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

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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 construction 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 Fe2O3 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™ 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.

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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|<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. 

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 L1 as the contact length of the right contact, L2 as the length of the MWCNT between the two contacts, and L3 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 L3 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

\[ R_{contact}(x) = \sqrt{\frac{r_{CNT}}{r_c}} \coth\left(\sqrt{\frac{r_{CNT}}{r_c}}x\right), \quad 0 < x \leq L_3, \quad (1) \]

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, \( r_c = \rho_c/(πd/2) \), where \( \rho_c \) 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

\[ R_{total}(x) = \sqrt{\frac{r_{CNT}}{r_c}} \coth\left(\sqrt{\frac{r_{CNT}}{r_c}}x\right) + r_{CNT}L_2 + \sqrt{\frac{r_{CNT}}{r_c}} \coth\left(\sqrt{\frac{r_{CNT}}{r_c}}L_3\right). \quad (2) \]

By measuring \( R_{total}(x) \) 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 \( r_{CNT} = (4.70 \pm 0.01) \text{kΩ}/\mu\text{m} \) and \( r_c = (1.6 \pm 0.1) \text{kΩ} \mu\text{m} \). The uncertainties listed for different parameters are derived from the uncertainties in the fitting parameters determined by the least-square fitting procedure.

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 (≈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 (≈63 nm thick) Ag films, the sample with the thinner Ag film has a specific contact resistance that is ≈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 ≈1 µm and only increases when the contact length is less than ≈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 ≈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 5×100% increase from the asymptotic \( R_{contact}(x=\infty) \) 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>
<thead>
<tr>
<th>Sample no.</th>
<th>Metal contact thickness (nm)</th>
<th>MWCNT diameter (nm)</th>
<th>( r_{CNT} ) (kΩ/µm)</th>
<th>( r_c ) (kΩ µm)</th>
<th>( \rho_c ) (µΩ cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>23</td>
<td>59±5</td>
<td>4.2±0.5</td>
<td>38±7</td>
<td>35±7</td>
</tr>
<tr>
<td>6</td>
<td>63</td>
<td>148±5</td>
<td>0.2±0.1</td>
<td>3±1</td>
<td>7±2</td>
</tr>
<tr>
<td>7</td>
<td>63</td>
<td>52±5</td>
<td>4.70±0.01</td>
<td>1.6±0.1</td>
<td>1.3±0.1</td>
</tr>
<tr>
<td>8</td>
<td>63</td>
<td>164±5</td>
<td>0.7±0.1</td>
<td>0.5±0.2</td>
<td>1.3±0.5</td>
</tr>
</tbody>
</table>
$R_{\text{contact}}(L_\beta) - R_{\text{contact}}(x = \infty) = \beta R_{\text{contact}}(x = \infty)$.

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

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

Solving for $L_\beta$ gives

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

Figure 2 plots the dependence of the contact length $L_\beta$ on $r_c/r_{\text{CNT}}$ as a function of $\beta$. For a fixed value of $r_c/r_{\text{CNT}}$, a smaller value of $L_\beta$ results in a greater value of $\beta$. The ratio of $r_c/r_{\text{CNT}}$ 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 $r_c/r_{\text{CNT}}$ 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, we can estimate the optimal contact length $L_\beta$ 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 $r_c/r_{\text{CNT}}$ for PECVD-grown MWCNTs lies in range of 0.3–3 $\mu$m$^2$, 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 ($\beta = 0.1$) in overall resistance from the infinite contact case, lies in the range of 1–3 $\mu$m, depending on the exact ratio of $r_c/r_{\text{CNT}}$.

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.

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