Fabrication of robust carbon nanotube microstructures by elastocapillary densification

M. De Volder a, b, D. Vidaud a, S. J. Park a, S. Tawfick a, A. J. Hart a

a University of Michigan, Ann Arbor, MI, 48109, USA
b KULeuven/IMEC, Heverlee, B-3001, Belgium
e-mail: michael.devolder@imec.be, ajohnh@umich.edu

Keywords: Carbon nanotubes, capillary, surface tension, microstructure, densification

Carbon nanotubes (CNTs) have been studied extensively because of their outstanding electrical, mechanical and thermal properties. A common way to integrate CNTs in microsystems is to “grow” them from a catalyst layer using Chemical Vapour Deposition (CVD) [1]. The shape of the microstructures is controlled by patterning the thin catalyst layer which agglomerates to form catalyst nanoparticles. This method is particularly interesting for fabricating high aspect ratio microstructures, as the CNTs self-organize into a vertically aligned forest. Although this process is well established, the resulting CNT density per area is low, and as a result, the bulk properties of these structures are far below those of individual CNTs. Therefore, methods have been developed to increase the CNT density after growth. This research focuses on the characterisation of a densification based on capillary self-assembly. Figures 1 and 2 illustrate the CNT structures investigated in this research before and after the densification process respectively.

The capillary densification process is governed by an equilibrium between surface tension and elastic restoring forces as described in former publications [2-4]. However, no in depth studies have been published on the influence of the CNT forest dimensions on the densification factor (i.e., the initial cross section divided by the densified cross section). We also present a new method for applying small amounts of densifying liquid in a controlled fashion. This avoid the formation of fluid menisci between CNT pillars, enhances control of the densification process, and allows using more viscous densification liquids in combination with delicate micropillars. In our experiments, we used acetone, IPA, ethanol and glycerol successfully to densify CNT forests.

As illustrated in figure 3, densification factors of more than 15 are achieved for pillars with a diameter of a few tens of microns. We found that the spacing of the pillars also plays an important role since it influences both the densification factor (figure 4) and the aggregation of the pillars after the densification process. Finally, the study on the influence of the pillar length revealed that short pillars tend to form foamy structures due to the capillary interaction instead of densifying uniformly. We present a mathematical model that predicts a minimal required pillar length in order to obtain uniform densification into a void-free structure.

Finally, compression tests on the densified CNTs pillars showed Young’s Moduli up to 5 GPa, which is a 100-fold enhancement over an as-grown CNT forest (E = 54 MPa), and exceeds the performance of typical microfabrication polymers.