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Fabrication of a rotary carbon nanotube bearing test apparatus

E H Cook¹, M S Weinberg¹, Z S Spakovszky² and D J D Carter¹

¹ Draper Laboratory, 555 Technology Square, Cambridge MA, 02139, USA
² Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge MA, 02139, USA

Email: ecook@draper.com

Abstract. Carbon Nanotubes (CNTs) are attractive elements for bearings in Micro-Electro-Mechanical Systems (MEMS), because their structure comprises nested shells with no bonding and sub-nanometre spacing between them, enabling relative motion with low friction and wear. A reliable bearing technology is critical to bringing rotating MEMS machines from laboratory demonstrations to common use. We report here the design and fabrication of a test rotor, a testing apparatus and testing attempts, and integration of CNTs with MEMS. The device improves on existing CNT bearing demonstrators by establishing a vertical bearing orientation (enabling superior rotor balance and speed, and drive mechanism placement flexibility) and a manufacturable process (employing CNTs grown in place by chemical vapour deposition (CVD)). The main outstanding challenge to demonstrating rotation is available CVD CNT quality.

1. Motivation

Micro- and Nano- electro-mechanical Systems (MEMS and NEMS) have proven effective at providing functionality similar to their larger-scale counterparts, with significant savings in cost, weight, size, and power consumption. Examples of commercially successful devices include pressure sensors, accelerometers, and inkjet printer heads. However, devices that feature moving contacts (such as micro mirror arrays or relays) are rare, and no widespread devices include rubbing surfaces. The tribological phenomena of interfacial friction and wear are responsible [1, 2] for the absence of any commercially successful devices requiring sliding motion. To overcome these issues it will be necessary to reduce friction at the interfaces, and especially to control the mechanisms that cause friction to increase over the device lifetime, with novel bearing technologies.

Recognizing the critical importance of bearing development for the future of MEMS, many have invested substantially in bearing research. From simple bushings, with parts rubbing directly on each other [3], to macro-inspired designs such as ball-bearings [4], to more complex systems such as gas [5] or liquid film bearings [6], a diverse array of approaches has arisen. While most of these solutions offer improved performance over bearing-less designs, they often come at the cost of fabrication complexity or design restrictions, and further performance improvements are desirable (figure 1).

Carbon nanotube (CNT) based bearings are a promising approach, as CNTs have long been known to exhibit low sliding resistance between adjacent walls [7] and several experimental demonstrations have been accomplished [8-13]. Other experimental work has shown that friction performance can decrease after “self-repair” of the CNT undergoing motion [14]. These encouraging properties can be
attributed to the energetically favorable and chemically stable structure of CNTs and the inability of debris to accumulate in the 0.34 nm gap between adjacent walls. Still, a quantitative understanding of the friction properties within the bearing system remains elusive [15]. Therefore, it is critical to develop a robust test article that can be used to measure CNT friction and to validate the existing friction models.

Figure 1. Performance characteristics of several small bearing technologies.

Figure 2. The rotor is supported by a cantilevered CNT, with multiple concentric shells. Cut-away for clarity.

2. Applications

The device presented here (figure 2) paves the way for a host of micromechanical devices. Any rotating mechanical device would be a candidate for miniaturization with CNT bearings. Power devices include turbines, compressors, reactant pumps, and active cooling systems. Propulsion devices such as wheels and propellers could enable micro robots. Bio-mems examples include pumps, valves, fluid shear stress control, viscometers, and centrifuges.

A few applications in particular stand to benefit significantly, such as flywheel energy storage. The energy storage density of a flywheel is limited by the strength of the flywheel material, and independent of volume. Stored energy density in silicon flywheels is comparable to batteries, but could be discharged faster. The CNT bearing could make such flywheels feasible by enabling high-speed rotation, and by providing a low-friction support that reduces unwanted energy dissipation.

The CNT bearing also has promise as a microscale rotating gyroscope. The bearing’s very low “wobble” (angular displacement of the axis of rotation, in the CNT case set by the inter-layer spacing of 0.34 nm) would reduce the dominant cause of errors in dynamically tuned gyroscopes. The high stiffness would enable high-speed operation, for improved bandwidth and sensitivity. Also, low friction suggests that the drive power to operate the gyro and associated errors could be very low.

3. Test apparatus design

Previous work showing rotary CNT bearings [8, 9] has used CNTs scattered randomly on a substrate, so that they are horizontally oriented. The devices must be made by painstakingly hand-selecting CNTs and patterning features by e-beam lithography around each one, and furthermore must be planar in shape. For the present device, a vertically oriented CNT was chosen (figure 2), enabling axisymmetric geometry to be defined lithographically.

The basis of the design is the well-known Stodola rotor model [16]. This model considers the overhung rotor to consist of a rigid disk supported on a shaft, which is treated as a classical beam element. The rigid rotor assumption is justified since the silicon rotor is two orders of magnitude thicker than the CNT axle. A more critical assumption is that the CNT can be treated in a continuum fashion,
using a classical beam model. Some \cite{17} have pointed out that molecular scale structures do not have truly uniform mechanical properties because of the quantized nature of the atoms. Furthermore, geometric features such as cross-sectional area are not well-defined for atoms. However, the CNTs used in this device are relatively large (50 or more walls) so that geometric ambiguities are less important. Furthermore, experimental investigations \cite{18} have indicated that for large tubes, mechanical properties that do not vary from tube to tube can be established with some degree of accuracy and repeatability. The Young’s modulus value from that study (1.28 TPa) was calculated from beam bending of CNTs, and is used to model CNT beam bending in the present model.

Within the envelope defined by the failure limits of the CNT and rotor, based on assumed rotor misalignments of 1 μm (from lithography) and 10° (from observed CNTs), an optimal design was selected by maximizing coast-down time, or the time the rotor would take to come to rest if given an initial spin rate. Maximum coast-down time provides the best possible precision in measuring the friction in the rotor via a coast-down experiment. Assuming a constant friction of 0.85 MPa \cite{9}, the coast-down time is proportional to both the maximum possible speed and the disk inertia, so that the maximum possible diameter of 20 μm was selected, taking into account the deflection and stress constraints, as well as fabrication limits for the CNT and the rotor disk itself. This corresponds to a disk thickness of 2 μm, a CNT length of 4 μm, and an expected coast-down time of about 1 ms, from a maximum speed of 3.2 Mrpm.

To actuate the rotor, electrostatic rotational motors \cite{3, 19, 20} were considered, and would likely be the obvious choice for eventual devices based on the bearing. They provide bi-directional actuation, uniform torque coverage, 360° actuation at high angular resolution, and precise electronic control. However, they introduce complexity, so it was decided to actuate the device using jets of air directed at blades attached to the rotor.

4. Fabrication

After thoroughly exploring the interactions of established MEMS processes with CNTs \cite{21}, a fabrication method leveraging these techniques was developed to build a CNT bearing test prototype. Fabrication begins with an isolated, vertically oriented CNT (Figure 3a), grown by CVD \cite{22, 23}. Isolated nanotubes are obtained \cite{24} by patterning the metal catalyst particles (via e-beam liftoff) to a size comparable to the CNT diameter. CNTs had diameters of 10-30 nm and lengths of 2-4 μm. With the CNT in place, a 2 μm PECVD SiO2 layer was deposited at 1 Torr and 380°C to act as the sacrificial layer. The SiO2 coats the CNT conformally. While it is possible to achieve release with a timed etch, in practice it was determined that better results can be obtained by securing the polysilicon rotor layer directly to the CNT, by removing the SiO2 around the upper portion of the CNT. This was accomplished by spin-coating a 0.5 μm layer of photoresist, which coats the flat substrate but lets the CNT protrude (Figure 3b). BOE was then used to strip the oxide from this exposed portion of the CNT (figure 3c). The polysilicon rotor layer was then deposited via LPCVD.

![Figure 3](image-url)

**Figure 3.** The fabrication process for the rotor includes CVD sacrificial and rotor layers on top of a vertical CNT, e-beam and optical lithography, and wet release etch.

A two-step lithography procedure was used to define the rotor so that a thick resist could cover the CNT protrusion, while a thin resist provided the necessary resolution. Two metal layers (Cr and Ti) were first sputtered on the sample (figure 3d). A thick negative resist (Futurrex NR-9-3000P, 5 μm) was applied, and an optical microscope was used to do the exposure at 100x magnification, 3 minute
exposure, 15 µm spot size. Contact lithography cannot be used because of the protruding CNTs. After etching the first metal layer with this thick resist mask (figure 3e), the rotor itself was then patterned using e-beam lithography (with 0.5 µm maN-2403) and the other metal layer was etched using that mask. Using the double-metal mask, the rotor was etched with a cryogenic SF6/O2 ICP-RIE process that provides smooth vertical sidewalls at this etch depth (figure 3f). Finally, the rotors were released in BOE (figure 3g). Transmission microscopy was used to monitor the progress of the release etch undercut front. The completed device is shown in figure 4.

**Figure 4.** A completed device in SEM. The central “dome” is the location of the CNT axle. The fins are for actuation via an external air jet.

**Figure 5.** The test setup is shown. The conical objects are the micro capillary tubes, blowing air onto the vanes of the rotor (center).

5. **Testing**

CNT rotors were tested by blowing air onto the rotor vanes, providing a torque. A microelectronics probe station was converted to interface with glass micropipettes (available from a medical equipment supplier) instead of electronic probes. These micropipettes with a tip orifice diameter of 5 µm can direct air at the vanes of the prototype device from opposite sides, providing a balanced torque. Given the small size of the pipettes and the sub-micrometer precision of the probe station manipulators, the tips of the pipettes can be brought within one blade length of the blades providing a jet of air to impinge on the blades (as seen in figure 5). The air to the micropipettes is supplied by a syringe pump, which provides air at flow rates from under a microliter per minute to milliliters per minute.

In order to observe any rotation, the microscope was fitted with a video recorder. To date, a successful test has not been performed. Although air has been confirmed to be flowing from pipettes (by a water submersion test), and hence a torque is applied, no motion of the rotor has been observed. The suspected reason is that the CVD-grown CNTs used in construction of prototype devices thus far have exhibited poor crystalline quality (figure 6).

To address the crystalline quality issue, we have also considered the use of arc-discharge CNTs (figure 7), such as those used in previous demonstrations [8, 9]. These CNTs are produced at much higher temperatures than CVD CNTs, (4000°C vs. 600°C) and therefore are annealed into the more energetically favourable concentric tube structure [25]. However, arc-discharge CNTs are available as individual tubes and must be manipulated and attached to the substrate before being incorporated into the device. We have used a SEM/FIB tool with integrated nanomanipulation probes to pick-and-place CNTs. The tool uses in-situ FIB-enhanced amorphous carbon deposition to weld CNTs to the probe and to the substrate, and then FIB cutting to detach. While it is possible to move and attach CNTs in this manner, it is difficult to achieve a vertical orientation because of the limited viewing angle.

Further work in improving the available CNT quality, either by manipulation of high-quality tubes into place or improving the quality of CVD-grown tubes, is required to achieve a functional prototype.

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Figure 6. A CVD-grown CNT is shown. It is thicker than a typical arc-discharge tube, and includes many structural defects.

Figure 7. An arc-discharge CNT is shown. The concentric rings are visible as lines in this high resolution TEM image. The structure is close to ideal.

References