Carbon Nanotube-Based Magnetic Actuation of Origami Membranes

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The Nanostructured Origami process has been previously developed as a method for creating nanostructured devices with a three-dimensional (3-D) geometry[1]. Furthermore, it has been shown that the nanopatterned membranes can be magnetically folded, aligned, and latched by directly patterning nanomagnet arrays onto the membranes[2]. In this work, we show that similar magnetic actuation of membranes can be achieved by directly growing multi-walled carbon nanotubes (MWCNTs) on the membranes.

For our experiment, a dense array of MWCNTs approximately 5μm in lengths were grown on 100nm thick TiN membranes using either nickel or cobalt as the catalyst as shown in Figures 1 and 2. Since a PECVD-based CNT growth method was used, the nanotubes were vertically aligned, and the catalyst material remained at the top of each nanotube. Additionally, since the catalyst tips were made of either nickel or cobalt, their magnetic properties could be utilized. For example, in the presence of an external magnetic field, each teardrop-shaped magnetic catalyst tip magnetizes to saturation and receives a torque as the field rotates. Although the torque from each nanotube is quite small, there are approximately 10^6 nanotubes on each membrane, and collectively, the magnetic torque is sufficient to actuate the entire membrane. By simply rotating the external field, the rectangular membrane shown in Fig 2 was rotated up to 180º about both the x and the y axes. Oxidation of the nanomagnet tips was eliminated due to the carbon encapsulation of the magnetic particles that resulted from the CNT growth process.

In addition to membrane actuation, the magnetic tips of the MWCNTs can be used to attract and latch two CNT-covered membranes that are in close proximity to each other since two vertically opposed MWCNTs with magnetic tips will be attracted to each other as shown in Fig 3. Once the bottom membrane in Fig 2 is rotated 180º about the x-axis and brought into contact with the other array of MWCNTs shown at the top, the membrane should adhere due to the magnetic attraction between the vertically opposed nanomagnet tips. We are in the process of finalizing the membrane magnetic adhesion demonstration, as well as characterizing this attraction force and showing that other factors (e.g. van de Waals force) are not playing a significant role. Interestingly, when two detached membranes are brought together manually, several nanotube pairs from each surface latch to magnetically stable equilibria in close agreement with theoretical results from FEMM simulations. An example is shown in Fig 3.

Our initial work with PECVD-grown MWCNTs on origami membranes shows that the magnetic properties of the nanotube tips can be used to actuate and attach not only the individual nanotubes but entire membranes that are covered by such nanotubes.

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[1] H. J. In *et al.*, Appl. Phys. Lett. **88**, 083104 (2006).

[2] A. J. Nichol *et al.,* Micro. Eng. **84**, 1126 (2007).

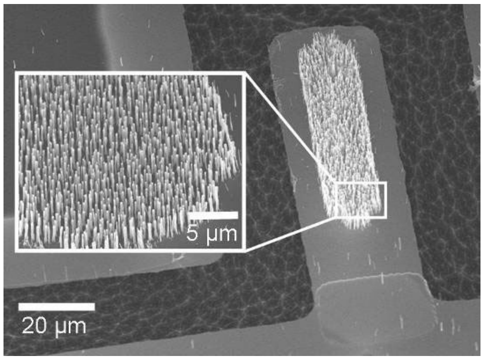

Fig 1: Ni based MWCNTs grown on a TiN membrane.

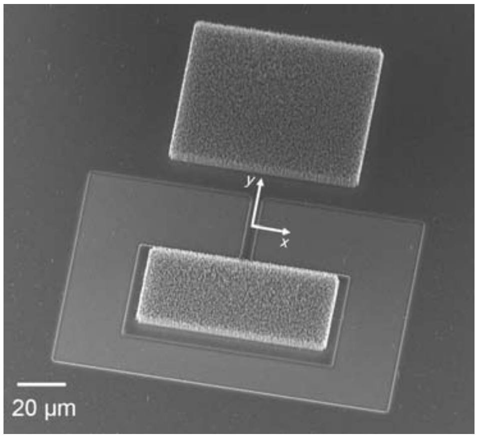

Fig 2: Co based MWCNTs grown on TiN. The rectangular flap on the bottom, once released, could be rotated 180^{o} *about both the x and the y axes in the presence of a rotating, external magnetic field.*

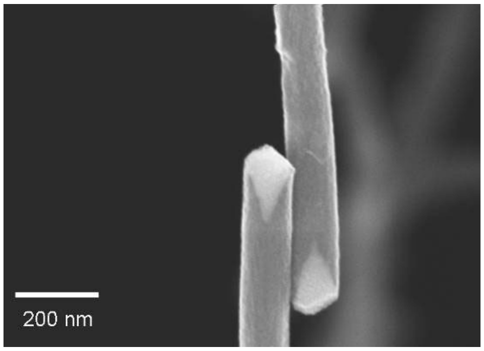

Fig 3: Two MWCNTs brought into contact under an external, vertical magnetic field. The relative vertical position is predicted by FEMM simulations.