the molecule and observe its movement. The STM tip applied a voltage pulse (> 500 mV), and after 10 pulses, the nanocar moved 6 nm across the copper surface.

Kudernac and his colleagues will now focus their research on the next critical challenges, one of which is to perform the same results at ambient conditions; the current findings were obtained at very low temperatures (7 K) and in ultrahigh vacuum (less than $10^{-10}$ mbar). Because STM requires a conductive substrate, they will also experiment with using light to provide energy to the nanocar, which will make their work applicable to a variety of substrates.

## Nanomaterials Improve Biosensor Performance

Purdue Univ. researchers have designed a biosensor made of carbon nanotubes, DNA, and platinum black that significantly outperforms today's biosensing technology — a development that could lead to more accurate measurements for biological research and medical diagnostics.

Today's biosensors, such as those used by patients with diabetes to measure glucose levels, rely on metal electrodes coated with enzymes that react with chemicals and produce an electrical signal. These sensors suffer from low sensitivity and low spatial resolution.

Nanomaterials offer a solution to these issues. In particular, carbon