Suspended Multiwalled Carbon Nanotubes as Self-aligned Evaporation Masks

S.-B. Lee,[a,b,*] L. A. W. Robinson,[b] K. B. K. Teo,[c] M. Chhowalla,[c] G. A. J. Amaratunga,[c] W. I. Milne,[c] D. G. Hasko,[b] and H. Ahmed[b]

[a] *Department of Nanotechnology, Hanyang University, Seoul 133-791, Korea*
[b] *Microelectronics Research Centre, Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, United Kingdom*
[c] *Engineering Department, University of Cambridge, Cambridge CB2 1PZ, United Kingdom*

RESEARCH ARTICLE

We describe the nanofabrication study of self-aligned electrodes on suspended multiwalled carbon nanotube structures. When metal is deposited on a suspended multiwalled carbon nanotube structure, the nanotube acts as an evaporation mask, resulting in the formation of discontinuous electrodes. The metal deposits on the nanotubes are removed with lift-off. Using Al sacrificial layers, it was possible to fabricate self-aligned contact electrodes and control electrodes nanometers from the suspended carbon nanotubes with a single lithography step. It was also shown that the fabrication technique may also be used to form nano-gapped contact electrodes. The technique should prove useful for the fabrication of nano-electromechanical systems.

Keywords: Nanofabrication, Self-aligned Electrodes, Suspended Carbon Nanotubes, Nanotube Evaporation Mask.

1. INTRODUCTION

The superior mechanical properties of carbon nanotubes (CNTs) make them ideal candidates for nanoelectromechanical system (NEMS) applications.[1–3] Most of the proposed NEMS applications of CNTs, such as nano-bearing[2] and nano-actuators,[3] require the nanotubes to be suspended above the supporting substrate if it is to be integrated into a chip. There have been several reported methods for reliably suspending CNTs, such as the poly-methyl methacrylate (PMMA) suspended dispersion method,[4,5] where the PMMA holds the nanotube in suspension during contact metal deposition, resulting in CNTs being suspended between metal contacts, and the sacrificial layer etching method,[6] where after contact fabrication on the nanotubes, the SiO_x under the nanotubes are chemically etched away, resulting in suspended CNTs.

More importantly, for electrical access and control of the suspended CNT structures, a method of placing individual control electrodes with nanoscale precision must be investigated. Conventional methods used to apply electric fields to the suspended CNTs are substrate gating[6] and lithographically defining electrodes.[4] In the former method, the distance between the gate and the CNTs can be controlled by controlling suspension height, but it suffers from the fact that applying localized electric fields to individual CNTs is not possible. The latter method of defining the contact with lithographic methods gives the possibility of individual access but suffers from alignment errors, which may lead to shorting. An insulating layer may be deposited on the suspended nanotube to prevent shorting. However, this may restrict the mechanical movement necessary for NEMS operation, and for electrical device fabrication this may also alter the transport properties of the nanotube.[7,8]

In this paper, we present a study on the fabrication of self-aligned electrodes on suspended multiwalled carbon nanotube (MWNT) structures. The method of suspension uses a metal sacrificial layer with the metal support used to suspend the nanotubes acting as electrical contacts. Furthermore, metal evaporated through an etch mask results in a discontinuous split-gate structure with the nanotube placed between the nano-gapped electrodes. This leads to perfect alignment between contact electrodes, control electrodes, and the nanotube. We will discuss the results of fabrication studies and suggest using this method to create electrodes with nanoscale gaps.

2. EXPERIMENTAL DETAILS

The fabrication steps are illustrated in Figure 1. We use oxidized Si as the insulating substrate. First, Cr/Au alignment marks are defined on the substrate. These marks are used as reference points for defining the positions of the nanotubes. On top of the marker defined substrate, an Al thin film of ∼50 nm was deposited and MWNTs were dispersed on the surface as shown in Figure 1a. The thickness of the Al determines the suspension height of the

*Author to whom correspondence should be addressed.

  1533-4880/2003/04/325/328/$17.00+.25 doi:10.1166/jnn.2003.204

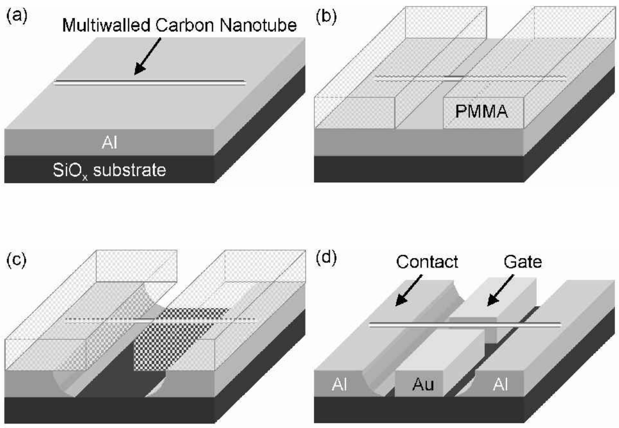

Fig. 1. Schematic diagrams of the fabrication processing steps. (a) Multiwalled carbon nanotubes dispersed on top of an Al thin film. Oxidized Si was used as the substrate. (b) PMMA spin coating followed by electron beam lithography to define the etch window. (c) MWNT suspended after timed chemical etching of the Al layer. (d) Contact metal deposition and lift-off.

nanotubes above the substrate. The MWNTs were mixed in a solution of dichlorobenzene and were treated with ultrasound, to increase the density of separated individual MWNTs, before being spin-coated onto the sample surface. The positions of the MWNTs were then mapped with the use of using a scanning electron microscope (SEM) image of the sample surface. Then PMMA was spin-coated onto the surface, and electron beam lithography was used to define the pattern in the resist that will be used as the chemical etch mask and for control electrode deposition and lift-off (see Fig. 1b).

Chemical etching is performed through the pattern in the resist to remove the Al under the nanotube and suspend the nanotube above the substrate. The Al etching was performed with an ammonium disulfide solution and was timed so that an undercut may form beneath the resist, which would result in the Al forming a gap that was wider than the window defined in the PMMA. This will reduce the probability of shorting between the contact Al and the metal deposited through the window, as illustrated in Figure 1c. Finally, metal electrodes are deposited through the window used for chemical etching and after lift-off, result in the fabrication of a suspended carbon nanotube structure with self-aligned split gates. The whole process requires only one stage of lithography. As illustrated in Figure 1d, the metal deposited on the nanotube was removed during the lift-off process, which will be discussed later.

3. RESULTS AND DISCUSSION

An SEM image of a suspended CNT structure with self-aligned electrodes is shown in Figure 2. The diameter of the MWNT was ~20 nm. It can be seen that the nanotube was suspended above the substrate by Al electrodes. The

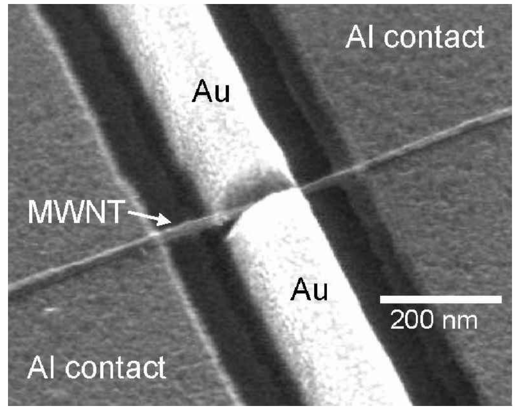

Fig. 2. A SEM of the fabricated self-aligned suspended MWNT structure. The sample is tilted by 40°. The thickness of the Al layer was ~50 nm, and the thickness of the Au was ~150 nm. The diameter of the MWNT was ~20 nm.

gap between the Al electrodes was ~400 nm. The width of the deposited Au wire was ~200 nm, which was the width of the window defined in the PMMA resist. The defined Au wire was not continuous and forms a nano-gap. The width of the gap was slightly wider that the diameter of the nanotube. The lift-off edges of the Au wire show a smooth surface and do not contain sharp protrusions. This shows that the prolonged chemical etching of the Al layer was successful in creating an undercut beneath the PMMA. It can also be seen that the Au deposited on top of the MWNT was removed. This process is better illustrated in Figure 3.

In Figure 3a, it can be seen that the metal deposited on the MWNT still remains and has formed an island. It can also be seen that there is a region under the nanotube that has no Au deposited. This shows that the suspended CNT is acting as an evaporation mask when Au is evaporated through the gap in the PMMA. In Figure 3b, it can be seen that the contact point of the nanotubes with the Al layer has been shifted and the MWNT has collapsed and is now curved toward the substrate. From the SEM images

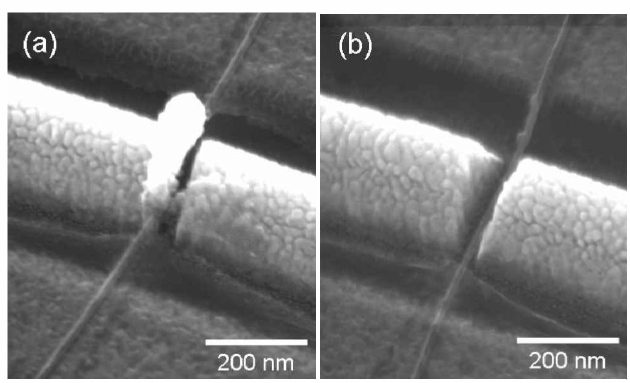

Fig. 3. SEM images of the Au electrode deposition result on suspended MWNTs. (a) Au island formed on top of the suspended MWNT. (b) A collapsed MWNT bridge. The diameter of the MWNT was ~20 nm.

of Figure 3, the following process may be inferred about the Au island removal from the nanotube surface.

Initially, the nanotube acts as the evaporation mask and Au is deposited discontinuously on the substrate and the nanotube. Then as the evaporation continues the grain on the Au grows in diameter and increases beyond the nanotube diameter. And the top of the evaporated Au island makes contact with the Au deposition on the PMMA. Then during the lift-off process the Au island may be pulled off with the rest of Au that was deposited on the PMMA. Therefore, it may be that the Au remaining on the MWNT in Figure 3a is due to the Au island not making contact with the Au deposited on the PMMA. Furthermore, the displaced and collapsed MWNT shown in Figure 3b may be from the suspended part of the nanotube being pulled during lift-off. It should also be taken into account that the adhesion of metals to carbon nanotubes is poor[9, 10] and is presumably van der Waals in nature. This means that the adhesion force between Au grains would be higher than the Au-CNT adhesion. Another factor that would determine the removal of Au islands from the nanotube surface would be the contact area. Therefore, if the contact area of the Au island to the Au on the PMMA became wider and the contact between the Au island and the nanotube became smaller, the probability of the Au island being removed should increase.

The results of Cr electrode deposition on suspended MWNTs are shown in Figure 4. For the samples used here, the nanotubes were directly dispersed on the SiO_x surface, and silicon dioxide etch was used to suspend the nanotube. It can be seen in Figure 4a that the Cr wire deposited also formed a gap around the suspended nanotube. The Cr thickness was ~200 nm, and the etched SiO_x depth was ~80 nm. The width of the gap in the Cr electrodes increases from ~20 nm at the bottom to ~100 nm at the top of the electrode. The change in the width of the gap is more noticeable than the change in gap width seen in Figure 3b between the Au electrodes. This may be due to the difference in grain morphology that is produced during the deposition of the component metal on the surface of the suspended CNTs, since the width of the gap at a certain deposition thickness reflects the size of the island deposited on the suspended CNTs. The distance between the nanotube and the electrode is therefore wider in the Cr electrodes (~30 nm) than in the case of Au electrodes (~10 nm).

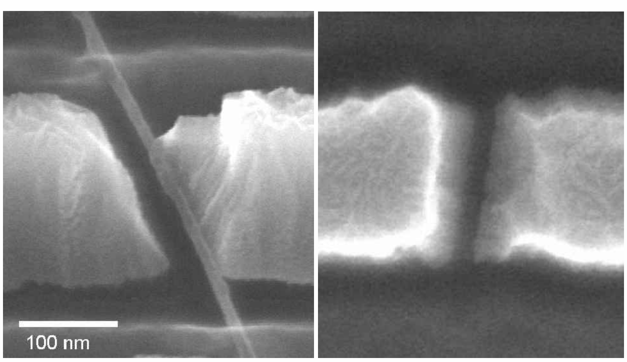

Fig. 4. SEM images of split-gate electrodes formed from Cr deposition on suspended MWNTs. (a) Cr split gates formed on suspended MWNTs. (b) 15-nm gap formed between Cr electrodes.

An SEM image of the result of Cr deposition after the nanotube was removed is shown in Figure 4b. The image clearly demonstrates the effectiveness of the suspended MWNTs as evaporation masks. A ~15-nm gap has formed between Cr electrodes, and the width of the gap at the bottom of the wire is maintained through the wire width. This indicates that this fabrication technique may be used to form nanoscale gaps between electrodes, which may be used to measure the conductance of nanoscale materials.

As indicated earlier, this method allows the fabrication of self-aligned contact electrodes and control electrodes to suspended carbon nanotube structures, which may be used to fabricate self-aligned carbon nanotube actuators and carbon nanotube high-frequency oscillators. The reliability of the fabrication process depends on the adhesion strength between the metal and the carbon nanotube, which may be improved through reduction of the contact area. Therefore, a smaller diameter nanotube, such as single-walled carbon nanotubes and a narrower wire definition, should improve the reliability of the process. Moreover, through variation of the deposition metal and deposition rates, it may be possible to control the gap between the suspended nanotube and the control electrode.

4. CONCLUSIONS

We have demonstrated the fabrication of self-aligned split-gate electrodes on suspended multiwalled carbon nanotube structures. It was found that metal wire deposition on suspended MWNTs resulted in the deposited metal wire being discontinuous, and the metal deposited on the MWNTs was removed. The suspended MWNT acts as an evaporation mask during the metal deposition, which results in the discontinuity of the deposited metal. The removal of metal islands from the suspended nanotubes may be due to the poor adhesion of metal to the carbon nanotube surface, combined with the pulling action on the metal island by the side deposits of metal on the resist walls during lift-off. It may be possible to use this technique to fabricate suspended nanoscale electromechanical systems.

References and Notes

1. E. W. Wong, P. E. Sheehan, and C. M. Lieber, *Science* 277, 1971 (**1997**).
2. J. Cumings and A. Zettl, *Science* 289, 602 (**2000**).

RESEARCH ARTICLE

3. R. H. Baughman, C. Cui, A. A. Zakhidov, Z. Iqbal, J. N. Barisci, G. M. Spinks, G. G. Wallace, A. Mazzoldi, D. De Rossi, A. G. Rinzler, O. Jaschinski, S. Roth, and M. Kertesz, *Science* 284, 1340 (**1999**).

4. S.-B. Lee, K. B. K. Teo, M. Chhowalla, D. G. Hasko, G. A. J. Amaratunga, W. I. Milne, and H. Ahmed, *Microelectron. Eng.* 61–61, 475 (**2002**).

5. G.-T. Kim, G. Gu, U. Waizmann, and S. Roth, *Appl. Phys. Lett.* 80, 1815 (**2002**).

6. J. Nygård and D. H. Cobden, *Appl. Phys. Lett.* 79, 4216 (**2001**).

7. J. W. Park, J. B. Choi, and K.-H. Yoo, *Appl. Phys. Lett.* 81, 2644 (**2002**).

8. M. Suzuki, K. Ishibashi, T. Ida, D. Tsuya, K. Toratani, and Y. Aoyagi, *J. Vac. Sci. Technol., B* 19, 2770 (**2001**).

9. Y. Zhang, N. W. Franklin, R. J. Chen, and H. Dai, *Chem. Phys. Lett.* 331, 35 (**2000**).

10. Y. Zheng and H. Dai, *Appl. Phys. Lett.* 77, 3015 (**2000**).

Received: 14 October 2002. Revised/Accepted: 17 February 2003.