

***2006 Advanced Research Workshop***

**FUTURE TRENDS IN MICROELECTRONICS:  
*Up the Nano Creek***

***June 26–30, 2006: Crete, Greece***



**20061010228**

***Scientific Program***

CSP 06-5030  
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**REPORT DOCUMENTATION PAGE**

Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.  
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<b>1. REPORT DATE (DD-MM-YYYY)</b> 15-08-2006	<b>2. REPORT TYPE</b> Conference Proceedings	<b>3. DATES COVERED (From - To)</b> 26 June 2006 - 30 June 2006
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<b>4. TITLE AND SUBTITLE</b>  Future Trends in Microelectronics Up the Nano Creek	<b>5a. CONTRACT NUMBER</b> FA8655-06-1-5030
	<b>5b. GRANT NUMBER</b>
	<b>5c. PROGRAM ELEMENT NUMBER</b>

<b>6. AUTHOR(S)</b>  Conference Committee	<b>5d. PROJECT NUMBER</b>
	<b>5d. TASK NUMBER</b>
	<b>5e. WORK UNIT NUMBER</b>

<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Brown University 182 Hope St. Providence 02912 USA	<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  N/A
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<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>  EOARD PSC 802 BOX 14 FPO 09499-0014	<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>
	<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b> CSP 06-5030

**12. DISTRIBUTION/AVAILABILITY STATEMENT**  
Approved for public release; distribution is unlimited. (approval given by local Public Affairs Office)

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**  
  
The Final Proceedings for Future Trends in Microelectronics FTM-2006, 26 June 2006 - 30 June 2006  
  
CMOS technology issues: smaller transistors; making transistors with different or better materials; the real limit to shrinking devices - technological or economic; Beyond CMOS; Femto-electronics; Molecular electronics; Superconductors and molecular-conductors; Bio-nanoelectronics ; Self-assembling of top-down lithography; Evolution/revolution in computing architectures; Optical Computing; Bio-informatics; Non-lithographic nanofabrication; Non-semiconductor electronics; Macro-electronics; Non-von Neumann computing; DNA assisted self-assembling and packaging; Carbon nanotubes; Views from industry

**15. SUBJECT TERMS**  
EOARD, Electronic Devices, semiconductor devices

<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b> UL	<b>18. NUMBER OF PAGES</b>  62	<b>19a. NAME OF RESPONSIBLE PERSON</b> GEORGE W YORK, Lt Col, USAF
<b>a. REPORT</b> UNCLAS	<b>b. ABSTRACT</b> UNCLAS	<b>c. THIS PAGE</b> UNCLAS			<b>19b. TELEPHONE NUMBER (Include area code)</b> +44 (0)20 7514 3154

**FTM-2006 PROGRAM AND SCHEDULE**

**Monday, June 26**

**Morning Session:** *Captains of industry and Solomon the wise*  
**Chairs:** Marie D'Iorio and Donald Silversmith

- 8:30–8:45 Welcoming remarks by S. Luryi
- 8:45–9:25 Mark Pinto "Nanomanufacturing technology: Exa-units at nano-dollars"
- 9:25 – 10:05 Jos Benschop "32 nm: Lithography at a crossroad"
- 10:05 – 10:45 Michel Brillouët "Physical limits of Si CMOS: Real showstopper or wrong problem?"
- 10:45 – 11:00 *Coffee Break*
- 11:00 – 11:40 Boaz Eitan "NVM future trends – from floating gate to trapping devices"
- 11:40 – 12:20 Paul Solomon "Carbon-nanotube solutions for the post-CMOS-scaling world"
- 12:20 – 13:00 Henk van Houten "Towards nanomedicine"
- 13:00 *Lunch*

**Evening Panel:** *Prospecting up the nano creek*  
18:00 – 20:00 **Moderator:** Michael Shur  
**Panelists:** Yoshio Nishi and others to be announced

**Tuesday, June 27**

**Morning Session:** *Bio-el: the infectious adventure*  
**Chairs:** Michael Milligan and Nadia Lifshitz

- 8:30 – 9:10 Peter Gammel "Androids in our future: Towards networked, intelligent bioelectronics"
- 9:10 – 9:50 Arto Nurmikko "Reading/writing your brain: Not just another micro/optoelectronic interconnect challenge"
- 9:50 – 10:30 Cees Dekker "Nanoscience from carbon nanotubes to single-molecule biophysics"
- 10:30 – 10:45 *Coffee Break*

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10:45 – 11:25	Eckard Wimmer	"Synthetic biology: Synthesis and modification of a chemical called poliovirus"
11:25 – 12:05	Robert Austin	"Directed evolution on a nanofabricated chip: Electronic hydrogen gas detection"
12:05 – 12:45	Nadrian Seeman	"Using structural DNA nanotechnology to organize matter"
13:00	<i>Lunch</i>	
<b>Evening Panel:</b>	<i>Poster Presentations and Discussion</i>	
18:00 – 20:00	<b>Chair:</b> Yacov Shamash	

**Wednesday, June 28**

**Morning Session:** *It's all done with mirrors*

**Chairs:** Vladimir Mitin and Dan Botez

8:30 – 9:10	Claude Weisbuch	Improvements in light emitters by controlling spontaneous emission: From LEDs to biochips
9:10 – 9:50	Edmund Linfield	"Terahertz spectroscopy and imaging"
9:50 – 10:30	Federico Capasso	"Nanophotonics: Searching for new phenomena and devices"
10:30 – 10:45	<i>Coffee Break</i>	
10:45 – 11:25	Boris Spivak	"Does a theory of the laser linewidth exist?"
11:25 – 12:05	David A. B. Miller	"Silicon photonics – optics to the chip at last?"
12:15	<i>Departure for boat excursion and lunch</i>	

**Evening plenary:** Harry Kroto "Architecture in NanoSpace"  
19:00 – 20:00

**Thursday, June 29**

**Morning Session:** *Spins, fluxes and other spooky quanta*

**Chairs:** Dan Purdy and Sorin Cristoloveanu

8:30 – 9:10	Emmanuel Rashba	"Semiconductor spintronics: Progress and challenges"
9:10 – 9:50	Igor Zutic	"Semiconductor spintronics: From spin injection to spin-controlled logic"
9:50 – 10:30	Stuart S. P. Parkin	"Spintronic devices for nonvolatile memory and logic"

10:30 – 10:45	<i>Coffee Break</i>	
10:45 – 11:25	Alexei Efros	"Optical properties of materials with negative refraction: Perfect lenses and cloaking"
11:25 – 12:05	Pawel Hawrylak	"Designing nanoscale solid state systems for quantum information processing"
12:05 – 12:45	Michel Dyakonov	"Is fault-tolerant quantum computation really possible?"

13:00 *Lunch*

**Evening Panel:** *Fashions, fads, fades, fates, and faith*  
 18:00 – 20:00 **Moderators:** Serge Luryi and Jimmy Xu  
**Panelists:** TBA  
**Best poster vote:** at the conclusion of the panel

**Banquet:** *Workshop Banquet 20:30 onwards*

**Friday, June 30**

**Morning Session:** *Recent results hot off the press*  
**Chairs:** Hiroshi Iwai and James DeCorpo

8:30–9:05	Upendra Singh	"The future of single- to multi-band detector technologies"
9:05 – 9:40	Olof Engstrom	"Will the insulated gate transistor concept survive next decade?"
9:40 – 10:15	Michael Kelly	"Alternatives to silicon: Will our best be anywhere good enough in time?"
10:15 – 10:50	F. Arnaud d'Avitaya	"MRAM scaling-down challenges"
10:50 – 11:00	<i>Coffee Break</i>	
11:00 – 11:35	Martin Green	"A new class of semiconductors using quantum confinement of silicon in a dielectric matrix"
11:35 – 12:10	Mihai Banu	"Ultimate VLSI clocking using passive serial distribution"
12:10 – 12:45	Best poster winner	"To be announced"
12:45	Closing remarks, S. Luryi and J. M Xu	
13:00	<i>Lunch and end of Workshop Program</i>	



**FTM-2006 ORAL PRESENTATION SESSIONS**

**Monday, June 26**

Mark Pinto  
Jos Benschop  
Michel Brillouët  
Boaz Eitan  
Paul Solomon  
Henk van Houten

**Tuesday, June 27**

Peter Gammel  
Arto Nurmikko  
Cees Dekker  
Eckard Wimmer  
Robert Austin  
Ned Seeman

**Wednesday, June 28**

Claude Weisbuch  
Edmund Linfield  
Federico Capasso  
Boris Spivak  
David Miller  
Harry Kroto [evening plenary]

**Thursday, June 29**

Emmanuel Rashba  
Igor Zutic  
Stuart Parkin  
Alexei Efros  
Pawel Hawrylak  
Michel Dyakonov

**Friday, June 30**

Upendra Singh  
Olof Engstrom  
Michael Kelly  
François Arnaud d'Avitaya  
Martin Green  
Mihai Banu  
Best poster winner





**Nanomanufacturing technology: Exa-units at nano-dollars**

Mark R. Pinto  
*Applied Materials, USA*

The history of steel and silicon suggest that measured by number of papers, the non-IC nanotechnology industry should exceed US\$1 trillion in revenue. Meanwhile Moore's law marches on, with the increased importance of consumer devices emphasizing cost per bit rather than GHz, drives investment in the IC industry. In 2006 alone,  $\sim 3 \times 10^{18}$  flash bits will be produced at average costs of  $\sim$ US\$10n per (good) bit. As a result, nanoelectronics will remain the predominant commercial embodiment of nanotechnology for the foreseeable future.

This presentation explores key technology challenges in IC nanomanufacturing and reviews some of the main industry directions that will sustain the pervasive growth of semiconductor content. Additionally, the precision, repeatability, reliability and cost effectiveness of the IC-proven nanomanufacturing technology platforms – which have already impacted wide screen TVs – will enable more new markets in the future, especially where technology-induced cost reduction leverages demand elasticity.

### **32 nm: Lithography at a crossroad**

J. Benschop

*ASML Inc., The Netherlands*

Microlithography is used to define patterns on ICs. The workhorse for the lithography is optical projection lithography whereby a pattern on a mask is imaged on wafer with 4:1 reduction ratio.

Using water immersion objectives, a production-worthy lithography system using 193 nm wavelength and a numerical aperture  $NA = 1.2$  has been shipped in early 2006. This system is capable of printing lines and spaces below 45 nm.

The next step will be a water-based system with an  $NA = 1.35$ , capable of printing lines and spaces below 40 nm.

Several options are pursued to extend the lithography roadmap down to 32 nm dense lines and spaces. Leading candidates are EUV, double patterning using water-based immersion and immersion using non-water based liquids.

EUV, having a wavelength of 13.5 nm, has the potential to be extended down to 22 nm and below. Significant progress has been made on this technology over last years: first full field tools became available early 2006. However additional progress will be needed on tools, resists and masks before this technology is suitable for mainstream production.

Double patterning, using water-based immersion, is the most straightforward extension but could almost double the cost of lithography and has a severe impact on tool requirements like overlay. Finally non-water based immersion liquids offer the prospect of increasing the  $NA$  beyond 1.5, but will require lens materials currently not available.

Since there is no clear winner and all options have their own technical and economical challenges, the industry could face a paradigm shift, by the end of this decade, at the 32 nm node.

An assessment of various leading alternatives will be given; an attempt will be made to rank the technical and economical challenges. Finally it will be speculated whether the 32 nm node offers an opportunity for technologies other than optical projection lithography (e.g. imprint, e-beam) to enter into mainstream IC fabrication.

**Physical limits of Si CMOS: Real showstopper or wrong problem?**

Michel Brillouët  
*CEA-LETI-Grenoble, France*

From more than two decades technical papers announced the imminent dismissal of Si CMOS stressing the 1  $\mu\text{m}$  barrier, then the 100 nm brick walls and recently the 10 nm limit: until now they all proved to be wrong. After analyzing the reasons of the failure of such claims we will look at the latest versions of the same theme, trying to outline the underlying assumptions of such assertions and possible shortcomings.

Assuming the "classical" Si CMOS will hit some limits in the future, the latest version of the ITRS roadmap gives a thorough analysis of possible candidates in this "Beyond CMOS" era. We will review the necessary criteria for a successful replacement of Si CMOS gate for information processing and make a critical assessment of such proposed devices.

However the question is: are we looking at the right problem? The focus on logic gates may just be the tree hiding the forest of issues to be addressed in information processing. We will also look at major pending problems like interconnecting those gates, making complex circuits manufacturable or even asking if any alternative information processing schemes may solve present hot topics in nanoelectronics.

## **NVM future trends – from floating gate to trapping devices**

B. Eitan, I. Bloom, G. Cohen, M. Janai, E. Lusky, and A. Shappir  
*Saifun Semiconductors Ltd., Israel*

Non-volatile memory (NVM) has experienced tremendous growth in the past five years. This trend is expected to continue in the coming years. The workhorse of most NVM products is the floating gate (FG) device. The last few years have focused on scaling and increasing the number of bits in a multi-level cell (MLC) and on new emerging technologies, either based on trapping-concepts (NROM, nanocrystals and SONOS) or based on new physics and material concepts (FERAM, MRAM and phase-change).

The scaling of area per bit in the FG NVM memories is focused on traditional shrinking of the lithography and increasing the number of bits to two (MLC). The lithography scaling path suffers from the non-scalability of the voltages, as the tunneling oxide has only changed from 10 nm in 1980 to 8.5 nm in 2005. Another great limitation is the gate to FG coupling ratio: scaling the cell reduces the FG capacitance and hence results in a smaller number of stored electrons, limiting the reliability of the MLC devices. These scaling difficulties in the FG devices are creating a significant opportunity for the emerging NVM technologies.

Among the trapping devices, mainly the NROM family, scaling is progressing faster than the lithography road map. This paradigm shift is enabled by increasing the number of bits per cell from two to four and reducing the cell size below the  $4F^2$  lithography limit. In this presentation, we will show that this faster downscaling is enabled by the NROM device physics, including:

- program and erase with hot carriers that reduces the operating voltages ;
- tunnel oxide scaling (to 3 nm) based on storage on a dielectric rather than on a conductor;
- coupling ratio of one and no FG-related cross talk;
- and a very simple manufacturing process with great similarity to CMOS scaling flows.

The NROM concept, based on trapping in the ONO dielectric, is already in volume production for code, data and embedded applications. Of the same family, the nanocrystal memories are having major process integration problems and offer no advantage over the ONO-based devices. The SONOS-based devices rely on tunneling program and erase, hence suffer from the very high voltage requirements.

The second category of technologies is based on new physics and material concepts. For this category to make an impact they must have a small cell size with at least two bits per cell. Unfortunately all these new concepts have more than one element per bit. They also suffer from material science complications. This makes them unlikely candidates to replace any of the technologies that are already in production.

The system architecture that supports the memory is becoming an important part of the scaling path. Concepts like error detection and correction, wear leveling and bad block management will become a must in the future, when redundancy techniques will no longer be sufficient. We will discuss how the choice of trapping technology makes a major impact on the simplicity and efficiency of the system integration.

The scaling limitation of the FG NVM products is already very visible. The NROM, as a charge trapping based technology, avoids these limitations. Together with the proven ability to deliver four bits per cell and a good system compatibility, NROM is an interesting example for the CMOS technologies that "straight forward" scaling is not the only option.

**Carbon-nanotube solutions for the post-CMOS-scaling world**

Paul M. Solomon  
*IBM Research, Yorktown, U.S.A.*

The CMOS research world has been up-ended in the past few years with the realization that the end of scaling is indeed approaching fast and that other, more radical solutions need to be found. Much work has been focused on investigating a radical (for CMOS) set of new geometries and materials, including strain engineering, 2D electrostatically confined structures, and 3D heterogeneous integration. These approaches extend the technology and provide a more powerful end-point, but do not drastically alter the scaling scenarios. The capabilities projected for future CMOS are enormously larger than even today's gigascale integrated product so the question arises as to the need for any CMOS follow-on at all. An interesting feature pertaining especially to the silicon-on-insulator approaches is that the "silicon" technology is becoming divorced from the bulk silicon material – indeed, for these technologies any convenient material could, in principle, be used for the substrate.

Of the various alternative "nano-offerings" investigated in the past few years, none can be seen as a serious competitor for this evolved CMOS. Device characteristics are poor, unreliable and noisy, and manufacturing methodologies are uncertain at best. A possible exception, at least in terms of the intrinsic device, is the carbon nanotube (CNT), and this will be the topic of my presentation. Carbon nanotubes can be thought of as perfect electron waveguides where electrons can be transported through unimaginably small channels without scattering off the boundaries. In addition phonon interactions are weak. This results in per-unit-channel-area properties vastly superior to silicon, with the additional advantage that these properties are symmetric for both  $p$  and  $n$  channel transport. Challenges to implementing this technology and realizing these intrinsic advantages in terms of system performance are formidable. Firstly, how do we place, or grow, CNTs of desired properties on the circuit substrate. Then, given such placement, how do we fabricate FETs with specific and tightly controlled characteristics, and with low parasitic capacitances and resistances. Last, but not least, how do we best use CNTs in circuits and systems, and what performance advantages are expected.

Two interesting application regimes are identified. Firstly in the low-power regime, the high intrinsic packing density and low intrinsic capacitance gives the CNT an advantage both in intrinsic and wiring capacitance. This could be further improved if metallic CNTs were used for the wires (taking the kinetic inductance into account). Secondly, their intrinsic high speed coupled with their ballistic properties open up the possibility of uses as discrete traveling wave-type amplifiers and oscillators up to the THz range.

## Towards nanomedicine

Henk van Houten

*Philips Research, The Netherlands*

Throughout the existence of mankind, man has lived with the expectation to die quite young from violent external factors or from infectious diseases. During the 20th century, there has been considerable progress in world health, but this can mostly be attributed to improvements in living conditions – hygiene, access to safe drinking water, improved quality and variety of nutrition – rather than to breakthroughs in medical science or practice. As a result, life expectancy has increased dramatically, first in Europe and North America, but now also in countries such as China. Unfortunately, this is going hand in hand with an increase in the number of people affected by chronic or degenerative diseases, which also are at the origin of the current explosion of the costs of the healthcare system. Typically, treatment for these diseases is palliative in nature – mostly there is no cure and at best the progression of the disease can be delayed.

The basis for radical change in medical practice has to be found in molecular biology. During the last half century, the scientific understanding in this field has progressed very rapidly. It is now well accepted that most diseases have their origin in disturbances of the delicate balance in molecular processes taking place at the cellular and sub-cellular level. This is currently leading to a paradigm shift in medicine: from a focus on dysfunctional organs to an understanding of disease pathways at the cellular and molecular level. This shift is underlying the vision that genetic predisposition testing, early diagnosis, and personalized treatment will transform clinical practices, and lead to improved patient outcomes. Aspects of this vision are referred to as evidence-based medicine, personalized medicine, molecular medicine, or nanomedicine. Relevant to this paper, intended for physicists and engineers with an interest in nanotechnology, is the understanding that this vision can only come about by matching the progress in molecular biology with advances in medical microdevices, nanotechnology and physical instrumentation, and by inventing new ways of dealing with complex data, a field referred to as bioinformatics.

Biomarkers are signatures of relevant disease pathways. They can be molecules found in body liquids of patients, such as blood, urine, or saliva. It is then possible to design molecular targets (DNA molecules or antibodies) that bind selectively to such biomarkers. This can be exploited to develop biosensors for *in-vitro* molecular diagnostics tests. As an example, I will discuss the biosensors currently in development at Philips Research labs, which are based on magnetic detection. Such biosensors can be used for early detection of disease, thus for patient screening. However, a positive detection using a biosensor does not tell the physician where the diseased cells are located inside the body.

Biomarkers can also be specific biomolecules expressed on the surface of diseased cells, or contained within such cells. These can be targeted by contrast agents, administered into the bloodstream. Nanotechnology is an enabler for designing and manufacturing such contrast agents. By providing contrast agents with an appropriate physical label (a radioactive or magnetic atom, a fluorescent dye molecule or a nanoparticle), their prevalence in the body can be imaged using techniques such as positron emission tomography, magnetic resonance imaging, or optical imaging. Molecular imaging is an *in-vivo* technology that can be used to localize disease where it occurs inside the body. In the talk, I will present some existing and novel imaging modalities and their characteristics.

Finally, biomarkers can also be used to design targeted molecular drugs. Molecular imaging can be used to stage the disease progression, and to monitor the effectiveness of such therapies in individual patients. In addition, the imaging modalities can be used to trigger the controlled release of drugs from nanomolecular constructs, such as targeted microbubbles.

## Androids in our future: Toward networked, intelligent bioelectronics

Peter L. Gammel  
*AdvanceNanotech, Inc., U.S.A.*

Nanotechnology research has made great strides in biological sensing and therapeutics through controlled or targeted drug release or electrical stimulation. Today, however, the loop closure is reminiscent of needing to call a plumber if the thermometer in your house indicates the temperature is uncomfortable. Having humans in the feedback loop is a waste of time and money, and degrades the efficacy of treatment. Up to 30% of U.S. healthcare costs are attributable to long term patient monitoring, an ideal insertion point for networked, intelligent biosensors. Diabetics require tight control of blood glucose levels, which has been demonstrated to strongly correlate with health benefits.

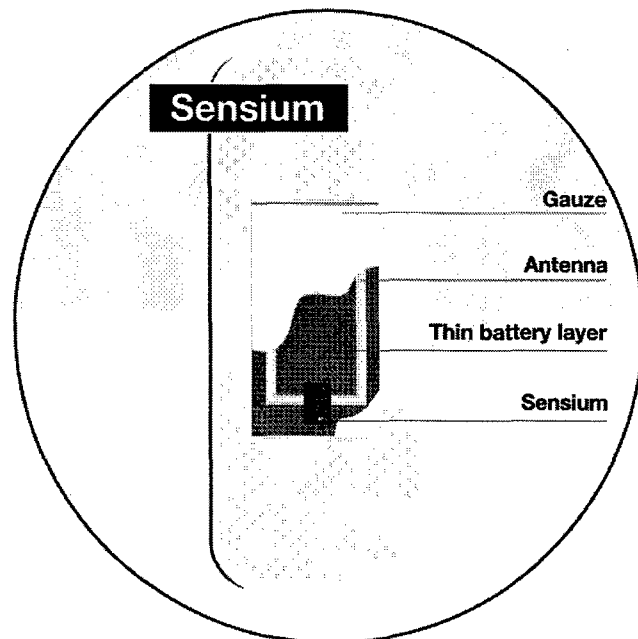
Closed loop bioelectronics for

- diabetes - blood glucose monitoring and insulin delivery;
- epilepsy – integrated ekg monitoring and Vagus nerve stimulation; and
- macular degeneration – sensitization and stimulation of the retina

are the examples in this presentation used to illustrate the opportunities for intelligent, networked bioelectronics. Closed loop control of biological function, however, entails significant technical and social challenges.

Resolving the technical hurdles will involve skills outside of the microelectronics industry. For example, surface- and bio-chemistry are required for interface to and packaging within biological systems. Many biosensors and drug delivery circuits rely on gold metallization and MEMS processing for microfluidics, both of which are currently niche technologies. Trends in ultra low power, such as deep subthreshold signal processing and communications will need to be married with autonomous networking and energy scavenging.

Social issues involve issues of both regulation and indemnification, both of which are poised to significantly slow the acceptance of intelligent bioelectronics.



**Reading/writing your brain: Not just another  
micro/optoelectronic interconnect challenge**

Arto V. Nurmikko  
*Brown University, U.S.A.*

Neuroscience has made remarkable progress in understanding the machinery of the human (mammalian) brain, both at the cellular (individual neuron) and "systems" level (brain as a neural network computer). From this has emerged a fascinating contemporary technical (and ethical) opportunity and challenge for engineers/physicists: how to implement a direct and functional interconnect between the biological neural circuitry and micro/optoelectronic circuits, for creating a "brain-machine" interface for medical and other applications, including the rapidly growing field of neural prosthetics. Extrapolating to the extreme, or perhaps the absurd: can we envision connecting the brain directly e.g. to the Internet, and if so, how would we want to embark on such a journey, literally at the interface of life and physical sciences?

This presentation will selectively highlight current research which points to the prospect of an electronic/photonic communication link via chip-scale, implantable recording and stimulating micro/nanodevices to the brain. At the cellular level, for example, a single neuron acting as a nonlinear biological oscillator and an interconnected matched nonlinear microelectronic oscillator can reach a strong coupling regime which results in phenomena such as spontaneous "sleep", i.e. quenching the coupled oscillations.<sup>1</sup> At the neural "systems" level, advances of recording of electrical impulses from regional neuronal assemblies by microelectrode arrays implanted to the motor cortex, with signal decoding, have led to a recent demonstration of "thought-to-action" control by a paralyzed human patient of a device such as a computer cursor (mouse).<sup>2</sup> While the system electronics in this breakthrough are presently bulky and tether the human subject to complex lab instrumentation, work is underway to compact the electronics on a chip which directly integrates to the micro/nanoscale neural probes.<sup>3</sup> The ultralow power requirements associated with implanting of such chips within the brain, and telemetry of signals to the exterior of the body draw on innovations both in micro/nano electronics and photonics. Finally, as a means to input cues to the brain from external sources, application of spatio-temporally patterned stimulation directly to the cortex is being pursued by both electrical and optical means. In one recent example, genetic engineering techniques have created photoresponsive neurons in mouse brains, which can be directly triggered by (blue) light impinging on the cortex.<sup>4</sup> This suggests the implant of ultracompact semiconductor light emitter arrays for projecting specific excitation patterns for neural activation by predetermined encoding approaches. Brainpods, anyone?

1. I. Ozden *et al.*, *Phys. Rev. Lett.* **93**, 158102 (2004).
2. L. R. Hochberg *et al.*, "Nature and use of neural control signals", Society for Neuroscience Annual Meeting (2005).
3. Y.-K. Song *et al.*, *IEEE Trans. Neural Rehab. Engineering* **13**, 220 (2005).
4. E. Boyden *et al.*, *Nature Neuroscience* **8**, 1263 (2005).



## Nanoscience from carbon nanotubes to single-molecule biophysics

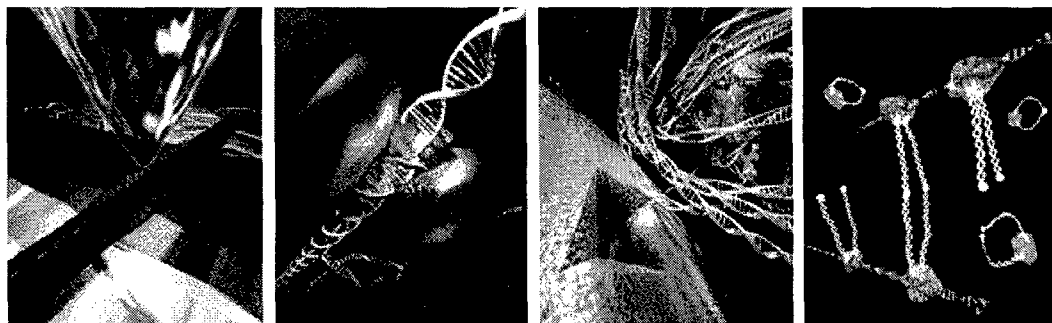
Cees Dekker

*Delft University of Technology, The Netherlands*

I will attempt to illustrate recent scientific results and potential of carbon nanotubes for nanoelectronics and single-molecule techniques for biophysics of DNA-enzyme interactions.

I will start by reviewing some of the work on electrical transport through single carbon nanotubes, cylindrical all-carbon molecules with unprecedented electrical and mechanical properties. The atomic structure and molecular orbitals can be studied by STM spectroscopy in nanotubes of finite length. Electrical transport has been studied through individual nanotube molecules between nanofabricated metal contacts, demonstrating that nanotubes are excellent coherent conductors. A wealth of single-molecule devices at room temperature has been established. The main challenges are in assembly and architecture.

In the second part of my talk, I will discuss the application of nanotechnology techniques to biology. Single-molecule techniques, such as scanning probes and tweezers, provide powerful new entries to study the structure, dynamics and function of biomolecules, molecular motors, DNA-enzyme interactions, and the like. I will discuss a number of examples such as DNA-processing enzymes, motion on kinesin motor proteins in fabricated nanostructures, and in particular the use of solid-state nanopores for DNA translocation, which is relevant for DNA sizing and potentially DNA sequencing.

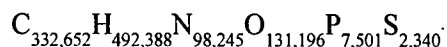


### Synthetic biology: Synthesis and modification of a chemical called poliovirus

Steffen Mueller, Dimitris Papamichail, John Robert Coleman, Jeronimo Cello, Aniko Paul, Steven Skiena, and Eckard Wimmer  
*SUNY–Stony Brook, U.S.A.*

Synthetic biology is a newly emerging scientific field, encompassing knowledge of different disciplines, such as engineering, physics, chemistry, computer sciences, mathematics, and biology. Synthetic biology aims to create novel biological systems with functions that do not exist in nature. There seem infinite possibilities of constructing unique derivatives of existing organisms (bacteria, yeast, viruses). Apart from designing novel building elements for engineering biological systems, a fundamental requirement in synthetic biology is the ability of large-scale DNA synthesis and DNA sequencing.

Viruses can be described in chemical terms; the empirical formula of the organic matter of poliovirus being:<sup>1</sup>



Placing these atoms into order, a particle of high symmetry emerges<sup>2</sup> with all the properties required for its proliferation and "survival" in nature. These properties are encoded in the viral genome, which is a single stranded nucleic acid (RNA) of about 7,500 nucleotides. Guided by the published nucleotide sequence,<sup>3</sup> we have recently synthesized the DNA equivalent of the polio RNA genome and converted it by simple biochemical manipulations in a cell-free environment (outside living cells) into authentic poliovirus particles.<sup>4</sup> The synthesis of a replicating "organism" in the absence of a natural template was without precedence at the time of publication<sup>4</sup> and it provoked widespread responses – good and bad.

Poliovirus is a human virus that replicates after ingestion in the gastrointestinal tract. Infrequently, the virus invades the central nervous system (CNS) where it targets those cells (motor neurons) for destruction that control muscle movement.<sup>5</sup> This results in irreversible paralysis, and sometimes death, a disease called poliomyelitis. The virus has caused horrific epidemics in the first part of last century until two vaccines were developed controlling effectively the disease. We are studying the possibility to generate by chemical synthesis novel polioviruses whose ability to proliferate in the CNS is debilitated whereas its efficiency to replicate in tissue culture cells remains largely unchanged. The basis of the engineering of these new viruses is altered codon usage. We will present our results and discuss the possibilities that the synthesis of novel viruses offers to combat human disease.

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**Directed evolution on a nanofabricated chip: Electronic hydrogen gas detection**

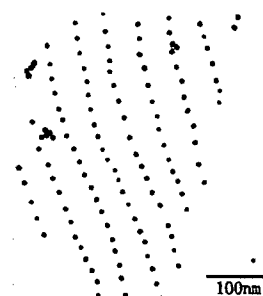
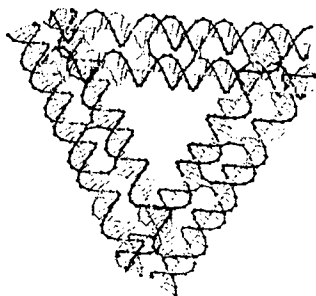
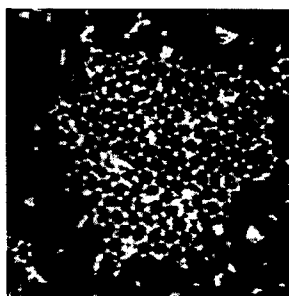
Robert H. Austin  
*Princeton University, U.S.A.*

Ordinarily evolution experiments are done in chemostats which maintain a constant inflow of nutrients and outflow of waste in a stirred vessel containing a colony of bacteria or similar microorganisms in solution. We wish to take the present chemostat design a dramatically big step further using our micro/nanofabrication technology to construct interacting arrays of chemostats, and then use our ability to sense the level of hydrogen gas production within each microchemostat to punish colonies that have low hydrogen gas production and reward colonies that have high hydrogen gas production. As part of this project to evolve efficient bioenergy production, we are fabricating electronic hydrogen gas sensors on our chips. I will give a progress report on how well this project is proceeding.

## Using structural DNA nanotechnology to organize matter

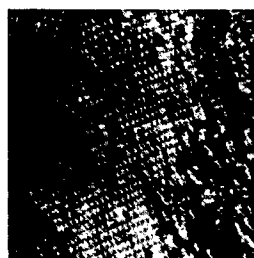
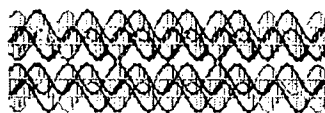
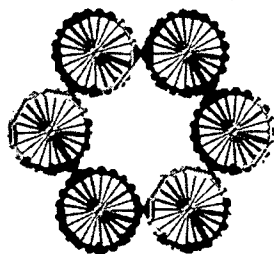
Nadrian C. Seeman  
*New York University, U.S.A.*

Structural DNA nanotechnology uses branching to produce unusual motifs that can be self-assembled into objects, lattices and devices. The self-assembly process is directed by programmable cohesive interactions between the ends of the helices, typically using single-stranded overhangs called 'sticky ends'. The strength of sticky-ended cohesion is that it produces predictable adhesion combined with known structure. Initial constructions included stick-polyhedra, knots and Borromean rings. These were followed by the self-assembly of two-dimensional arrays built from simple motifs, such as double (DX) and triple (TX) crossover motifs. Recent array components include planar and skewed triangular motifs whose edges are DX molecules. The former leads to honey comb-like arrangements, as shown on the left below. We combine DNA motifs to produce specific structures by using sticky-ended cohesion (below, left).



Three-space-spanning motifs can be developed readily. These are motifs that contain intramolecular vectors that can be used in sticky-ended self-assembly to fill space. Using only two of these directions leads to two-dimensional arrays that have a feature that can be used to organize nanoelectronic components, such as gold nanoparticles. The 3D-DX triangle (middle above) is such a motif. It has been used to produce the array of nanoparticles shown in the transmission electron micrograph at the right above. Note that the spacing in the vertical direction is roughly twice the spacing in the horizontal direction, because only one of the two triangles contains a nanoparticle.

Another 3-space-spanning motif with the potential to organize matter is the 6-helix bundle. This motif (shown in cross-section and laterally) also can be built into a 2D array. The images on the right are an AFM of an array and its autocorrelation function.



**Improvements in light emitters by controlling spontaneous emission:  
From LEDs to biochips**

Claude Weisbuch

*Ecole Polytechnique, Palaiseau, France and UC-Santa Barbara, U.S.A.*

The need to control electron and photon motions in solids, which would in particular enable better optoelectronic devices, has driven the field of light-matter interaction for the past thirty years.

For photons, some degree of control can be provided by *geometrical optics* concepts, which are currently being used in mass-produced LEDs. A more complete control relies on *wave optics* and optical mode quantization, which be achieved in a number of ways, through microcavities of varied photonic dimensionalities (which include photonic crystals), or simpler interference systems.

We will describe our recent results on photonic crystal LEDs. It will be shown that in order to obtain a significant improvement in extraction efficiency, the structures must be fully designed, to control both in-plane and vertical modes of spontaneous emission.

The concepts used for semiconductor devices can be fruitfully applied to biological systems. Like LEDs, fluorescent DNA or protein microarrays suffer from a poor luminescence efficiency. Fluorescent spots originating from the spatially selective attachment of fluorescent species on glass surfaces mostly emit into the substrate, and the remaining light is poorly collected for detection. We will describe amplifying substrates and integrated CCD/biochips which lead to greatly enhanced fluorescence collection, translating into economies of biological material, improved detection of genes with low expression, real-time measurements of hybridization, all achieved in high-functionality integrated systems.

## **Terahertz spectroscopy and imaging**

Edmund Linfield

*University of Leeds, United Kingdom*

Internationally, over the last three years, the field of terahertz spectroscopy and imaging has undergone extremely rapid growth, with major developments being seen in terahertz components, terahertz systems and potential application areas. To name just three:

- Terahertz quantum cascade lasers have been demonstrated to operate at frequencies below 2 THz, and at temperatures above 160 K. They are also being incorporated into terahertz imaging systems;
- Terahertz spectroscopy and imaging systems, based on ultrafast (femtosecond) lasers, are being marketed to pharmaceutical companies, and used for the analysis of pharmaceutical compounds (for example, polymorphic transformations, and drug distributions in tablets);
- Terahertz spectroscopy is being considered by security agencies, around the world, as a potential technique for identifying drugs-of-abuse and explosives.

What developments will we see in the next three years and beyond?

- How much further will it be possible to develop quantum cascade laser based systems, and how well will they compete long-term with the already established commercial pulsed (femtosecond) spectroscopy and imaging systems?
- Will we see terahertz systems being used for security applications at airports, and will we see stand-off detection being implemented in real-life situations?
- Will we find on-chip terahertz systems being used commercially as biological sensors?
- What are the prospects now for using terahertz radiation for medical and dental imaging?
- What new applications may emerge, which hitherto have not been considered?

In this context, I will discuss our latest research in the field and survey what the international community has achieved.

The development of terahertz technologies is currently in an extremely exciting phase and it is an excellent time to discuss what the future may hold.

**Nanophotonics: Searching for new phenomena and devices**

Federico Capasso  
*Harvard University, U.S.A.*

Scaling of nanophotonic components to their ultimate dimensions, new phenomena and device concepts for a potentially wide range of applications will be discussed. I will focus in particular on devices based on optical antennas, nanowires and coupled waveguides.

A new class of devices called *near-field laser antennae* consisting of metallic nanostructures defined on the facet of a semiconductor laser will be discussed. We have directly observed the highly localized enhancement of the laser intensity produced by surface plasmons in the nanometric gap of the antenna using apertureless NSOM. These active optical antennas have potentially wide ranging applications such as ultrahigh density optical recording, high-resolution spatially resolved imaging and spectroscopy, and laser assisted processing and repair of masks and circuits.

Imaging and spectroscopy of novel nanowire photonic crystal structures with engineered artificial defects demonstrate localized emission and light suppression in the region of the photonic crystal. One-dimensional photonic crystal cavities have been used to improve the reflectivity of the nanowire end facets and nanowire racetrack resonators have been implemented. Next I will discuss the fabrication and characterization of free standing gold nanowires. These nanowires are made by a novel fabrication technique that combines photolithography, thin-film metal deposition, and thin-film sectioning and produces nanowires with high aspect ratio cross-sections. This method allows one to reproducibly make high aspect ratio nanowires without requiring the use of e-beam lithography.

In the last part of the talk calculations of the forces arising from the overlap between the guided waves of parallel nanophotonic waveguides are presented. Both repulsive *and* attractive forces, determined by the choice of the relative input phase are found. Using realistic parameters for a silicon-on-insulator material system, we have estimated that the forces are large enough to cause observable displacements, making them suitable for a broad class of optically tunable microphotonic devices such as new optical routers.

This work is in collaboration with the groups of Ken Crozier, George Whitesides, Charlie Lieber (Harvard University) and John Joannopoulos (MIT).

**Does a theory of the laser linewidth exist?**

Boris Spivak and Serge Luryi  
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Contemporary theory of laser linewidth was pioneered by Schawlow and Townes. The theory is essentially based on the assumption that in the mean-field approximation, for the intensity of injection  $I$  larger than a critical injection level  $I_C$ , one has singular frequency generation.

The finite linewidth then results from the account of fluctuations associated with the random spontaneous emission processes. In the framework of this theory, one finds the laser linewidth to be inversely proportional to the injection intensity  $I$ .

We discuss both the experimental and the theoretical status of the basic assumption in the instance of semiconductor lasers.

It is unclear whether the available experimental data on semiconductor lasers really support the theory of Schawlow and Townes. On the other hand, the solution of the kinetic equations for the electron and photon energy distributions shows that even on the mean field level (before the fluctuations related to spontaneous photon emission are taken into account), the generation of light occurs in a finite interval of energies and, as a consequence, the linewidth increases with the injection intensity.

We will discuss the relevance of this picture to the experimental situation and the theoretical scenarios, which provide narrow laser line width in the framework of the mean field approximation.



## Silicon photonics – optics to the chip at last?

David A. B. Miller  
*Stanford University, U.S.A.*

Optics dominates long distance communications, but will it ever be useful on silicon chips or their successors? Early interest in optics for logic faded as integrated circuits advanced, but optics for communication and interconnect has become increasingly interesting. There, optics is competing against copper, not silicon. Basic issues of physics favor optics for communication anywhere a high density of information has to be communicated over any substantial distance.<sup>1,2</sup>

Despite physical advantages, and despite growing problems with interconnection at all levels, optics has never made any impact at the level of integrated circuits. Why? The physical arguments for using optics off chip are particularly strong, with possible substantial reductions in power and increases in communication density, but the cost targets are daunting for introducing a new technology such as optics. Prior technologies have never been integrated well with silicon. Silicon itself is a frustrating optoelectronic material, because of its indirect gap. III-V materials, which give good optoelectronic devices, are not easy to integrate with silicon processes.

The idea of on-chip optics on silicon is gaining momentum in research. Significant advances have been made in the past year or so in silicon optical systems (waveguides, couplers), and in active optoelectronic devices (modulators). Low-cost optical connections off of silicon are becoming more realistic. Serious attempts are being made at commercializing optoelectronic chips made entirely in a CMOS platform. A possible path for the introduction of optics to silicon is the progressive evolution of integrated optoelectronics on silicon for transceivers, leading to technology we may be able to use for other applications, such as possibly optical interconnects on chip.

At the same time, radical ideas are emerging from nanophotonics, in dielectrics, semiconductors, and now also nanometallics, all in principle compatible with CMOS. With such nanotechnologies, it is possible to make optical devices much more compact than before, and to contemplate completely new kinds of structures, such as miniaturized metallic optical antennas and 50 nm sized waveguides that could concentrate and guide light into high-speed, low-capacitance photodetectors the same size as current transistors. We can only speculate on what the impact of such ideas would have, but they all make optical interconnects even more interesting, and, who knows, maybe some of us will even start thinking about optical logic again?

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## Architecture in NanoSpace

Harold Kroto  
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As chemistry and physics at one borderline and chemistry and biology at the other begin to become indistinguishable, multidisciplinary research is leading to the fascinating "new" field of nanoscience and nanotechnology (N&N – not to be confused with M&M). Ingenious strategies for the creation of molecules with complex exactly-specified structures, as well as functions, are being developed – basically molecules that do things can now being made. In fact, N&N may be considered the frontier chemistry of the 21st century.

When the molecule  $C_{60}$ , Buckminsterfullerene, and its elongated cousins, carbon nanotubes (or "Buckytubes"), were discovered, it suddenly became clear that our previous understanding of the structural and dynamic factors governing carbon chemistry at nanometer scale was wrong. New experimental vapor and condensed phase approaches, often involving metal cluster catalysis, have led to the production of novel refractory nanostructures. Studies of composites involving these new materials are beginning to exhibit interesting advanced materials behavior. Fascinating fundamental insights into their formation mechanisms have also been revealed and the creation of nanoscale devices, which parallel devices used in standard engineering, are now being made.

On the horizon are numerous exciting possible applications in diverse areas, ranging from civil engineering to advanced molecular electronics, that promise to transform our lives and global economics. We now know we should one day be able to build buildings so strong that they will survive earthquakes and aeroplanes so light that they will be able to glide to safety if the engines fail. We should be able to construct supercomputers that will fit in a wristwatch and surgical techniques which will enable us to carry out medical operations almost non-invasively. If these prospects are to be realized, however, a paradigm shift in synthetic control strategies will be necessary to create really large molecules with accurately defined structures at the atomic level. This presents one of the greatest technical challenges for 21st century chemists. From a fundamental research strategy viewpoint it is worth noting the fact that the original  $C_{60}$  discovery experiments were carried out as a consequence of earlier molecular spectroscopy/radioastronomy discoveries relating to material in interstellar space and red giant carbon stars, together with the development major advances in our techniques for studying small refractory clusters.

## **Semiconductor spintronics: Progress and challenges**

Emmanuel I. Rashba  
*Harvard University, U.S.A.*

Spin is the only internal degree of freedom of an electron. Employing it for creating new electrical, optical, and optoelectronic solid-state devices, including spin qubits for quantum computing, is the ambitious goal of semiconductor spintronics. Initial concepts included:

- injection of nonequilibrium spin populations from ferromagnetic sources;
- using spin-orbit coupling for achieving spin precession;
- employing static and resonant electric and magnetic fields for manipulating spin precession; and
- employing interference phenomena and quantum phases for modulating electric currents and producing pure spin currents.

Eliminating magnetic elements and time-dependent magnetic fields and using spin-orbit coupling for producing and manipulating spin populations by means of static and resonant electric fields only, is in the focus of the more recent work. Therefore, spin-orbit coupling becomes the central paradigm of semiconductor spintronics.

I will review current status of the theoretical work on spin dynamics and spin transport in media with spin orbit interaction, and also the related experimental work. The main difference between the charge and spin transport stems from the fundamental fact of charge conservation and spin non-conservation. As a result, the very terms in which these theories are formulated are different. For example, while the elements with spin-orbit coupling are considered as sources of spin currents injected into non-spin-orbit elements, inside the former elements spin currents cannot be properly defined. A consistent theory is formulated in terms of "observables", the components of the spin polarization and the electron concentration. Recent years witnessed fast progress in the development of the theory. However, it depends critically on the specific spin-orbit coupling mechanisms and geometric scales involved, and still remains highly challenging. In this context, concepts of a number of spintronic devices and model experiments demonstrating the basic principles at work will be presented.

**Semiconductor spintronics: From spin injection to spin-controlled logic**

I. Zutic  
*SUNY-Buffalo, U.S.A.*

Conventional spintronic devices are based on metallic magnetic multilayers which utilize the magnetic moment associated with the spin to read magnetically stored information, leading to a nonvolatility and an impressive improvement in the performance of computer hard drives and magnetic random access memories. However, these applications employ two-terminal spin valves which are of limited use for advanced functionalities appropriate for signal processing and digital logic. While semiconductor-based three-terminal devices are natural candidates for spin logic, they remain inadequately investigated and even a simple understanding of their integration with CMOS is still missing.<sup>1</sup>

In this talk we address several basic elements and current challenges relevant for schemes in semiconductor spintronics. We focus on the process of spin injection and contrast conventional methods for optical detection of spin in semiconductors with those which could also be applied to indirect band-gap semiconductors such as silicon. In particular, we consider an interplay of nonequilibrium spin and equilibrium magnetization leading to the spin-voltaic effect, a spin-analog of the photo-voltaic effect. The direction of the charge current, which can even flow at no applied bias, can be switched by reversal of the equilibrium magnetization or by reversal of the polarization of the injected spin. We discuss some implications of the spin-voltaic effect in magnetic bipolar transistors, active spintronic devices, which could provide spin-switching and spin-controlled gain.

Supported by the U.S. ONR, NSF CAREER, DARPA, and the National Research Council.

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## Spintronic devices for nonvolatile memory and logic

Stuart Parkin

*IBM Almaden Research Center, USA*

Spintronic materials and devices take advantage of the electron's spin to create novel nano-devices. Examples include magnetoresistive sensors, in particular, the giant magnetoresistive spin-valve, based on spin-dependent scattering in magnetic metallic multilayers, and the magnetic tunneling junction (MTJ), based on spin-dependent tunneling across ultra thin dielectric layers. These spintronic devices facilitated a thousand-fold increase in the storage capacity of magnetic hard disk drives since their first use in commercial products in late 1997. A magnetic random access memory (MRAM) using MTJ storage elements, developed over the past decade, promises a solid state memory with an unrivaled combination of non-volatility, performance and cost, which is likely to enter the marketplace later this year.

In this talk, future directions for spintronic technologies are discussed. In particular, a proposal for a novel storage-class memory is described in which magnetic domains are used to store information in a "magnetic race-track".<sup>1</sup> The magnetic race-track shift register storage memory promises a solid state memory with storage capacities and cost rivaling that of magnetic disk drives but with much improved performance and reliability.

The magnetic race track is comprised of tall columns of magnetic material arranged perpendicularly to the surface of a silicon wafer. The domains are moved up and down the race-track by nanosecond long current pulses using the phenomenon of spin momentum transfer: experiments exploring the current induced motion and depinning of domain walls in magnetic nanowires with artificial pinning sites will be discussed. The domain wall structure, whether vortex or transverse, and the magnitude of the pinning potential are shown to have surprisingly little effect on the current driven dynamics of the domain wall motion. By contrast, the domain wall motion varies in an oscillatory fashion with the current pulse amplitude and length (with a characteristic frequency of a few hundred MHz). The domain walls in the magnetic race-track are read using magnetic tunnel junction magnetoresistive sensing devices arranged in the silicon substrate.

Recent progress in developing magnetic tunnel junction devices with giant tunneling magnetoresistance exceeding 350% at room temperature will also be discussed.<sup>2</sup> These devices involve sandwiches of thin ferromagnetic layers separated by ultrathin insulating layers through which spin polarized electrons tunnel. By electron wavefunction engineering and via control of the chemical bonding at the interfaces between the ferromagnetic and insulating layers<sup>2,3</sup> dramatic increases in the degree of spin polarization of the tunneling current is possible even for conventional transition metal ferromagnets. Engineering thin film heterostructures at the atomic level promises novel spintronic materials with unforeseen properties.

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**Optical properties of materials with negative refraction: Perfect lenses and cloaking**

A. L. Efros  
*University of Utah, U.S.A.*

It has been shown recently that some photonic crystals might be the left-handed materials with both negative  $\Sigma$  and  $\Gamma$  for propagating modes.<sup>1</sup> They provide negative refraction at the interface with a regular material and they may be used for creation of the Veselago lens. These negative  $\Sigma$  and  $\Gamma$ , however, are properties of the separate modes rather than properties of the whole crystal. For example, the amplification of the evanescent waves in photonic crystal does not follow from the fact that propagating modes with the same frequency in this crystal have negative  $\Sigma$  and  $\Gamma$ . The reason is that the spatial dispersion makes  $\Sigma$  and  $\Gamma$  for propagating modes completely different from those for the evanescent modes. This is important because, following Pendry,<sup>2</sup> the amplification of evanescent waves provides a possibility of creating a lens with an image much sharper than the wavelength (the so-called "superlens").

We consider the case when evanescent waves do not play any role in creation of the image of the Veselago lens and find some unusual features of this image, including perfect imaging in the lateral direction of the phase-shifted part of the point source. This happens because this part *does not* contain evanescent waves. Simple analytical calculations of the field near focus are in a perfect agreement with the results of computer simulation. On the other hand, in some cases there are surface waves that have nothing in common with the bulk properties of material. Those waves may improve the sharpness of the focus beyond the diffraction limit in the near-field regime.

The construction of the multi-focal Veselago lens predicted earlier is proposed on the basis of a uniaxial photonic crystal consisting of cylindrical air holes in silicon that make a triangular lattice in a plane perpendicular to the axis of the crystal. The object and image are in air. The period of the crystal should be  $0.44 \mu\text{m}$  to work at the infrared wavelength  $1.5 \mu\text{m}$ . The lens does not provide superlensing but the half-width of the image is  $0.5 \lambda$ .

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## Designing nanoscale solid state systems for quantum information processing

P. Hawrylak

*Institute for Microstructural Sciences, NRC-Canada*

Quantum processing of information requires the development of quantum systems that are at the same time coherent and quantum in nature, and yet easily manipulated to process and extract classical information. To meet this challenge we have embarked on the development of technologies which would allow us to design and build nano-scale scalable and coherent solid state systems<sup>1</sup> using elementary building blocks such as single electron spins, single excitons, and single photons using semiconductor quantum dots. We show how gated quantum dots allow to localize individual electrons, control their spin properties by their number, form of confinement, and the magnetic field, enabling nano-spintronics.<sup>2</sup> The spin can be probed and exploited by connecting quantum dots to spin polarized reservoirs. The resulting spectroscopic tool, the spin blockade spectroscopy, will be described as well as a prototype nano-spintronic device, the "single spin transistor".<sup>2</sup> By combining the single spin transistors into coherently coupled devices we are attempting to build an electron spin-based quantum computer.

I will describe double and triple quantum dots and extrapolate to the exciting physics such new capabilities enable. In order to combine the control over spin with the control over photons we need to confine both electrons and valence holes. This is done by transferring the gated technology to self-assembled quantum dots. I will review progress in our understanding of the electronic and optical properties of InAs-based self-assembled quantum dots<sup>3</sup> emitting at 1.5  $\mu\text{m}$ . By combining lithography with self-assembly, single InAs dots can be positioned on InP nanotemplates. This control allows integration of quantum dots with photonic cavities and opens up possibility of "manufacturing" a single photon gun for quantum cryptography and communication. Finally, building on the newly acquired capabilities with quantum dots, we will venture into combining information processing and storage using quantum dots containing both electrons and magnetic ions, a step toward control of magnetism on nanoscale.<sup>4</sup>

This work was done in collaboration with A. Sachrajda, M. Korkusinski, W. Sheng, R. Abolfath, F. Qu, and R. Williams.

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## Is fault-tolerant quantum computation really possible?

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*Université Montpellier II, France*

The answer that the quantum computing community currently gives to this question is a definitive "yes". The so-called "threshold" theorem says that, once the error rate per qubit per gate is below a certain value, estimated as  $10^{-4}$ – $10^{-6}$ , indefinitely long quantum computations are feasible, even if all of the  $10^3$ – $10^6$  qubits involved are subject to relaxation processes, and all the manipulations with qubits are not exact. By active intervention, errors caused by decoherence can be detected and corrected during the computation. Though today we may be several orders of magnitude below the required threshold, quantum engineers may achieve it tomorrow (or in a thousand years), making large-scale quantum computation possible *in principle*.

The purpose of this talk is to explain these ideas and to examine in some detail the technical prescription for fault-tolerant quantum computing, first put forward by Shor and elaborated by other mathematicians. Special care will be taken to reveal the hidden assumptions on which it is based. It seems that the mathematics behind the threshold theorem is somewhat detached from the physical reality. This raises serious doubts on the possibility (even as a matter of principle) of quantum computing on times exceeding the typical relaxation time.



## The future of single- to multi-band detector technologies

Upendra N. Singh

*NASA Langley Research Center, U.S.A.*

Using classical optical components such as filters, prisms and gratings, to separate the desired wavelengths before they reach the detectors, results in complex optical systems composed of heavy components. A simpler system will result by utilizing a single optical system and a detector that responds separately and individually to each wavelength band. Therefore, continuous endeavors to develop the capability to reliably fabricate detector arrays that respond to multiple wavelength regions are needed.

This presentation will review the state-of-the-art single and multicolor detector technologies over a wide spectral-range, for use in space-based and airborne remote sensing applications. Discussions will be focused on current<sup>1,2</sup> and the most recently developed focal plane arrays (FPA)<sup>3,4</sup> in addition to emphasizing future development in UV-to-far infrared multicolor FPA detectors<sup>5,6</sup> for next generation space-based instruments to measure water vapor and greenhouse gases. This novel detector component will make instruments designed for these critical measurements more efficient while reducing complexity and associated electronics and weight.

This presentation will focus on the on-going multicolor detector technology efforts at NASA Langley Research Center, NASA Jet Propulsion Laboratory, Rensselaer Polytechnic Institute, and others.

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**Will the insulated gate transistor concept survive next decade?**

Olof Engström

*Chalmers University of Technology, Sweden*

One of the most challenging problems in the present development of electronics is to find an alternative to silicon dioxide as a gate insulator for MOSFETs. As no obvious solution exists today, it may be relevant to estimate the risk that CMOS technology development is thwarted.

The need for increasing capacitive coupling between gate and channel region has brought the thickness of the presently used silicon dioxide down to a limit, where current leakage is too high to be accepted. The solution is to be found among materials with higher dielectric constant.

For the 45 nm CMOS-node, currently moving from the research to the development phase to be in production in 2010, nitrided silicon dioxide may still be a solution. On the other hand, for the coming 32 and 22 nm generations a new material is a necessity. A wide research activity in the past 10–15 years has focused an interest on  $\text{HfO}_2$  as the next gate insulator material. However, it is questionable whether the properties of this material will fulfill the demands beyond, or even at, the 45 nm node. Beside rigorous production requirements concerning, for instance, thermal stability,  $\text{HfO}_2$  or other high- $\kappa$  materials need to fulfill other fundamental requirements. In particular, in order to limit current leakage at a high enough channel coupling, not only a high dielectric constant, but also high electron and hole barriers between the energy bands of the silicon and the insulator are necessary.

The paper presents guidelines for finding an appropriate material, points out the very limited number of possible candidates for the 22 nm low-power applications, and discusses the probability for the "CMOS-show" to stop.

**Alternatives to silicon: Will our best be anywhere good enough in time?**

M. J. Kelly  
*University of Cambridge, U.K.*

With reference to several projects, I will discuss the progress being made towards achieving manufacturable processes on the nanometer scale: in the case of III-V materials, these processes have to be foundry compatible.

- Tunnel device reproducibility is not yet good enough;
- Quantum dot volumes are not sufficiently under control;
- Implantation is not longer adequate to modify materials;
- Split gate devices are not reproducible;
- We are going to need  $10^{13}$  switches to extrapolate beyond CMOS.

The longer CMOS continues, the harder it is going to be to extrapolate.

**MRAM scaling-down challenges**

François Arnaud d'Avitaya, Viatcheslav Safarov, and Antoine Filipe  
*CRMCN-CNRS and Spintron, France*

In the last five years, there has been a buzz around magnetic random access memory (MRAM) as the future universal memory for computing and mobile applications. For example, in 2004, Infineon and IBM have presented at the VLSI conference the world's first 16 Mbit MRAM, the highest density reported to date. In 2005, Cypress sampled fully functional MRAM to several key OEM customers.

Nevertheless, despite over a decade of work by some of the world's most prominent semiconductor companies, the year 2005 has seen several major component manufacturers withdraw from the MRAM race.

Starting with the initial motivations for MRAM, ranging from speed, low power consumption and non-volatility, we will then present the several hurdles that appeared during the race, leading to the development of the 2nd generation of MRAM. We will conclude our talk by some options now evaluated by research labs which could lead to the development of the 3rd generation of MRAM.

## A new class of semiconductors using quantum confinement of silicon in a dielectric matrix

Martin A. Green

*University of New South Wales, Australia*

The use of silicon in photovoltaics is booming, with the *area* of silicon wafers used in this application now exceeding the use in integrated circuits. Silicon has a number of attractions for on-going use in photovoltaics, including abundance, stability and non-toxicity, but is constrained by less material design flexibility than available, for example, in the III-V material system.

In photovoltaics, bandgap control and strengthened absorption properties would be ideal in terms of reaching the ideal of low-cost, thin-film, high-performance, silicon-based photovoltaic devices. This would allow implementation of advanced designs such as those based on stacked or tandem cells of differing bandgap. An approach demonstrated by Zacharias and co-workers<sup>1</sup> and illustrated in Fig. 1 is being explored as a way of synthesizing silicon-based semiconductor material of controlled bandgap and improved optoelectronic properties.

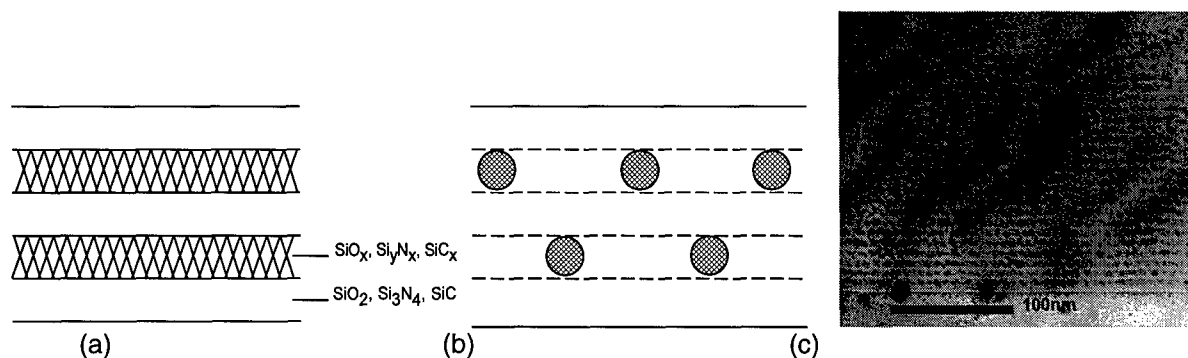


FIG. 1. (a) Precursor stoichiometric and non-stoichiometric, Si-rich layers for forming Si quantum dots; (b) precipitation of dots within the Si-rich layers; (c) TEM image (cross-sectional view) of Si quantum dot layers prepared in an oxide matrix.

The precursor material is formed by depositing alternating thin layers of stoichiometric followed by Si-rich silicon oxide, nitride or carbide. On heating, silicon in the Si-rich material precipitates out as quantum dots with diameter controlled by the initial layer thickness. Work to date has shown that the optical bandgap in such synthesized material using both oxide and nitride matrices can be controlled over the range required for tandem cells (1.7 eV) and that optical properties initially strengthen as dot size decreases. Present work is directed at characterizing transport in such layers, where mobilities of around  $1 \text{ cm}^2/\text{V}\cdot\text{s}$  are sought for the targeted application. Other issues such as doping and *pn* junction formation in such synthesized material is being explored both experimentally and theoretically, using tools such as *ab initio* atomic cluster simulations.

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**Ultimate VLSI clocking using passive serial distribution**

Mihai Banu and Vladimir Prodanov  
*MHI Consulting LLC, U.S.A.*

Despite the impressive transistor speeds of scaled VLSI technologies, clocking large chips such as microprocessors, FPGAs and ASICs at multi-GHz frequencies suffers from severe limitations. The main culprit is the well trusted but dated active tree clocking method, used in virtually all VLSI applications. Typically, a central PLL-synthesized clock signal is distributed to local areas through a very complex tree network including thousands of branches, amplifiers, buffers, phase adjustment circuits, *etc.* Maintaining low skew and low jitter with such "brute force" active clocking systems is extremely challenging and requires substantial power dissipation even at low GHz speeds. Noise leakage from adjacent digital blocks, power supply lines, *etc.* and absolute skew uniformity over all chip areas are particularly difficult to control. Clearly, there is an urgent need to develop a totally different and scalable solution to the VLSI clocking problem, a topic of worldwide research activities.

We introduce a new general principle for VLSI clocking using passive serial distribution. This approach is capable of very high operating speed, minimum jitter, and minimum power dissipation. We assume the availability of on-chip transmission lines. These can be either electrical lines built with standard CMOS metal levels or on-chip optical wave guides fabricated through additional processing steps. In the latter case, optical detectors are also necessary. The proposed architecture is a simple serial connection passing through all local clocking regions. For electrical lines with nonnegligible loss, a two-tier network would cover the largest chips in existence without excessive individual line lengths.

As the passive propagation of signals on transmission lines is insensitive to circuit noise, power supply voltage variations, *etc.*, the clock signals are distributed easily and accurately to any local area on the chip. However, for serial distribution very large skews accumulate quickly. The novelty of our approach consists of a simple signaling method allowing efficient and precise skew removal at any arbitrary clock drop-point along the transmission line. This open-loop synchronization technique is naturally insensitive to nonideal effects, such as ohmic losses, transmission line termination errors, and amplitude noise. We will discuss this signaling scheme and the supporting circuits, which are straightforward and easy to design. In addition, we will show simulation results using complex transmission line models and standard production CMOS transistor models.

In addition to frequency scalability and superior jitter/skew performance, our method promises a major simplification in the VLSI design methodology. While in the conventional case, the architecture, size, and physical position of the logic blocks are in close functional relationship with the clocking tree, this complicated interdependence is almost totally eliminated in our approach. The decoupling between the clocking system and its clocked "clients" brings a major simplification in the design methodology, transforming the clocking system design from a black art into a standard platform technology, a future CAD tool will implement automatically.

**Best poster**

Best poster author

*Affiliation as yet unknown*

As nominated by an authoritative best poster committee and voted by the participants of the Workshop during the Thursday evening panel, the author of the best poster will be invited to make an oral presentation in the final Friday time slot.





**FTM-2006 POSTER SESSION**

**Tuesday, June 24  
18:00–20:00**

**Chair: Yacov Shamash**

**Poster presenters:**

Gregory Belenky  
Dan Botez  
Sorin Cristoloveanu  
Michel Dyakonov  
Detlev Grützmacher  
Qing Hu  
Hiroshi Iwai  
Yong Jin  
Nikolai Ledentsov  
Vladimir Mitin  
Junichi Murota  
Yoshio Nishi  
Alik Palevski  
Enrico Sangiorgi  
Michael Shur  
Margarita Tsaousidou  
Alex Zaslavsky  
Nikolai Zhitenev  
Peter Zory

**Widely tunable type-II interband cascade laser**

S. Suchalkin, M. V. Kisin, S. Luryi, G. Belenky, J. Bruno, F. J. Towner, and R. Tober  
*SUNY–Stony Brook, Maxion Technologies Inc., and Army Research Lab–Adelphi, U.S.A.*

We discuss a novel ultra-wide, voltage tunable type-II mid-IR interband cascade laser. Its novel design has a charge accumulation layers outside of the optically active quantum wells that unclamps the electron-hole concentrations and facilitates above-threshold Stark shifts. Our results demonstrate laser tuning of 120 nm ( $120 \text{ cm}^{-1}$ ).

**Intersubband quantum-box lasers: An update**

D. Botez, D. Xu, M. D'Souza, G. Tsvid, J. C. Shin, A. Khandekar, T. Kuech,  
A. Lyakh and P. Zory  
*Univ. of Wisconsin-Madison and Univ. of Florida, U.S.A.*

Semiconductor lasers whose active region is composed of a 2D array of intersubband quantum boxes (IQBs) hold the promise<sup>1</sup> to be significantly more efficient and reliable than multi-stage intersubband lasers (i.e., quantum-cascade lasers). That is a direct consequence of the fact that the electron-relaxation times in deep, unipolar QBs are at least a factor of 20 times larger than in quantum wells, as experimentally confirmed by several groups.<sup>2</sup>

We have reported<sup>3</sup> on efficient 4.7  $\mu\text{m}$  emission from deep-well, GaAs-based single-stage devices. Electron-beam patterning and transfer to  $\text{SiO}_2$  has provided 33 nm-diameter disks on 80 nm centers, to be used as the mask for IQB fabrication via *in-situ* gas etching and regrowth in an MOCVD crystal-growth system.

Key issues related to the fabrication of IQBs have been addressed and resolved. We have achieved controlled *in-situ* etching and regrowth of high-crystalline-quality, high-resistivity GaAs in 40 nm-deep trenches. While intersubband-transition devices are by and large not affected by the presence of exposed surfaces, that is not the case at the nanoscale level, since Fermi-level pinning can lead to full depletion of the devices. Etch-and-regrowth experiments have been carried out on (110)-oriented GaAs substrates, which basically correspond to the IQB edges. Special treatment of dry-etched surfaces followed by *in-situ* gas etching and regrowth has led to the elimination of charge-trapping states at the interfaces, and thus to the elimination of Fermi-level pinning for the proposed IQB-device fabrication.

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## Concluding a noisy debate

S. Cristoloveanu, K. Akarvardar, and P. Gentil  
*IMEP-ENSERG, France*

The  $1/f$  noise in semiconductor components is well documented, enthusiastically explored, and definitely feared. There are two distinct camps in the  $1/f$  world. For McWhorter's partisans, there is no doubt that the noise originates from fluctuations in the carrier number. In MOS devices for example, carrier trapping is related to the presence of slow traps in the gate oxide. MOSFET results accumulated for years are rather convincing in this respect, except for Hooge and disciples. For them, there is even less doubt that the  $1/f$  noise in semiconductor devices proceeds from carrier mobility fluctuations. The universality of  $1/f$  noise is actually packed in an empirical model.

The aim of our paper is to show that the  $G^4$ -FET SOI transistor is a competent referee for this rivalry. The  $G^4$ -FET has four independent gates, offering tremendous versatility of operation. In depletion-all-around mode (Fig. 1, left), the channel is merely a wire composed of majority carriers. The key point is that the carriers flow in the volume, being safely separated from the Si/SiO<sub>2</sub> interface by depletion and inversion regions. There is no possible carrier trapping in the oxide, and indeed the  $1/f$  noise does feature the pattern predicted by Hooge. However, by changing the top gate bias, an accumulation channel can be formed at the front interface (Fig. 1, right). This triggers a sudden increase in noise. Even more spectacular is the chameleon-like metamorphosis of the noise, which now reflects the McWhorter model.

Besides this first fundamental demonstration of the noise transformation, we discuss potential applications for low-noise  $G^4$ -FET circuits. What about the conclusion of the noisy competition between the two camps? One set each.

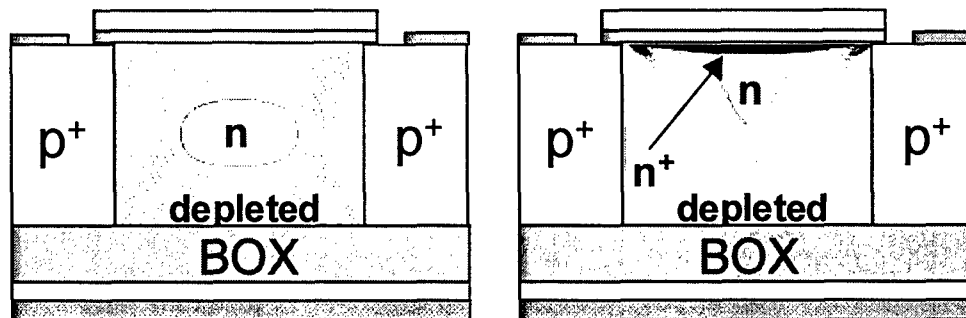


FIG. 1. Cross-section of the  $G^4$ -FET channel. The noise transforms from mobility fluctuations (Hooge) to number fluctuations (McWhorter) when the channel is moved from the volume towards the surface.

**Absolute negative resistance in ballistic field effect transistor**

Michel I. Dyakonov and Michael S. Shur

*Université Montpellier II, France and Rensselaer Polytechnic Institute, U.S.A.*

At small feature sizes (25 to 45 nm or so for silicon transistors), the electron transport becomes ballistic (collisionless) or quasi-ballistic and the average electric field in the channel reaches well into the MV/cm range even at reduced power supply voltages. The lateral control of the electron concentration in the channel under the conditions of the ballistic transport becomes very important even for the mainstream silicon technology.

In this paper, we analyze ballistic transport in a ballistic variable threshold field effect transistor<sup>1,2</sup> (which is a transistor in which the threshold voltage in the device channel varies as a function of distance). Using hydrodynamic equations, we show that a change in the threshold voltage along the channel leads to a jump in the channel potential, which is independent of the current direction and depends on the magnitude of the device current (being proportional to device current squared at relatively small channel currents). Thus, for one current direction, the current flows opposite to the voltage drop, i.e. the resistance becomes locally negative. This predicted voltage jump and the electron flow "choking" analyzed earlier<sup>3</sup> are similar to the pressure jump and fluid flow choking in a frictionless pipe with a variable cross section. These unusual features of a ballistic variable threshold FET could be used for novel circuit applications and for the measurements of the threshold voltage distribution in the device channel.

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## Silicon microdisk structures with rare-earth doped amorphous silicon

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The development of silicon-based active optical devices has been a target of constant interest in recent years due the possibility of integration with CMOS technology. Silicon doping with rare-earth elements is an alternative for efficient light emission in the C-band. Particularly, erbium doped hydrogenated amorphous silicon (a-Si:H<Er>) is of interest given the high  $\text{Er}^{3+}$  doping concentration that can be achieved and the efficient defect related Auger excitation process. Microdisks with whispering gallery modes offer a great advantage for stimulated emission generation in small volumes where long photon lifetime is achieved with simple processing steps. Also, the emission along the substrate plane is suitable for photonic integration. Moreover, with the use of non-cylindrically symmetric stadium structures, one may achieve higher directional and spectral control over the emission, thereby expanding the integration possibilities.

In this work we present our results on microdisks and stadium resonators based on a-Si:H<Er> and (a-SiO<sub>x</sub>:H<Er>) layers sandwiched in air and SiO<sub>2</sub>, obtained by wet oxidation of Si substrates. Rutherford backscattering spectroscopy (RBS) results show erbium concentrations of  $1.0 \times 10^{20}$  atoms/cm<sup>3</sup> that is responsible for large photoluminescence emission at 1540 nm, shown Fig. 1. Also, we will describe the photoluminescence dependence on annealing temperature and oxygen content. Finally, we will be presenting our preliminary results on resonant structures focused on directional and spectral properties of the emission.

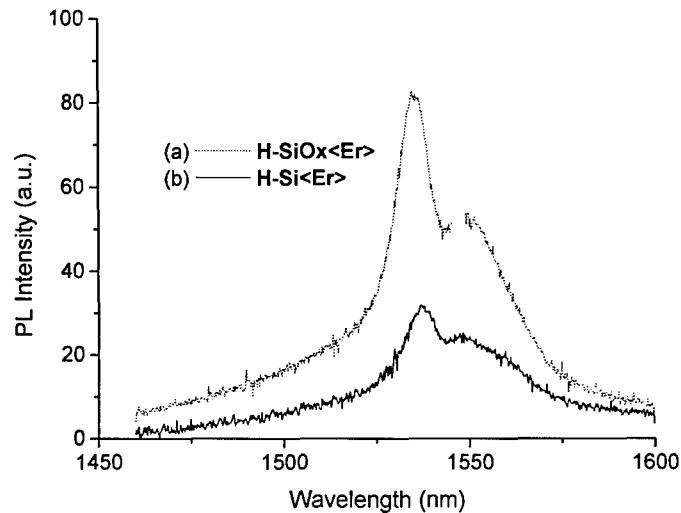


FIG. 1. PL emission from amorphous silicon co-deposited with erbium: (a) SiO<sub>2</sub> target; (b) Si target.

### Three-dimensional Ge quantum dot crystals prepared by templated self-organization

D. Grützmacher, C. Dais, P. Käser, E. Müller, H. Solak, Y. Ekinici, H. Sigg,  
J. Stangl, T. Lechner, and G. Bauer

*Paul Scherrer Institute, Switzerland and Johannes Kepler Universität Linz, Austria*

Quantum dots provide possible routes towards the realization of beyond-CMOS device processing,<sup>1</sup> as well as for driving CMOS technology to its limits.<sup>2</sup> The capability of addressing individual quantum dots might be crucial to open new paths for the fabrication of high speed Si compatible electronics. Self-assembled Ge dots, which nucleate randomly on the surface, have been studied intensively, but the addressing of individual dots will require the positioning of dots on predefined spots. To achieve lateral ordering, most approaches employed self-assembled deposition on substrates pre-patterned by either e-beam or optical lithography.<sup>3-8</sup> Here we present the lateral and 3D ordering of small Ge clusters on surfaces pre-patterned by x-ray interference lithography (XIL). The XIL approach provides precise control of the periodicity even for periods smaller than 50 nm<sup>9</sup> over areas as big as 2x2 mm with a single exposure. By choosing appropriate growth conditions, 2D dot arrays, quantum dot molecule arrays, as well as 3D quantum dot crystals have been realized.

The structural properties of the samples were subject to careful analysis using AFM, TEM and grazing incidence X-ray diffraction. We obtain a narrow size distribution of the dots, shown in Fig. 1. No degradation of the ordering was obtained by the stacking of the dots into ordered 3D dot crystals with up to 10 dot layers. Cross-sectional TEM reveals accurate stacking of the dots in vertical direction, whereas TEM using Z-contrast imaging suggests a high Ge fraction in the Ge dots.

The samples have been investigated by absorption spectroscopy and photoluminescence in the near to mid-IR spectral range at low temperatures. Narrow, phonon-resolved photoluminescence was observed from ordered Ge islands in 3D dot crystals. These first experiments of the optical properties are promising for future analysis to study effects of correlated Ge quantum dots in 3D quantum dot crystals.

This work was supported by the Swiss National Foundation and the European Community.

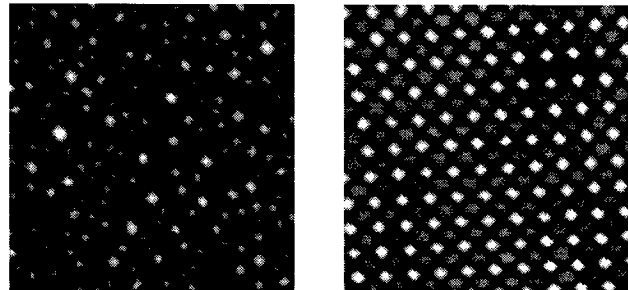


FIG. 1: AFM images of a 1x1  $\mu\text{m}$  area showing Ge dots (light colour) on (a) bare Si and on (b) Si pre-patterned by x-ray interference lithography.

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**Terahertz quantum cascade lasers and real-time T-rays imaging**

Qing Hu

*Massachusetts Institute of Technology, U.S.A.*

The terahertz frequency range (1-10 THz) has long remained undeveloped, mainly due to the lack of compact, coherent radiation sources. Semiconductor electronic devices (such as transistors) are limited by the transient time and  $RC$  roll-off to below 1 THz. Conventional semiconductor photonic devices (such as bipolar laser diodes) are limited to above 10 THz even using small-gap lead-salt materials. Transitions between subbands in semiconductor quantum wells were suggested as a method to generate long wavelength radiation at customizable frequencies. However, because of difficulties in achieving population inversion between narrowly separated subbands and mode confinement at long wavelengths, lasers based on intersubband transitions were developed only recently at THz frequencies. The THz quantum-cascade lasers (QCL) hold great promise to bridge the so-called "THz gap" between conventional electronic and photonic devices.

Based on two novel features, namely resonant-phonon-assisted depopulation<sup>1</sup> and metal-metal waveguides for mode confinement,<sup>2</sup> we have developed many THz QCLs with record performance. They include by not limited to: a maximum pulsed operating temperature of 164 K and a maximum cw operating temperature of 117 K,<sup>3</sup> the longest wavelength ( $\sim 160$   $\mu\text{m}$ , 1.9 THz) QCL to date without the assistance of magnetic fields,<sup>4</sup> and  $\sim 250$  mW power level.<sup>5</sup> Using a high-power THz QCL and a  $240 \times 320$  focal-plane array camera, we are now able to perform real-time THz imaging at video rate, that is, taking movies in "T-rays".<sup>6</sup> These rapid developments indicate great potentials for THz QCLs in various applications. We will present more detailed results and our perspective at the workshop.

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## **Future of nano CMOS and its manufacturing**

Hiroshi Iwai  
*Tokyo Institute of Technology, Japan*

Recently, CMOS downsizing has been accelerated very aggressively both in production and at the research level, and even transistor operation of a 5 nm gate length CMOS was reported in a conference. However, many serious problems are expected for implementing small-geometry MOSFETs into large scale integrated circuits even for 45 nm technology node, and it is questionable whether we can successfully introduce sub-10 nm CMOS LSIs into market for many reasons, ranging from insufficient current drive to huge manufacturing costs. In this presentation, technology and manufacturing issues for future CMOS scaling towards its limits are described. In order to solve the problems, the introduction of quite new technologies, such as new materials, processes, and structures are inevitable. Some of those efforts made in my laboratory are presented. They are high- $\kappa$  dielectrics for gate insulators and plasma doping for ultra-shallow source and drain junctions. Furthermore, solutions and problems of the manufacturing cost increases will be discussed. Finally, the outlook for the post-scaling era will be predicted.

**One-dimensional quantum ballistic field effect transistor**

Y. Jin, E. Grémion, A. Cavanna, B. Etienne, U. Gennser, and C. Ulysse  
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During the last two decades, the size of a typical field effect transistor (FET) in a microcomputer chip has been continuously reduced to the current value of just a few hundred nanometers. Its operation however remains essentially classical, i.e. in the diffusive regime.

An FET operating in the ballistic regime has been investigated by physicists and electrical engineers alike for several decades. A ballistic FET – a perfect FET – has no defects, kinks or obstacles other than a connection at each end to allow current flow through an external circuit. In the ballistic FET, significant performance improvement is expected as a consequence of the ballistic transport, and in addition the heating induced by collisions can be greatly reduced. The power dissipation or overheating caused by FETs is recognized as a major obstacle for further increase of integrated circuit (IC) densities. Therefore, the ballistic FET is set to be a new building block of ICs in the next decade or so.

Progress in nano-fabrication and optimization of a very high mobility two-dimensional electron gas (2DEG) in AlGaAs/GaAs heterostructure by molecular beam epitaxy (MBE) have allowed many laboratories to make various field effect ballistic devices. New quantum transport properties of electrons in the linear regime have been extensively investigated and demonstrated. However, turning this kind of device to a functional transistor has not yet been made possible, the key issue being the achievement of voltage gain (higher than unity). It is well known that in a classical (diffusive) FET, voltage gain is in general reached when the device operates in the non-linear or saturation regime. In the same way, voltage gain for a ballistic FET can be expected when a ballistic non-linear regime is attained.

In this work, a one-dimensional ballistic transistor has been fabricated and characterized at liquid helium temperature. The device is based on a one-dimensional channel of width a few tens of nanometers obtained by a quantum point contact (QPC) or split gate configuration on a high mobility 2DEG. High transconductances owing to one-dimensional subbands can be obtained under low drain bias and current in the quantum ballistic regime. On the other hand, the drain current-voltage characteristics as a function of the drain bias at different gate bias show that the non-linearity (leading to a low output conductance) takes place when there is a difference in the number of occupied one-dimensional subbands by the source reservoir and by the drain reservoir. We obtain a voltage gain of 2 with a drain bias of 8 mV and a power consumption of only 1.2 nW. To our knowledge, this is the first demonstration of a voltage gain in the quantum ballistic regime, and hence a 1D quantum ballistic FET.

**THz and far-IR sensors: Looking for optimal nanodesign**

A. Sergeev and V. Mitin  
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The steady and impressive progress in the nanotechnology of superconducting and semiconducting structures leads to new intriguing possibilities for sensors of electromagnetic radiation. A wide range of novel properties, unattainable in microstructures, may be realized through manipulations at nanoscale level.

The sensitivity and energy resolution of a quantum detector is limited by the fluctuations of the number of quasiparticles (electronic excitations) in the sensor. The detector performance can be improved by decreasing its volume (i.e. quasiparticle number, heat capacity and etc.). Potentially, nanosensors might have the sensitivity several orders of magnitude higher than that of state-of-the-art microdetectors. However, simple shrinking of the sensor dimensions to the nano-scale will not do the job. Energy exchange between electrons in nanoscale structures and the environment turns out to be excessively fast for most of applications. Another substantial problem is related to inefficient electromagnetic coupling to nanostructures comprised small number of electrons.

Taking in mind the above challenges and new technological opportunities, we consider novel approaches to practical realization of controllable electron kinetics in nanostructures. We review recent experiments in this field and discuss new ideas in design of ultimate detectors, photon counters and calorimeters based on superconducting and semiconducting nanostructures. Novel nanosensors are expected to deliver the unique performance: the noise equivalent power of the order  $10^{-20}$  W/ $\sqrt{\text{Hz}}$  and the energy resolution of  $10^{-21}$ - $10^{-23}$  J. These sensors are of great interest for single-molecule spectroscopy, submillimeter astronomy, and nanoscale thermophysics and chemistry.

**Atomically controlled processing for future Si-based devices**

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Atomically controlled processing has become indispensable for the fabrication of Si-based ultrasmall devices and Si-based heterodevices, because high performance Si-based devices require atomic-order abrupt heterointerfaces and doping profiles. Our concept of atomically controlled processing is based on atomic-order surface reaction control. The final goal is the generalization of the atomic-order surface reaction processes and the creation of new properties in Si-based ultimate small structures which will lead to nanometer scale Si devices as well as Si-based quantum devices.

Self-limiting formation of 1-3 atomic layers of group IV or related atoms in the thermal adsorption and reaction of hydride gases on Si(100) and Ge(100) have been generalized based on the Langmuir-type model. By the epitaxial growth of Si and SiGe over the material already-formed on (100) surfaces, atomic layer doping of a half atomic layer of N and P and a single atomic layer of B have been achieved. Atomic layer doping results indicate that new group IV semiconductor of very high carrier concentration and higher mobility is prepared compared with doping under equilibrium conditions. The atomically controlled processing for the base doping of SiGe:C HBTs has been demonstrated. These results propose that atomic layer-by-layer epitaxy of group IV materials as well as atomic layer doping are possible with well-controlled initiation of the reaction governed by Langmuir-type self-limited kinetics in many cases, and open the way to atomically controlled CVD technology for ultra-large-scale integrations.

Plasma assisted processing is one of the candidate techniques for very-low-temperature growth of heterostructures with an abrupt heterointerface. By the electron-cyclotron resonance Ar plasma enhanced chemical vapor deposition, Si and Ge epitaxial growth on Si(100) were achieved without substrate heating using SiH<sub>4</sub> and GeH<sub>4</sub>, respectively. In the nitrogen plasma irradiation of Si(100), we find that the nitridation of the deeper Si atoms below the surface is enhanced with increasing ion energy as well as the Si surface temperature. Silicon epitaxial growth on atomic-order nitrided Si(100) was also achieved without substrate heating, and it is confirmed that N atoms of about 0.8 atomic layer are confined within about 3nm-thick region under the present accuracy. These results open the way to atomically controlled processing at around room temperature.

## Scaling limits of Si-CMOS and non-Si opportunities

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Scaling of CMOS and its limits has been a continuous subject for debates for a long time since as early as late 1970's. In some cases the limits were attributed to lithographic limitations, whereas in some other cases they were derived from some set of physical constraints under likely assumptions for device physics and process controllability for stochastic nature of parameters. However, up until now, either evolutionary or revolutionary breakthrough solutions were found resulting in enabling continuous scaling of CMOS up until now.

As we look at the future, it is more difficult to be as optimistic as we used to be, because a variety of issues and more importantly the magnitude of challenges which we can anticipate may not be as easily overcome as those of the past two decades. Not only difficulty in cost-effective processing equipment and process parameter controls, but also perceived limit in device operation improvement itself will depart from what we have experienced previously. At the device level, rapidly increasing leakage current of MOSFETs at the gate, drain/source terminals and less than expected improvement in the drive current with reduced channel length will prompt us to consider non-Si materials for the channel of MOSFETs. At the integration level, the interconnect delay which has been predicted as the stumbling block for high performance large chips will certainly become worse, coupled with power consumption and heat dissipation management challenges. As we will have more areas dedicated to high-speed embedded memory (mostly static random access), memory stand-by power will become a major problem with MOSFETs operated at much lower  $I_{ON}/I_{OFF}$  ratio than previously. Furthermore, general trends for system-on-a-chip driven by significant growth of wireless systems needs for mostly consumer products do require heterogeneous integration of digital, analog/RF, power management and more, making the magnitude of challenges worse than ever.

This talk will first discuss scaling trend of CMOS, coupled with possibility of new channel materials, metal gate/high- $\kappa$  dielectric gate stacks and source/drain structures, followed by several possibilities and opportunities for non-Si devices, including new material-based non-volatile memory structures.

## Oscillatory frequency dependence of ballistic mobility

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In very short semiconductor structures, the electron transport becomes ballistic and collisions with impurities and crystal vibrations are not important.<sup>1</sup> When the 25 nm node of the International Technology Roadmap for Semiconductors is reached in 2009, nearly all transistors will operate in the ballistic or near-ballistic regime.

As was shown in Refs. 2–4, at low voltages, the dc current-voltage characteristic in the ballistic regime is still linear and can be described using the so-called "ballistic mobility" with the effective electron relaxation time on the order of the electron transit time,  $\tau = L/v$ , where  $L$  is the distance between the contacts and  $v$  is the Fermi velocity for the degenerate electrons and the thermal velocity for the non-degenerate electrons. The electric current is determined by the difference between the electron fluxes injected from the opposite contacts, so that the current is essentially contact limited.

In this work, we derive a general expression for the dc ballistic mobility in two-dimensional structures (for an arbitrary degeneracy level) and investigate its dependence on frequency,  $f$ . We show that the current-voltage characteristic is an oscillatory function of the  $f\tau$  product. This oscillatory dependence is caused by the phase difference between the electrons injected from the opposite contacts. The physics of this effect is similar to that of the oscillatory frequency conductivity behavior previously predicted for quantum ballistic wires.<sup>5</sup>

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**Mysteries of persistent noise in single-wall carbon nanotubes**

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Our experimental studies of  $1/f$  noise in single wall metallic and semiconducting carbon nanotubes (M-SWNTs and S-SWNTs) reveal an extreme sensitivity of noise to the nanotube environment persisting much longer than vacuum induced changes in carbon nanotube conductivity.

Nanotubes were grown by thermal CVD on oxidized 100 nm Si conducting substrates and contacted with Ti/Au electrodes with 1  $\mu\text{m}$  separation. Metallic and semiconducting nanotubes were randomly obtained during the growth.

Metallic nanotubes had linear and symmetrical current-voltage characteristics. Semiconducting nanotubes demonstrated non-linear, exponential current voltage characteristics typical for the Schottky contacts:  $I \sim \exp(eV/3.5kT)$ . Current in the semiconducting nanotubes at fixed voltage increased with the increase of the negative voltage applied to the substrate, indicating  $p$ -type conductivity.

The low frequency noise studies in all nanotubes followed  $\sim 1/f$  and  $I^2$  dependences on frequency,  $f$ , and current,  $I$ , respectively. Semiconducting nanotubes had three orders of magnitude higher noise level than metallic nanotubes. Since resistance of semiconducting nanotubes was dominated by the Schottky contacts, we assume that  $1/f$  noise was originated from the contacts and/or from the part of the nanotube adjacent to the contacts.

In vacuum, noise decreased quickly (during the pumping out time of about a few tens of minutes) by over an order of magnitude for both metallic and semiconducting nanotubes. When the devices were restored to the atmospheric pressure, the resistance and noise levels were restored to the original values, however, the noise level took a much longer time to recover compared to the resistance. Several tens of hours were required to restore noise level to its original value in the atmosphere compared with several tens of minutes required to restore the initial value of the resistance.

High sensitivity of noise to the environment shows a potential for chemical sensor applications based on carbon nanotube noise characteristics.

**Quantum control of the dynamics of a semiconductor quantum well**

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In recent years the quantum control of semiconductor quantum wells is a topic of increasing interest due to the significant potential applications of those structures. One of the most important problems in this area is the potential for controlled population transfer and Rabi oscillations in a two-subband semiconductor quantum well (QW). In a QW the many-body effects arising due to the macroscopic carrier density play a significant role and make the system behaving quite differently from a simple atomic-like two-level system.<sup>1</sup>

In this work we study the potential for quantum control of electron dynamics in a symmetric double QW that is coupled by a strong electric field. We consider only the first two subbands. The system dynamics when the electron-electron interactions are taken into account is described by using the effective nonlinear Bloch equations derived recently by Olaya-Castro *et al.*<sup>2</sup> We first simplify the nonlinear Bloch equations by using the rotating wave approximation and present analytical solutions in cases that the two-subband system interacts with pulsed and continuous wave (cw) electric fields. Conditions that lead to complete inversion of the electronic population in the two-subband system are also presented. In addition, strongly modified Rabi oscillations are found in the case that the QW structure interacts with a cw electric field. We finally compare our analytic findings with numerical solutions of the effective nonlinear Bloch equations for a realistic semiconductor QW. In all the cases, significant population inversion is found in the presence of dephasing.

We thank the European Social Fund (ESF), Operational Program for Educational and Vocational Training II (EPEAEK II), and particularly the Program PYTHAGORAS II, for funding this work.

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## Flexible metallic interconnects for displays and large-area electronics

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Large-area flexible electronics applications, ranging from displays on nonplanar surfaces to conformable bioelectronic applications, require an interconnect technology that can withstand bending and possibly stretching without losing electrical integrity. We will present a robust metallization scheme based on a layer of ductile metal islands, that can be deposited on a variety of compliant substrates and can withstand very large mechanical strains without rupture.

Thus, metallization containing a  $\sim 50$  nm thick granular indium interlayer combined with a stiff chromium adhesion layer, can be deposited on highly formable film substrates and strained up to 40% without loss of integrity and with an increase in resistance of less than a factor of two. The working mechanism is the bridging of cracks in the stiff adhesion layer by ductile indium. The same islanded metallic interconnects can withstand low-strain 2% fatigue loading for tens of thousands of cycles without a measurable change in resistance.<sup>1</sup>

In addition to flexible LCD-based displays, this type of interconnect may be promising for bioelectrical applications, including implantable electronics, given an acceptable encapsulation technique.

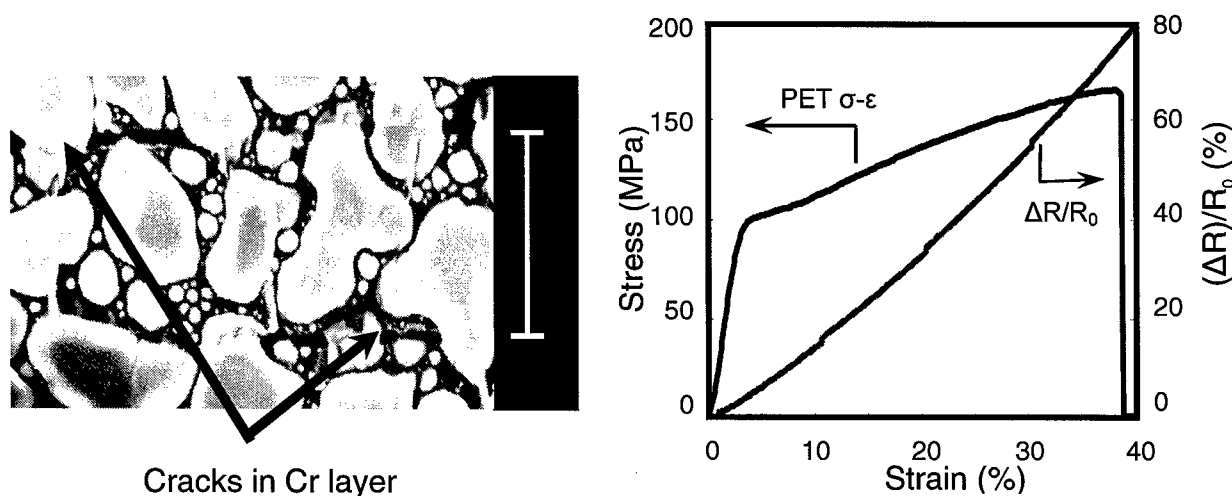


FIG. 1. SEM micrograph of Cr/In metallization showing the bridging of cracks in the stiff Cr adhesion layer by ductile In islands (left; marker corresponds to 1  $\mu$ m); stress-strain curve showing relative change in resistance of Cr/In interconnect on a compliant polyethylene terephthalate (PET) substrate strained up to 40% (right).

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**Nano- and mesoscale molecular junctions: Control of defects, chemical bonds and surface topography at metal-molecule interface**

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Using molecules in electronics has an enormous appeal. Reaction chemistry offers vast diversity of molecular substructures and chemical transformations. However, wiring the molecules in a macroscopic circuit remains a challenging problem.

I present three approaches that we use to build small molecular structures. The first group of experiments is targeted toward wiring of a single or just a few molecules. We found that the conductance mechanisms observed in such ultrasmall devices differ dramatically from the predicted transport through molecules. The electronic states mediating the transport are low energy defect states rather than the electronic states of the molecules. To detect the conductance associated with the molecular states, we have developed high-yield process based on prefabricated nano-templates to screen the properties of larger molecular junctions with characteristic size of ~50–300 nm. The approach readily permits to experiment with the topography, the chemical bonding at metal-molecule interface and to significantly reduce the defect density. For the first time, we directly compare the properties of conjugated versus saturated molecules with the length of ~1.5 nm. Finally, we build molecular junctions by imprinting ~100 nm Au pads on top of self-assembled monolayers. The pads are contacted by conducting AFM. Surprisingly, the results of all experiments show that the conductance of molecules is 4–5 orders of magnitude smaller than is commonly believed.

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