Wafer Level Assembly of Single-Walled Carbon Nanotube Arrays with Precise Positioning

J. Cao, A. Arun, K. Lister, D. Acquaviva, J. Bhandari, A. M. Ionescu

Ecole Polytechnique Fédérale de Lausanne, Nanolab
CH-1015 Lausanne, Switzerland, ji.cao@epfl.ch

ABSTRACT

A novel wafer level assembly method to fabricate Single-Walled Carbon Nanotube (SWCNT) arrays with precise positioning of the individual SWCNT by dielectrophoresis (DEP) is proposed and validated. Unlike previous CNT assembly performed directly between the guiding electrode pairs, in this work, by means of patterned trenches in some unique "sandwich"-like resist layers, super-aligned SWCNT arrays with controllable density and location can be achieved on various electrode dimensions and geometries. We demonstrate very high densities (~100 million/cm^2) of doubly clamped suspended SWCNT arrays, which is two orders of magnitude higher than earlier works. This self-assembled technique could enable a precise positioning with deep sub-micron control at the wafer level for the fabrication of future NEMS devices, such as SWCNT resonator arrays for RF or sensing applications.

Keywords: SWCNT array, assembly, precise positioning, dielectrophoresis, SWCNT resonator

1 INTRODUCTION

Single-walled carbon nanotubes (SWCNTs) have been intensively studied as a potential building block for future Nano-Electrical-Mechanical-System (NEMS) [1], owing to their unique mechanical and electrical properties [2], e.g., high Young's modulus and good conductivity. Despite significant research in this field, the controllable and precise integration of SWCNTs into underlying silicon NEMS circuitry at the wafer level still remains a great challenge for the engineering applications of CNTs [3].

Two methods of manipulating CNTs have attracted significant research interests: the directed CNT growth onto a desired location [4] and the deposition of CNTs by dielectrophoresis (DEP) between guiding electrodes [5]. The dielectrophoresis technique was first brought into SWCNT manipulation by Krupke *et al.* [6, 7]. Dielectrophoresis has already proven its potential for the fabrication of CNT-integrated microchips for relatively simply structured NEMS, in which two opposing electrodes build the interface for the connection between CNT and NEMS. Many efforts have been made to develop this method till now. The simultaneous and site-selective deposition of single SWCNT bundles onto a large number of contacts was reported [8]. Recently, A. Vijayaraghavan et al. presented directed and precisely assembled SWCNT arrays by applying dielectrophoresis to capacitively coupled electrodes [9]. Although inspiring progress has been made, present approaches still lack the desired controllability in the arbitrary positioning of SWCNTs, the higher density, the uniformity over large scales and the flexibility to complex structural configurations on substrates, all of which are essential for complex CNT based NEMS.

To address this issue, we propose a novel approach of fabricating well-aligned assembled dense SWCNT arrays with precise positioning of individual SWCNT with high uniformity and reproducibility simply by dielectrophoresis. Instead of performing CNT deposition directly on electrodes as reported earlier [6-8], both single and highly dense parallel SWCNT arrays can be assembled uniformly on electrodes with flexible dimensions and geometry by means of defining patterned trenches in the "Sandwich"-like resist layers. This is of great importance since various applications have different criteria for the desired device characteristics, e.g., some demanding high density while others requiring high current drives. The proposed method gives access to a wider range of electronic device structures based on SWCNTs.

Meanwhile, clamped-clamped SWCNT arrays with very high densities (beyond 100 million devices per square centimeter) are successfully fabricated; this density is about two orders of magnitude higher than the previous work [8], with a yield of at least 85%. This versatile assembly strategy also leads the way to a wafer-level uniform fabrication of future NEMS RF devices. Two typical super-aligned SWCNT resonator arrays for RF or sensing applications are demonstrated.

2 DESIGN AND FABRICATION

The SWCNT suspension used in the experiment is prepared by dispersing commercially available SWCNTs in deionized (DI) water with Sodium Cholate Hydrate (1%wt) as surfactant. The assembly of SWCNT was performed on a test wafer in a simple experimental setup under ambient conditions with CNT suspension following the process flow described in Figure 1.

First, Chromium/Platinum guiding electrodes were patterned by a metal lift-off process on a (100) Si substrate protected by 500nm dry oxide (Figure 1a). The substrate was then coated with a thin photoresist layer and a thin e-

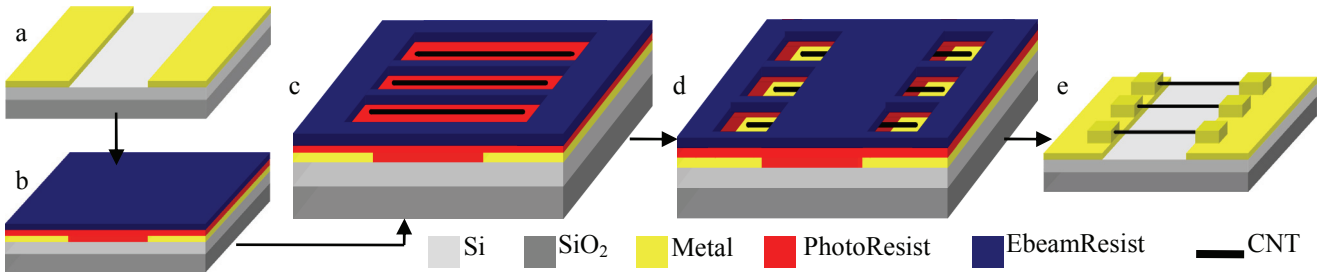

Figure 1: Bottom-up integration scheme used to fabricate suspended SWCNT arrays. a), Guiding electrodes are patterned. b), A photoresist layer and an e-beam resist layer are coated. c), Dielectrophoresis is applied to preferentially align single SWCNTs in trenches patterned in the e-beamresist layer. The photoresist thickness determines the SWCNT suspended height. d), Metal clamp windows are defined in a second e-beamresist layer. e), Metal clamps are deposited around the SWCNT tips. The resists are dissolved to suspend the clamped SWCNTs and lift off misaligned ones (unclamped).

beamresist layer (Figure 1b). Arrays of trenches with a typical width of 100nm were transferred to the e-beamresist layer by e-beam lithography, exposing the photoresist layer.

Then, dielectrophoresis [10] is applied to deposit SWCNTs in the trenches (Figure 1c). SWCNTs are attracted to the sample surface and aligned along the electric-field gradient by long-range dielectrophoretic forces. By stronger local electric field and capacitive forces in the trenches, SWCNTs were further preferentially aligned and centered in the trenches. The SWCNTs were retained in the trenches by capillary forces produced during evaporation of the suspending liquid within each trench. The metal clamp windows were defined on a second e-beamresist layer by e-beam lithography and by dissolving the resists on the unmasked metal electrodes region (Figure 1d). The final metal clamps were deposited by another metal lift-off. Lastly, the double clamped SWCNTs were released by stripping the resists and by using a critical point dryer (Figure 1e). Misaligned SWCNTs outside the trenches were lifted off at the same time.

3 RESULTS AND DISCUSSION

3.1 Experimental results

The alignment of SWCNTs was imaged by Scanning Electron Microscopy (SEM). The standard electrical transport characterization of the clamped-clamped SWCNTs is carried out by means of the Cascade probing system and the Agilent 4156C analyzer. During electrical transport measurements, one Cr/Pt electrode served as the source and the other as the drain. The Si substrate was used as the gate electrode.

Figure 2a shows an individual SWCNT or a small SWCNT bundle (diameter<4nm) placed precisely in a pre-defined 100nm wide trench on the resist layers with nanometer precision by means of this self-assembly method. The trapped SWCNT or the small SWCNT bundle is fixed by a pair of Pt clamps after a second metal lift-off (Figure 2c).

The dielectrophoresis duration decides the amount of SWCNTs in each trench. The longer the dielectrophoresis is performed, the more SWCNTs will be attacted per trench. With the same SWCNT suspension concentration, by applying V_{ac} for additional 25s, one more SWCNT was deposited in each trench (Figure 2b). Figure 2d corresponds to the 2 SWCNTs / trench case after metal clamp deposition.

Furthermore, the higher the SWCNT suspension concertration is, the more SWCNTs will be trapped per trench with the same dielectrophoresis duration and applied voltage. Thus, it is more controllable to undertake the SWCNT assembly by relatively lower SWCNT suspension concertration.

Simply by adjusting the number and interval of the trenches on top of the guiding electrodes, uniform assembly of SWCNT devices with an arbitrary density is feasible at the wafer level.

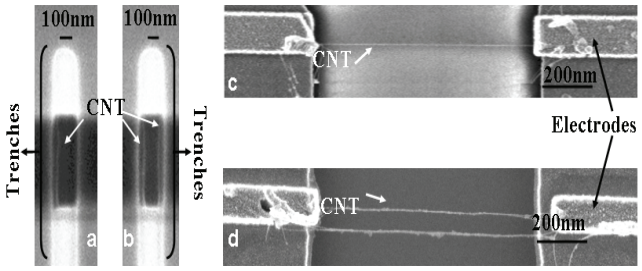

Figure 2: SEM pictuures of: 1.SWCNTs in a trench before (a,b) and after clamp deposition (c,d);
2.Effects of dielectrophoresis duration on the amount of SWCNTs aligned by a pair of electrodes.
a, c: One SWCNT deposited after 45s (8 V_{pp}, 5 MHz);
b, d: Two SWCNTs deposited after 70s (8 V_{pp} , 5 MHz).

Figure 3 show the representatives of large-scale aligned arrays with individual SWCNTs brigding each metal clamp

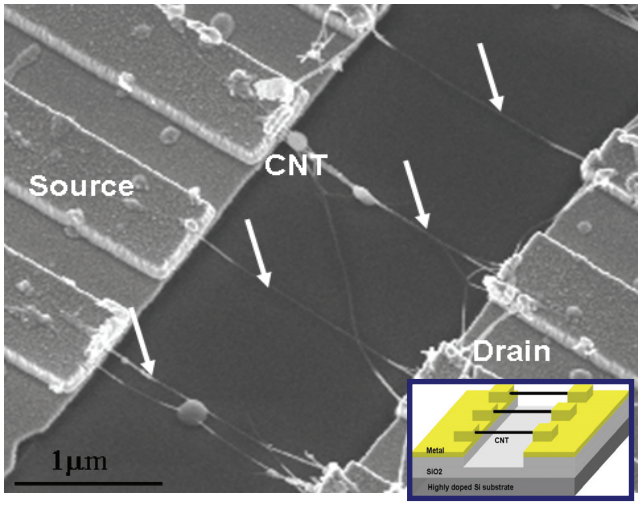

Figure 3: Four adjacent (1μm spacing) highly doped substrate bottom gate SWCNT resonators (device schematic shown in insert) shown as the representative of the whole array, with each electrode pair bridged by mostly one SWCNT or a small SWCNT bundle.

pair with no misalignment. We observe high yields (over 85%) of the well-aligned metal clamp pairs spanned by single SWCNT or single small SWCNT bundle in arrays. Even higher yields and better quality are expected by using more optimized and uniform SWCNTs and adjusting the dielectrophoresis duration with proper suspension concerntration.

High density of SWCNT arrays was achieved with arbitrary metal clamp spacing (500nm in Figure 3). According to the dimensions of the electrode gap between each metal clamp (2um), the width of a metal clamp (100nm) and the interval between adjacent metal clamp pairs (1um), a ultra-high density of more than 100 million SWCNT devices per square centimeter was demonstrated, two orders of magnitude denser than the previous work. In fact, the metal clamp interval is even arbitrary, which makes the potential array density higher and this techinque more flexible for NEMS applications.

The ability to uniformly assemble highly dense parallel arrays of SWCNTs on substrates in large-scale meets various application criteria for device characteristics. The proposed technique enables a robust way for fabricating and exploring a broad field of SWCNT electronic devices.

3.2 I-V characteristics

To confirm that the devices fabricated by the proposed method are electrically active and robustly assembled, we used the Cascade probing systems to contact the individual electrode pairs (100μm x 50μm) and the Agilent 4156C analyzer to measure the electronic transport through the individually accessible SWCNT-electrode pairs. All SWCNTs on the sample were suspended by BHF etching for 1 min and dried by a critical point drier (CPD).

Over 60 pairs of bridged electrodes pairs were measured and all of them turned out to be functioning devices, indicating the reliability of our self-assembly technique. The smaller electrodes (~150nm x 3μm) were too small to be probed by our probing systems for electrical characterization. Figure 4 shows source-drain current (I_{DS}) vs. voltage (V_{DS}) of a semiconducting SWCNT with gate grounded. Semiconducting SWCNTs show nonlinear I-V curve due to the Schottky barrier at the CNT-metal contact and and its dependence on the substrate bias (acting as a transistor gate).

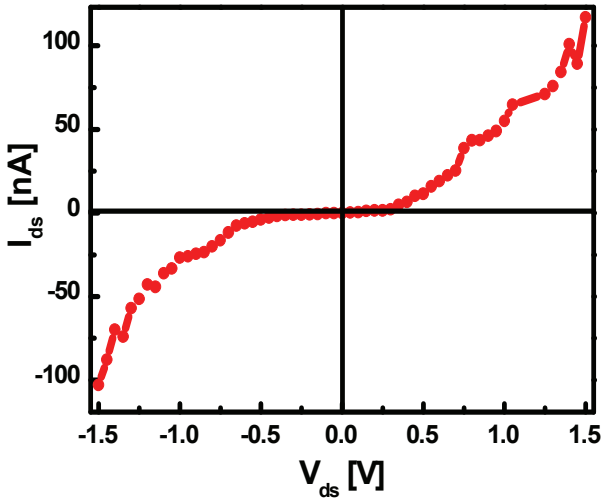

Figure 4: Nonlinear I-V characteristics of the semiconducting SWCNT in Figure 3, due to the Schottky barrier at the CNT-metal contact and dependence on substrate bias.

It is proved that typical contact resistances of our SWCNT bridging devices range from 0.5-3MΩ, which means the contact between SWCNT and evaporated metal clamp is of good quality. Improved contacts can be achieved by annealing the devices at 200°C for around 2h to improve the interfaces between the CNTs and the metal.

3.3 SWCNT resonator arrays

The proposed assembly approach enables the fabrication of ultra-dense well-aligned SWCNT NEMS devices for RF and sensing applications, such as clamped-clamped SWCNT resonator arrays. Two types of doubly clamped SWCNT resonator arrays with different gate configurations were demonstrated.

Figure 3 shows four adjacent well-aligned SWCNT resonators with highly doped Si substrate as back gate, as representatives of the whole dense array. Figure 5 shows four neighboring self-aligned SWCNT resonators with metal bottom gate, as representatives of the whole parallel

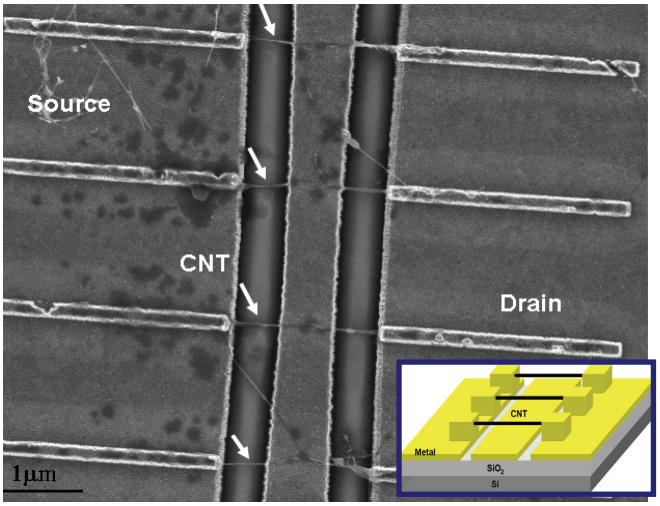

Figure 5: Four adjacent (1.5μm spacing) metal bottom gate SWCNT resonators (device schematic shown in insert) shown as the representative of the whole array, with each electrode pair bridged by one SWCNT or a small SWCNT bundle.

array. Most of the resonators are spanned by a single SWCNT or a small SWCNT bundle. As the proposed process can be carried out at die or wafer level, a yield of ~85% is observed in both SWCNT resonator arrays.

4 CONCLUSIONS

In conclusion, we have proposed a novel wafer level self-assembled technique for fabricating both single SWCNT and ultra dense SWCNT arrays with precise positioning and with individual and reproducible clamps by dielectrophoresis. Combing the four mechanisms: long range and local electric-field forces, capillary forces and SWCNT lift-off, high-yield positioning of SWCNT arrays with ultra-high density (>100 million SWCNT devices/cm^2), two orders of magnitude higher than previous reports, were successfully realized. The SWCNTs are proved to have reliable contacts to the clamping electrodes. In addition, arrays of two typical SWCNT resonators were fabricated, exhibiting the potential of our method for integrating SWCNTs for NEMS applications. Also, the method described in this report is very versatile as it is fully compatible with silicon-based microelectronics fabrication technologies and a variety of pre- and post-processing micro-fabrication techniques. At the wafer level, this approach allows for the self-aligned fabrication of large-scaled individually addressable SWCNT devices for future RF and sensing commercial applications.

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