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One Dimensional Electronics: Physics or Technology?

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1. Introduction

Nanoscience has opened up new possibilities for novel electronic devices that might address several of society's grand challenges in the 21st Century. Semiconductor nanowires, in particular, present interesting possibilities. They provide a remarkable playground for exploring electronics in one dimension. Carbon nanotubes, for example, have been the subject of many scientific studies, and several technological applications are being explored. Nanowires can be fabricated by so-called 'top-down' techniques based on traditional semiconductor process technology, or by 'bottom-up' methods. Individual transistors, macroelectronic technologies, sensors for bio-molecules, and energy conversion devices such as photovoltaics and thermoelectrics have all been explored. Where is this all leading? Research will undoubtedly lead to a deeper understanding of semiconductor electronics and to new techniques to simulate, characterize and fabricate devices and structures, but will it also lead to new device technologies? If so, what are the applications that are most likely to emerge? These questions will be addressed in this talk.

2. Device Physics in One Dimension

One-dimensional devices are interesting for several reasons. Some have to do with fabrication technology. Some of the very best results have been with nanowires fabricated by traditional semiconductor technology, but some of the most interesting possibilities come from nanowires fabricated differently, for example by Vapor Liquid Solid (VLS) growth [1, 2]. Compositional control in both the radial [1] and longitudinal [2] directions provide opportunities for producing sophisticated heterostructures. Catalyst-assisted growth may also make heterogeneous materials integration a reality. Transferring nanowires from the growth substrate to other substrates opens up possibilities for integration with conventional silicon technology and for macroelectronic applications such as displays, and electronic paper. Novel fabrication technologies could lead to important new applications. Even more interesting, however, is the possibility that electronics in one dimension can provide electronic device with greatly improved or novel characteristics.

A one-dimensional (1D) device has a single transport channel. The electronic density of states for a 1D conductor is strikingly different than for 2D or 3D conductors. The 1D density of states should affect the so-called quantum capacitance and carrier scattering rates as well as optical properties. Thermal transport also changes in 1D. In some cases, the changed external environment is responsible for dramatically different results – rather than changes in the nanowire itself. My focus in this presentation is on interesting physics in 1D that may lead to important technological applications.

Carbon nanotube electronics is a 1D nanowire technology that has progressed very rapidly. Within only a few years, the field progressed from proof-of-concept transistors to rather sophisticated structures with high-k gate dielectrics, self-aligned gate structures, and low-resistance contacts [3]. Low-field and high-field transport was carefully characterized and understood theoretically, and RF performance is being explored. Techniques to simulate dissipative quantum transport in 1D were developed, implemented, and tested against experiments. The result was a deep understanding of CNT electronics and new simulation techniques that are generally applicable to nano-devices.

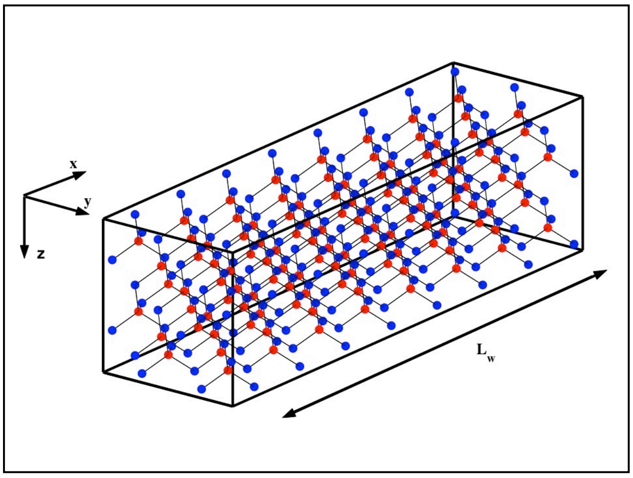

Fig. 1. Atomistic image of a silicon nanowire. (Courtesy Mathieu Luisier, Purdue University.)

3. One-Dimensional Devices

Over the past decade, we have learned much about the science of electronics in 1D. What can we now say about the possibilities for technologically important devices? What is special about electronics in 1D and what technological possibilities do those special properties open up?

The **transistor** transformed the 20th Century and will continue to have enormous impact in the 21st Century. What do nanowires offer? It has long been known that a coaxially gated transistor is optimum for electrostatic integrity [4]. Large diameter wires with many conduction channels would enjoy this benefit, but they would not be 1D conductors. Would a 1D transistor be fundamentally different from a planar MOSFET? Nanowire transistors could, indeed, display distinct IV characteristics, but it appears to be difficult to observe these distinctive features at room temperature. The need for drive current favors large diameter, multi-moded wires that behave much as conventional MOSFETs do. If, however, nanowires could be integrated into silicon manufacturing processes, they might play a role in digital electronics by providing a new, high-performance channel materials for transistors.

Nanowires can also provide nanostructured materials that may be suitable for **macroelectronic** applications. Carbon nanotube networks are an example [5], but similar work for semiconductor nanowires is also underway [e.g. 6]. These nanostructured materials can be characterized by macroscopic parameters such as mobility, but care is needed because the macroscopic parameters depend on the wire density, degree of alignment, wire length in relation to the channel length, wire to wire contacts, etc. in a nontrivial way. Considerable progress has been made in the theoretical understanding of these material and in the demonstration of circuits of considerable complexity [e.g. 7]. The use of nanowires to engineer the properties of materials for electronics is a promising possibility.

Energy conservation and the development of alternative energy sources are key challenges that **thermoelectrics** might address. Many new possibilities for efficient electronic refrigeration and for electric power generation would be enabled if the thermoelectric figure of merit, ZT, could be increased. What do nanowires have to offer? The use of nanostructures has recently led to promising results, and nanowires are especially interesting [8, 9]. The figure of merit consists of two factors, the Seebeck coefficient and the ratio electrical to thermal conductivity. Predictions suggest that ZT will increase in 1D [10]. The current focus, however, is on lowering the thermal conductivity, and it appears that in nanowires, the thermal conductivity can be substantially lowered without severely degrading the electrical conductivity [9]. If successful, this work could lead to very important applications, but the challenge will be to devise structures that can cool or generate power on the macroscale with arrays or composites of nanowires.

As the world's population grows and ages, health care has become a grand challenge. Low cost, label free sensing of bio-molecules could revolutionize health care. What do **nanowire bio-sensors** have to offer? The results have been dramatic – the sensitivity of a nanowire bio-sensor is orders of magnitude higher that that of a planar MOSFET sensor [11]. The reason primarily has to do with the nature of the diffusion of the target molecules to the sensor itself and less to do with the electrical response induced by the bio-molecule in the nanowire [12]. Bio-sensor technology is sophisticated and current technologies are advancing rapidly, but it is clear that nanowires are very promising for such applications.

As economies across the globe develop, energy has become a grand challenge. Part of the solution is likely to be photovoltaics – if the cost per watt can be reduced. What are the possibilities for **nanowire photovoltaics** ? Several ideas are being explored, such as high density nanowire arrays that may be suitable for thin-film photovoltaics [13] and very recently, the possibility of using tapered nanowires to separate charge [14]. This work is at an early stage, but it is an example of the kind of creative thinking necessary to identify relevant application for nanowires.

4. Conclusions

Semiconductor nanowires provide a new playground to research and a new sandbox for the device designer. There is no question that nanowire devices promise new capabilities – but significant challenges must be addressed. It is never clear what new applications will emerge from research. As research progresses, however, it is important to identify potential applications for which nanowire devices are especially well-suited. I hope that this presentation contributes to the on-going discussion.

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