Horizontally Aligned Carbon Nanotube Composite Beams

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Abstract:

Microelectromechanical systems (MEMS) resonators have many applications in a variety of fields from biosensors, to radio frequency (RF) filters and transmitters. Materials suitable for nanostructured beams include metals, ceramics, aligned carbon nanotubes (CNTs), and CNT composites. It has been proposed that the high strength per low density of CNT composite beams could yield higher strengths and resonant frequencies. As an initial step toward this goal, this project focuses on creating micro-beams of horizontally aligned CNTs (HA-CNTs). This is achieved by growing vertically aligned CNTs and then, by mechanically rolling them, they adhere to the substrate and become horizontally aligned with ~ 25% packing density. Atomic layer deposition (ALD) of alumina then creates the matrix of the CNT composite material. We are able to control the CNT density and thickness of ALD coating, and future work will aim to control beam modulus and stiffness.

Introduction:

MEMS have many applications in a variety of fields from biosensors, to RF filters and transmitters. One of the most important components in a MEMS device and one of the most difficult to manufacture is a cantilever or suspended beam. The cantilever is used as a resonator that, depending on material properties, will respond to or create vibrations only at a specific frequency. Current MEMS devices make use of traditional beams composed of metal or ceramic. Others have shown that aligned carbon nanotubes (CNTs) [1], and CNT composites [2] can function as resonators.

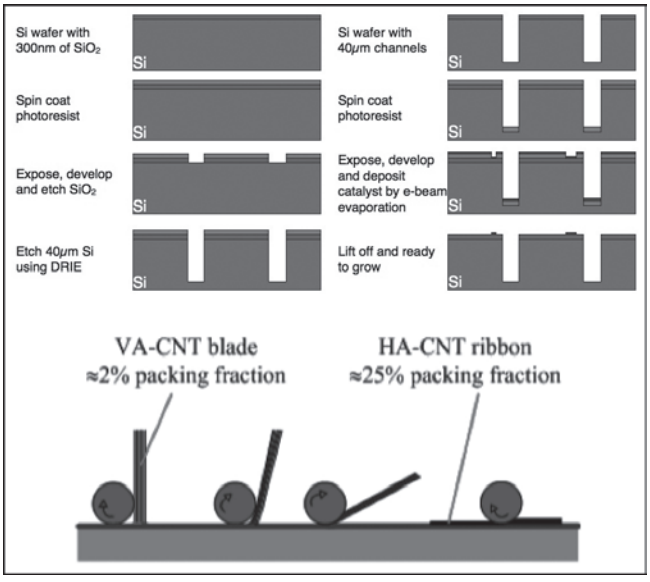


Figure 1: Processes for fabricating wafer and rolling VA-CNTs.

Experimental Procedure:

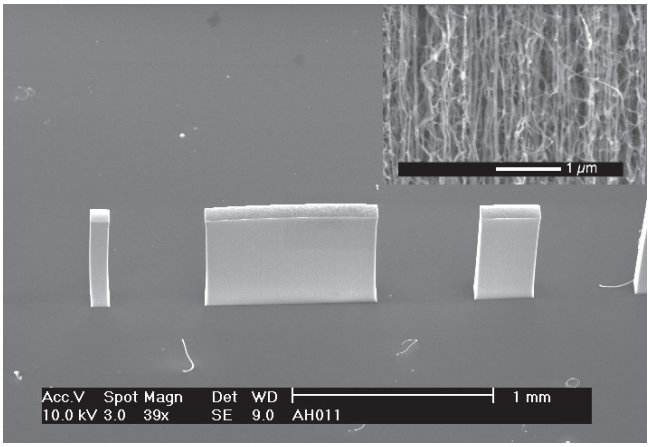
The fabrication process begins with a 4-inch silicon (Si) wafer coated with 300 nm of SiO_2 grown by thermal oxidation at 1100°C. Then, lithographic patterning was done twice on the wafer to make channels 200 to 1000 μm long and 5 to 50 μm wide, and CNT growth catalyst islands 100 to 900 μm long and 20 or 100 μm wide as shown in Figure 1. 10 nm aluminum oxide and 1 nm iron was the catalyst for CNT growth.

Once the substrate was fabricated, it was cut into 15 × 15 mm samples. CNTs were then grown in a tube furnace by first annealing the substrate in 100 sccm He and 400 sccm H2 at 775°C for 10 min. and then growing with 400 sccm He, 100 sccm H_2, and 100 sccm C_2H_4 at 775°C for 30 min. This process resulted in vertically aligned CNTs (VA-CNTs) characterized by their low areal density (2.5×10^{10} CNTs/cm^2) and the presence of entanglement along their length (Figure 2).

CNTs were then rolled [3] onto the substrate, forming horizontally aligned CNT (HA-CNT) beams (Figure 1), increasing their density and preparing them for mechanical beam characterization. When grown on substrates with etched channels, they were rolled over the channels forming suspended HA-CNT beams. The length and width of the beams corresponded to the dimensions of the catalyst island, and the channels defined the beam span. This device design allowed for beams with thicknesses below 1 μm, depending on the width of the VA-CNT bundles.

Material Characterization:

ALD can be used to create composite CNT beams by growing the deposited material via gas precursors from the CNTs at



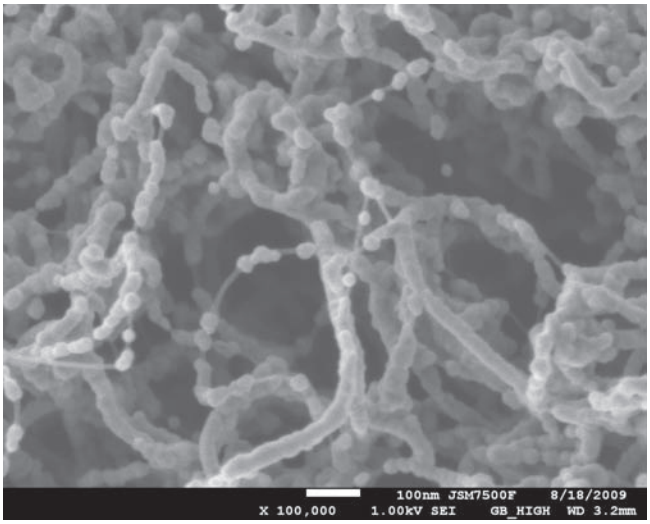


Figure 2, top: HA-CNT pattern with close up of CNTs.

Figure 3, bottom: Al2O3 coated CNTs by ALD.

variable thicknesses. The resulting matrix is expected to have higher strength based on the volume fraction of CNTs in the composite. A major challenge with designing ALD-coated CNT assemblies is penetration depth of the gases, which would yield a uniform coating throughout the CNT bundles.

Depth of aluminum oxide coatings on the nanotube beams was characterized with thermogravimetric analysis (TGA). A series VA-CNTs were grown in patterns of pillars with diameters ranging from 30 μm to 600 μm. These CNT samples were coated with alumina by 100 ALD cycles of trimethylaluminum and H2O at 250°C. These samples were then analyzed with TGA to determine the penetration depth of the alumina coating.

Results and Conclusions:

VA-CNTs were successfully grown on substrates that had been fabricated with the channels and rolled to form suspended HA-CNTs. The alumina coating of the CNT bundles was characterized using TGA, for pillars with diameters of 30 μm and 600 μm. The results of TGA (Figure 4) show clearly that at around 700°C, the CNTs burn away, decreasing the mass of the sample. Based on the CNT aerial density (2.5×10^{10} CNTs/cm^2), the diameter of CNTs (12-15 nm), and the thickness of the alumina coating (~ 12 nm); an ideal, fully coated sample of CNTs would have ~ 83% mass remaining after the CNTs burned away. Based on this, the 30 μm pillars seemed to be fully coated while the 600 μm pillars were not. Assuming that CNTs were either fully coated or not coated at all, it can be estimated that the ALD gasses penetrated ~200 μm into the 600 μm pillars.

Future Work:

Further characterization of the ALD coating needs to be done to determine the maximum size of a fully coated CNT buddle. Also, the suspended CNTs must be tested for strength and stiffness. Experiments can also be done to determine an appropriate thickness of alumina to maximize device properties.

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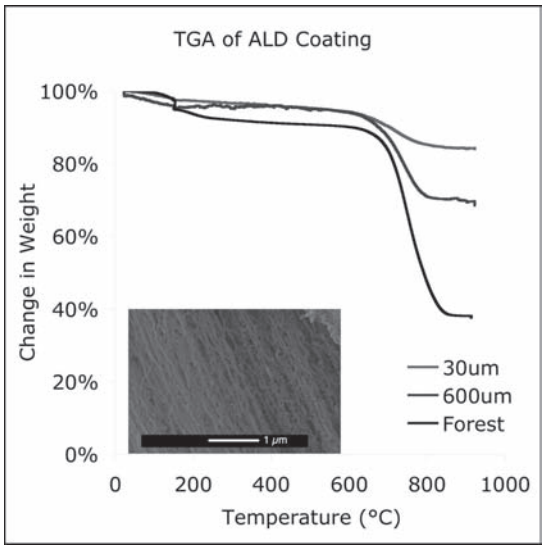

Figure 4: Results of TGA analysis and residual alumina coatings after TGA.