

NanoMeter

The newsletter of the Cornell NanoScale Science & Technology Facility

Spring 2006 • Volume 16, Number 1

Director's Column

As the current interim Director of CNF, I would like to use this opportunity to thank Professor Sandip Tiwari for his outstanding work as Director of this facility during the last 6 years. Under his leadership, the lab was moved into the brand new 16,000-square-foot clean room in Duffield Hall, the technical capabilities and instrumentation were vastly improved to match the state of the art, the users' base grew by more than 50% to currently 650 users per year with more than 40% from outside Cornell, and the National Nanotechnology Infrastructure Network came to life. This outstanding contribution to the Science and Technology community will have a long lasting impact not only at Cornell but in the whole of the US and beyond.

Sandip Tiwari will continue in his role as Director of the NNIN and is currently on sabbatical at Harvard. Dr. Jurriaan Gerretsen has taken on the responsibility of Associate Director in addition to his role as Associate Director of the Center for Nanoscale Systems in Information Technologies. The search for a 'permanent' Director continues.

Regards, John Silcox, Interim Director, CNF

In This Issue...

... you will find an update of the latest additions to the facility and upgrades of equipment.

The celebration of the 25th anniversary of the Cornell NanoScale Science & Technology Facility coincided with the formal dedication of Duffield Hall on Oct. 6, 2004, which was only one event among many in the celebration of Cornell's leadership in nanotechnology research and education.

As part of the NNIN initiative CNF has created a new computation facility headed by Dr. Derek Stewart to support numerical modeling and simulation for nanoscience and technology with a rapidly growing users base from both inside Cornell as well as a large number of external users.

Finally, we have had several donations of equipment and software to note.



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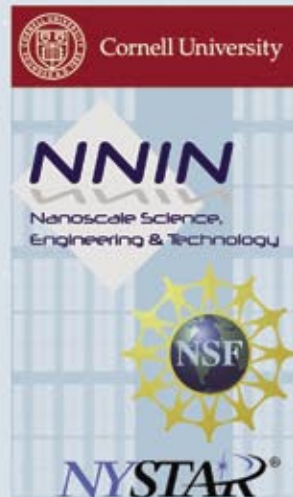
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Silcox named Interim Director of NSF's Cornell NanoScale Science and Technology Facility



John Silcox

By Krishna Ramanujan

ITHACA, N.Y. -- While faculty and administrators at the National Science Foundation (NSF)-funded Cornell NanoScale Science and Technology Facility (CNF) search for a new director, John Silcox, the David E. Burr Professor of Engineering at Cornell University, will take over Oct. 1 as interim director.

"We're very fortunate that John Silcox, an experienced and effective science administrator with deep roots in the materials community at Cornell and CNF, has agreed to serve once more," said Joseph A. Burns, vice provost for physical sciences and engineering. In the past, Silcox has served twice as director of the School of Applied and Engineering Physics, as director of the Cornell Center for Materials Science and as vice provost for research for physical

sciences and engineering prior to Burns' appointment.

"This is an extremely important facility for Cornell and many others who visit us, so it will be a challenge to keep it going as successfully as it has been over the past 25 years," said Silcox, one of the world's leading researchers in the field of electron microscopy.

CNF is a national facility serving Cornell and external users for research and instruction in nanoscale science and technology. Researchers and students encompassing astronomy,



Jurriaan Gerretsen

plant pathology, materials science, physics, chemistry, life sciences, various departments of engineering and industry use the tools available in the facility for building structures, devices and systems from atomic to complex large-scales.

Jurriaan Gerretsen, currently the associate director of the NSF-funded Center for Nanoscale Systems, will serve part time as interim associate director of CNF.

Meanwhile, a search committee, led by Burns, has been formed to permanently replace the previous director, Sandip Tiwari, who has moved to a new position as director of the National Nanotechnology Infrastructure Network, a nanoscience research consortium of 13 universities. The search is expected to take a year. The committee includes faculty members in physics, chemistry, electrical and computer engineering, material science and engineering, and applied and engineering physics.

"We are looking for an internationally known scientist or engineer to lead CNF and join the faculty," said Burns.

The CNF is supported by the NSF, NYS Office of Science, Technology and Academic Research, Cornell University, industry and users.



Sandip Tiwari

Photos this page, University Photography

From Silver Anniversary to Media, CU Celebrates Nanotech



Dr. Jeffrey Lehman salutes David Duffield, namesake of CNF's new home.

alumni, among them Irwin Jacobs '54, founder and CEO of Qualcomm Inc., and Jeff Hawkins '79, inventor of the Palm Pilot.

Speaking at Barnes Hall on Oct. 6, Jacobs warned that "we have to remain more innovative if we are going to generate jobs." An example, he said, was the cell phone, which holds the promise of new medical and educational uses, such as transmitting video by bringing materials into the

classroom through high data rate connections.

Giving the closing address for the CNF celebrations on Oct. 7, also in Barnes Hall, Hawkins said of Duffield Hall: "We imagine new products that will benefit humankind. We imagine new manufacturing processes, a whole new world of the small and even a hope for new discoveries about the nature of life."

Earlier in the day, at the CNF anniversary luncheon in the Memorial Room, Willard Straight Hall, [then] President Jeffrey S. Lehman had saluted Professor Emeritus of Electrical Engineering Joseph Ballantyne, who in 1977 led the faculty team that put together the original proposal that led



to the creation of CNF and who later became its founding director.

Said Lehman: "Today as we celebrate CNF's anniversary, I want to thank Professor Ballantyne for his outstanding contribution and service. By opening the door to the very small so many years ago, and by his continued leadership, he has helped Cornell earn a very large distinction as the leading academic nanotechnology facility in the world."

The week began on Sunday, Oct. 3 with more than 25 journalists from around the country who arrived on campus for a two-day nanotechnology



The actual dedication of Duffield Hall on Oct. 6, 2004, was only one event among many in a week of lectures, lunches and workshops celebrating Cornell's leadership in nanotechnology research and education.

The major tenant of the \$58.5 million center is the Cornell NanoScale Science & Technology Facility (CNF), now ensconced in the new Lester B. Knight Laboratory, with its 16,000-square-foot clean room. So it was only appropriate that the other major event of the week was the 25th anniversary of the founding of CNF, a National Science Foundation-funded national user facility for nanotechnology research and microfabrication.

The anniversary celebrations began on Oct. 6 and continued on Oct. 7 with talks by researchers and distinguished



• Scenes from a Poster Session • Scenes from a Poster Session • Scenes from a Poster Session •

workshop sponsored by the Kavli Institute at Cornell for Nanoscience, a new institute headed by Robert Richardson, senior vice provost for research, who opened the event at a dinner at the Statler Hotel.

The workshop, organized by Research Projects Coordinator Lesley Yorke and the Cornell News Service, began Oct. 3 with a primer course, "Nanotechnology 101," during which journalists were introduced to the concepts of the world of the very small by Cornell faculty members Carl Batt, professor of food science, and George Malliaras, assistant professor of materials science and engineering.

The journalists then actually entered the world of nanotechnology in the CNF clean room in Duffield Hall. Here, they were able to see for themselves how nanoscale devices are made by both the "top-down approach," which describes chiseling away at silicon to get to the nano size desired, as well as the "bottom-up approach," which involves laying down single molecules to build a device.

Ellen Simon, a writer for the Associated Press, viewed the two day event as tremendously helpful.



Kavli & Nanotechnology 101



"This has been a great primer. It has really helped me to distinguish what is currently happening in nanotechnology — and what technologies aren't out there yet."

By David Brand and Sarah Davidson. Originally published in the Oct.14, 2004 Cornell Chronicle.



The CNF directors at the CNF 25th Anniversary. From the left: Dr. Edward Wolfe, 1978-88; Prof. Noel MacDonald, 1995-97; Dr. Jeffrey Lehman, Former Cornell President; Prof. Joseph Ballantyne, 1977-78, 1998-99; Prof. Sandip Tiwari, 1999-2005; Prof. Harold Craighead, 1989-1995.

Channel-Select RF Micromechanical Filters

The vast majority of radio frequency (RF) systems currently in production implement the heterodyne architecture developed by Edwin Armstrong 75 years ago. Today, this architecture relies on discrete components such as quartz crystals and ceramic filters to provide stable references and frequency selection. However, quartz and ceramics are not easily integrated with on-chip circuits, preventing the fabrication of a fully monolithic radio. In recent years, high quality factor (Q) micromechanical resonators have emerged as a possible alternative to quartz and ceramic components. The key benefit of these lateral-mode MEMS resonators is the ability to fabricate multiple frequencies in a single lithography step.

The OxideMEMS Lab at Cornell University is developing sub-10microWatt power consumption receivers for sensor network radios operating in the ISM bands. ISM band receivers require narrow channels and are susceptible to nearby strong interferers. To filter out unwanted frequencies, channel-select filter arrays with small bandwidth, good stop-band rejection, and excellent shape factor must be implemented.

We have designed and fabricated RF MEMS resonators with high Q (> 7000) and low motional

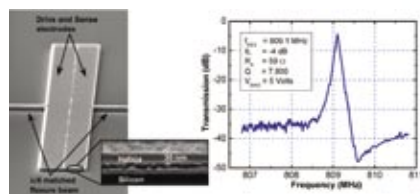


Figure 1. (a) SEM of a hafnium dioxide-on-silicon fully released bar resonator, (b) SEM of the 30 nm hafnium dioxide layer on the top of Si resonator and (c) Measured transmission response of a half-wave thickness shear mode resonator in air. The $f \cdot Q$ product of the resonator is 6.2×10^{12} Hz.

impedance ($R_x < 60 \Omega$) using high-K dielectric transducers [1] (Figure 1). Channel-select filters are formed by electrically and mechanically coupling these resonators.

Electrical coupling is achieved by routing the electrical signal from successive resonators in a ladder configuration. In a typical ladder filter configuration, the parallel frequency $f_{parallel}$ of the shunt resonator is matched to the series frequency f_{series} of series resonators, defining the filter center frequency (f_c). The filter bandwidth is determined by notches on either side of the passband and is twice the pole-zero separation of the series and shunt resonators. Figure 2(a) shows an SEM of two dielectrically transduced thickness shear mode ladder filters. The filter array's frequency characteristics are provided in figure 2(b) [2].

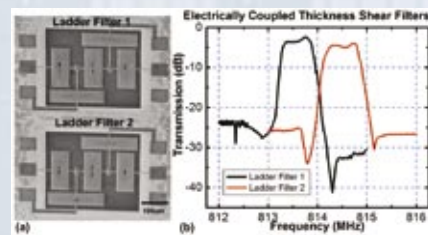


Figure 2. (a) SEM of an array of ladder configuration electrically-coupled thickness shear filters. (b) Measured filter transmission response showing two 650 kHz channel-select filters at 814 MHz center frequency.

Mechanically coupled channel-select filters use soft beams to couple an array of MEMS resonators. The coupling spring network serves to pull the resonant frequencies apart, creating two or more distinct resonant frequencies in the coupled resonator network. Figure 3(a) shows two different mechanically coupled filter designs that were fabricated in the Cornell Nanofabrication Facility (CNF). The filters demonstrate insertion loss (IL) of < 8 dB (Figure

3(b), which is the best insertion loss reported to date for contour-mode MEMS filters [2,3].

Presently the OxideMEMS Lab is fabricating new resonators with frequencies up to 3.5GHz and developing a voltage tuning scheme to dynamically tune the filter center frequency and bandwidth for channel agility.

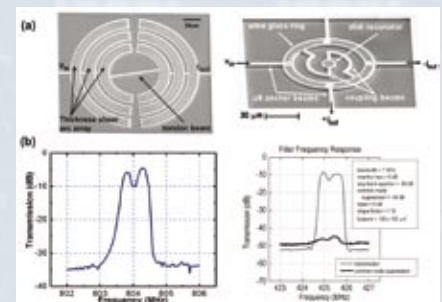


Figure 3. (a) SEMs of 804 MHz thickness shear-mode arc array filter and 425 MHz single-ended to differential contour-mode filter fabricated in CNF, (b) Transmission response of the filters measured in CNS Shared Testing Facility.

References:

- [1] H.Chandrahali, D.Weinstein and S.A.Bhave, "Thickness shear mode vibrations in silicon bar resonators," IEEE International Ultrasonics Symposium (Ultrasonics 2005), Rotterdam, The Netherlands, September 18-21, 2005, pp. 898-901.
- [2] H. Chandrahali, D.Weinstein, L.F.Cheow and S.A.Bhave, "Channel-select micromechanical filters using high-K dielectrically transduced MEMS resonators," 19th IEEE International Conference on Micro Electro Mechanical Systems (MEMS 2006), Istanbul, Turkey, January 22-26, 2006, pp. 894-897.
- [3] D.Weinstein, H.Chandrahali, L.F.Cheow and S.A.Bhave, "Dielectrically transduced single-ended to differential MEMS filter," IEEE International Solid-State Circuits Conference (ISSCC 2006), San Francisco, California, Feb. 5-9, 2006, pp. 318-319.

Prof. Sunil Bhave, Electrical & Computer Engr, Cornell University

**OxideMEMS Lab URL:
<http://mems.ece.cornell.edu>**

AMD Day

Metrology and Characterization

On February 23, 2005, Cornell and CNF celebrated AMD Day!

Zeiss SEMs + EDX

On that day, AMD officially donated 15 Opereron 64™ workstations and a Quad Opereron 64™ server to the CNF, and made donations to both the Cornell University Autonomous Underwater Vehicle competition and the Cornell DARPA Grand Challenge Team. In addition, they spent the day in the Duffield Atrium meeting with students regarding career options.



The Opereron 64™ workstations have been deployed throughout the CNF and our CAD facility, and are the main workstations for our users. The high performance quad server is used for advanced video processing.

CNF is grateful to AMD for these donations in support of our program.

Exploring the unique properties of materials at the nanoscale often requires advanced processing capabilities, the fabrication of innovative measurement structures and a set of specialized analytical tools. Scanning electron microscopy is critical for the analysis of nanoscale materials and structures.

To adequately serve user demand, CNF has acquired two field emission scanning electron microscopes (SEMs) for imaging and an energy dispersive X-ray (EDX) system for sample analysis. Both of the SEMs are capable of imaging nanometer sized features at accelerating voltages below 1keV. While these capabilities will foster strong inter-disciplinary and innovative uses of these instruments that will impact science and engineering on many levels, collectively, this suite of tools is ideally appropriate for characterizing novel nanoscale materials, complex devices and structures.

imaging materials that are prone to charge- induced image distortions. Examples of these materials include bulk ceramics and polymers. When operated in the variable pressure (VP) mode, the chamber pressure is increased to eliminate the accumulation of excess charge on the specimen.

The system is equipped with a TTL through the lens and an Everheart Thornley secondary electron detector. The Supra 55 is also equipped with a EDX system used to create detailed compositional maps.

Zeiss Ultra 55 is designed to maximize imaging resolution at low beam energies. It is equipped with a through-the-lens backscatter detector engineered to image electrons with energies less than 2keV. An energy filter incorporated into the detector enables energy selective backscatter (ESB) imaging. The signal can be used to obtain contrast between regions of different composition.

Zeiss Supra 55 is ideally suited for

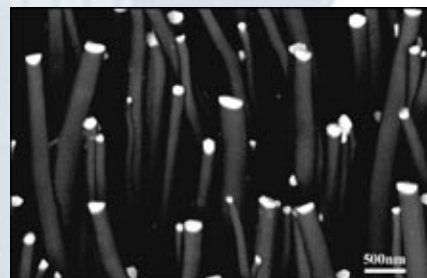
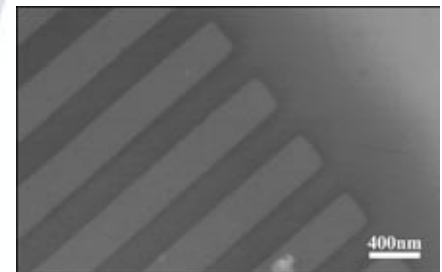
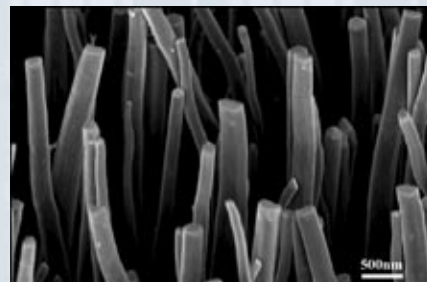


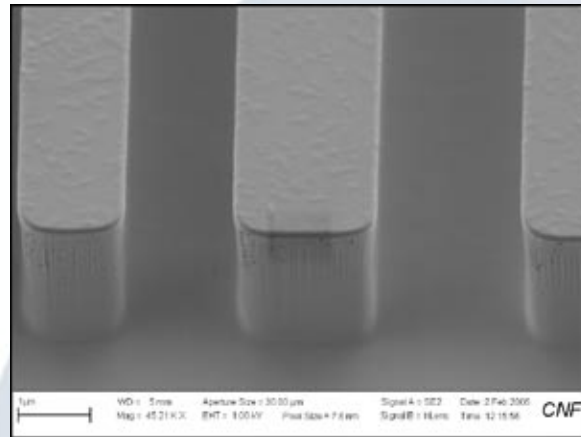
Figure 1: Secondary (above left) and backscatter (below left) SEMs of carbon nanofibers produced using catalytic plasma enhanced chemical vapor deposition. Figure 2, above: Variable pressure scanning electron micrograph of 400 nm platinum lines on pyrex. (SEMs by Rob Ilic.)

Plasma Etching

Since our last update, the etch group is pleased to announce the latest developments. We reached an agreement with Oxford Instruments that provides service coverage for the 2 Oxford PlasmaLab 80 Plus RIE's and the Oxford 100 ICP etcher, as well as opens a direct line of communication for process support with their applications lab in the UK. We have recently completed baselining most of the standard established etch processes. We plan to repeat this survey on a semi-annual basis.

We have increased the number of available processes in cooperation with some members of the user community. For the Oxford PlasmaLab 80's, we've added the ability to etch HfO_2 and Al_2O_3 . An SF_6/O_2 based isotropic silicon etch that delivers ~1 micron/min etch rate with ~50:1 selectivity to silicon dioxide is available. An $\text{SF}_6/\text{CHF}_3/\text{O}_2$ based anisotropic silicon etch process is slated to be investigated. We've explored the capability of using CF_4/O_2 , CHF_3/O_2 , or SF_6/O_2 to etch silicon carbide (SiC) and have found etch rates to be between 60 and 400 nm/min with the selectivity to silicon ranging from 0.8:1 to 2.5:1. The $\text{CHF}_3/\text{CF}_4/\text{Ar}$ based silicon dioxide etch process is still under development, but currently has an etch rate of ~50 nm/min with a selectivity to non-hard baked photoresist of ~1.8:1. In addition, a CHF_3/Ar based silicon dioxide etch process has been characterized and added to Oxford 80 #2.

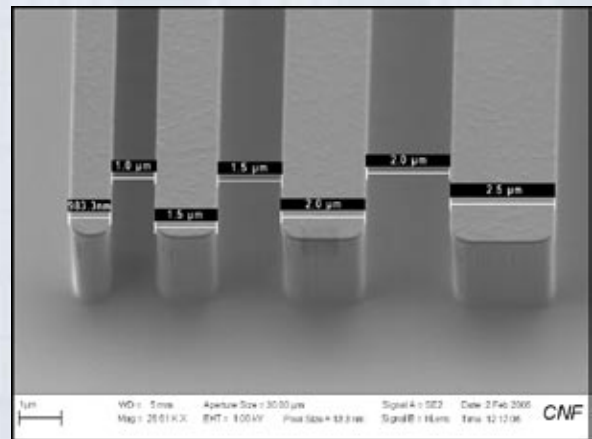
The Oxford System 100 ICP380 is installed and functioning well. We have a base etch process for SiO_2 utilizing CHF_3/O_2 with a



GaAs ICP Etching with 400 nm PECVD SiO_2 Mask, using Pure BCl_3

$\text{Cl}_2/\text{BCl}_3/\text{Ar}$ 0/20/0 sccm
Pressure5 mtorr
DeV-45 V
RF2(ICP Power)... .. .500 W
Etch Rate... .. .~550 nm/min

The total depth of the etch was around 2800 nm and the total etch time was 5 minutes. Photo courtesy of Faisal Ahmad. Principal investigator is Farhan Rana, ECE Dept, Cornell.



typical etch rate of 150 nm/min and a selectivity to photoresist of 2:1. We have investigated the use of $\text{C}_4\text{F}_8/\text{O}_2$ and $\text{C}_4\text{F}_8/\text{Ar}$ to etch thermally grown silicon dioxide, fused silica, quartz, and borofloat glasses using photoresist, SU-8, polysilicon and metals as etch masks. Etch rates for these processes are ~150-200 nm/min with selectivities ranging from 0.7:1 to 2:1 and > 25:1 in the case of an aluminum etch mask. We've also implemented a CF_4 based process for patterning alignment marks used in hybrid photo/ebeam lithography. We plan to investigate C_2F_6 based etch processes as well as investigating the feasibility of etching silicon carbide.

One of the PlasmaTherm 770 ICP chambers, formerly providing Bosch based deep silicon etching, has been converted to etch III-V compounds utilizing Cl_2 , BCl_3 , SiCl_4 , SF_6 , O_2 , Ar, H_2 , and CH_4 . We plan to be able to effectively etch GaAs, InGaAs, AlGaAs, GaN, AlGaN, InGaN, InP, InN, AlN, GaP, GaSb, InAlAs, and others. Substrate sizes from small pieces up to 4" wafers can be accommodated. The inclusion of SF_6 will allow processes with raised selectivity to aluminum containing layers to be developed. The SiCl_4 will assist in producing a more anisotropic etch profile and is also favorable to the formation of low resistance ohmic contacts. So far, we

have successfully etched GaAs, GaN, and InP with photoresist, PECVD silicon dioxide and PECVD silicon nitride etch masks.

The PlasmaQuest ECR is being retired. In its place we will be installing a dual chamber PlasmaTherm 720/740 that the CNF recently acquired. This is slated to replace the functionality of the existing PlasmaTherm 720 by providing a dedicated process chamber for shallow silicon etching with high selectivity to silicon dioxide and silicon nitride and also a dedicated process chamber for the aluminum etch. This aluminum etch process will also be able to incorporate a post etch high pressure plasma passivation step to improve and minimize the susceptibility to undercutting.

At the beginning of summer '05 we installed a XeF₂ plasmaless based etch system from Xactix. The system is designed for etching silicon isotropically with a high selectivity to photoresist, silicon dioxide, silicon nitride, and most metals. It is capable of handling sample sizes from individual die up to 6" wafers. This process is ideally suited for releasing MEMS structures.

We will soon be receiving a Minilock II from Trion Technology. This system is loadlocked, ICP equipped, and will be capable of processing 3", 4", 6", 8" wafers with mechanical clamping, active He backside cooling, and substrate heating, as well as, 5", 6", and 7" square substrates. We will be plumbing the system with Cl₂, BCl₃, SiCl₄, SF₆, O₂, Ar, and N₂ gasses to allow quite a bit of flexibility in materials to be processed.

K&S Bonder

We now have two wire bonding systems for use in making electrical connections from microelectronic chips to commercially available chip packages (or to other non-standard chip holding devices).

In addition to our West Bond model 7400A ultrasonic wedge bonder, we now have a Kulicke and Soffa model 4124 thermsonic gold ball bonder. One difference between these machines is that the West Bond makes connections between two bonding pads with aluminum wire, and the recently acquired Kulicke and Soffa, makes these connections with gold wire. Another difference is that the West Bond is set up to use 0.00125 inch (32 μm) diameter wire, and the Kulicke and Soffa is set up with 0.001 inch (25 μm) diameter wire. This allows the K&S to make bonds on significantly smaller bonding pads. While the West Bond ultrasonic bond is made at ambient temperature, the bond using the K&S is made with a combination of ultrasonic energy and heat. To do this, the device which needs connections is mounted firmly on a heated stage, and the bonds are made at about 160°C.

This K&S bonder is on permanent loan from the "Retinal Implant Group", courtesy of Dr. Douglas Shire. This group is a CNF user and is based at MIT. The bonder was purchased with a grant from V.A. Funds, which supports this project.

Electroplating

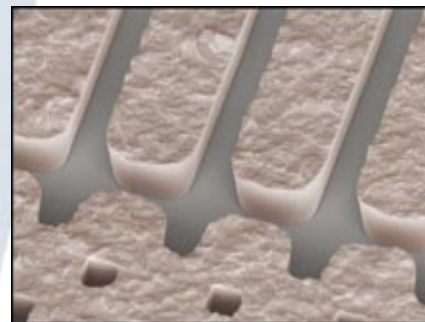
The electroplating setup has been upgraded to allow for greater film thickness control and for easier use. The film properties of the electro-deposited Cu and Au films have been characterized and are repeatable.

Copper Deposition

Film Stress ~ 0 MPa
Uniformity ~ 15-25% 1 sigma
Deposition Rate: 200-350 nm/min
RMS Roughness ~ 5 nm

Gold Deposition

Film Stress ~ 0 MPa
Uniformity ~ 6-15% 1 sigma
Deposition Rate: 90-250 nm/min



SEM of 2 μm wide copper lines electroplated using a photoresist mold that has since been removed. (Colorized photo by Dan Woodie)

E-Beam Lithography

AS200 JEOL Integration

As critical-feature patterning processes increase in complexity and sensitivity, the ability to rapidly pattern surfaces on a nanometer length scale in conjunction with micro and mesoscopic features is of great importance for future technological innovations.

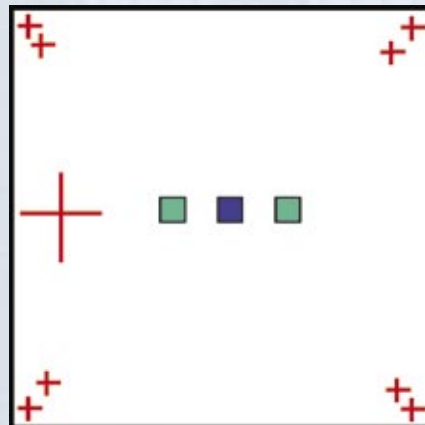
In particular, our results illustrate a powerful approach for a hybrid technique employing the integration of GCA Autostep 200 and JEOL9300FS for the production of features ranging from 20 nm and above. The stepper is used to pattern the zero-layer alignment pattern for both tools. Subsequent alignment levels between these two tools facilitate controlled integration between nanoscopic and mesoscopic dimensions.

Process Flow:

Zero level alignment marks are defined by either etching 2 μm into silicon via 5 loops in the Unaxis 700 or 100 nm Au lift-off. In both cases, SPR220-3 is spun at 4 krpm, baked at 115°C for 90 sec, exposed with AS200 at ~ 0.44 sec, post exposure baked at 115°C for 90 sec and developed in MIF 300 for 60 sec. The resist serves as a mask for subsequent deep plasma etching or

following a de-scum in the Branson (recipe #2) for 3 mins for lift off. Each die should have 1 global and 4 local marks for the JEOL, as well as 1 global and various tones of the 2 types of DFAS marks for the AS200.

The JEOL global marks are composed of 2 mm long by 3 μm wide crosses and the local marks are 30 μm long 3 μm wide crosses. For each alignment level a set of four local marks is included. Additional sets of local marks should be included. AS200 marks can be found at <http://www.cnf.cornell.edu/doc/AS200.zip>.



Above: Example of a field containing a JEOL global (large red cross), 2 sets of JEOL local marks (4 smaller red crosses at the edge of the field), AS200 global (blue square) and local marks (green squares depicting various tones of DFAS marks).



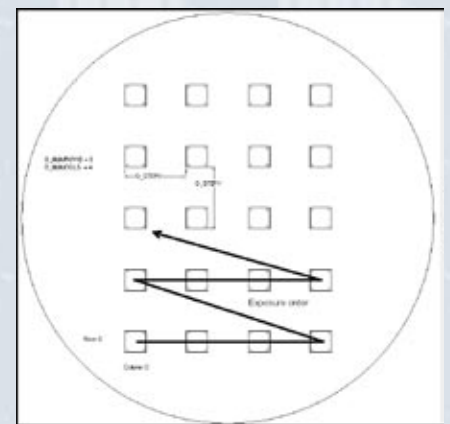
Participants of the June 2005 CNF TCN. More about the CNF short course on page 18.

Leica VB6 Update

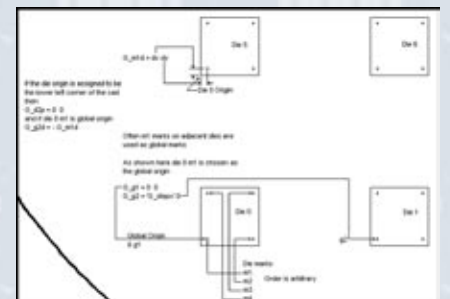
Users of the Leica VB6-HR electron beam lithography system have benefited from new software written by CNF staff member John Treichler. It is a general template for job files. Users copy the template and change parameters appropriate to their job, and then a general exposure program (also written by John) is called.

The template handles many combinations of automatic alignment schemes and alignment mark geometries. If automatic mark location fails, users can locate marks manually and continue. It is more powerful and flexible than templates which were available previously.

VB6 users are encouraged to use the new template whenever possible to maximize their productivity when using the system.



Two views of the new General Template



Thin Film Deposition and Growth

Parylene Deposition

Model PDS 2010 LABCOTER deposition system, currently running on the 2nd floor of Duffield Hall, is the first portable system designed for deposition of protective Parylene conformal coating. This unit is suitable for laboratory research applications, circuit board repairs, electronic sensors, medical components, organic samples, and many other substrates.

The deposition process begins with the granular form of Parylene, a raw material Dimer. The material is vaporized under vacuum and heated to a dimeric gas. The gas is then pyrolyzed to cleave the dimer to its monomeric form. In the room temperature deposition chamber, the monomer gas deposits as a transparent polymer film. The required thickness of a coating can vary based on the application, but thickness can range from the hundreds of angstroms to several microns.

Good to excellent adhesion of Parylene to a wide variety of substrates can be achieved with the simple treatment of a dilute solution of an organic silane prior to the Parylene coating.

Parylene exhibits very little absorption in the visible region and is, therefore, transparent and colorless. Below about 280 nm, Parylene C absorbs strongly. The Parylenes withstand room temperature chemical attack and are insoluble in all organic solvents up to 150°C. Furthermore, chemical resistance and moisture vapor permeability rates for Parylene C are superior to almost all polymeric materials.



Phil Infante explains the furnace area to CNF TCN participants.

Furnace Processing

Our furnace capabilities have continued to improve as more processes are brought online. Four oxidation and anneal furnaces are currently available, these provide services for wet and dry oxidations of Silicon with options for various in-situ pre-cleans. Wet and Dry oxidation data and graphs have been updated and posted in the tool manuals. For general MEMS type processing, three LPCVD processes have been online and process data has been collected and posted in the respective tool manuals as well. LPCVD silicon nitride has continued to offer a consistent low stress (150-200 MPa tensile stress) film. We have added a high temperature deposited oxide (HTO) recipe to this furnace. This oxide offers a higher quality oxide with better conformality than the low temperature CVD oxide. The LPCVD low temperature oxide and in-situ doped polysilicon tubes have

work on various glass substrates used in the LCD industry. In-situ doped polysilicon deposition, low temperature oxide deposition using either silane or diethylsilane (LTO 410), and standard oxidation/anneal processes are available for these glass substrates.

Lastly, high purity furnace tubes restricted for CMOS device work will start coming online this year to further improve our support for cutting edge device research. Two oxidation processes, a dry gate oxidation furnace and a wet oxidation process will be available this spring. The dry oxidation tube will offer O₂ oxidations as well a N₂O oxidations for growth of oxy-nitride dielectrics. Tighter restrictions will be placed on samples to ensure these furnaces offer the highest quality films. Contact Phil Infante for further information.

been operational. In the next few months an LPCVD TEOS deposition tube will come on line. TEOS (Tetraethyl-ortho-silicate) is a source material for silicon oxide deposition that gives a high quality, low stress, conformal coating on the wafers.

Three furnace tubes are also available for processing of thin film transistor

Photolithography

We have continued to add capabilities and improvements to the Photolithography area since our last report. Many of the changes that were in progress or still in planning have now been completed.

The wafer-coating room now contains eleven hotplates for post-apply baking and post-exposure baking. An additional hotplate tower has been added to house a second Blue M gravity oven and more hotplates.

The Karl Suss RC-8 automated wafer spinners have been installed by SussTec service and will be in use within a few weeks. These units will provide automatic resist dispensing, backside rinse, and GYRSET controlled evaporation technology for exceptional uniformity.

CEE's new contact tool for spin-on planarization is still in the shake-down phase, but a visit from the manufacturer's FSE should help it to begin its contribution to the lab. It can planarize wafers up to 150 mm using a UV-cured polymer, and may be used for imprint lithography as well.

Two Hamatech-Steag HMP 900 units are now available for single-wafer photoresist developing; one in the stepper room and one in the contact lithography room.

The mask-making area now has two Hamatech-Steag mask processing tools. One of these tools, an HMP 900, automatically develops the photoresist and/or etches the chrome layer, while the other, an HMR 900, can perform a Piranha or ammonia clean on wafers or photo masks. This tool can utilize a motorized PVA brush assembly as well as a high-pressure jet during processing.



Our new laser mask writer, the Heidelberg DWL 66, has been integrated into the mask-making process stream and sees an increasing amount of use. A grayscale-patterning feature for the tool has now been implemented with 32 levels of gray.

The GCA Autostep AS200 has had software modifications to allow leveling of 2" wafers, and for leveling of pieces as small as 15 mm. A new 2" wafer chuck has been added to the mix. We also just finished a complete rebuild of the Maximus 2000 illuminator for the system. This should bring the exposure uniformity and intensity back to specifications.

Many of the standard processes for the most commonly used

photoresists have been documented and are available on each tool's web page. (The CNF equipment list is online at http://www.cnf.cornell.edu/cnf5_tool.taf.) This information will help reduce time spent doing processes characterization for both new and more experienced visitors by providing starting points and expected ranges of parameters for operation.

Finally, we will soon be installing PROLITH, the popular photolithography modeling software package from KLA-Tencor, on networked workstations. During the evaluation period there will be up to four simultaneous user sessions available at any given time. We will have access to all four available software modules, which include the primary modeling software with 3-D analysis and Yield Analyzer, the Mask Defect option, the Etch option, and the Mask Topography option. This software will be available to academic users of the CNF. Training sessions will also be scheduled for interested users.

CNF & KLA-Tencor

As a result of a donation from KLA-Tencor, CNF will soon make the PROLITH photolithography modeling software package available to on-site academic researchers. PROLITH is widely used in the semiconductor industry for simulating process results because of its accuracy and ease of use. Results are displayed on-screen for analysis in 3-D, allowing the user to visually determine the impact of process variations. Data can also be output in various forms for use with external programs, inclusion in publications, or graphical printing.



Computing: Nanoscale Modeling at the CNF

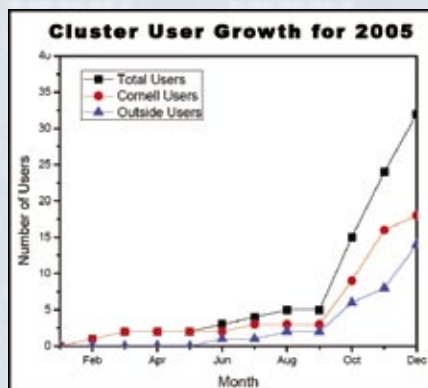


The CNF Cluster

Through generous donations by Intel Corporation, the Cornell NanoScale Science & Technology Facility has been able to provide high performance computing capabilities to users since early 2005. This effort is part of the greater computational initiative in the NNIN to provide nanoscale modeling resources that accelerate research and innovation.

The Nanolab cluster consists of 48 dual processor (3.06 GHz) Xeon nodes linked with gigabit Ethernet connections. Users at the CNF now have access to a platform for large scale computations that complements the various fabrication resources currently available. The cluster hosts an ever-expanding and diverse suite of simulation tools for nanoscale systems including codes for first principles calculations, photonic devices, molecular dynamics and nanoscale transport. While

numerous standard packages exist for well-known systems in different fields, cutting edge research often requires developing new algorithms or approaches to address unique problems. To this end, the CNF is dedicated to not only providing simulation tools, but also playing a role in their development. Dr. Derek Stewart serves as the scientific computation research liaison for the NNIN at the CNF and works with users to modify existing codes or should need require, constructing new approaches. During the last year, the number of users taking advantage of the cluster has increased steadily.



Since this is one of the few tools at the CNF that can be accessed from virtually anywhere, it can also have a dramatic impact on research from both local and remote users. The cluster also serves as a crucial test-bed where codes developed in research groups can be tested by users and develop the robustness necessary for wide spread distribution.

Modeling the Nanoscale World

In addition to providing an arena where experienced users can excel, the CNF is committed to helping new



Modeling the Nanoscale World Workshop

users overcome the learning curve associated with these approaches so that they easily incorporate these tools in their research program. To this end, the CNF hosted its first Fall Workshop, “Modeling the Nanoscale World” in October 2005 that focused on codes for nanomaterials, nanochemistry, and nanophotonics. This three-day event consisted of morning lectures that addressed the underlying theory behind different modeling approaches, while afternoon *hands-on* sessions gave participants the chance to try out codes, adapt input files, and in some cases, learn directly from code developers. Participants arrived from seven different states, Canada and Japan, and brought a wide range of fields and backgrounds that helped fuel discussion.

Due to the success of this event, another NNIN event will be held at the Harvard node from May 31st-June 3rd, 2006 (see the NNIN website for more details). Additional workshops at Cornell and other NNIN sites focused on specific codes are also being considered.

continued on next page

Things to Come in 2006

In the near future, the Nanolab cluster will be relocated to a new location to make way for the addition of the Ion Implanter to the CNF's fabrication repertoire. During this short transition period, a new job submission system will be implemented on the cluster as well as any necessary upgrades. Due to the increasing use of the cluster, work is underway to provide more nodes for calculations as well as a faster network fabric for memory intensive parallel calculations. In addition, the collection of simulation tools available will continue to grow to address the various needs of CNF users.

If you would like to learn more about the computing capabilities available at the CNF and how to become a user, please do not hesitate to contact Derek Stewart for more information (stewart@cnf.cornell.edu). In addition, if you would like to make your own simulations tools available to the greater CNF community through the Nanolab cluster, we would gladly welcome your contribution.

New CNF Staff



In December 2004, **Dr. Derek Stewart** joined the CNF staff. Derek earned his Ph.D. in physics from the University of Virginia, however much of his graduate research was conducted at the Oak Ridge National Lab. During a post-doc at Sandia National Labs in Livermore, CA, Derek expanded existing first principles codes and examined electronic transport in nanoscale structures ranging from resonant tunneling devices to nanotube photodetectors. Derek

currently supports NNIN scientific computing, the CNF Nanolab Cluster and assists users in the application of advanced simulation and modeling codes for nanoscale systems. In addition, Derek continues to expand the modeling capabilities available at the CNF and also develop new simulation tools for nanoscale research. Trading California sun for Ithaca snow, Derek, his wife, Isabella, and their children, Ariella and Dario, are now learning the finer points of ice skating, sledding, and skiing. *(Derek's photo was taken by Dan Woodie.)*

Also in December 2004, **Dr. Ana Viseu** joined the CNF staff as a Research Associate to support the NNIN's efforts in the Social and Ethical Dimensions of Nanotechnology. Ana, a native of Portugal, comes with a degree from the University of Toronto. She, along with Prof. Bruce Lewenstein of the Dept. of Communications, is coordinating the activities of NNIN is promoting discussion and analysis of the Social and Ethical Dimensions of Nanotechnology.



Ana has another nano-project — on Tuesday, January 17th, she gave birth to Mathias Barros Viseu Hessenbruch! *(Ana & Mathias in a photo from Ana's Mom.)*



CNF was fortunate to receive several significant donations to our computing capability. In December 2004 we received a donation from Intel of 16 dual Xeon™ Dell processors and clustering components in support of our scientific computation initiative. These join the 32 dual Xeon™ computers donated in the previous year. Courtesy of Intel, CNF now has a 48-node Linux scientific computing cluster available to users for scientific modeling and simulation. A range of solid state and chemical based codes will be supported by CNF staff as part of our NNIN commitment to nanoscale computation.

2005 NNIN REU Program



The 2005 NNIN REU Interns at the Stanford University convocation, August 2005

2005 was the second year of the Research Experience for Undergraduates Program for the National Nanotechnology Infrastructure Network.

Providing a focused experimental research experience in nanotechnology and its foundational subjects in a 10 week period is a challenging task; the research reports found at www.nnin.org demonstrate that enthusiastic participating students coupled to the sustained support from staff, faculty, and graduate students leads to significant accomplishments. The NNIN partnership, through our complementary strengths, inter-disciplinary efforts, multi-site education, and use of each other's resources, provides exciting projects and the means to achieve them in a reasonable time. Each student in the NNIN REU completes an independent research project, undergoes strong hands-on training and education (also available through our web-site www.nnin.org in the multimedia section), participates in a convocation at individual sites and at a common site to present their research efforts, and works to time-tested program expectations.

81 interns from 66 different institutions across the United States and representing 37 fields of study participated in the program this year. All came to us with the common goal of gaining significant experience in hands-on, advanced research. I wish the participants the best wishes for future technical careers; NNIN hopes to see them build on this summer's experience, and my thanks to the staff, the graduate student mentors, and the faculty for their participation and involvement. Particular thanks are due to Melanie-Claire Mallison at Cornell, Michael Deal at Stanford, and Nancy Healy at Georgia Institute of Technology for making their contributions in organizing and the logistics of the program and the convocation.

Find all the technical reports for the 2005 NNIN REU at www.nnin.org.

Sandip Tiwari, Director, NNIN

2005 CNF REU



The 2005 CNF REU Interns

For the 2005 NNIN REU program, CNF hosted 17 students, the largest number in the 14 year history of our program. The students began their summer by participating in the TCN (page 18) and then moved on to their individual projects, which came from Electrical Engineering, Materials Science, and Biomedical Engineering, as well as projects directed by CNF Staff.

Above are the CNF REUs at the convocation at Stanford, also attended by Ms. Melanie-Claire Mallison (far left), NNIN REU Program Assistant and CNF REU Program Coordinator, and Dr. Lynn Rathbun (far right), NNIN Program Manager.

It was a good summer and we thank the interns, the CNF staff, PIs and mentors, Intel Foundation (*see below*), NSF and NNIN for making it possible.



In support of our REU program, CNF received funds from the Intel Foundation to support five additional minority students, allowing us to expand our program from 12 to 17 interns. We thank the Intel Foundation and Intel Academic Relations for their continued support of this and other CNF programs.



Intel Undergraduate Research Interns

CNF's 2005 Nellie Yeh-Poh Lin Whetten Memorial Award Winner; Xi Chen

Xi Chen is currently a graduate student working under the guidance of Prof. Amit Lal in the *SonicMEMS* Laboratory in the School of Electrical and Computer Engineering at Cornell University. Xi received her bachelor's degree in E.E. from Nanjing University, China, and M.S. in Biomedical Engineering from University of Wisconsin-Madison. She came to Cornell in 2002 to pursue a Ph.D degree in BioMEMS.

Xi is one of the recipients of the 2005 CNF Nellie Yeh-Poh Lin Whetten Award (with Vera). The Whetten Award recognizes an outstanding female graduate student at CNF, who shows spirit, commitment to professional excellence, and professional and personal courtesy.

One of the theme topics in the *SonicMEMS* group is the novel application of various ultrasonic effects in microscale devices. Xi has worked on several exciting projects in this field. Her very first microfabricated device was a silicon ultrasonic surgical tool with integrated pressure and flow sensor for phacoemulsification-cataract removal surgery (Figure 1). The integrated sensors made the ultrasonic cutter a smart surgical tool that can monitor the eye chamber pressure during surgery and prevent damages resulting from the excessive pressure to the patient's eyes.

Xi also worked on transdermal interstitial fluid extraction for health monitoring and pathogen detection. An ultrasonic ISF sampler, developed together with former *SonicMEMS* member Chung-Hoon Lee, has been tested on *in-vivo* animals and interstitial fluids successfully collected.

In 2003, Xi served as mentor for the NNUN REU program working with intern Andy M. Newton from Kansas State University. Xi and Andy fabricated ultrasonically actuated silicon microneedle arrays and showed that ultrasonic actuation reduces skin deformation and decreases penetration force, therefore facilitating skin penetration by the microneedles.

Recently Xi has been working on ultrasonic actuation of silicon microprobes for 3D electrical activity recording in whole heart. 3D mapping of physioelectrical activities in cardiac tissues is highly desirable for the study of the mechanism and development of cardiac arrhythmias. Important information can be obtained for prediction and prevention of arrhythmias, especially ventricular arrhythmia—one of the leading causes of mortality in the USA.

The device consists of a silicon ultrasonic horn actuator that generates high amplitude vibration at the end of the horn (Figure 2). Under ultrasonic actuation, both longitudinal and flexural vibration modes are excited in the silicon microprobes to facilitate penetration into heart tissue. Cardiac signal recording was conducted on isolated and perfused canine heart. The probes successfully penetrated

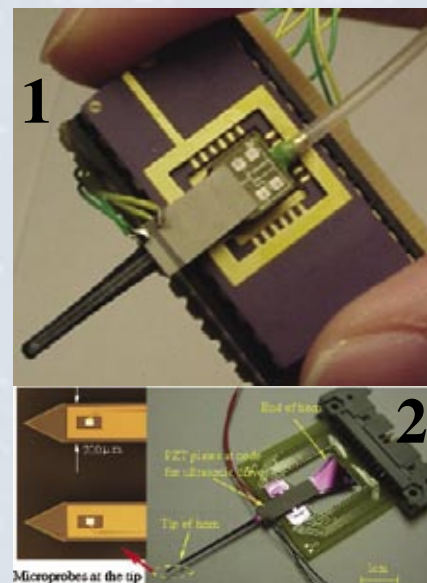


Figure 1: Silicon ophthalmic surgical tools with integrated sensors. **Figure 2:** Ultrasonic microprobes for cardiac signal recording.

the *in-vitro* beating heart at 6~10Vpp driving voltage and both spontaneous fibrillation and externally stimulated rhythmic signals were recorded with qualities comparable to those obtained by conventional metal wire probe. Signals recorded with/without the presence of ultrasound showed little difference other than some easily filtered high frequency noise, indicating the low voltage ultrasonic driving posed no significant modification on heart cell activities.

Xi is also currently working on micro-fluidic problems such as high flow rate ultrasonic horn pump and droplet handling by vibrating substrate. Xi's perception of her research area is that to be a good engineer in BioMEMS means to have a good understanding of electrical engineering, mechanical engineering, fluidic mechanics...and of course, biology. The highly interdisciplinary nature of this field is what's challenging and attracting to her.



Figure 3: Xi often works on animals (shown here testing the interstitial fluid sampler on an anesthetized pig), and she's an animal lover!

CNF's 2005 Nellie Yeh-Poh Lin Whetten Memorial Award Winner; Vera Sazonova

Vera Sazonova is currently a graduate student in the department of Physics at Cornell University and is one of the 2005's corecipients of the CNF Nellie Yeh-Poh Lin Whetten Award (together with Xi Chen). The Whetten Award recognizes an outstanding female graduate student at CNF who shows spirit, commitment to professional excellence, and professional and personal courtesy.

Vera came to Cornell in 2000 after she received her Bachelor of Science in Physics and Computer Science degrees from University of Mississippi. In 2001 she joined Paul McEuen's research group as a Ph.D. candidate. Since then she has been working on building a nanoelectromechanical system (NEMS) based on a carbon nanotube and studying its properties.

NEMS have been the subject of extensive research as they hold promise for a number of scientific and technological applications. In particular, they have been proposed for use in ultrasensitive mass and force detection, RF signal processing, and as a model system for exploring quantum phenomena in macroscopic systems. The sensitivities in such applications increase with decreasing mass of the system and increasing frequency of operation, which ultimately leads to further and further miniaturizing of the devices.

Scaling down the fabrication of resonating devices from conventional material and scaling down their measurement techniques has proved to be challenging. Additional complications come from increasing relative energy losses in small resonators. It has been observed that

the quality factor in NEMS decreases almost linearly with decreasing size of devices. Carbon nanotubes (NTs) provide a solution to several of these issues. They are the stiffest material known, have low density, ultrasmall cross sections and can be defect-free enabling them to be light, high frequency resonators with a promise of low dissipation. Equally important, a nanotube can act as a transistor and thus is able to sense its own motion, eliminating the need for additional detector circuitry.

Since she joined McEuen's group, Vera, with her fellow group member Yuval Yaish, developed a measurement scheme for studying NT resonators. In 2004 a setup actuating and detecting the guitar-string oscillation modes of doubly-clamped NT was realized. The NT resonators exhibited a wide range of vibraton frequencies (4MHz – 400MHz), tunable by a voltage applied to an underlying gate electrode.

Despite the expectations the resonators exhibited relatively low quality factors in the range of 30-200. Even though the exact origin of dissipation is still unknown, several mechanisms such as air friction, ohmic losses and clamping losses could be ruled out. Currently, together with her fellow group member Arend van der Zande, Vera is studying the temperature dependence of the NT resonator performance, in particular, the quality factor. At low temperatures quality factors in excess of 1000 have been obtained.

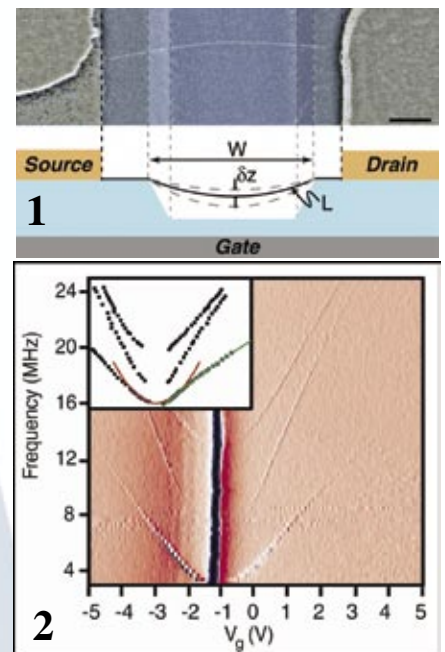


Figure 1. Device geometry and experimental setup schematic. A false colored SEM of a suspended device. Scale bar is 300 nm. Metal electrodes (Au/Cr) are shown in yellow, and SiO surface in grey. The sides of the trench, typically 1.2-1.5 μm wide and 500 nm deep, are marked with the dashed lines. A suspended nanotube can be seen bridging the trench. **Figure 2.** Measurements of the resonant response. Detected current (plotted as a derivative in color scale) as a function of gate voltage and driving frequency. Insets show the extracted positions of the peaks in the frequency-gate voltage space for the respective color plots. A parabolic and a $V_g^{2/3}$ fit of the peak position are shown in red and green, respectively.



CNF Short Course: Technology & Characterization at the Nanoscale



Is it possible to teach the concepts of nanofabrication in only three days? The nanofabrication short course taught at the CNF facilities attempts to do just that. This 3-day, non-credit course introduces interested students to the technologies that enable nanoscale research in electronics, photonics, MEMS and many other areas.

CNF's Technology & Characterization at the Nanoscale (TCN) short course is taught during the summer and winter break, and aims to be an alternative to a full semester / in depth class for students, faculty and professionals who seek to develop a good understanding of the technology without committing to a semester-long course. CNF especially invites those researchers to the TCN who plan on nanotechnology research in areas not traditionally associated with the technology.

The content of the course is designed to provide a comprehensive introduction to nanotechnology as well as to the techniques used to characterize nanoscale devices. Lectures focus on topics such as nanoscale device design, photolithography, e-beam lithography, etching, characterization and process integration. The morning lectures are complemented by laboratory demonstrations in the afternoon. Along the way, attendees have the opportunity

to interact with members of the CNF staff, who are available to discuss general questions as well as specific ones pertaining to existing or potential projects.

The TCN is prepared and taught by the CNF staff team whose members have developed and fabricated devices with nanoscale-size features for a wide variety of applications and who can provide knowledge and insight into all aspects of the fabrication process.

By the end of the course, attendees understand the core concepts in nanofabrication, are able to design a process flow for a simple device, and can choose appropriate characterization methods for devices at the nanoscale. Information and insight into CNF's capabilities also gives attendees the opportunity to explore what further role CNF could play in their pursuits in nanotechnology.

CNF plans to conduct the next TCN at the beginning of the summer break in June. The exact coordinates for the course will be announced via the CNF user email list and the CNF website at www.cnf.cornell.edu. In the meantime, interested students can view in-depth lectures of a 3-week course taught at CNF in previous years at the CNF website at www.cnf.cornell.edu/cnf5_courses.html.

For more information on course registration, please contact Melanie-Claire Mallison. Information on course content is available from Michael Skvarla.

CNF TCN Summary:

Next offering: June 2006

Lectures: 12 hours

Laboratory demos: 6 hours

Textbook:

CNF course notes (provided)

Cost:

\$300 (academic), \$750 (industrial)

A Selection of CNF-Related Patents, Presentations & Publications

“3D Analytical Modeling of Nanocrystal Memory Electrostatics”; U. Ganguly, V. Narayanan, C. Lee, T. Hou and E. C. Kan. Accepted, J.Appl.Phys, 2006.

“Carbon Nanotube Based Non-Volatile Memory with Charge Storage in Metal Nanocrystals”; U. Ganguly, E.C. Kan and Y. Zhang, ApplPhysLett, v87, p.043108, 2005.

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“Development of a Microfluidic Biosensor Module for Pathogen Detection”; N.V. Zaytseva, V.N. Goral, R.A. Montagna and A.J. Baeumner. Lab Chip, The Royal Society of Chemistry Journal, V5, 805-811, 2005.

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“DNA-Based Biosensors”; N. Cady, and C.A. Batt. Encyclopedia of Sensors, In press.

“Electrical Modulation of Silicon-Based 2D Photonic Bandgap Structures”; M. Haurylau, S.P. Anderson, K.L. Marshall, and P.M. Fauchet, Appl.Phys.Lett. 88(6) 2006.

“Fast and Sensitive Electret Polymer Characterization by Extended Floating Gate MOSFET”; M.Kim, Y.N.Shen and E.C. Kan, IEEE Trans. Dielectric and Electric Insulation, V12:N5, pp. 1082-1087, Oct. 2005.

“Microfabricated Torsion Cantilevers Optimized for Low Force and High Frequency Operation in Fluids”; A. Beyder, and F. Sachs. Ultramicroscopy, in press, 2006.

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“Microreaction for Microfuel Processing: Challenges and Prospects”; X. Ouyang Shah, and R.S. Besser, Invited Paper, Chemical Engineering Technology, 28:3, 1, 2005.

“Modeling and Evaluation of an Integrated Microfluidic Fuel Processor for Miniature Power Sources”; K. Shah and R.S. Besser, Accepted, AIChE Spring Mtg, April, 2006.

“Molecular Manipulation and Identification in Nanofluidic Devices”; H.G. Craighead, Invited Speaker. Gordon Research Conference, Physics & Chemistry of Microfluidics, Magdalen College, Oxford, UK, 8/2005.

“Molecular Templates for Bio-Specific Recognition by Low-Energy Electron Beam Lithography”; W. Senaratne, P. Sengupta, C. Harrett, H.G. Craighead, B. Baird, and C. Ober. NanoBiotechnology, 1, 023-034, 2005.

“On-Chip Planar Solenoid Inductors using Magnetite (Fe₃O₄) Nanorod Cores for High Frequency Applications”; J. Kim, W. Ni, I.D. Hosein, Y. Song, C. Liddell and E.C. Kan, MatResSymp, Boston, MA, 11/2005.

“Optical Excitation of Nanoelectromechanical Oscillators”; B. Ilic, S. Krylov, K. Aubin, R. Reichenbach, and H. G. Craighead, App. Phys.Letters, 86, 193114-1:193114-3, 2005.

“A Polymeric Microchip with Integrated Tips and *In Situ* Polymerized Monolith for Electrospray Mass Spectrometry”; Y. Yang, C. Li, J. Kameoka, K. Lee and H.G. Craighead, Lab on a Chip, 5, 869-876, 2005.

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“Real-Time Detection of Microorganisms using an Integrated Microfluidics Platform”; N. Cady, S. Stelick, M.V. Kunnavakkam, and C.A. Batt. U.S. Patent Application Filed July 22, 2005: No. PCT/US05/21790.

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“Rotational Disk Sensor Platform”; Dr. Cetin Cetinkaya, Infotonics Technology Center, Canandaigua, NY, December 12, 2005.

“Rotational Oscillator Design for MEMS Biological and Chemical Sensors”; Dr. Cetin Cetinkaya, Provisional Patent App, 10/2005.

“Single Electrospun Regioregular Poly (3-hexylthiophene) Nanofiber Field-Effect Transistor”; H. Liu, C.H. Reccius, and H.G. Craighead, Applied Physics Letters, 87, 253106-1:253106-3, 2005.

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The 2004-2005 CNF Research Accomplishments are available in PDF at www.cnf.cornell.edu



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