Challenges in Nanotechnologies and Nanomanufacturing Processes

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Abstract

The tasks that have to be fulfilled by photonics and electronics, one-dimensional nanosystems, the nanomanufacturing, and the world's smallest transistor, phase change memory (PCM), and single-walled carbon nanotubes (SWCNTs) are described. Nanoelectronics needs research tied to two features: barriers arising from device implementations and utilization of unique properties correlated with nanostructure.

Keywords: nanotechnology, photonics, electronics, nanomanufacturing, nanotubes, reliability

1. Introduction

The first transistors built in 1947 were over 1 cm in size; the smallest transistors today are less than 30 nm long – over three hundred thousand times smaller. The results of these efforts are billion-transistor processors where a billion or more transistor-based circuits are integrated into a single chip. But this development cannot continue for much longer. One of the increasingly difficult problems that chip designers are facing is that the high density of components packed on a chip makes interconnections increasingly difficult; and, as conventional chip structures continue to shrink; Moore's Law is on a collision course with the laws of physics. The key to fabricating a junctionless gated resistor is the formation of a semiconductor layer that is thin and narrow enough to allow for full depletion of carriers when the device is turned off. The semiconductor also needs to be heavily doped to allow for a reasonable amount of current flow when the device is turned on. Putting these two constraints together imposes the use of nanoscale dimensions and high doping concentrations. The key to success was the ability to fabricate silicon nanowires with a diameter of a few dozens of atomic planes, enabled by the electron-beam writing techniques and expertise available today. The electrical current flows in this silicon nanowire, and the flow of current is perfectly controlled by a 'wedding ring' structure that electrically squeezes the silicon wire in the same way that you might stop the flow of water in a hose by squeezing it. These structures are easy to fabricate even on a miniature scale which leads to the major breakthrough in potential cost reduction. Another key challenge for the semiconductor industry is reducing the power consumption of microchips. Minimizing current leakage is one of the main challenges in today's complex transistors. Junctionless devices have near ideal electrical properties and behave like the most perfect transistors. Moreover, they have the potential of operating faster and using less energy than the conventional transistors used in today's microprocessors. The new smaller junctionless transistor is now 30% more energy efficient and outperforms current transistors on the market. Nevertheless, fabricating these junctionless transistors is not without challenges. The main task is to obtain ultrapure, defect-free silicon crystals with a thickness and a width of a few atoms. This requires the use and control of high-precision instruments like electron-beam lithography equipment and highly skilled operators [1][1a].

2. Combining photonics and electronics

Combining ordinary electronics with light has been a potential way to create minimal computer circuits with super fast information transfer. Researchers at Umeå University in Sweden and the University of Maryland in

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the U. S. are now showing that there is a limit. When the size of the components approaches the nanometre level, all information will disappear before it has time to be transferred [2]. The electronics we know in our computers today is, as the name suggests, based on the transfer of information with the help of electrons. Using electrons has allowed us to shrink the size of computer circuits without losing efficacy. At the same time, communication with the help of electrons represents a rather slow means of transmission. To alleviate this problem, light can be used instead of electrons. This is the basis of so-called photonic components. While the transfer speed in photonics is extremely high, the size of the components cannot be shrunk to the same level as 'ordinary' electronics. For a number of years, so-called plasmonic components have proven to be a possible way around the dilemma of electronics and photonics. By combining photonics and electronics, scientists have shown that information can be transferred with the help of so-called plasmons[1]. But difficulties arise when the size of such components is reduced to the nanometre level. At that point it turns out that the dual nature of electrons makes itself felt: the electrons no longer act like particles but rather have a diffuse character, with their location and movement no longer being clearly defined. This leads to the energy of the plasmon being dissipated and lost in the transfer of information. For nano-components, this consequence cannot be fully avoided, but the behaviour of the plasmons might nevertheless be controlled by meticulous component design that takes into consideration the quantum nature of the nanoscale.

3. The world's smallest transistor

Researchers have used the world's thinnest material to create the world's smallest transistor, one atom thick and ten atoms wide. Reporting their peer-reviewed findings in the journal *Science*, Dr. Kostya Novoselov and Prof. Andre Geim from the School of Physics and Astronomy at the University of Manchester show that graphene can be carved into tiny electronic circuits with individual transistors having a size not much larger than that of a molecule. The smaller the size of their transistors the better they perform. At the heart of the problem is the poor stability of materials if shaped in elements smaller than 10 nm in size. At this spatial scale, all semiconductors - including silicon - oxidise, decompose and uncontrollably migrate along surfaces like water droplets on a hot plate. Six years ago, Geim and his colleagues discovered graphene, the first known one-atom-thick material which can be viewed as a plane of atoms pulled out from graphite. Graphene has rapidly become the hottest topic in physics and materials science. The Manchester team has shown that it is possible to carve out nanometre-scale transistors from a single graphene crystal. Unlike all other known materials, graphene remains highly stable and conductive even when it is cut into devices one nanometre wide. Graphene transistors start showing advantages and good performance at sizes below 10 nm - the miniaturization limit at which the silicon technology is predicted to fail. It is too early to promise graphene supercomputers while unfortunately, no existing technology allows the cutting materials with true nanometre precision. But this is exactly the same challenge that all post-silicon electronics has to face [3].

4. Variation aware design

Presently, the scaling tendency is toward higher speed, and lower power consumption, resulting in cost reduction, but the cost reductions cannot be expected without a reduction in chip area using miniaturized devices, when producing the same functionality. Process and material developments as well as physical design are big challenges in the development of nano-complementary metal-oxide-semiconductors (CMOS) large- and very large-scale integration (LSI and VLSI). The circuit operation is strongly affected by variations in device performance, which become large and the device size is miniaturized. Taking measurements and achieving understandings of such variation are the first steps in developing a variation-aware circuit design. Comprehensive work has been undertaken by STARC [4], using a device matrix array; research into understanding performance variation resulted, for example, in a new V_{th} variation plot called the

[1] Plasmons are surface waves, like waves in the ocean, but here consisting of electrons, which can spread at extremely high speeds in metals.

Takeuchi plot. The scaling down of the MOSFETs has increased the variability in device characteristics, and the significance of the problems has become increasingly evident. Currently, such variability can be explained by aspects of the device structure such as surface edge-roughness, impurity distribution, or distortion/stress. Among these it was shown that the discrete distribution of channel impurities causes variability in threshold voltage V_{th} [5]. However, the origin of on-state drain current (I_{ON}) variability has not been well distinguished.

To discuss the semiconductor device structures in relation to their electrical characteristics, various measurement methods can be considered. For instance, scanning probe microscopy, such as atomic force microscopy, seems effective. However, the internal structure of the devices is difficult to be measured since the interaction between the probe and the sample surface is used for imaging [6].

Nanosystems are devices that are in the size range of a billionth of a meter (1×10^{-9}) and therefore are built necessarily from individual atoms. The one-dimensional nanosystems or linear nanosystems cover all the nanosized systems which possess one dimension that exceeds the other two dimensions, i.e. extension over one dimension is predominant over the other two dimensions. Here only two of the dimensions have to be on the nanoscale (less than 100 nanometers). It is considered a linear nanosystem at a fixed moment of time, say the present moment, and it is assumed that the present state of the linear nanosystem depends only on the present states of its atoms [7].

5. Nanomanufacturing

Nanomanufacturing remains the essential bridge between discoveries of the nanosciences and real-word nanotechnology products. Advancing nanotechnology from the laboratory into high-volume production requires careful study of manufacturing system issues including product design reliability and quality, process design and control, shop floor operations and supply chain management. Nanomanufacturing is the controllable manipulation of materials structure, components, devices/machines, and systems at the nanoscale in one, two and three dimensions for large-scale reproducibility of value-added components and devices. Nanomanufacturing encompasses bottom-up directed assembly, top-down high resolution processing, molecular systems engineering, and hierarchical integration with larger scale systems. As dimensional scales of materials and molecular systems approach the nanoscale, the conventional rules governing the behaviour and properties of these components, devices, and systems change significantly. As such, the behaviour of the final product is enabled by the collective performance of the nanoscale building blocks. The critical challenges are the need to control assembly of three-dimensional heterogeneous systems, to process nanoscale structures in high-rate/high-volume applications without compromising their inherent properties, and to ensure the long-term reliability of nanostructures through testing and metrics [8]. These challenges reflect the need for research in the characterization of nanomaterials and nanoparticles as the building-blocks of nanostructures and in the fabrication and synthesis of both top-down and bottom-up process. Further they require advanced instrumentation to characterize and measure nanostructures in order to provide predictive simulation of nanostructures behaviour, and to contribute to the design and integration of nanodevices and systems. Finally, knowledge sharing and outreach is a challenge to the overcome to enable technology transfer and to contribute to public awareness of nanotechnologies.

Areas of applications for nano-manufacturing include electronics and semiconductor, energy and utilities, IT and telecommunications, automotive and aerospace industries, green technologies and environmental remediation, pharma-ceuticals, biomedical and biotechnology, national security.

6. Phase change memory (PCM); quantum phenomena; single-walled carbon nanotubes (SWCNTs)

Integrated manufacturing processes must achieve targeted product quality via regulation of events at molecular and nano length while controlling process variables at macroscopic length scale. In order to achieve sustainable levels of quality and reliability in manufacturing environments, the target properties and performance must be defined, experimental measurements conducted, relevant models established, and data analysed, with subsequent iterations for optimization, and ultimately end-to-end process control. Integrated nanomanufacturing processes require systematic integration of product design, process design and control. Challenges[2] to resolve in achieving this goal are methodologies for experimental design, execution, and translation to control of process variables, development of combined statistical and physical models, and ultimately control system structure, design, and implementation.

Presently, the predominantly approach to nanomanufacturing process control incorporates experimental design in order to establish viable models for process control. With sufficient factorial design, and appropriate definition of the process objectives, statistical models and nonlinear feedback can be effective in optimising nanomanufacturing processes. Careful selection of process variables, anticipated responses factorials, and sufficient sophistication of sensors for experimental data collection and analysis can result in highly effective process control. The shortcomings of the experimental design approach to nanomanufacturing process design include adaptability to new processes and equipment, limited knowledge of the physical mechanisms applied to the process development and the time necessary to conduct sufficient experiments to achieve the desired process performance. These limitations are further complicated at the nanoscale where novel physics and materials are exploited to achieve new products, requiring new sensors and diagnostics to validate both the mechanistic models[3] and the results of experimental design [8].

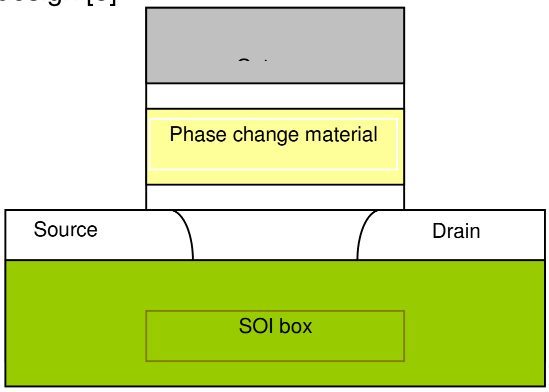

Figure 1. The schematic of phase change memory (PCM).

Nanoelectronics based on nanoscience and nanotechnology is prevailing in our lives with satisfying our demand for faster, smaller and ubiquitous devices. Nanoscience and technology expects ~5 nm manipulated dimensions adopting novel operational principles, materials and structures. It was encountered so many scientific challenges- power, speed, design, multifunctions, reliability and energy, etc., where ideas from multiple disciplines must come together so that efficiencies can be extracted at all levels [9]. The initial effort for implementing nanoelectronics is to confine electrons allowed to tunnel to metallic leads, that is a single electron transistor (SET) [10]. The SET using quantum phenomena turns on and off as a single electron is tunnelling into islands surrounded by an insulator. Another electronics using nanosciences are nanocrystal (NC) memory devices associated with quantum effects [11]. The advent of nanocrystal memory has accelerated the development of non-volatile charge trapping memories such as SONOS [12]. Recently, was reported a fast single element non-volatile memory that employs amorphous to crystalline phase change as shown in Figure 1 [13]. The phase of a single electronic element in confined geometry transistors can be changed by thermal shot or electric field. These devices need still

[2] These challenges include data acquisition, analysis and information processing of multiscale variables with different frequencies and categories.

[3] Incorporation of mechanistic modelling of the underlying physics, chemistry, or biology in combination with the statistical models established through experimental design leads to enhanced process control wherein improved understanding of the products and processes is developed. Such a model-based approach to process and controller design uses first principles and system specifications for model construction, thereby naturally accounting for inherent process characteristics including nonlinearities, spatial variations, and multiscale behaviour. For many processes, large disparities exist in time and length scales of phenomena occurring within the processes thereby requiring the establishment of multiscale models coupled through appropriate boundary conditions. Control of nonlinear distributed systems is possible by combing nonlinear models describing macroscale process control with localized physical kinetic models. Combining this with practical control and process feedback, facilitated by optimal placement of sensors for real time analytical data, an integrated nanomanufacturing capability can be realised that is robust, scalable, and adaptable to a range of processes and products.

further study and challenges in materials, principles, physics and analysis. As a nanomaterial, carbon is a very useful chemical element in nanotechnology applications. Some allotropes of carbon-0D of buckyballs, 1D of carbon nanotube and 2D of graphene, are getting more focus to explore novel composites/materials after silicon era. Among these carbon forms, graphene overcomes the random distributions occurring in carbon nanotubes applications and the planar structure also allows for the simple device implementations and its integrations [14]. Now, most efforts have been given to modify its properties to apply it into electronics/systems with keeping its own superior characteristics.

Nanoelectronic devices such as field effect transistors and molecular electronic devices have been currently demonstrated by utilizing single-walled carbon nanotubes (SWCNTs) with a shortened length provided as connectors and components [16-18]. Considering the explosive growth of the mobile device market and intrinsic attributes of SWCNTs, one of expected applications of SWCNTs is a non-volatile memory (NVM) based on a CMOS process [19].

7. Future and reliability

Looking into the future, nanoelectronics needs research tied to two features: barriers arising from device implementations and utilization of unique properties correlated with nanostructure. Various scientific challenges and efforts can overcome these barriers by using nano-material/structure and new phenomena [15]. The general reliability theory remains unchanged, but when it is used at nano level, some adjustments must be made. Reliability theory and physics of failure of macro- and micro-world are only partially applicable on the nanometer scale. Physical processes not scaling linearly with size and time dramatically change mass and heat diffusion, electrical conductivity, reaction kinetics, corrosion processes, etc. [20]. Fatigue, friction, damping, wear-out and repair mechanisms have a different physical meaning on atomic or molecular scales. Redundancy and correlation of quantum systems require quantum statistics of states and entanglement of wave functions.

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