Carbon Nanotube Array:

Scaffolding Material for Opto-, Electro-, Thermo-, and Mechanical Systems

Carbon nanotube array, wall and forest; Photo: KEYENCE

Nanomaterials, unlike bulk materials, can be grown bottom up in a controlled manner. The ability to accurately control their behaviour and properties are a great asset for applications requiring design for reliability. Carbon nanotubes (CNTs) have a set of particular optical, electrical, thermal, and mechanical properties and thus offer very attractive and promising possibilities for a range of applications. From an academic perspective, CNTs are praised to be the next scientific discovery that would revolutionise many industrial areas, especially those in which material strength is a key property. However, from a commercial perspective, the current state of the art is not sufficient for practical applications and therefore more research is needed. Here, we present a brief overview of our research activities regarding future applications of CNTs in opto-, electro-, thermo-, and mechanical microsystems.

Carbon nanotubes (CNTs) have attracted great interest since their discovery in 1991; both from a fundamental scientific point of view and for future applications. Scientists have demonstrated extraordinary properties of CNTs, including thermal conductivity higher than diamond, mechanical strength higher than steel, electrical conductivity better than copper, and the possibility to absorb more light than super-black paint. Because of these extraordinary properties, researchers from the 'Electronic Components, Technology and Materials (ECTM)' group of Delft University of Technology (TU Delft) are investigating the use of CNTs as a building block and scaffold for enabling unique micro/nanostructures for opto-, electro-, thermo-, and mechanical applications. In this paper, several examples of significant breakthroughs that resulted from our group research on CNTs are highlighted.

Synthesis at low temperature

Catalyst nanoparticles typically require a high temperature to start the catalytic reaction for growing high density CNTs. This is undesirable when the CNTs have to be integrated on top of electronics or with polymers, as a high growth temperature can damage the existing devices. By optimizing the catalyst-support layer stack to reduce the activation energy, we achieved a record-low temperature (350 °C) wafer-scale deposition process of CNTs to make them compatible with

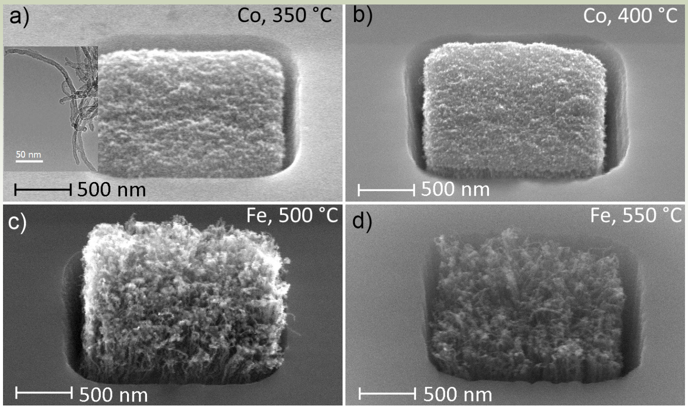

Figure 1. Holes filled with CNTs grown at different catalysts and temperatures: (a) Co, 350 °C; (b) Co, 400 °C; (c) Fe, 500 °C; and (d) Fe, 550 °C; Image adapted from [1].

standard back-end-of-line semiconductor fabrication and to allow potential integration with modern dielectrics and some types of flexible substrates. Figure 1 shows images of CNTs grown in a hole with commonly used cobalt and iron catalysts at different temperatures [1]. The average diameter of a single CNT is about 10 nm with a density in the order of 5.1010 tubes/cm^2.

Tailoring the mechanical properties

The porous nature of CNT arrays allows for the unique opportunity to tailor their mechanical response and functionality by the infiltration and deposition of nanoscale conformal coatings. CNT arrays with various thicknesses of SiC coating allow the tuning of the mechanical properties of CNT bundles over a wide range: starting from foam-like behavior to materials as hard as ceramics [2]. Simulation and experimental observations in Figure 2 have shown that a SiC coating can change the failure mode from collective buckling to fracture [3].

Investigating thermal performance

The performance of modern high-density and highly functional devices are often severely limited by overheating. Therefore, the thermal management may well be the major bottleneck of the next electronics revolution. Since carbon allotropes and their derivatives possess superior thermal properties, are inert and have low density, carbon-based nanostructured materials appear to be the most promising candidates for achieving lightweight and local heat dissipation.

In order to make a step toward the implementation of high aspect ratio CNTs as effective thermal management solution it is necessary to quantify their as-grown thermal properties. A non-destructive in situ characterization method for hierarchical structured porous materials, which combines MEMS technology, electrical characterization and high-resolution thermographic analysis, was developed [4]. Moreover, the foam-like morphology of CNTs allows the infiltration of conformal coatings within the array, achieving a hybrid composite with enhanced thermal performances [5]. Last but not the least, the CNT scaffold concept opens the route toward the application of vertical CNTs as thermal interposer. In fact, the integration of coated high aspect ratio CNTs in an epoxy molding compound demonstrates that, next to the required thermal conductivity, the mechanical compliance for thermal interface applications can be achieved [5].

Application in optical systems

CNTs are one of the blackest materials known and can absorb radiation over a broad wavelength range. Combined with optically transparent silicon rubber, this allows us to create Fresnel lenses of which the focal point can be changed by stretching [6]. The low cost and scalable manufacturability of this device provides solutions for disposable microscopes, which are valuable for health diagnostics. Figure 4 shows the fabricated device. Such flat optics find their way into miniaturized photonic chips, integrated optics, optical interconnects, beam focusing or mask-less lithography systems, but can also be used for deflecting and collimating tasks in optical sensor systems or for optical data transfers.

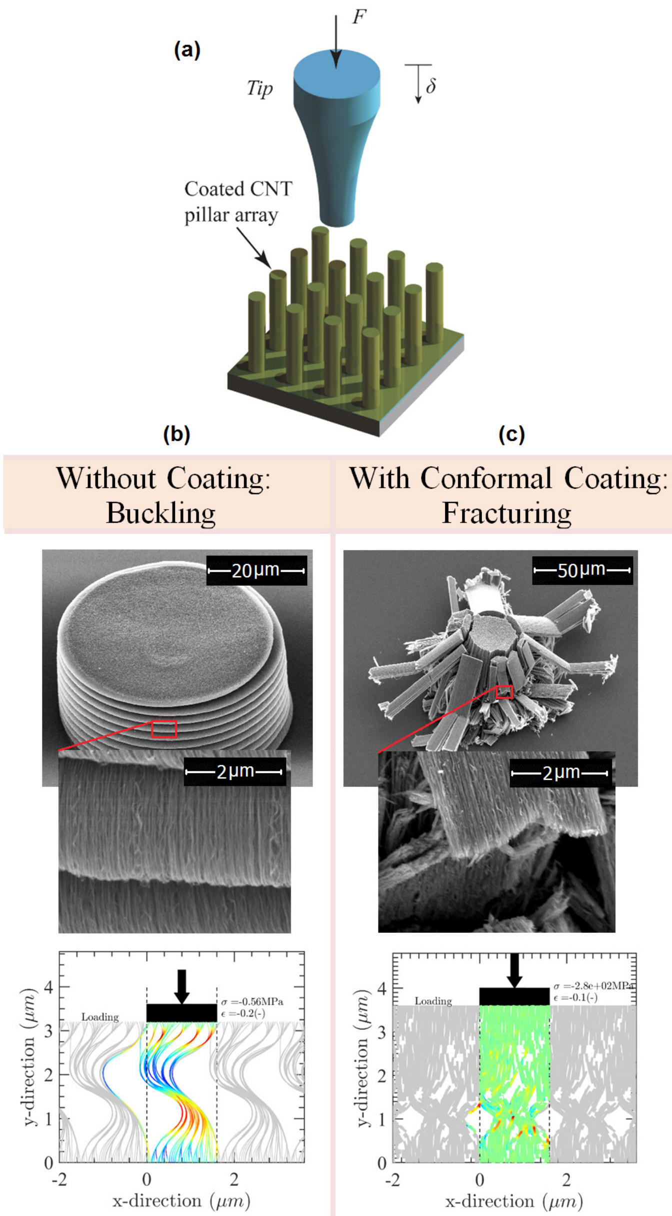

Figure 2. Mechanical compression of CNT's (a) Flat-punch nano-indentation on a vertically aligned a CNT pillar, (b) Smooth localized micro buckling on CNT pillar, (c) Fracturing deformation on a CNT pillar with 10.5 nm a-SiC coating; Image adapted from [3]

Electrical interconnect

CNTs have been proposed for many applications in integrated circuits (IC): ranging from transistors and interconnects to sensors and actuators. For these applications it is crucial to integrate CNTs directly alongside electronics. In comparison to traditional approaches using a vertical electrical interconnect access (via) through silicon or polymers, the use of CNTs can provide a higher aspect ratio interconnect with increased density. This is relevant for 3D integration of microelectronics [7]. Development of new CNT based material is of great interest for further applications. To demonstrate the potential of integrating CNT as interconnects in integrated circuits, we combine our CNT process with a 3D monolithically integrated CMOS process, to successfully realize the first 3D IC's with CNTs as vias.

Superconductor interconnect

In the research project 'Super Conducting Nanotubes', performed within the framework of the 4TU.High-Tech Materials research program 'New Horizons in designer materials', vertically aligned CNTs with a superconductor coating are proposed as a superconductive interconnect. Superconductor materials have essentially no electrical resistance below a certain critical temperature, which provides increased performance in integrated circuit devices. The foregoing trend and demand also drives a need for low-loss superconducting integrated circuits and interconnect structures which enable assembly of superconducting integrated circuits. As is also known, superconducting quantum circuits are a leading candidate technology for large-scale quantum computing. Scalable quantum bits (qubits) integration encounters significant engineering challenges in new materials, fabrication process, and connectivity between the qubits. Superconducting vertical interconnects for 3D qubits integration is in great demand for future quantum computers which require billions of qubits. Since CNTs have a very low coefficient of thermal expansion, high aspect ratio, and are less susceptible to electro-migration, they are used as a vertical interconnect in room temperature microelectronic integration. By mimicking this approach, a solution to fabricate a high aspect ratio superconductive interconnect for cryogenic temperature can be found in the conformal coating of superconductor material on vertically aligned CNT arrays. In that case, the exceptional properties of individual CNTs can provide sufficient toughness and a high aspect ratio matrix. Meanwhile, superconductor coatings not only provide the superconductivity, but can also improve the morphology and density of the CNT array, and ultimately the mechanical properties of the array. Figure 6 shows a photo-lithographically defined CNT pillar, composed of nominally vertical, interwoven, multi-wall CNTs, which are conformably coated with the superconductor material of NbTiN. The proposed structure provides a reliable superconducting interconnect suitable for use in future quantum computers and superconductor applications.

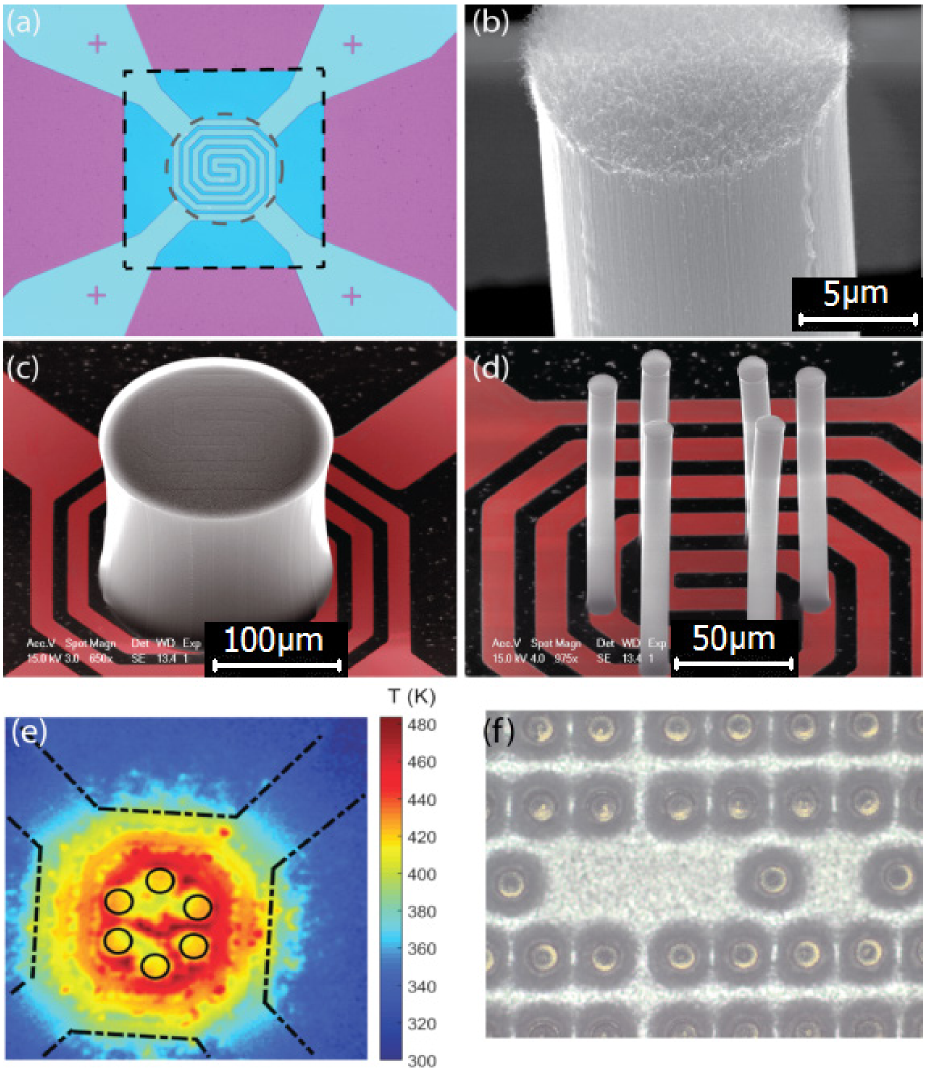

Figure 3. CNT array synthetized on top of the suspended MEMS structure. (a) MEMS structure that can be heated up by Joule heating. (b) Tip of a high aspect ratio CNTs; (c) CNTs structure called single micropin; (d) Multi-pin configuration. (e) Infrared thermal maps of the micropin configuration. (f) Thermal interposer made of coated high aspect ratio CNTs integrated in epoxy molding compound; Image adapted from [4] and [5]

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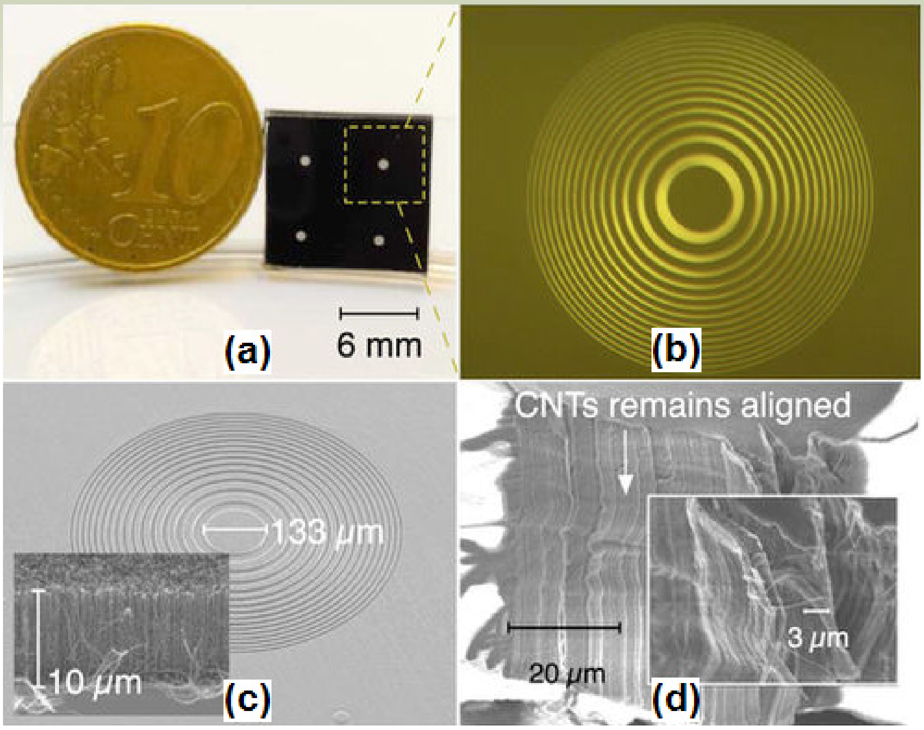

Figure 4. (a) Fabricated stretchable Fresnel lens containing 2 × 2 lens units, (b) Optical microscope image of one lens, (c) Tilted SEM image of the diffractive CNT pattern, the inset shows a close up view of the vertically aligned CNT, (d) SEM image of the CNT with the PDMS percolated thoroughly into the CNT bundles; Image adapted from [6]

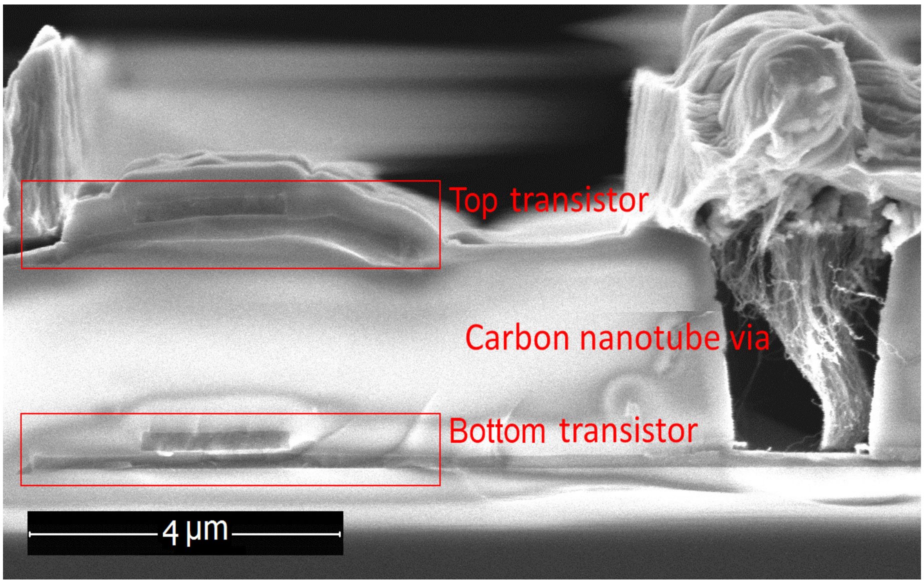

Figure 5. Wafer containing the 3D devices: cross-section of two-layer showing the active areas and CNT via; Image adapted from [7]

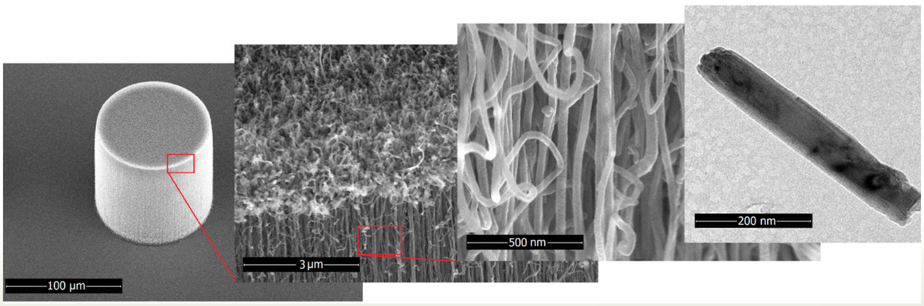

Figure 6. Coated CNT pillar as a superconductor interconnect

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Parts of this research have been performed within the framework of the 4TU. High-Tech Materials research program 'New Horizons in designer materials' (www.4tu.nl/htm).

The project page can be found here:

https://www.4tu.nl/htm/en/new-horizons/super-conducting-nanotubes/