Inkjet printing of carbon nanotube arrays at low density for CMOS-compatible fabrication of nanoscale transistors

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Continuous miniaturization of electronics brings the dimensions of the key devices, Si transistors, well into the nanoscale [1]. There are several challenges emerging at these scales due to random dopant distribution, leakage currents or uncontrollable fabrication. Carbon nanotubes (CNTs), such as single-wall CNTs, have been widely explored as an alternative for future organic electronics, specifically because of their outstanding transport properties, nanoscale dimensions and flexibility [2]. By implementing suitable fabrication techniques, SW-CNTs can be also regarded as suitable transport channels on CMOS-compatible platforms.

CNTs are generally grown or deposited by solution processing, by approaches that do not allow a suitable control of CNT density and/or local positioning. Further manipulation of CNTs is required to achieve more controlled distributions that can be used for device fabrication. Here, we further explore a pathway of using inkjet printing technology for locally depositing low-density SW-CNT arrays, aiming to design CMOS-compatible CNT-devices.

As a first stage for inkjet printing, we optimized the homogeneity and dispersion conditions of SW-CNTs from dimethylformamide (DMF) solutions. It is known that obtaining a stable solution for a suitable dispersion is critical, since the van der Waals attractive forces between the CNTs can lead to the formation of nano-bundles, ropes, or agglomerates [3]. By long-time sonication, a good homogeneity of the solution was achieved, and conditions for drying on the Si/SiO_2 surfaces, as well as Al surfaces, have also been analyzed.

A second stage is to analyze inkjet-printing conditions by FE-SEM measurements. For this analysis, **Fig. 1** shows a comparison between CNT-solutions deposited by pipette dropping (without control), as shown in **Fig. 1(a)**, and deposited by inkjet printing, as shown in **Fig. 1(b)**. It can be clearly seen that a complex network of CNT-structures is formed on a large area by pipette dropping, while a localized array of CNT-structures can be formed on an area with dimensions on the order of a few µm by inkjet printing with optimized conditions. In both cases, the underlying surface is a thin SiO_2 layer, thermally grown in cleanroom conditions.

A next stage consists in depositing CNT-solution in a nanoscale gap (with dimensions on the order of 300-1000 nm), formed by Al lift-off process using electron-beam lithography. **Fig. 1(c)** shows an example of such a nanoscale Al gap (with Al thickness of ~100 nm), with CNT-solution deposited by inkjet printing. It can be observed that a low-density array of CNT-structures (likely CNT-bundles) is formed. As marked in the image, only a few CNT-structures bridge the two Al electrodes, potentially contributing to transport. Further optimization of the solution (solvent, homogeneity, drying conditions), as well as of the inkjet printing, can allow an even more precise deposition of CNTs on CMOS-compatible structures (Al/SiO_2/Si stacks).

It can be expected that these results provide a facile pathway to design hybrid organic-inorganic electronic devices for future generations of electronics and for sensing applications.

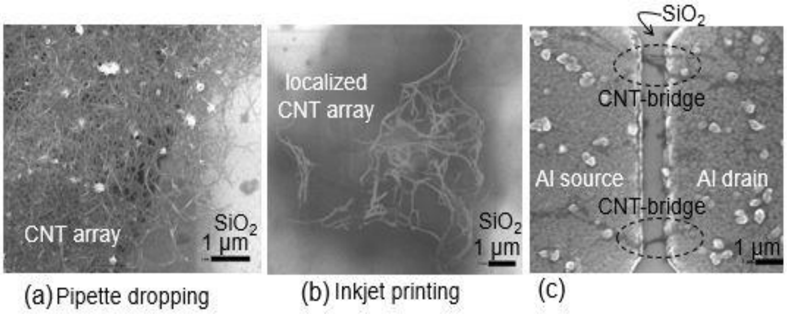

Fig. 1 FE-SEM images of CNT-structures from DMF-solution deposited in various configurations: (a) by pipette dropping on SiO_2; (b) by inkjet printing on SiO_2; (c) by inkjet printing in an Al gap, with a few CNT-structures bridging source and drain electrodes.

References [1] M. M. Waldrop, Nature **530**, 144-147 (2016). [2] R. Saito *et. al*, “Physical Properties of Carbon Nanotubes”, Imperial College Press, London (1998). [3] R. P. Tortorich and J. W. Choi, Nanomaterials **3**, 453-468 (2013).