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Current nanoscience and nanoengineering at the Center for Nanoscale Science and Engineering

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Abstract. The Center for Nanoscale Science and Engineering (CeNSE) at the University of Kentucky is a multidisciplinary group of faculty, students, and staff, with a shared vision and cutting-edge research facilities to study and develop materials and devices at the nanoscale.

Current research projects at CeNSE span a number of diverse nanoscience thrusts in bio- engineering and medicine (nanosensors and nanoelectrodes, nanoparticle-based drug delivery), electronics (nanolithography, molecular electronics, nanotube FETs), nanotemplates for electronics and gas sensors (functionalization of carbon nanotubes, aligned carbon nanotube structures for gate-keeping, e-beam lithography with nanoscale precision), and nano–optoelectronics (nanoscale photonics for laser communications, quantum confinement in photovoltaic devices, and nanostructured displays).

This paper provides glimpses of this research and future directions.

Keywords. Nanotechnology; nanoscience; nanoengineering; nanomedicine; Center for Nanoscale Science and Engineering; Kentucky.

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1. Introduction

The Center for Nanoscale Science and Engineering (CeNSE) is located in ASTeCC, the Advanced Science and Technology Commercialization Center, on the University of Kentucky campus in Lexington. It aims to develop materials and devices at the nanoscale. An initial investment of $2 million in speciality fabrication techniques for thin-film deposition, lithographic pattern definition, and etching, has recently been augmented by a National Science Foundation (NSF) infrastructural grant of $2.7 million. Participants include 15 distinguished UK faculty members from the Departments of Electrical and Computer Engineering, Chemical and Materials Engineering, Physics, Mechanical Engineering, and Chemistry, and the Colleges of Medicine and Pharmacy. In addition to the associated faculty, CeNSE is staffed by an Interim Director.

These faculty associates support many student researchers; of these, about 52 graduate research assistants, five post-doctoral associates, and a number of undergraduate students use CeNSE equipment and facilities.

CeNSE also serves as a resource for Kentucky's development of innovative academic research and the realization of emerging commercial opportunities.

2. Capabilities

The process of engineering and fabricating structures 1–100 nm in size, which defines 'nanoscale', is not straightforward. Understanding the science of nanoscale world is very important; yet, using these fundamental principles to engineer 'bottom-up' processes in nanoscale world is equally challenging. Cutting-edge research facilities to carry out 'top-down' and 'bottom-up' nanofabrication include the following capabilities currently operational:

Thin film deposition

The capabilities include a thickness-controlled e-beam evaporator, thermal evaporation systems, a three-target sputter evaporation system, electrochemical deposition, and plasma-enhanced chemical vapor deposition. An atomic layer deposition system is being installed.

Thermal and chemical processing

The capabilities include oxidation, diffusion and annealing furnaces including a 4-furnace bank of 3-zone oxidation and dopant diffusion furnaces, chemical treatment facility (cleaning, etching functionalization), plasma oxidation, plasmatic reaction etching, and ion-beam etching.

Device fabrication

The capabilities include photolithography with a class 100 clean room, wafer coating and spin-coating station, alignment station, profilometer, and e-beam lithography with 60 mm resolution. An e-beam lithography system with 7 nm resolution is currently being installed.

Metrology

The capabilities include four-point resistance, ellipsometer, optical microscopes, scanning electron microscope, parameter analyzers, and variable-temperature probe stations. Processing equipment currently being installed includes state-of-the-art rapid thermal processing (RTP), reactive ion etching (RIE), and focused ion

milling/patterning. New characterization facilities include a multi-mode scanning probe/atomic force microscope (AFM) with electrochemical pattern capability, a field-emission SEM with e-beam lithography, and a precision quartz crystal microbalance for biosensor development.

3. Current research

Current research projects span a number of diverse nanoscience thrusts in bioengineering, pharmacy, and medicine (nanosensors and nanoelectrodes, nanoparticle-based drug delivery), electronics (nanolithography, molecular electronics, nanotube FETs), nanotemplates for electronics and gas sensors (functionalization of carbon nanotubes, aligned carbon nanotube structures for gate-keeping, e-beam lithography with nanoscale precision), and optoelectronics (nanoscale photonics for laser communications, quantum confinement in photovoltaic devices, nanostructured displays). We discuss below some of the on-going research.

Integrated photonics

Hastings *et al* study nanostructured, high-index contrast planar waveguides, which will offer smaller, higher-performance filters, switches, and dispersion compensators. Figure 1 shows scanning-electron micrograph of a silicon-on-insulator integrated-photonic device designed to provide increased optical communications bandwidth while reducing equipment size and cost. Electron-beam lithography and reactive-ion etching were used to form a waveguide with Bragg reflection gratings in each side. The structure allows one to filter and re-route optical signals on a silicon chip [1].

This novel design and fabrication techniques for nanoaccurate gratings in optical waveguides [1–3] are ideal for communication devices based on InGaAsP (1550 nm wavelength) lattice matched to InP and for sensor devices fabricated using GaAs

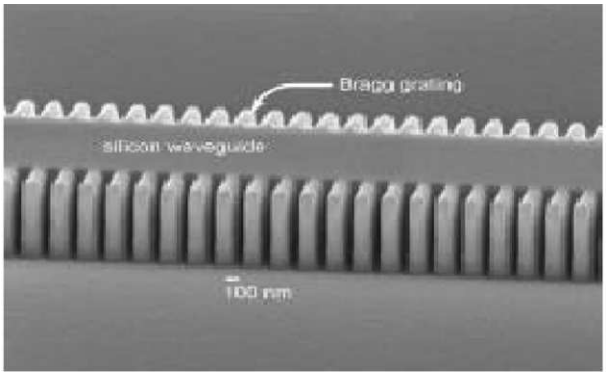

Figure 1. Scanning-electron micrograph of a silicon-on-insulator integrated-phontonic device [2,3].

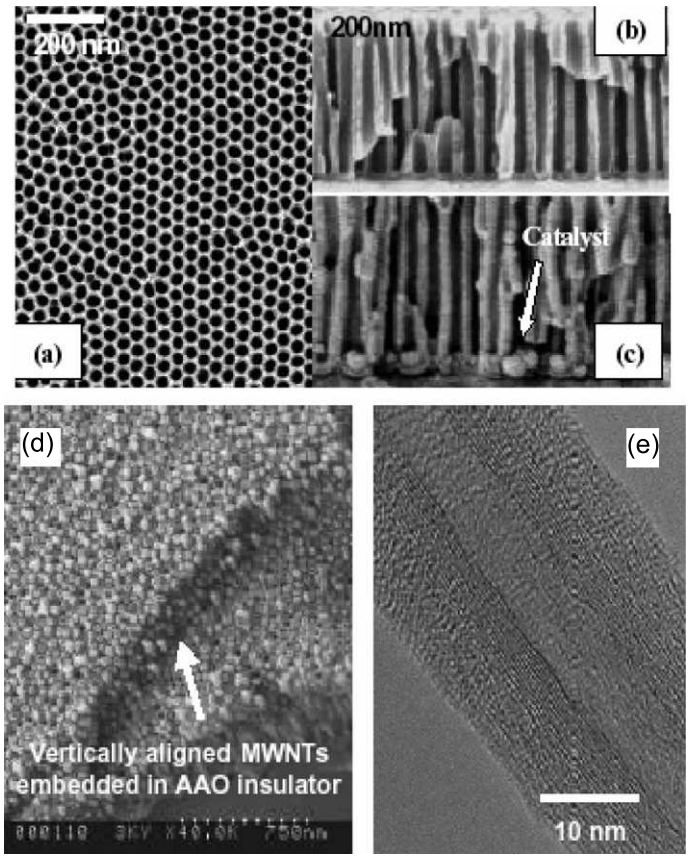

Figure 2. (**a**) Nanostructure of anodically formed Al_2O_3 template, (**b**) its cross-section, (**c**) catalyst deposited at the bottom of the pores, (**d**) vertically aligned nanotubes, and (**e**) TEM image of a nanotube.

substrates and AlGaInP (visible wavelengths) and InGaAs (near-IR wavelengths) active regions.

Nanostructure modification and nanotube growth

In most cases, the as-grown carbon nanotubes are entangled ropes. It is difficult to fabricate robust and manufacturable devices without organized nanotubes. Zhi Chen [4] has successfully made a nanotemplate using anodization of aluminum as shown in figure 2. Hu *et al* have successfully made vertically aligned carbon nanotubes using nanotemplate on silicon substrate for the first time [4,5]. The nanotemplate shown in figure 2a exhibits periodical-pore structure. The pore diameter and the thickness of pore walls are determined by the voltage and types of electrolyte [6]. The nanostructure of the template can be modified through the anodization processes. Thus, the nanotube arrays can be controllably grown with

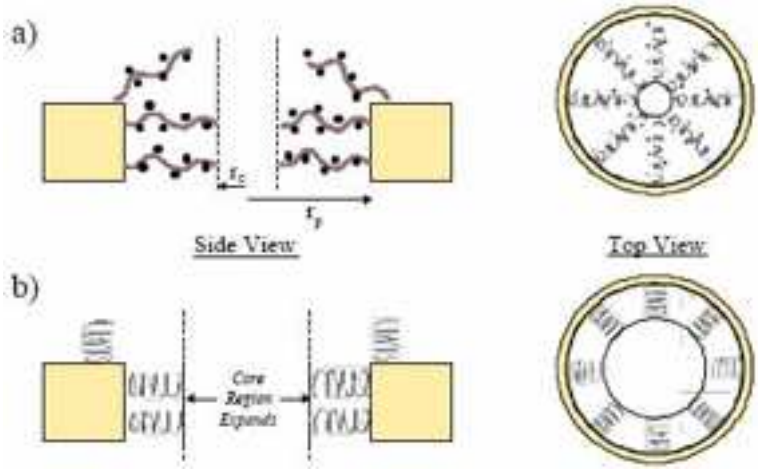

Figure 3. Schematic representing the helix-coil transitions within the pore of a poly-L-glutamic acid functionalized membrane. (**a**) Random-coil formation at pH > 5.5, (**b**) helix formation at low pH (<4).

predetermined tube diameter and spacing between nanotubes. Prior to defining electrical contacts to the individual SWNT, DWCNT, and MWCNT, micro-Raman spectroscopy is being used to identify the chirality of the nanotubes by studying the radial breathing mode (RBM).

Environmental sensors

Hollman and Bhattacharyya have developed tunable membranes for selective separations and permeability control. These membranes contain covalently attached polyamino acids in the membrane pores where helix-coil changes in the nanodomain can be manipulated by pH alterations [7]. A schematic representation of helix-coil transitions in membrane pores is shown in figure 3. The procedure is being extended to the formation of layer-by-layer self-assembly of alternating (anionic–cationic–anionic, etc.) polyamino acid layers. This provides further selectivity required for sensing and separations.

Biosensor research

Rankin *et al* have used self-assembly techniques [8] to form thin films and bulk materials with controlled pore structures to enhance chemical and biochemical interactions. Similar templating is being done with added biological templates (such as glucose or polypeptides) to create selective components for separations, sensors and biomaterials. One example uses mimics of bone morphogenic proteins as templates to encourage bone growth near orthopedic and dental implants. The interface between these films and their environment controls their effectiveness. Quartz crystal

microbalance (QCM) devices are used for detecting the attachment of species from a fluid phase onto a solid surface. In a traditional device, one applies a fixed frequency oscillation (typically 5–10 MHz) to a single crystal of quartz and measures the offset of the frequency. This offset increases as more material becomes attached to the solid surface. Penn *et al* are currently studying the adsorption of surfactants and polymers on inorganic surfaces [9], and use a specialized dynamic QCM device to study the adsorption of soft materials from liquid solution onto the surface of quartz and thin films deposited onto quartz. The Q-sense QCM-D device [9] uses the dynamic response of the crystal after a steady current is shut off to determine not only the quantity of material attached to a layer, but also its viscoelasticity [10]. The QCM-D provides a unique opportunity to see how biomolecules change their conformation and organization as they interact with inorganic surfaces.

Bachas's group currently use several microfabrication techniques to develop novel analytical systems. One of the current projects involves the fabrication of nanoliter-sized electrochemical systems by coupling screen-printing techniques and laser micromachining. Another active project involves the development of micro total analysis systems (μ-TAS). This requires the coupling of a microfluidics platform with an appropriate detection system. The fabrication of the microfluidics platform is achieved by photolithography and CNC machining. Photolithography is also employed in the third project that has as a goal fabrication of microchannel fluidic structures with integrated patterning of biomolecules.

Chopra and Hinds [11] are currently studying the functionalization of entrance to the CNT cores in CNT membranes described in a previous section. When the biotin-functionalized membrane is in a solution with streptavidin, ionic current through the membrane is shut down [12]. This approach can be applied to numerous complementary biochemical pairs, thus acting as the basis for a highly selective sensor.

Symons *et al* use analytical spectroscopy in integrated sensing and processing (ISP) research. ISP was originated at the US Defense Advanced Research Projects Agency to bring processing and recognition functions closer to the point of the detection function. In this way ISP units can be constructed more rapidly than traditional sensors, in larger numbers, and at lower cost. The ISP approach drives their molecular-computing nearfield [13], micro- and nanospectrometers and is applicable to diverse analytical methods, including biosensors, separations, and spectrometric image technology.

Nanoscale hydrodynamics: Enhanced flow in carbon nanotubes

Biological channels act as chemically selective gatekeepers and have protein walls that allow extremely rapid transit [14]. Nanometer-scale pores with chemical selectivity have been prepared [15,16] but fluid flow through them is slow: this limitation is predicted by the Hagen–Poiseuille equation and is because conventional laminar flow has zero fluid velocity at the pore walls.

Majumder *et al* have found [17] recently that flow rates of water are four to five orders of magnitude faster than what conventional fluid flow would predict through pores of 7 nm diameter. Contrary to predictions based on hydrodynamics, the flow

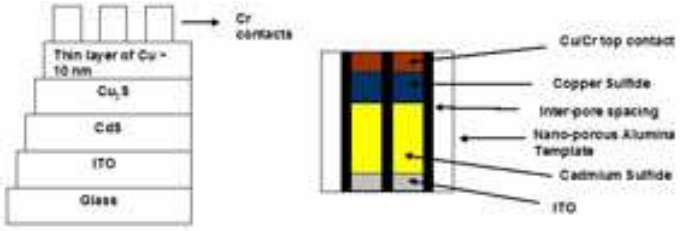

Figure 4. Side views of planar and nano–heterojunction solar cells.

rate does not decrease with increased viscosity. The researchers have concluded that these high fluid velocities are possible because of a frictionless surface at the carbon nanotube wall.

The finding adds weight to the idea that nanotube membranes possibly could be used to form fast, highly efficient filters for all kinds of uses. It might be possible, for example, to fashion military uniforms that could 'breathe', but also filter out chemical agents like nerve gas. Our researchers have already made highly efficient nicotine patches that use nanotube membranes to quickly and efficiently regulate nicotine flow. (The patches have yet to be tested on humans.) In the future, the technology could lead to inexpensive, but highly efficient filters for manufacturing or processing items as common as cheese and milk, or for more sophisticated medical applications.

Fabrication of nanostructured CdS/Cu_2S devices in a porous alumina template

Singh *et al* [18] have made nanostructured CdS/Cu_2S junctions inside a nanoporous alumina template, as shown schematically in figure 4. A vacuum-evaporation process was employed in the fabrication of these devices. Well-ordered porous alumina templates with a pore diameter of 30 nm and a pore depth of 4 microns were used for this purpose. The nano-heterojunction device yielded a V_{oc} of 367 mV and a J_{sc} of 0.0178 mA·cm^{-2}.

For comparison, bulk heterojunctions of Cu_2S/CdS were fabricated on ITO-coated glass substrates. The cells had a V_{oc} of 445 mV, a J_{sc} was 20.3 mA·cm^{-2} and an efficiency of 5.73%.

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