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Fabrication of self-aligned side gates to carbon nanotubes

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Abstract
We have fabricated self-aligned, side-gated suspended multi-walled carbon nanotubes (MWCNTs), with nanotube-to-gate spacing of less than 10 nm. Evaporated metal forms an island on a suspended MWCNT, the island and the nanotube act as a mask shielding the substrate, and lift-off then removes the metal island, leaving a set of self-aligned side gates. Al, Cr, Au, and Ti were investigated and the best results were obtained with Cr, at a yield of over 90%.

1. Introduction

The mechanical properties of carbon nanotubes (CNTs) make them ideal candidates for nano-electrical mechanical system (NEMS) applications [1–4]. Most of the proposed NEMS applications of CNTs, such as nano-tweezers [2], nano-bearings [3] and nano-actuators [4], require the nanotubes to be suspended above the supporting substrate. For electrical access and control of the suspended CNT structures, a method of placing individual control electrodes with nanoscale precision is required. Top gates are often not appropriate for such applications as the insulator makes direct contact to the CNT. A better choice would be a precisely aligned side gate. However, current lithographic alignment techniques, although sufficient for making contacts, do not allow alignment of gates with sufficient accuracy. This paper addresses this alignment problem for side-gating CNTs, and presents a method for self-aligning side gate electrodes to multi-walled carbon nanotubes (MWCNTs) with nanotube-to-gate spacing of less than 10 nm. The method used is similar to that shown in [5] where a CNT is used as an evaporation mask to make small gaps in an evaporated metal.

CNT-based devices require good electrical contact between the CNT and contacts and an efficient way to modulate the properties of the device. Electrical devices are usually modulated via the presence of a local electric field by placing a gate in close proximity to a CNT. As CNTs cannot be imaged in conventional electron beam lithography (EBL) machines, it is difficult to make precisely aligned contacts and control electrodes.

There are two main methods for making contacts and aligning gates to CNTs. In the first method, CNTs are randomly dispersed onto a substrate that contains a grid of alignment marks (sets of metal crosses with known dimensions and separations). The chip is then imaged to find a suitable CNT. Following this, the position of the selected CNT is mapped in relation to the alignment marks. These coordinates are then used in conjunction with the alignment marks to write contacts to the mapped CNT using EBL.

In the second method, a CNT is grown in a specific location on a substrate associated with specific alignment marks. These alignment marks are then used to position the contacts to the CNT. The second method removes the mapping requirement present in the first method, but requires growth equipment. Both methods are limited by the accuracy of the position of a CNT as defined by the alignment marks. The alignment marks are limited by the electron beam (EB) spot size. The EB spot size used in this work was 80 nm.

The precise alignment of contacts is generally not as stringent as that needed for placing side gates alongside a CNT. The closer the gate to the CNT, the higher the efficiency of the gating and the smaller the region of the CNT the gating effect

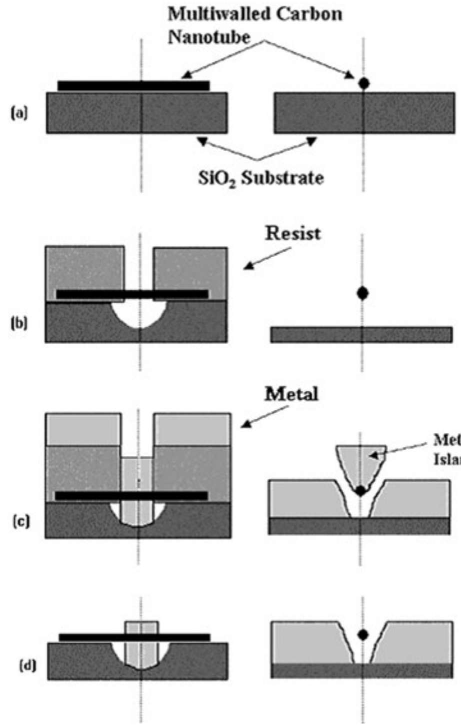

Figure 1. Fabrication steps used for generating self-aligned side gate structures. Two different 2D cross-sections are presented. The nanotube is shown out of proportion. (a) A solution of MWCNTs in chlorobenzene was spun onto a silicon dioxide substrate containing alignment marks. Appropriate tubes were then mapped in relation to the alignment marks. (b) PMMA was spun onto the chip and EBL was used to write lines into the resist. The SiO_2 substrate was etched with SILOX, leaving the MWCNT suspended. (c) Metal is evaporated onto the chip. (An island of metal forms on the suspended nanotube visible in the right cross-section.) (d) Lift-off in acetone removes the metal island, leaving a set of self-aligned side gate electrodes.

will be confined to. Top gates are an alternative method for placing gates in close proximity to a CNT, but they have a disadvantage in that they make contact with the CNT, which can modify the properties of the CNT. Hence side gates have an advantage over top gates in that they do not actually make contact with the CNT, as there is an air gap between the tube and the side gate.

This paper presents a technique for placing self-aligned metallic side gates in very close proximity to a MWCNT without the need for precise alignment. The paper shows that Cr gates can be placed routinely with 10 nm spacing between gates and the CNT.

2. Self-aligned split gate fabrication

As-prepared arc discharge MWCNTs with a diameter of 10 nm and an average length of 2 μm were used. The substrates used had a 400 nm oxidized silicon surface. The MWCNTs were dispersed in chlorobenzene at a concentration of $\sim$0.0001 g ml^{-1} and the solution was sonicated for 10 s in order to facilitate dispersion of the tubes. Approximately five drops of the solution were successively spun onto a 5 mm $\times$ 5 mm chip (containing alignment marks) at 6000 rpm with $\sim$10 s delay between each drop. The chip was then imaged

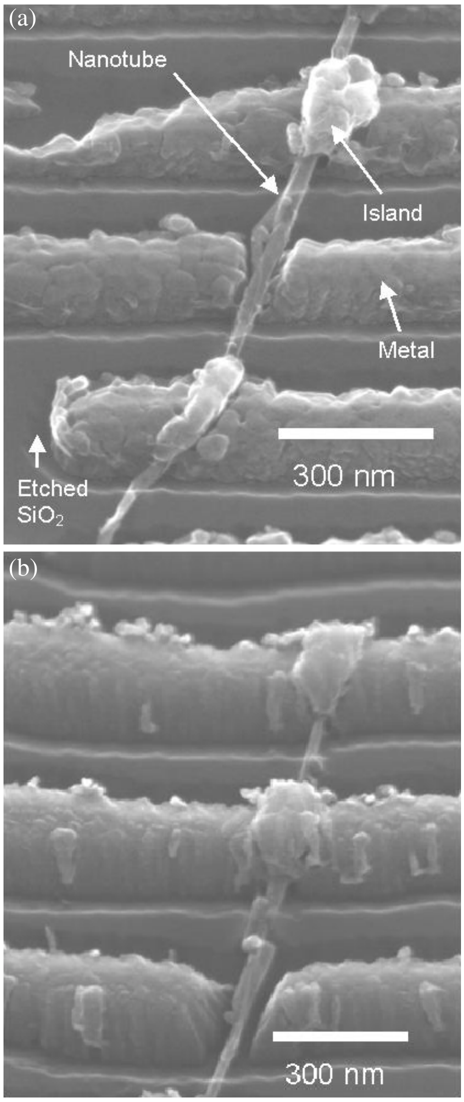

Figure 2. (a) Three horizontal Al lines have been evaporated over a suspended MWCNT. The MWCNT is running from top right to bottom left and is suspended near the Al lines. At the top and bottom Al–MWCNT junctions, Al islands are present on the MWCNT, whereas in the central junction no island is present and a self-aligned side gate structure is formed. (b) Three horizontal Ti lines are seen in this micrograph. The bottom line has formed a self-aligned side gate structure with the vertically orientated MWCNT. Ti seems to form a higher percentage of self-aligned side gate structures than Al. The metal has grown in a columnar fashion, which may facilitate the lift-off of the metal island that forms on the nanotube.

in a scanning electron microscope (SEM), and appropriate MWCNTs were mapped in relation to alignment marks. This process is represented in figure 1(a). Electron beam resist (PMMA) was then spun onto the chip at 5000 rpm for 30 s and baked for 30 min at 180 °C. Where self-aligned side gates were required, 200 nm lines were written into the resist. The chip was developed in 2:1 MIBK:IPA for 10 s.

To suspend the MWCNT the chip was wet-etched in SILOX for 60 s. The SILOX removed part of the SiO_2 layer in an isotropic manner, leaving the MWCNT undercut as seen in figure 1(b). The etch rate was around 80 nm min^{-1} at room temperature. Metal was then evaporated onto the chip from a point source at a rate of 0.1 nm s^{-1} and at a pressure of

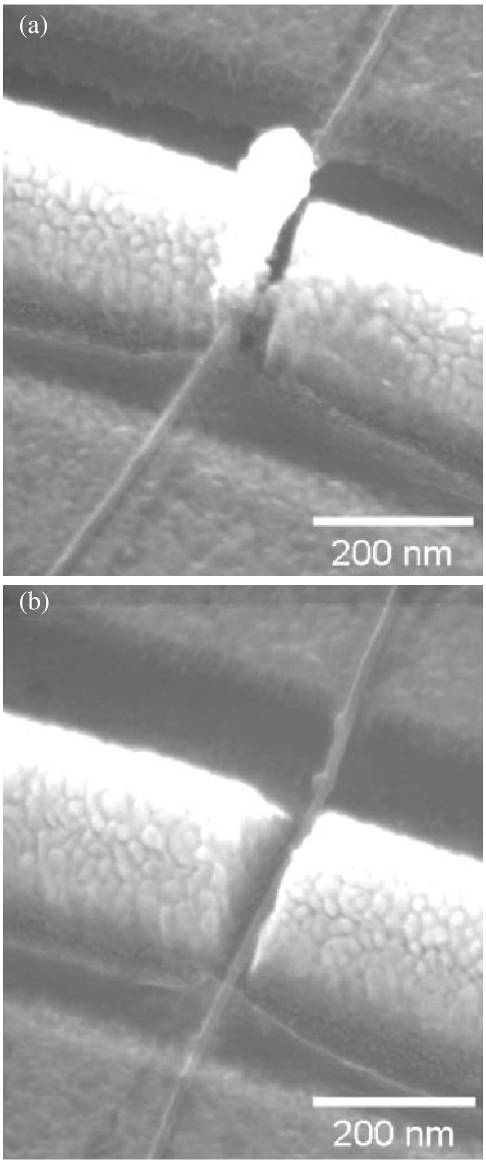

Figure 3. (a) An island on a CNT inside a 20 nm gap formed in 300 nm thick Au wire. (b) CNT inside a 20 nm gap formed in 300 nm thick Au wire.

$\sim 8 \times 10^{-7}$ mbar. In this process an island of metal forms on the suspended nanotube; the island and the nanotube act as a mask, shielding the substrate, as seen in figure 1(c). Following this, lift-off is then performed in acetone. Lift-off removes the island, and leaves a set of self-aligned side gate structures, as seen in figure 1(d).

3. Results and discussion

SEM images of metal deposition on MWCNTs are shown in figure 2. When the evaporated lines of metal running over a suspended MWCNT are analysed, some of the lines were discontinuous; the metal forms an island on the tube, and this island appears to be distinct and separated from the bulk metal deposited around the tube. In many cases the isolated island of metal is removed in the lift process, leaving a pair of self-aligned side gates to the MWCNT.

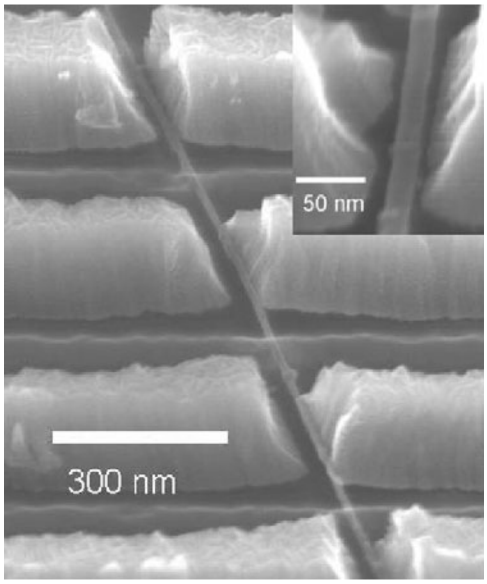

Figure 4. Chrome was the most successful metal for the creation of self-aligned side gates. The nanotube is running from top left to bottom right. Four 200 nm horizontal self-aligned Cr side gates are seen. The inset in the top right corner highlights the small nanotube-to-gate spacing.

The formation of these self-aligned side gate structures was investigated for Al, Ti, Au and Cr, with evaporated metal thickness of around ∼100 nm. The following results were found. In Al, seen in figure 2, only a small fraction of the evaporated metal lines have formed self-aligned side gates. This may be a result of Al's large grain structure; it may also be due to insufficient suspension of the MWCNT above the substrate. When Ti was evaporated over a suspended MWCNT a large fraction of the junctions between the tube and metal formed successful self-aligned side gate structures. The deposited metal grew in a columnar fashion (see figure 2(b)), which may have facilitated the lift-off of the metal island that forms on the MWCNT.

When Au was evaporated, a high percentage of self-aligned side gates formed. The mechanism that allows their formation can be easily understood from figure 3. The MWCNTs were well suspended above the substrate, and acted as an evaporation mask. In figure 3(a) an isolated island can be clearly seen and a similar structure with the island removed is seen in figure 3(b).

Chromium produced self-aligned side gates in over 90% of cases. A distinct granule structure is not clearly visible in Cr; the metal surface appears smooth with clean edges and sides. The Cr around the MWCNT appears to lift-off from the substrate seen in figure 4; this may facilitate removal of the nanotube metal island. If the success of Cr is largely a result of the compression it is placed under after evaporation, then it could be speculated that AuPd may also be a candidate metal for self-aligned side gates.

There are three main factors likely to contribute to the successful formation of self-aligned side gates. First, metal landing on the nanotube will shield the substrate due to a point source evaporation. Second, the metal grain structure grows predominantly vertically, as a result of which the metal island on the nanotube is unlikely to join the metal on the substrate. Third, island removal should be relatively simple as the nanotube metal–island contact area is small. The shielding process is visible in figures 1(d) and (e) and further highlighted in figures 3(a) and (b).

The differences in self-aligned side gate success rate for different metals could be attributed to the variation in binding energies between the metal atoms and carbon MWCNTs [6]. The differences in binding energies could lead to different island growth characteristic and different island lift-off energies.

4. Conclusions

Metal evaporation produces an island on a suspended MWCNT, the island and the nanotube act as a mask shielding the substrate, lift-off then removes the metal island, leaving a set of self-aligned side gates. These self-aligned side gate structures can be fabricated in Cr with nanotube-to-gate spacing of less than 10 nm, and with more than 90% efficiency. We expect that this technique could be applicable to a range of different suspended nanotube and nanowire structures.

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