Synthesis of Nanowire Heterojunctions for Advanced Nanoelectronic Devices

Introduction

Nanoscience is a growing field of research merging chemistry, physics and biology, with sweeping implications for new technologies. One particular topic of interest within this field is the electronic properties and applications of nanowire materials. Researchers have primarily focused on making interesting circuits with these "wires," and the work was named "Breakthrough of the Year, 2001" in Science magazine [1].

Besides having potential electronic applications, these nanocircuits are also known to be extremely sensitive to their surroundings. Researchers have demonstrated the ability to detect molecules such as gases, liquids, proteins and viruses using nanowires [2,3]. Therefore these circuits are particularly exciting because they begin to combine the fields of physical sciences, engineering, and the life sciences.

A great deal of the existing research has been done on nanowires called carbon nanotubes [4]. Carbon nanotubes are fullerene-related structures composed of a single layer of carbon wrapped around to form a cylinder. These wires tend to have diameters of only 1 nanometer (approximately 6 atoms). Depending on their structure, they can be metals or semiconductors. They are also extremely strong materials and have good thermal conductivity, making them very dependable components for nanocircuits. In fact, their unique characteristics have generated strong interest in their use in nano-electronic and nano-mechanical devices.

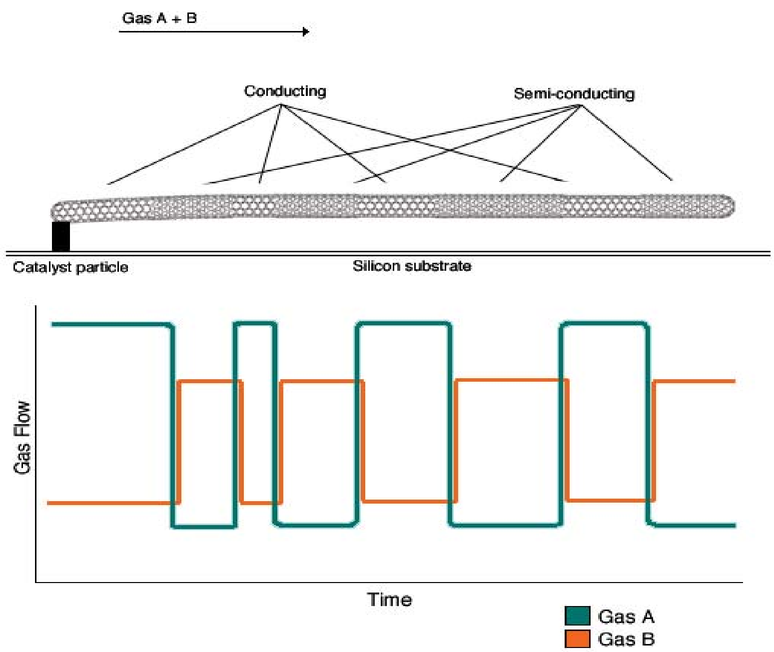
Of the various methods available for producing carbon nanotubes, Chemical Vapor Deposition (CVD) stands out as most useful for electronics applications. Using CVD, the nanotubes can be grown in specific locations and directions on a silicon wafer, which is ideal for incorporating them into electronic devices using standard lithographic methods [5]. In the CVD process, a high temperature oven in used to change a gaseous carbon source (e.g. methane) into reactive atomic carbon and a gaseous byproduct. The reactive carbon normally forms soot but under proper conditions and in the presence of specific catalyst particles, carbon nanotubes will form. One key to growing nanotubes that are clean and long is to mix several additional gases such as argon and hydrogen with the methane while it flows over the hot substrate and catalyst. These conditions also determine the conductivity of the grown nanotubes.

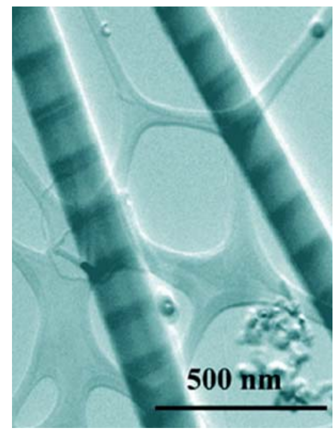
The research group of Professor Collins currently grows high quality carbon nanotubes by CVD and incorporates them into nanoelectronic circuits for testing. The focus and expertise of the group is the interaction of these circuits with different environments and the potential sensor applications. However, numerous problems exist with such circuits. The nanotubes are weakly sensitive to chemicals all along their length, with most of the sensitivity concentrated at point defects in the nanotube structure. At present, these defects happen by chance in random positions, making it difficult to further optimize them for applications.

In traditional microelectronics, one way to concentrate a particular effect at a known location is to form a junction between two different materials. For example, a diode is a junction between p-doped semiconductor and n-doped semiconductor. The special properties of the junction allow a diode to detect light (a photodiode) or emit light (an LED), even though the different semiconductors themselves only have weak optical properties. By incorporating similar junctions into our nanotube devices, we aim to build similar improvements into our chemical detectors.

Project Focus and Objective

The primary aim of this project is to modify the currently used CVD techniques to enable the growth of well-defined nanowire junctions. The principle is to precisely control the feedstock gas, abruptly changing its composition for a chosen period of time. This change of feedstock has the effect of growing nanowires with length-dependent compositions, naturally converting from one stoichiometry to another, as depicted below in Figure 1. Ultimately, by controlling the speed of growth and the gas flow profile, we intend to develop techniques for growing junctions at particular places on a silicon chip.





From the research website of Peidong Yang, UC Berkeley

Figure 1. A schematic of the CVD process. A nanowire grows out from a catalyst particle in the direction of the gas flow. By changing the proportions of the growth gases A and B as a function of time, the composition of the nanowire can be tailored to include sharp or diffuse junctions. Previous research at Harvard University and UC Berkeley has already proven this concept [6-8]. The electron micrograph at left shows two striped nanowires grown in time-varying gases.

Research Plan

The research project will be broken into three parts, all of which will be the primary responsibility of myself as a SURP Fellow. First, the existing CVD system must be modified and automated so that gases can be switched on and off with precise timing. Second, the gas switching must be tested and the wires grown must be imaged by microscopy to determine the position and character of the junctions. Third, we will focus on determining parameters that allow junctions to be reliably formed at reproducible distances from the catalyst spot. In this way, simple lithography can later be used to connect and interconnect multiple junctions for sensor testing.

A. Automation of the CVD System

The first phase of the proposed project is already underway. During the 2003-04 academic year, I have been volunteering time in the Collins research group. I have been trained in the operation of the existing CVD system, which at present is controlled manually. In preparation for the proposed research, I have also begun to learn the LabVIEW programming language, which the group uses for computer control of laboratory instruments.

Automation of the CVD system will require the construction of various electronic circuits as well as software to control them. At present, I am planning a computerized control system under supervision of the graduate student who built the original. The computerized version will allow for greater control of multiple gases and the conditions within the oven. For example, I will install relays into the gas flow control box so that gas flow valves may be switched by computer. I will also modify the gas flow rate controllers so that they can be controlled by analog computer signals rather than by the potentiometers used presently.

The controlling program will be created using LabVIEW and will communicate with the flow control box via a data acquisition card. I have recently installed this card into the laboratory computer, and I have already begun to develop a simple version of this program.

Besides allowing for gas switching, this computerized control system will ultimately provide numerous benefits in the synthesis of nanodevices over the current manual system. More consistent nanotube production will result from better recordings of gas flows during each CVD run. The quality of the tubes produced directly correlates with the growth conditions, and the computer control will more accurately set those conditions. The computerized system can also record the settings for each run, saving them to a text file for future reference. In this way, we will be able to refine our production techniques through examination of what quality of nanotubes were grown at each particular setting.

B. Growth and Characterization of Junctions

Once computer control has been implemented and tested, I will next focus on the growth of nanowire junctions. Using the recording system described above, various experiments will be performed using abrupt changes in gas flow. By switching the settings mid-growth, we hope to reproduce previous results [6-8] as well as grow nanotubes with novel properties. For example, it may be possible to produce a nanotube that is conductive in one section and semi-conductive in another. This example could be extended to any other set of characteristics where the nanotube exhibits one characteristic in one segment and a different characteristic in an adjacent segment.

To characterize the nanowire junctions, I will use a combination of microscopies including Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Electrostatic Force Microscopy (EFM). Each of these techniques is the specialty of other members of the Collins group, who will help me with this aspect of the project. Of these, AFM and SEM are the simplest to perform and I expect to be able to do my own microscopy as the project proceeds. However, TEM and EFM are more useful for imaging the fine structure around the junctions, so these will also be important to the ongoing project.

Once junctions have been produced, we will continue to perform various growth runs using different parameters. Aided by the automated logging of data, my goal is to build a library comparing the actual growth parameters and the micrographs of the materials grown. Ultimately, we seek to find correspondences to help understand which parameters are more or less successful for initiating junctions. This portion of the project will require ongoing record keeping and statistical data analysis.

C. Growth and Characterization of Junctions

Once we are capable of producing reliable junctions, we can use information already recorded on the lengths of nanotubes grown under certain conditions to make junctions at specific locations. This will be the third phase of the experiment, but it depends critically on the sections described above. We must first be able to generate gas pulses at precise times, and study correlations between the synthesis timing data and the microscopy images.

For example, imagine a sample substrate heated up to reaction temperature in the CVD setup. The first pulse of gas A initiates growth, and at a later time t the second gas B is introduced. Then, the nanowire can be imaged to determine the length of its "A" segment, the length of its "B" segment, and the absolute positions of the junction with respect the catalyst spot. Since many nanowires can be grown in a single run, we can do a statistical analysis to determine the mean growth rate and the probabilities of forming junctions at particular places.

The specific gases used for this experiment will depend on what we are most successful with in Part B. However, we anticipate trying at least two different experiments. In the first, we will reproduce Ref. 6 and join a carbon nanotube to a silicon nanowire. This particular structure is straightforward to image by SEM and it could be important for studies of chemical sensors ongoing in the Collins group. In the second experiment, we will grow a conductive carbon nanotube for lengths of approximately 10 micrometers, then introduce diborane to grow a segment of boron-doped carbon nanotube for another 10 micrometers. This would give us a carbon nanotube with a boron-doped segment, which might be very effective at improving contact resistance in nanotube circuits.

Proposed Project Timeline

The Research Plan described above is sequenced chronologically. I anticipate working on the project part time during the remainder of the Spring Quarter. Then, with the assistance of a SURP Fellowship, I hope to work full time in the research lab during the summer. A specific timeline for the project is as follows:

Spring Quarter

April - May	Continued development of LabVIEW control program
	Installation of relays into flow control box
June	Test operation of program and valve controls (cold furnace)

Summer Quarter

July	Begin nanowire growth in hot furnace
	- compare results to manually-controlled synthesis
	Further development and refinement of control software
	First attempts at switching gases during nanowire growth
August	Inspect and analyze grown nanotubes using microscopies
	Produce nanotube junctions reliably
	Assemble an image database matched with synthesis parameters
September	Summary presentation: Growth parameters of nanowires
	Using results, attempt to produce junctions at specific locations

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