Design and Fabrication of Microfluidic Devices for the Study of Flow through Carbon Nanotubes

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Abstract:

Carbon nanotubes (CNTs) have been investigated for manifold applications due to their amazing properties, including stiffness and strength exceeding steel, thermal conductivity exceeding diamond, and ballistic electron transport over micron scales. Additionally, fluid flow experiments through CNTs have shown extraordinarily high slip, reflecting unique flow dynamics. Voltages induced by flow over the length of nanotubes have also been observed. Relevant applications include the use of CNTs in flow sensors, filtration, energy conversion, and the study of chemical reactions where nanotubes may be used as "miniature test tubes." Previous studies of flow through CNTs have primarily investigated flow through membranes containing low densities of short nanotubes. This study is focused on developing methods for fabricating flow cells and permeable membranes with pores of CNTs using millimeter long, dense bundles of CNTs grown by chemical vapor deposition (CVD).

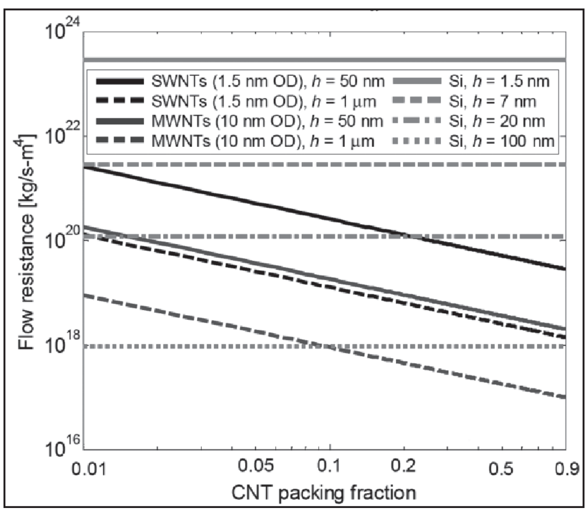

Figure 1: Chart comparing flow resistances of CNT pipes and Si channels.

Introduction:

Fluidic devices for the purposes of studying nano-scale confined flow have been fabricated [1]. At these scales flow rates are usually limited due to the no slip condition at the channel walls. Experimental results have shown high slip for fluid flow through CNTs and a lack of interaction between molecules inside the CNT, leading to greatly enhanced flow rates over hydrodynamic flow [2]. Figure 1 compares flow resistance through a "CNT pipe" consisting of a packed bundle of aligned nanotubes to that of shallow channels in silicon. In this model, h is channel depth and CNT packing is the fraction of cross sectional area of the bundle taken up by CNTs.

Procedure:

Two initial designs were pursued. The first allows for fluid flow through a polydimethylsiloxane (PDMS) membrane with nanotube pores produced by spin-coating PDMS (an elastomer commonly used for microfluidics) onto vertically aligned CNT columns. This design will be used for early investigations of flow dynamics and shows potential for applications requiring large scale filtration. Advantages include relatively quick processing with limited clean room fabrication but provide limited control over CNT characteristics such as packing.

Columns of aligned nanotubes ranging from 75×75 to $200 \times 200\ \mu m$ were grown on a silicon substrate with patterned iron

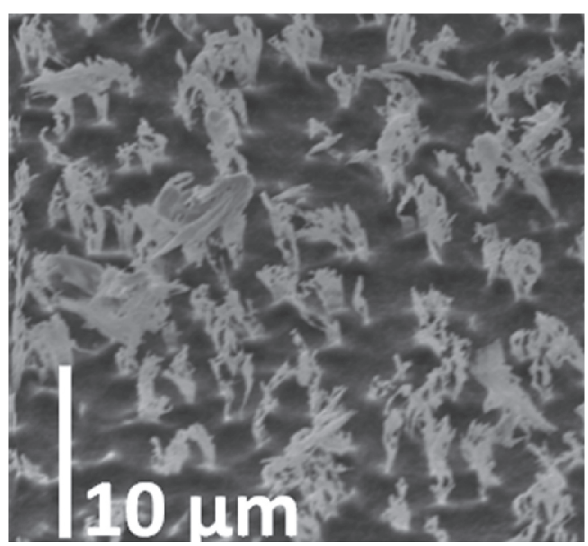

Figure 2: Surface of an etched CNT membrane.

catalyst [3], then spin coated with PDMS. Vacuum degassing ensured the removal of all air from the CNT bundles to produce a sealed membrane. A PDMS etch with CF_4 and O_2 followed by a CNT etch with O_2 and Ar, was performed to expose and open the CNTs to enable flow [4]. Figure 2 shows an SEM image of a membrane with CNT bundles exposed by etching.

The second design utilizes microfluidic channels patterned by UV lithography into SU-8 photoresist. Highly densified, horizontally aligned CNTs are embedded in a membrane across these channels, forming a "CNT pipe" to facilitate flow. Advantages of this design include potential for integration with microfluidic systems and precise control of CNT characteristics such as length and packing. This comes at the cost of extensive clean room fabrication.

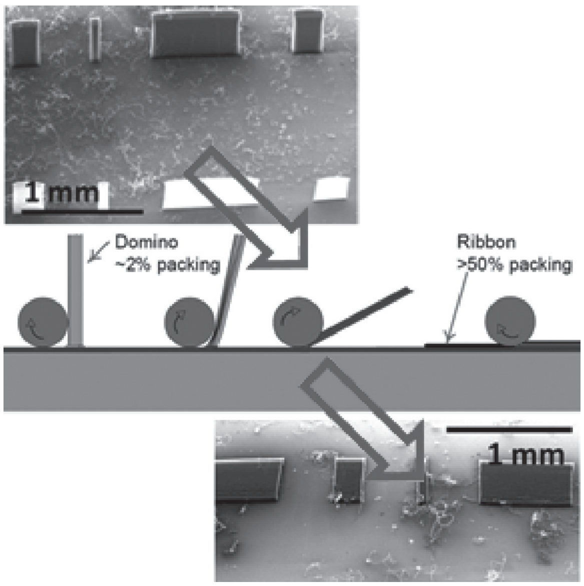

Figure 3: Schematic of CNT growth rolling.

Growth of vertically aligned "dominos" of CNTs is followed by a rolling process developed by the Mechanosynthesis group at UMich to horizontally align and densify the CNTs, as shown in Figure 3 [5]. This produces the dense bundles of CNTs that will form the "CNT pipes." Spin coating the rolled bundles with SU-8 and performing UV lithography produces the channels of the microfluidic device. A wall of SU-8 across the channels with the "CNT pipes" embedded within it restricts flow through the CNTs. A CNT etch is used to open up the pipes to allow flow. Figure 4 shows an overview of a "CNT pipe" device before etching and an etched "CNT pipe." The device is packaged by bonding a PDMS cover to the SU-8. Inlets for pressure sensors and fluid flow into and out of the device are punched into the PDMS cover.

This process requires further improvement to produce useable devices. SU-8 bonding to the substrate and PDMS cover must be improved to provide a seal capable of withstanding pressures necessary to push fluids through the "CNT pipe." The infiltration of CNT bundles with SU-8 will be further examined by sectioning SU-8 infiltrated bundles with a focused ion beam and imaging to ensure no gaps are visible between the CNTs.

Future Work:

Future work will strive to solve the challenges faced in fabrication of functional microfluidic devices. Initial flow tests will be run to verify that flow travels exclusively through the CNTs by filtering a solution of nanoparticles with diameters greater than the interior diameter of the CNTs using the flow cells. A resulting nanoparticle free solution will help verify successful infiltration of the nanotubes bundles. Data from flow tests will enable development of flow dynamics and comparison to theoretical models.

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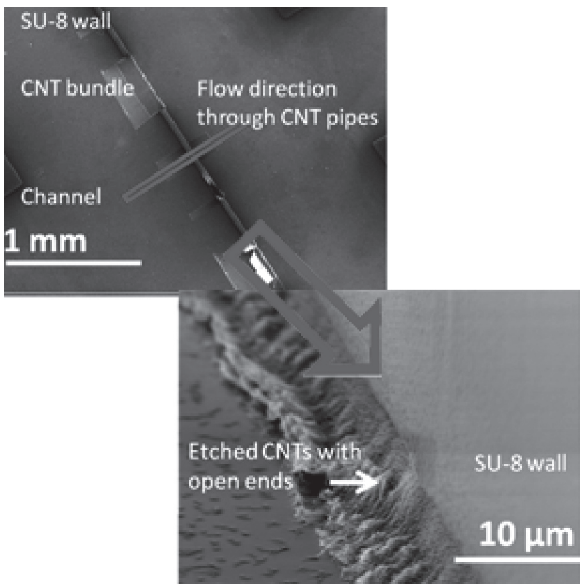

Figure 4: CNT pipe device before and after etching.

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