NANOTUBE ACTUATORS AND OSCILLATORS

Final Report

JPL Task 960

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A. OBJECTIVES

Nanoscale structures are becoming increasingly important to NASA because they provide the basis for instruments and spacecraft with dramatically reduced power and mass, and enhanced capabilities. Practical nanotechnology-based applications will require nanoscale sensors and actuators for characterization and manipulation on the molecular scale. Nanoscale mechanical structures also enable the fabrication of high-quality-factor (Q) mechanical resonators with high mechanical responsivity. Such devices can form very low-loss, low-phase-noise oscillators for filters, local oscillators, and other signal-processing applications. Carbon nanotubes exhibit a number of unique properties which make them well-suited for nanoscale sensors, actuators, and oscillators. In particular, carbon nanotubes have high mechanical strength and enable direct electromechanical transduction, because nanotube length depends on charge injection. The present effort has been focused on the fabrication and testing of prototype nanotube actuators and oscillators relevant to future NASA sensors, actuators, and computers. The major objectives of this work are summarized below.

B. PROGRESS AND RESULTS

1) Development of growth and processing techniques to control nanotube location and orientation

Practical applications of carbon nanotube-based actuators and oscillators depend on the development of growth and processing methods for control of nanotube placement and orientation. These techniques are also critical for a wide variety of other nanotube applications, including nanotube electronic systems. This subtask was aimed at development of novel techniques for controlling nanotube growth, both perpendicular to and in the plane of the substrate. The nanotube growth was done by chemical vapor deposition (CVD) using ethylene or methane at temperatures ranging from 410°C to above 900°C [1]. We have studied a variety of catalyst layers including Ti/Ni bilayers, Fe, and inorganic-based spin-on catalyst coatings. Since catalyst particle size controls the nanotube diameter and growth rate, we have recently investigated chemical synthesis techniques for production of uniform iron oxide nanoparticles. Figure 1 shows a TEM micrograph of a sample from the first Fe_2O_3 synthesis run, indicating crystalline nanoparticles with good uniformity. The initial methane growth runs with the iron oxide nanoparticles exhibit many long straight nanotubes, demonstrating that this basic process is a good approach. An example of a straight lateral nanotube, grown from chemically-synthesized nanoparticles, will be presented below. We have also studied vertical CNT growth on nanoscale catalyst dots patterned by e-beam lithography (EBL) or other techniques under a related program [1]. In addition, we have found that unpatterned sub-nm Fe layers lead to the growth of isolated near-vertical nanotubes, as will be seen in the next section. One technique for control of nanotube growth in the plane of the substrate was suggested by the observation that the nanotubes grow perpendicular to the local substrate surface. This indicates that a structure like that shown in Fig. 2a), in which a catalyst layer is capped by a refractory metal overlayer, should act to direct nanotube growth across a patterned trench. The refractory metal cap layer serves to prevent vertical nanotube growth, and also acts as an integrated metal electrode. Our initial experiments with this approach used an ethylene plasma-enhanced CVD process with Nb cap layers and Fe catalyst films. Typical results for this process are shown in Figure 2b), which is a top view of a somewhat defective nanotube bridging a 3μm-wide trench ion milled into a Nb/Fe/SiO_2 trilayer. More recently, we have discovered that much higher-quality CNT bridges can be produced using higher temperature methane growth, as will be seen in subtask 3.

2) Demonstration of a nanotube actuator based on a bimorph geometry

Because carbon nanotubes change length as a function of charge injection [2], a bimorph geometry structure (Figure 3a) can be used as a nanoscale actuator and force sensor. The basic idea is to grow single nanotubes on closely-spaced catalyst patterns with separate electrodes going to each tube. During growth, it is likely that the adjacent tubes will become attached along their sidewalls due to van der Waals attraction, as shown in the figure. Because the conductance perpendicular to the tube sidewalls is very low, this geometry should allow a significant differential voltage across the tube pair, which will result in one tube shrinking along its length, while the other tube expands lengthwise. The differential length changes produce a lateral motion of the paired tip ends as shown in Fig. 3a. Conversely, motion of the tube ends will generate a signal, so the device can act as a force sensor. We have recently taken a major step towards fabrication of a nanotube bimorph as shown in Fig. 3b. In this case, a sparse array of vertical CNTs was produced on a sub-nm layer of iron catalyst. The CNT density was high enough that bimorph configurations like that shown in the figure were quite common. While these structures do not include electrodes at this point, this is a very important demonstration of a key element of the proposed bimorph fabrication process. Future work on the nanotube bimorph will be funded by a new Code R BioNano program.

3) Demonstration and characterization of a nanotube oscillator

The primary oscillator geometry studied here was a nanotube bridge, suspended over a trench, with electrical contacts to both ends. Such a mechanical oscillator can operate with much higher-quality factors than conventional electronic resonators, and can have resonant frequencies in the GHz range for readily-achievable bridge lengths. Because the tube length depends on injected charge [2], a capacitively-coupled dc bias can be used to control the stress and resonant frequency of the suspended tube. To produce the required CNT bridge structures, we investigated high temperature CNT growth in methane, using the iron oxide nanoparticle catalysts of Figure 1 (in addition to the approach shown earlier in Fig. 2). Figure 4 is an SEM micrograph of a straight, high-quality nanotube bridge crossing a 100nm-wide SiO_2 trench patterned by e-beam lithography and wet etching. The calculated mechanical resonant frequency for this nanotube bridge *is close to 10 GHz*. This is a very important and promising initial result. To make this into a useful device structure, metal electrodes will have to be incorporated. This will occur under a new DARPA program on nanotube-based mechanical resonators, which was awarded, in part, on the basis of progress in this DRDF seed effort. The work on this subtask has resulted in two New Technology Reports listed below.

C. SIGNIFICANCE OF RESULTS

This effort developed basic fabrication processes needed for production of nanotube-based actuators and oscillators. Carbon nanotube-based actuators and oscillators promise to enable a number of important JPL applications, ranging from molecular-scale characterization and manipulation, to ultra-low-loss mechanical filters and local oscillators for communications and radar, to rad-hard, low-power mechanical signal processors. This program has demonstrated prototype nanotube actuators and oscillators and provides the foundation for a wide variety of future NASA sensors, actuators, and computers. Furthermore, this collaborative effort with Prof. Michael Roukes' group at Caltech has helped strengthen JPL-Caltech ties in the important area of nanotechnology. The progress made in this seed effort and in complementary programs has led to follow-on funding from DARPA in a new program aimed at using carbon nanotubes for high-Q resonators for signal processing applications ("High-Q Mechanical Resonator Arrays Based on Carbon Nanotubes", $2.3M over 3 years, starting 10/01). It has also contributed to the winning of new funding from the ASTID program for nanotube-based acoustic sensors ($230K, 1 year), and the NASA Code R BioNano program for development of carbon and Si nanowire biosensors ($1.3M over 3 years).

D. FINANCIAL STATUS

The total funding for this task was $150,000, all of which has been expended.

E. PERSONNEL

In addition to the people listed on the title page, other personnel active in this effort include Eric Wong, Mike Bronikowski, and Dan Choi.

F. PUBLICATIONS AND PRESENTATIONS

[1] B.D. Hunt, F. Noca, M. Hoenk "Carbon Nanotube Actuators And Force Sensors," NASA NTR, NPO-21153. (9/00), Patent application, 1/02.

[2] B.D. Hunt, D. Choi, M. Hoenk, R. Kowalczyk, F. Noca, "Pattern-Aligned Carbon Nanotube Growth," NASA NTR, NPO-30205 (3/01), Patent applic. 4/02.

[3] B.D. Hunt, F. Noca, M. Hoenk, "A Carbon Nanotube Tunable High-Q Resonator And Spectrum Analyzer," NASA NTR, NPO-30206 (3/01), Patent applic. 4/02.

[4] D. Hoppe, B.D. Hunt, M. Hoenk, F. Noca, J. Xu, "Waveguide-Embedded Carbon Nanotube Array RF Filter and RF Filter Bank," NASA New Technology Report, NPO-30207 (3/01), Patent application 4/02.

[5] M. Bronikowski and B.D. Hunt, "Regular Arrays of Carbon Nanotubes Produced Using Templates from Nano-Structured Block-Copolymeric Materials," NASA New Technology Report, NPO-30240 (5/01).

[6] F. Noca et al. "Nanotube-Based Sensors and Systems for Outer Planetary Exploration," Outer Planetary Exploration Workshop, Houston, 2/21/00.

[7] M. Hoenk et al. "Carbon-Nanotube-Based Sensors and Systems," Nanospace 2001, Galveston, TX, March 13-16, 2001.

[8] *Invited: M. Bronikowski, "Carbon Nanotube Growth by HiPCO Process," APS March Meeting, 3/01, Seattle.

[9] B.D. Hunt et al. "Nanomechanical Resonators Based on Carbon Nanotubes," Nanoscale/ Molecular Mechanics Meeting, Maui, Hawaii, 5/02.

G. REFERENCES

[1] B.D. Hunt et al., DRDF Annual Report on "Nanotube Engineering" (100656-00935, 10/02).

[2] R.H. Baughman, et al., "Carbon Nanotube Actuators," *Science,* 284, 1340 (1999).

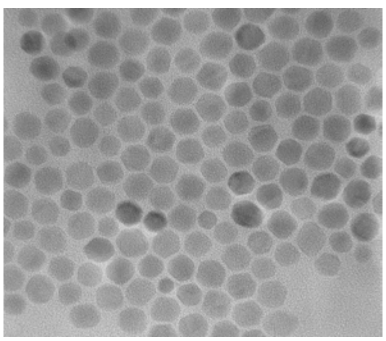

Figure 1. TEM micrograph of synthetic Fe_2O_3 nanoparticles with an average size of ~ 15 nm.

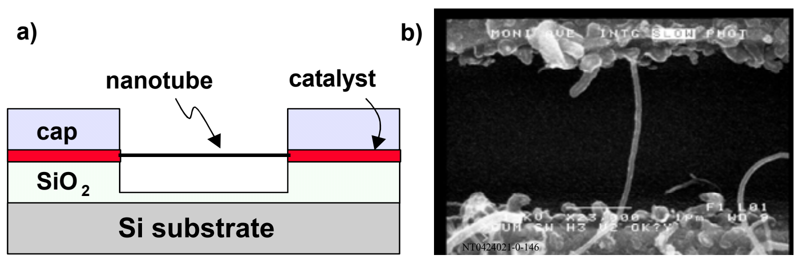

Figure 2. a) Side view schematic illustrating lateral nanotube growth from catalyst layer capped by a non-catalytic refractory metal overlayer. b) Top view of 3 μm lateral nanotube grown with ethylene PECVD process and capped catalyst structure.

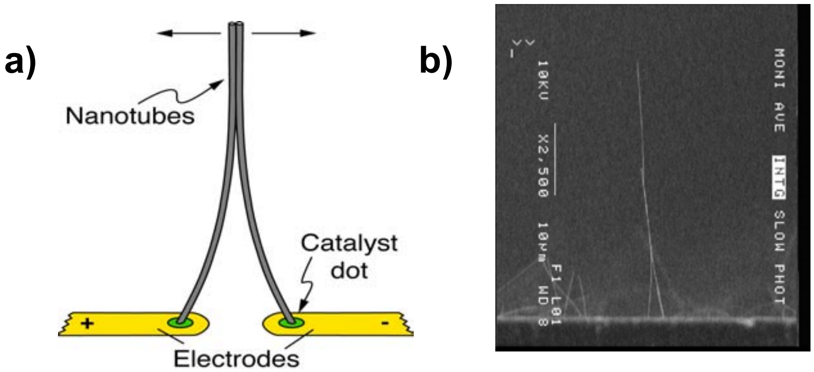

Figure 3. a) CNT bimorph force sensor and actuator. Motion of the tube ends generates a voltage, and conversely, charge injection results in deflection. b) SEM side-view micrograph of nanotube bimorph grown on sub-nm Fe catalyst layer.

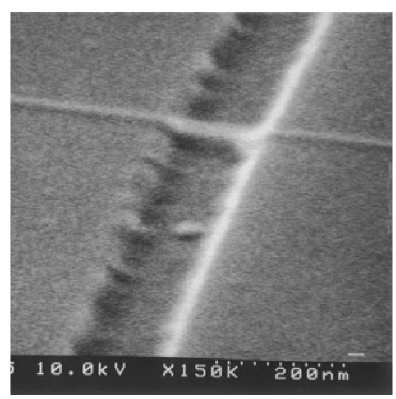

Figure 4. High quality nanotube produced by 900°C methane growth with Fe_2O_3 nanoparticles, spanning a ~100nm-wide SiO_2 trench patterned by e-beam lithography and wet etching.