

a general entry mechanism that is energy-dependent. Recently, however, N.W.S. Kam, Z. Liu, and H. Dai from the Department of Chemistry at Stanford University have demonstrated the SWNT cellular entry mechanism to be endocytosis.

As reported in a recent issue of *Angewandte Chemie International Edition* (DOI: 10.1002/anie.200503389), Dai and co-researchers undertook a systematic investigation of the cellular uptake mechanism of SWNTs. The researchers used sonication to obtain short (~50–200 nm) individual SWNTs and small SWNT bundles, which they characterized by atomic force microscopy. Non-oxidized SWNTs were used for complexation with nucleotides and acid-oxidized SWNTs for complexation with proteins. The researchers incubated the functionalized SWNTs with mammalian cells in solution at 37°C and observed cellular uptake of the nanotubes with confocal fluorescence microscopy and flow cell cytometry.

Cellular uptake of SWNTs was reduced substantially when incubation was performed at 4°C or under adenosine-triphosphate-depleted conditions, which indicated to the researchers that endocytosis is the internalization mechanism. Endocytosis encompasses several specific pathways, the most common of which takes place mainly through clathrin-coated pits in the cell membrane. Incubations performed under conditions known to disrupt the formation of clathrin-coated vesicles in cell membranes were found to drastically reduce cellular internalization of SWNTs. However, cells pretreated to disrupt an alternative caveolae endocytosis pathway, which involves membrane domains enriched with the protein cavelin, did not result in diminished SWNT cellular uptake.

These results suggested to the researchers that the specific mechanism for cellular uptake of short, dispersed, functionalized SWNTs is clathrin-dependent endocytosis. The researchers said, "Establishment of the entry mechanism is of fundamental importance and will facilitate future developments of carbon nanotube transporters for biological delivery applications."

STEVEN TROHALAKI

### Xenon Flash Lamp Annealing Shown to be Effective for Processing Ultrathin HfO<sub>2</sub> Films for Advanced CMOS Gate Dielectrics

To maintain the current pace of innovation in the silicon-based microelectronics industry, new materials with superior properties must be identified and integrat-

ed for next-generation devices. An excellent example is the search for alternative high-dielectric-constant (high- $\kappa$ ) materials to replace silicon dioxide (SiO<sub>2</sub>) as the gate dielectric in advanced complementary metal oxide semiconductor (CMOS) devices. Since candidate high- $\kappa$  materials lack the thermal stability of SiO<sub>2</sub> at temperatures used in CMOS processing steps, alternative annealing techniques are being explored. S. Kamiyama, T. Miura, and Y. Nara of Semiconductor Leading Edge

Technologies Inc. in Tsukuba, Japan, have determined that xenon flash lamp annealing (FLA) may be used to reduce the thermal budget during CMOS processing because of the short anneal times (<1 ms). They based their conclusions on their study of the effect of xenon FLA on the structural and electrical characteristics of hafnium dioxide (HfO<sub>2</sub>), a promising high- $\kappa$  material.

As reported in the December 2005 issue of *Electrochemical and Solid-State Letters*

### Single-Particle Microbatteries Exhibit Behavior Similar to Commercial Batteries

To further develop microsensor technology, reliable aqueous micropower sources such as microbatteries are needed. These microbatteries should demonstrate behavior comparable to those made by commercial manufacturers to be successful in applications ranging from bioengineering to defense. As reported in the December 2005 issue of *Electrochemical and Solid-State Letters* (p. A622), A. Palencsár and D.A. Scherson of Case Western Reserve University have developed a method for assembling and characterizing Zn-MnO<sub>2</sub> and Ni metal hydride—the two most common commercially used aqueous systems for alkaline batteries—using single microparticles of these materials. The results of this research suggest the microbatteries show voltage–time profiles similar to those of commercially available batteries involving the same chemistries.

For both the Zn-MnO<sub>2</sub> and Ni-MH systems, microparticles of the active materials were brought in contact with individual current collectors (typically gold microdisk electrodes or tungsten spears) and immersed in 9 M solutions of KOH. Assemblies of both microbattery systems are shown in Figure 1. The performance of these micropower sources was assessed in a fashion typical for commercial devices, that is, by measuring voltage versus time under constant charge or discharge currents, also referred to as the C-rate, where 1 C is defined as the current required for the nominal capacity of a battery to be consumed in one hour. The voltage versus time (or discharge) curve for a Zn-MnO<sub>2</sub> microbattery, incorporating a ~150- $\mu$ m-diameter particle of Zn and a ~30- $\mu$ m-diameter particle of MnO<sub>2</sub> and recorded at a rate of 2 C, is nearly identical to that of a commercial AA battery discharged at C/330. The Ni-MH model microbattery also displayed a behavior similar to conventional batteries. As in commercial devices, said the researchers, the microbattery cathode material, MnO<sub>2</sub> or Ni oxide, respectively, limited the capacity.

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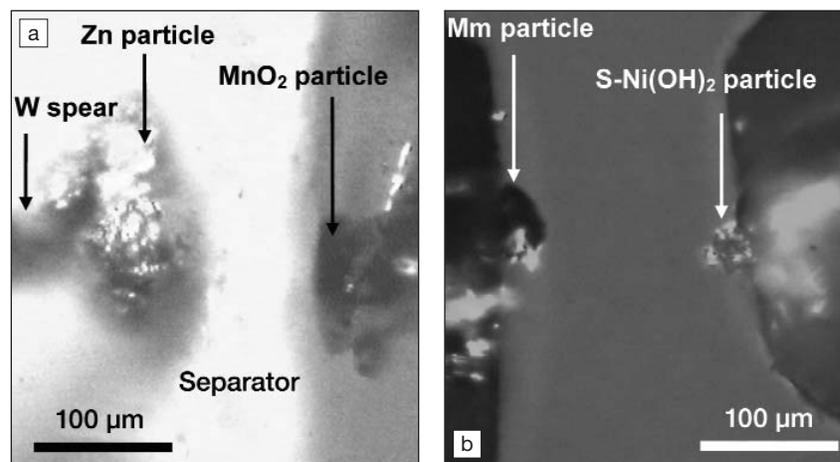


Figure 1. Micrographs of (a) assembled Zn-MnO<sub>2</sub> and (b) Ni-MH microbatteries. The separator in (b) was not included for clarity. Reprinted with permission from *Electrochemical and Solid-State Letters* 8 (12) (2005) p. A622. © 2005 The Electrochemical Society.

(p. G367), ultrathin (<5 nm)  $\text{HfO}_2$  films were grown using atomic layer deposition on 12-in. *p*-type silicon (100) substrates. Xenon FLA was then conducted at capacitor charging voltages of 3100–3500 V with a 0.8-ms pulse width. The samples were preheated to 400°C in a  $\text{N}_2$  atmosphere. X-ray diffraction (XRD) measurements were performed on the samples subjected to xenon FLA and conventional rapid thermal annealing.  $\text{TaSi}_{2.5}$  (10 nm)/  $\text{W}$  (100 nm) gate electrodes were then sputter-deposited for capacitance–voltage ( $C-V$ ) and current–voltage ( $I-V$ ) measurements.

According to Kamiyama and co-workers, the actual wafer temperature during FLA is not known. XRD measurements on  $\text{HfO}_2$  films after rapid thermal annealing suggest that the crystallization temperature of  $\text{HfO}_2$  films is ~600°C. The onset of post-FLA crystallization for similar films begins at capacitor charging voltages of 3300 V.  $C-V$  and  $I-V$  measurements on  $\text{HfO}_2$  gate dielectrics with  $\text{TaSi}_{2.5}/\text{W}$  gate electrodes after xenon FLA show an increase in dielectric constant, and leakage current values comparable with similar samples after annealing in  $\text{O}_3$ . Although the films show a slight decrease in equivalent oxide thickness (~5%) after FLA, the researchers said this process shows promise for manufacturing high- $\kappa$ -based transistors with metal gates.

JEREMIAH T. ABIADÉ

### ZnO Field-Effect Transistors Fabricated on Self-Assembled Colloidal Nanorods

Zinc oxide ( $\text{ZnO}$ ) is a transparent semiconductor with a large bandgap.  $\text{ZnO}$  thin-film field-effect transistor (TFT) devices fabricated with colloidal  $\text{ZnO}$  nanocrystals are particularly attractive because they are based on a low-temperature, solution-processible semiconducting material. Researchers Baoquan Sun and Henning Sirringhaus of the University of Cambridge have now fabricated high-performance  $\text{ZnO}$  TFT devices on a  $\text{SiO}_2/\text{Si}$  substrate by spin-coating an aqueous suspension of  $\text{ZnO}$  nanocrystals to form a thin film on the substrate.

As reported in the December 2005 issue of *Nano Letters* (DOI: 10.1021/nl051586w; p. 2408), the researchers investigated the effects of the nanocrystal shape on the colloidal self-assembly of the nanoparticles on the substrate and on the resulting device performance. They found that by changing the shape of the nanocrystals from sphere to rod, the semiconducting properties of the spin-coated  $\text{ZnO}$  films were greatly improved as the result of increased particle size and self-alignment along the substrate. Post-deposition hydrothermal growth of the nanorods in an aqueous zinc-ion solution was found to further enhance the nanorod dimensions and interconnectivity and significantly

improve the device performance. TFT devices made from 65-nm-long, 10-nm-wide nanorods exhibited a mobility of  $0.61 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  and an on/off ratio of  $3 \times 10^5$  after the post-deposition growth. These values are comparable to that of TFTs fabricated by traditional sputtering methods. The researchers also discovered that careful control of stoichiometry during the nanocrystal growth is crucial for achieving sufficiently low film conductivity and high field-effect mobility.

The researchers said that the use of nanorods instead of nanospheres as a seed layer for the hydrothermal growth resulted in long nanorods oriented preferentially in the plane of the substrate near the interface with the gate dielectric. This orientation is favorable for charge transport in TFTs. The researchers concluded, “making use of the self-assembly processes in colloidal nanocrystals is an attractive and simple route for controlling the microstructure and electronic properties of solution-processed semiconductor nanocrystal films.”

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