Semiconductor Nanowires: A Platform for Nanoscience and Nanotechnology

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Abstract- **Nanoscience offers the promise of producing revolutionary advances in many areas of science and technology, ranging from electronics and computing to biology and medicine, yet the realization of this promise will depend critically on the rational development of unique nanoscale structures whose properties and/or function are controlled during materials synthesis. This review will illustrate these concepts using nanowires as a platform material. First, a brief historical perspective on emergence of nanowires as a central material will be presented. Second, the 'chemical' synthesis, atomic-level structural characterization and properties of complex modulated nanowires will be discussed with an emphasis on structures with radial and axial dopant modulation, and novel but controlled structural modulations. The implementation of these functional nanowires as a platform for investigating fundamental properties and performance limits of nanoscale quantum electronic and photovoltaic devices at the single nanowire level will be described. Second, the development of active interfaces between nanowire nanoelectronic devices and biological systems will be discussed, including label-free electronic detection at the single molecule level and multiplexed recording from individual cells through complex biological tissue, such as the brain. In addition, the development of novel nanowire probes that exploit unique synthetic capabilities for the nanowire platform and move beyond capabilities of conventional electrophysiological techniques will be discussed. Last, a critical look at progress made and scientific challenges that remain to realize true technologies in the future will be reviewed.**

I. INTRODUCTION

Semiconductor nanowires (NWs) and carbon nanotubes offer many opportunities for the assembly of nanoscale devices and arrays by the bottom-up paradigm [1-3]. Moreover, these nanomaterials demonstrate new and/or enhanced functions crucial to many areas of technology. Central to realizing applications through a bottom-up paradigm is the rational control of key nanomaterial parameters, including chemical composition, structure, size, morphology, and doping. It is these parameters that determine, for example, electronic and optoelectronic properties critical to predictable device function. Significantly, semiconductor NWs represent the nanomaterial system where these key parameters have been best controlled to date.

II. SEMICONDUCTOR NANOWIRES

At the heart of the success of NWs as versatile building blocks for nanoscience is the development of a general strategy for the controlled growth of these materials [4]. We first reported that metal nanoparticles could be used as 'catalysts' within the general context of the vapor-liquid-solid growth to control the critical nucleation and subsequent elongation steps of NW growth (Fig. 1). Using this approach, we showed early on that a broad range of NWs with homogeneous composition and single-crystal structures could be prepared [4,5]. In addition, this earlier work on homogenous NW materials demonstrated that NW diameter is indeed controlled by the size of the nanoparticle 'catalyst', as suggested by the growth model, with diameters as small as 3 nm realized; that NW length is proportional to growth time; and, significantly, that specific dopants can be incorporated into NWs to control their electronic properties. The ability to control the fundamental electronic properties of NWs through doping has been central to much of our success in developing active electronic and optoelectronic nanodevices.

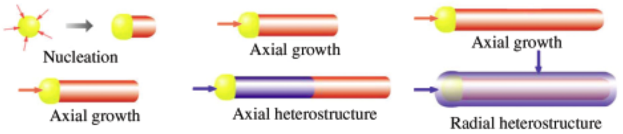

Fig. 1. Nanocluster-catalyzed growth and schematic structures of uniform single-crystalline semiconductor nanowires, axial nanowire heterostructures, and radial nanowire heterostructures.

Another critical breakthrough in the development of NW building blocks has been the recent demonstration of controlled growth of axial and radial heterostructures [6,7], where the composition and/or doping is modulated down to the atomic level along or perpendicular to the axes of NWs, respectively (Fig. 1). The growth of both types of heterostructure is possible because of our understanding of the growth mechanism first defined for homogeneous NW structures. In the case of axial heterostructures, one or more heterojunctions are created within the NW by alternating the flow of different reactants and/or dopants; this sequence can be repeated to make an arbitrary number of junctions. In the case of radial NW heterostructures, after growth and elongation of a crystalline NW core, conformal radial shell growth is carried out by altering the conditions to favor homogeneous deposition on the NW surface versus reactant addition at the nanoparticle

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catalyst. Subsequent introduction of different reactants and/or dopants produces multiple shell structures of nearly arbitrary composition. The ability to prepare controlled and diverse axial and radial heterostructures sets NWs apart from other nanomaterials, such as carbon nanotubes, and represents a substantial advantage for the development of increasingly powerful and unique nanoscale electronic and optoelectronic devices crucial to future applications.

III. NANOELECTRONIC DEVICES

To illustrate the unique advantages of seminconductor NWs for nanoelectronics and optoelectronics we first review advances in chemically-synthesized semiconductor NWs as nanoelectronic devices. We introduce basic NW field-effect transistor structures, and review results obtained from both p- and n-channel homogeneous composition NWs. Next, we describe NW radial heterostructures, and show that by using these heterostructures several limiting factors in homogeneous nanowire devices can be mitigated, and demonstrate that NW transistor performance can reach the ballistic limit and exceed state-of-the-art planar devices of industry.

In addition, recent work addressing the properties and potential of semiconductor NWs as building blocks for photovoltaic devices based on investigations at the single NW level will be reviewed. Two central NW motifs involving p-i-n dopant modulation in axial and coaxial geometries serve as platforms for fundamental studies. Research illustrating the synthesis of these structural motifs will be reviewed first, followed by an examination of recent studies of single axial and coaxial p-i-n silicon NW solar cells. Finally, challenges and opportunities for improving efficiency enabled by controlled synthesis of more complex NW structures will be discussed, as will their potential applications as power sources for emerging nanoelectronic systems.

IV. NANO-BIO INTERFACE

Last, we explore NW field-effect transistors (NWFETs) as powerful building blocks for nanoscale bioelectronic interfaces with biomolecules, cells and tissue (Fig. 2). First, we describe studies demonstrating the exquisite sensitivity of NWFETs for chemical and biological detection down to the single molecule level. Second, we describe rapidly expanding studies of coupled interfaces with cell membranes. We present a general scheme that can be used to assemble NWFETs on virtually any substrate, and demonstrate that these devices can be used to measure signals from neurons, cardiomyocytes, and heart tissue. Basic studies showing the effect of device sensitivity and cell/substrate junction quality on signal magnitude will be presented. Finally, our demonstrated ability to design high-density arrays of NWFETs enables us to map signals at the cellular and subcellular level, a functionality not enabled by conventional microfabricated devices. Opportunities opened up by these advances in cell drug assays, fundamental studies of cellular function, and development of powerful prosthetics will be discussed.

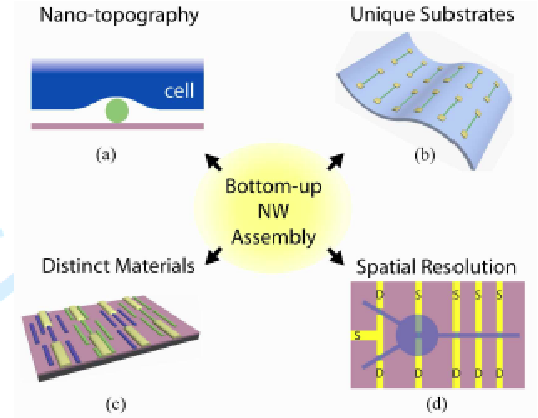

Fig. 2. Schematic illustrating unique advantages of bottom-up NW assembly, including (a) nanotopographic morphology, (b) ability to assemble devices on flexible, transparent substrates, (c) assembly of distinct NW materials on the same chip, and (d) high spatial resolution of NW devices.

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