May 2008

Determining the optimal contact length for a metal/multiwalled carbon nanotube interconnect

Chun Lan
Purdue University

Dmitri Zakharov
Birck Nanotechnology Center, Purdue University, zakharov@purdue.edu

R. Reifenberger
Birck Nanotechnology Center, Purdue University, reifenbr@purdue.edu

Determining the optimal contact length for a metal/multiwalled carbon nanotube interconnect

Chun Lan,[1,2,a)] Dmitri N. Zakharov,[1] and Ronald G. Reifenberger[1,2]
[1]*Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA*
[2]*School of Mechanical Engineering, Purdue University, West Lafayette, Indiana 47907, USA*

(Received 14 April 2008; accepted 16 April 2008; published online 29 May 2008)

A focused ion beam (FIB) is used to sequentially reduce the contact length of an evaporated metal film to a multiwalled carbon nanotube (MWCNT). By using this FIB contact cutback technique, the contact resistance between an individual MWCNT and evaporated thin films of Au, Au/Ti, and Ag are accurately determined. The data permit a rational way to specify the minimum contact length of a metallic thin film to a MWCNT. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2931081]

Engineering electronic devices to ever smaller dimensions has occupied the attention of many scientists worldwide. To downsize electronic devices into the nanoscale, minimizing contact area becomes a critical issue. An electrical contact with a size greater than device dimensions proves detrimental to scaling arguments, power dissipation, and noise. Thus, determining the optimal contact area required for a given nanowire becomes a major concern.

The underlying principles determining the interfacial (contact) resistance between a metallic contact electrode and a nanoscale device requires an understanding of current flow into a connecting nanowire.[1,2] At the most fundamental level, the resistance of a metal contact to a nanowire requires a calculation of the quantum mechanical transmission between the two objects.[3,4] Such theories usually assume an ideal interface between a nanowire and the metal contact. This is hardly the case in reality, as evidence for contamination layers of unspecified origin are often reported.[5] Often, such contamination layers are reduced by activating the contacts by an applied electric field,[6] by rapid thermal annealing,[7] or by current-induced Joule heating.[8] The constriction of injected electrons through localized defects along a nanowire is also possible, resulting in many parallel Sharvin-like points of contact between a metal film and a nanowire.[9] All of these effects conspire to produce an intrinsic contact resistance which depends on the processing conditions during metal contact deposition as well as the intrinsic properties of the nanowire. In spite of the general appreciation of these many factors influencing contact resistance to a nanodevice, a clear understanding of the roles played by contact length, nanowire dimensions, and contact metal still remains unclear.

To address this important problem, we have developed a versatile contact cutback laser ablation technique to measure contact resistance between an individual multiwalled carbon nanotube (MWCNT) and a thin metallic film.[10] We have shown that by using a focused laser beam to sequentially shorten the contact length between a MWCNT and an evaporated metallic thin film, the resistance per unit length of the MWCNT as well as the specific contact resistance between the MWCNT and a thin metallic film can be determined.

Although the contact cutback laser ablation method is completely general and can be used to investigate the contact resistance of contact electrodes to a wide variety of different nanowires, it does have some disadvantages. First, the cuts made by the laser are approximately 1–2 μm in diameter, a value which limits the precision of the cuts and reduces the total number of data points that can be acquired from a given nanowire. Second, the experiment requires a careful adjustment of the power in a focused pulsed laser beam. Lastly, the experiment is not readily amenable to real-time observation. While a camera can provide high magnification optical images to monitor the laser ablation process in real time, subsequent high resolution field emission scanning electron microscope (FESEM) images are required to better quantify the contact cutback experiment.

In this paper, we introduce a more advanced technique using a focused ion beam (FIB) that significantly improves all aspects of contact cutback experiments. By using a FIB to sequentially shorten the contact length along a nanowire, many of the disadvantages encountered using laser ablation can be circumvented. The cutting experiment can be performed in a more controlled way, the size of the cuts decreases by about a factor of ~10, and the entire experiment can be observed and controlled in real time.

The CNTs chosen for this study are MWCNTs grown from Fe_2O_3 nanoparticles at 900 °C in a microwave plasma-enhanced chemical-vapor deposition (PECVD) reactor. PECVD is known to introduce defects into the MWCNTs. The particular growth temperature of 900 °C was selected because prior studies have shown that this temperature gives the highest quality PECVD-grown CNTs.[10,11] A detailed description of the PECVD system and the relevant CNT growth conditions have been reported elsewhere.[12,13]

Individual MWCNTs were randomly selected for this study. After selection, an individual MWCNT was gently deposited onto a freshly cleaned transparent glass substrate, and metal electrodes were then thermally evaporated on top of both ends.[14] In this study, Au, Au/Ti, and Ag contacts were fabricated as contact electrodes. After the contact cutback experiments were performed, the thickness of the evaporated metal film on selected samples was determined by using a profilometer.

A Nova 200 Nanolab DualBeam™ SEM/FIB system was used to implement the contact cutback experiments. This instrument combines a high resolution FESEM having the capability to set accelerating voltages between 500 V and 30 kV with a precise FIB Ga-etch operating at 30 kV. The width of the ion beam cut is ~80 nm; the estimated precision in positioning the ion beam from one cut to another is ~50 nm.

[a)]Electronic mail: lan0@physics.purdue.edu.

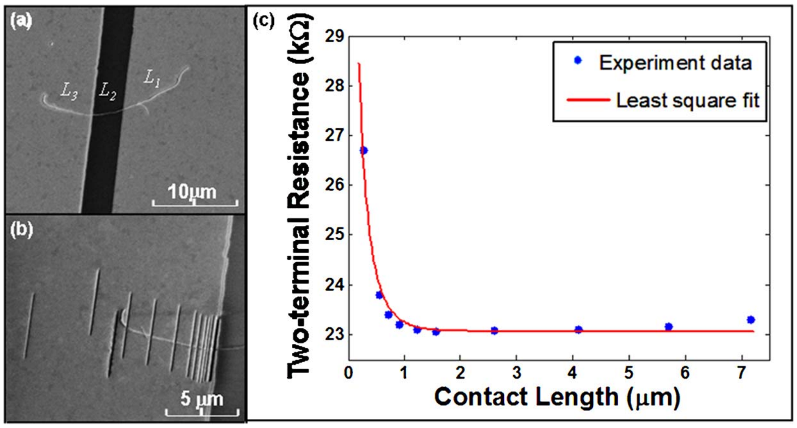

FIG. 1. (Color online) Representative FESEM images and data obtained from a typical MWCNT sample. In (a), a FESEM image of a MWCNT with two Ag thin film contacts before any FIB cuts were made. The Ag contacts covering both ends of the MWCNT (lengths L_1 and L_3) are evident. In (b), a FESEM image of a MWCNT after all FIB cuts were completed. In (c), data of resistance vs contact length obtained after each cut. For this MWCNT, nine cuts have been performed. The resistance plotted is the two terminal resistance which includes both the contact resistance and the MWCNT resistance of the 4 μm section of the MWCNT. The solid line is the best fit to the data and gives parameters $r_{\mathrm{CNT}}=(4.70\pm0.01)$ kΩ/μm and $r_c=(1.6\pm0.1)$ kΩ μm. The quoted uncertainties arise from the least-squares fitting procedure.

The Nova 200 FIB has been modified to allow *in situ* electrical characterization after each FIB cut. To avoid heating the MWCNT, $I(V)$ measurements were performed at low bias voltage ($|V|\leqslant 0.1$ V). The slope of the $I(V)$ data was used to measure the two terminal resistance of the device under study. After acquiring $I(V)$ data, the MWCNT/metal contact was sequentially shortened by controlled cuts by using the FIB. After each cut was performed, another $I(V)$ data set was obtained and a FESEM image was taken to accurately determine the length of the remaining contact. After the experiment was complete (approximately ten cuts), a high resolution FESEM image was taken to better determine the diameter of the MWCNT under study.[15]

A representative FESEM image of a typical MWCNT sample with Ag electrodes is shown in Fig. 1(a). The length of the MWCNT between the two electrodes is nominally 4 μm. The image in Fig. 1(a) was taken before FIB contact cutting was performed. Figure 1(b) shows the image of the MWCNT sample after the contact cutback experiment has been completed. The diameter of the measured MWCNT was 52 ± 5 nm.

In Fig. 1(a), we denote L_1 as the contact length of the right contact, L_2 as the length of the MWCNT between the two contacts, and L_3 as the contact length on the left. Assuming a uniform contact along the length of the MWCNT and assuming diffusive transport, if the contact length L_3 is shortened to a length x, the equation relating contact length x (units of micrometers) to contact resistance R_{contact} (units of kΩ) is given by[10]

$$R_{\mathrm{contact}}(x) = \sqrt{r_{\mathrm{CNT}} r_c}\coth\left(\sqrt{\frac{r_{\mathrm{CNT}}}{r_c}}x\right), \quad 0 < x \leqslant L_3, \quad (1)$$

where r_{CNT} is the MWCNT resistance per unit length (units of kΩ/μm) and r_c is the specific contact resistance per unit length (units of kΩ μm). Under ideal geometric conditions, $r_c=\rho_c/(\pi d/2)$, where ρ_c is the specific contact resistivity characterizing the contact to a MWCNT with a diameter d. The total two-terminal resistance as a function of contact length can be written as

$$R_{\mathrm{total}}(x) = \sqrt{r_{\mathrm{CNT}} r_c}\coth\left(\sqrt{\frac{r_{\mathrm{CNT}}}{r_c}}x\right) + r_{\mathrm{CNT}}L_2 + \sqrt{r_{\mathrm{CNT}} r_c}\coth\left(\sqrt{\frac{r_{\mathrm{CNT}}}{r_c}}L_1\right). \quad (2)$$

By measuring $R_{\mathrm{total}}(x)$ as the contact is cutback, estimates for r_{CNT} and r_c can be obtained.

The data points in Fig. 1(c) plot the measured two terminal resistance versus contact length for the same sample. The solid red curve is the least-square fit to the data obtained by applying Eq. (2). The fitting parameters are found to be $r_{\mathrm{CNT}}=(4.70\pm0.01$ kΩ/μm) and $r_c=(1.6\pm0.1$ kΩ μm). The uncertainties listed for different parameters are derived from the uncertainties in the fitting parameters determined by the least-square fitting procedure.[16]

Further tests were made to learn if the FIB contact cutback technique could detect the presence of poor contacts. For these tests, a MWCNT sample with an intentionally thin ($\sim$23 nm thick) Ag film was prepared. The thin Ag film is expected to oxidize to a greater extent than a thick Ag film, causing the contact resistance to increase. The results of these measurements are summarized in Table I and show that compared to samples with thicker ($\sim$63 nm thick) Ag films, the sample with the thinner Ag film has a specific contact resistance that is $\sim$13–75 times greater. This simple test indicates that the FIB contact cutback technique is capable of providing dependable estimates of contact resistance.

Lastly, it is worth noting in Fig. 1(c) that the two-terminal resistance of the measured MWCNT approaches an asymptotic value when the contact length was larger than $\sim$1 μm and only increases when the contact length is less than $\sim$1 μm. This observation indicates that the two-terminal resistance for PECVD-grown MWCNTs is nearly *independent* of contact length when the contact length is longer than $\sim$1 μm. An advantage of the FIB contact cutback technique is that it predicts the contact resistance for a given contact length. For the purpose of minimizing the size of the contact to a device, we define L_β as the optimal contact length required to produce a $\beta\times100\%$ increase from the asymptotic $R_{\mathrm{contact}}(x=\infty)$ value. Our model for contact resistance allows us to estimate L_β by calculating the increase in resistance from the asymptotic limit as follows:

TABLE I. Comparison between samples with different thickness Ag film contacts.

Sample no.	Metal contact thickness (nm)	MWCNT diameter (nm)	r_{CNT} (kΩ/μm)	r_c (kΩ μm)	ρ_c ($\mu\Omega$ cm^2)
5	23	59 ± 5	4.2 ± 0.5	38 ± 7	35 ± 7
6	63	148 ± 5	0.2 ± 0.1	3 ± 1	7 ± 2
7	63	52 ± 5	4.70 ± 0.01	1.6 ± 0.1	1.3 ± 0.1
8	63	164 ± 5	0.7 ± 0.1	0.5 ± 0.2	1.3 ± 0.5

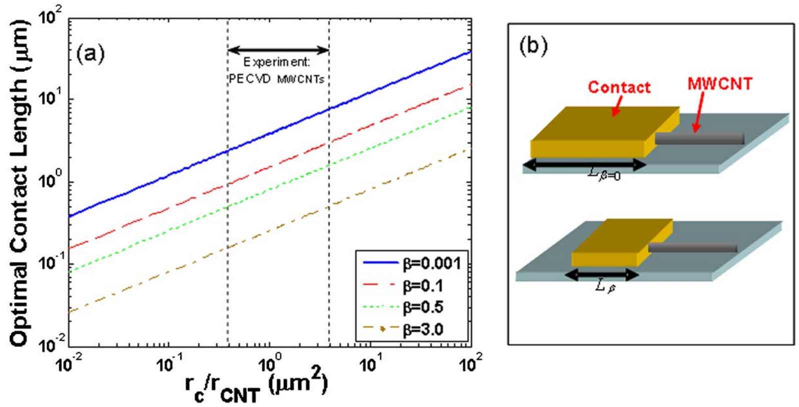

FIG. 2. (Color online) In (a), the relation between the optimal (buried) contact length L_β for different β, plotted as a function of r_c/r_{CNT}. The region between the two vertical dashed lines span the range of parameters measured for PECVD-grown MWCNTs contacted by Au, Au/Ti, and Ag metal films. For a particular value of r_c/r_{CNT}, the lines for β=0.001, 0.1, 0.5, and 3.0 indicate 0.1%, 10%, 50%, and 300% *increases* in resistance due to contacts that are shortened to the specified contact length L_β. In (b), a schematic comparison between a large contact ($\beta \to 0$; contact of infinite length) to a shorter contact of finite length L_β.

$$R_{\mathrm{contact}}(L_\beta) - R_{\mathrm{contact}}(x=\infty) = \beta R_{\mathrm{contact}}(x=\infty).$$

With this definition, from Eq. (1) it follows that

$$\sqrt{r_{\mathrm{CNT}} r_c}\,\coth\left(\sqrt{\frac{r_{\mathrm{CNT}}}{r_c}}L_\beta\right) = (1+\beta)\sqrt{r_{\mathrm{CNT}} r_c}.$$

Solving for L_β gives

$$L_\beta = \sqrt{\frac{r_c}{r_{\mathrm{CNT}}}}\,\coth^{-1}(1+\beta). \quad (3)$$

Figure 2 plots the dependence of the contact length L_β on r_c/r_{CNT} as a function of β. For a fixed value of r_c/r_{CNT}, a smaller value of L_β results in a greater value of β. The ratio of r_c/r_{CNT} is predetermined by the electrical properties of the MWCNT under measurement and the contact resistance produced by the process conditions while evaporating a thin metallic film onto the MWCNT. Figure 2 is therefore useful to estimate the optimal contact length required to produce a specified contact resistance once the approximate range of r_c/r_{CNT} is known. Figure 2 is quite general and can be applied to a wide variety of contacts between different metal films and different types of individual nanowires, assuming that diffusive electron transport is dominant.

From our work reported here and previously,[10] we can estimate the optimal contact length L_β for a contact between individual PECVD-grown MWCNTs and Au, Au/Ti, and Ag metal films. From experiment, we find that the measured ratio of r_c/r_{CNT} for PECVD-grown MWCNTs lies in range of 0.3–3 μm^2, as shown by the two vertical dashed lines in Fig. 2. It follows from Fig. 2 that the optimal contact length required to produce, say a 10% increase (β=0.1) in overall resistance from the infinite contact case, lies in the range of 1–3 μm, depending on the exact ratio of r_c/r_{CNT}.

While this study was confined to PECVD-grown MWCNTs, the techniques developed can be applied to a wide variety of different nanowires and nanotubes to systematically unfold the many factors influencing contact resistance at the nanoscale.

The authors would like to thank Professor T.S. Fisher and P.B. Amama for supplying the PECVD-grown MWCNTs. The authors have benefited from helpful discussions with J. Appenzeller and S. Datta during the course of this work.

[1]N. Nemec, D. Tománek, and G. Cuniberti, Phys. Rev. B **77**, 125420 (2008).
[2]S. E. Mohney, Y. Wang, M. A. Cabassi, K. K. Lew, S. Dey, J. M. Redwing, and T. S. Mayer, Solid-State Electron. **49**, 227 (2005).
[3]M. P. Anantram, Appl. Phys. Lett. **78**, 2055 (2001).
[4]F. Léonard and A. A. Talin, Phys. Rev. Lett. **97**, 026804 (2006).
[5]K. Biswas, Y. Qin, M. DaSilva, R. Reifenberger, and T. Sands, Phys. Status Solidi A **204**, 3152 (2007).
[6]Y. Jiang, M. Q. H. Zhang, T. Kwano, C. Y. Cho, and L. Lin, IEEE 21st International Conference on MicroElectro Mechanical Systems, 2008 (unpublished).
[7]J.-O. Lee, C. Park, J.-J. Kim, J. Kim, J. W. Park, and K.-H. Yoo, J. Phys. D: Appl. Phys. **33**, 1953 (2000).
[8]Y. Woo, G. S. Duesberg, and S. Roth, Nanotechnology **18**, 095203 (2007).
[9]A. Bachtold, C. Strunk, J.-P. Salvetat, J.-M. Bonard, L. Forró, T. Nussbaumer, and C. Schönenberger, Nature (London) **397**, 673 (1999).
[10]C. Lan, P. Srisungsitthisunti, P. B. Amama, T. S. Fisher, X. Xu, and R. G. Reifenberger, Nanotechnology **19**, 125703 (2008).
[11]C. Lan, P. B. Amama, T. S. Fisher, and R. G. Reifenberger, Appl. Phys. Lett. **91**, 093105 (2007).
[12]M. R. Maschmann, P. B. Amama, A. Goyal, Z. Iqbal, R. Gat, and T. S. Fisher, Carbon **44**, 10 (2006).
[13]P. B. Amama, M. R. Maschmann, T. S. Fisher, and T. D. Sands, J. Phys. Chem. B **110**, 10636 (2006).
[14]P. J. de Pablo, S. Howell, S. Crittenden, B. Walsh, E. Graugnard, and R. Reifenberger, Appl. Phys. Lett. **75**, 3941 (1999).
[15]We note that the exposure of the focused electron/ion beam to the nanowire/thin metal film on a glass substrate occasionally causes the measured resistance to increase slightly with time. Typically, the resistance increase is measured to be less than 1% of the resistance initially measured. This slight increase in resistance disappears after waiting for sufficiently long time intervals, indicating that it might be related to a charging effect. We correct for this by estimating the rate of resistance increase and subtracting it from the measured data. With this correction, the initial few data points (with large area contacts) are well described by a horizontal line.
[16]For a length of the MWCNT dx, the resistance from classical considerations is expected to be $\rho dx/A$, where ρ is the classical resistivity and A is the relevant cross-sectional area for current flow. If this expression is set equal to $r_{CNT}dx$, then, estimates of ρ for PECVD-grown MWCNTs, valid for diffusive current flow, can be obtained. From the values listed in Table I, we estimate that the resistivities for the larger diameter PECVD-MWCNTs lie between $(0.3-1.5)\times 10^{-5}\ \Omega$ m. These values are comparable to those found in the literature for carbon fibers. See, M. S. Dresselhaus, G. Dresselhaus, K. Sugihara, I. L. Spain, and H. A. Goldberg, *Graphite Fibers and Filaments*, Springer Series in Materials Science Vol. 5 (Springer, Berlin, 1988), p. 190.