

## ZnO nanowires match CNTs

### ELECTRONIC PROPERTIES

A new high-performance ZnO nanowire field-effect transistor (FET), developed by researchers in Korea and the UK, shows significant improvement in electrical characteristics. [Cha *et al.*, *Appl. Phys. Lett.* (2006) **89**, 263102]

The performance of these *n*-type ZnO nanowire transistors matches that observed for *p*-type carbon nanotube transistors, raising the possibility of using the two types of FET to replace Si channels in complementary integrated circuits. A single ZnO nanowire is suspended between Nb source and drain electrodes and separated from self-aligned Cr gate electrodes by well-defined air gap dielectrics. "There is no solid gate interface to the nanowire," says Gehan Amaratunga from the University of Cambridge in the UK. "This allows increased mobility without inducing excessive electron scatter at the gate/channel interface."

The wires are 3-10  $\mu\text{m}$  in length, with a diameter of 30-100 nm, and exhibit ohmic transport properties in air at room temperature. The FETs have a field-effect mobility of 928  $\text{cm}^2/\text{Vs}$ , a transconductance of 3.06  $\mu\text{S}$ , and an on/off current ratio of  $10^6$ .

Devices are assembled onto *n*-type Si substrates coated with a deposited  $\text{SiO}_2$  layer and an Al sacrificial layer. The ZnO nanowires are spin-coated onto these substrates and electron-beam lithography, together with Nb sputtering, create the source and drain electrodes at each end of the wire. The sacrificial layer is removed and the Cr gate electrodes are patterned onto the surface using a poly(methylmethacrylate) resist. Static gate bias stress measurements, under a gate bias of 1 MV/cm over 20 000 s indicate that, after some initial drift, the threshold voltage shift stabilizes and reaches saturation at 1000 s.

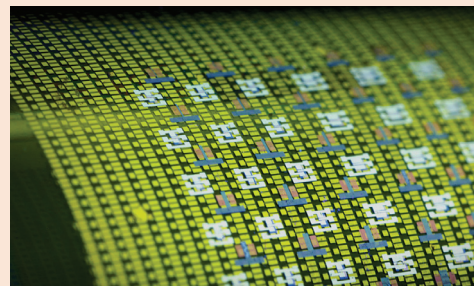
**Katerina Busutil**

## Gutenberg would be proud

### FABRICATION AND ASSEMBLY

Nanoelectronics systems must often be made with a wide variety of disparate materials, but the primary modes of manufacture – epitaxy or mechanical bonding – place stringent requirements on the ultimate scale or constituent materials of circuits. Researchers at the University of Illinois, Urbana-Champaign have developed a method for building two- and three-dimensional circuits using a process akin to the printing press [Ahn *et al.*, *Science* (2006) **314**, 1754]. The highly scalable method can employ any material as a substrate, including glass and plastic, providing an attractive alternative to organic semiconductors for flexible electronics. Crucially, the method can use any mixture of component materials, in contrast to epitaxial methods.

In the process, nanoscale semiconductor components such as GaN, GaAs, or Si nanowires or ribbons are first fabricated on a source substrate through standard lithographic procedures, with ohmic contacts formed by doping and annealing. These components are then lifted from the substrate by gentle van der Waals adhesion with an 'inking pad' made of polydimethylsiloxane, and then 'stamped' onto a target substrate prepared with a spin-cast prepolymer adhesive layer. The process can be repeated in the third dimension to create functional devices. The team reported high yields, >99% for Si and single-walled nanotube (SWNT) components. The room-temperature



A three-layer stack of GaN high-electron mobility transistors, Si metal oxide semiconductor field-effect transistors, and SWNT thin-film transistors on a flexible polyimide substrate. (Courtesy of John A. Rogers)

process reduces the thermal stresses that plague bonding approaches, and the finished circuits show little change as their temperature is cycled up to 90°C. Circuits manufactured on flexible substrates show no change in behavior under bending stress.

John A. Rogers says that manufacturing prototypes in his lab can already print on glass substrates up to 30 cm by 40 cm with an accuracy of 0.5  $\mu\text{m}$ ; further scaling will be supported by a startup company, Semprius, and several patents.

The group's current focus is on flexible emissive displays, curved focal plane array imagers, and large-area solar cells.

D. Jason Palmer

## SWNT conductor orchestrates functionalization

### CARBON MATERIALS

Although carbon nanotubes (CNTs) provide an ideal basis for single-molecule devices, the state of bonding to CNTs or the specificity to single molecules is often ill-defined in typical approaches to CNT functionalization. A team at the University of California, Irvine has demonstrated a new electrochemically driven method to induce chemical modifications [Goldsmith *et al.*, *Science* (2007) **315**, 77]. Further, they show that the conductance is a precise metric for the real-time observation and control of individual bonds in single-walled carbon nanotubes (SWNTs). The method tracks the changes in device behavior on the basis of the local chemistry, bond by bond, rivaling the best spectroscopic techniques.

Chemical vapor deposition (CVD)-grown SWNTs with lithographically added contacts were placed in an electrochemical cell with Pt electrodes. By monitoring SWNT conductance as a function of electrochemical potential, the team demonstrated profound changes in the conductance upon the bonding of various moieties. "I think it's fantastic to show experimentally that in a regular circuit, having millions

of atoms and passing microamps of current, the modification of a single bond can double the measured resistance," says group leader Philip G. Collins.

Although modifications are dependent on the electrolyte in the cell, the pattern of behavior is similar: beyond a given threshold of the potential, the conductance drops to zero – not abruptly, but in a series of steps and plateaus, corresponding to individual oxidation events. Oxidation in bases and weak acids is irreversible, whereas in strong acids the oxidation is reversible by cycling the electrochemical potential. Although the conductance returns to its initial value, the team found that the SWNTs do not return to their initial electrochemically inactive state, and residual modification sites (such as ethers and carboxy groups) can be used as 'chemical handles' for further functionalization.

The team has used its redox cycling technique to create electrochemically active sites to which Ni or Au-labeled streptavidin can be added.

**D. Jason Palmer**