Metal-Carbon Nanotube Contacts

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Outline

• Introduction: Contact Types and Applications
• Metal-CNT Contact Models
• CNT Nanoscale Probing
• Contact Engineering
• Summary
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Contact Schematics

(a) End Contact

(b) Side Contact

Metal electrode

CNT
Applications

Metal-CNT contact resistance impacts performance

De Volder et al., Science 339, 535–9
Applications

De Volder et al., Science 339, 535–9
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Contact Resistance Limits

• Quantum conductance for ballistic transport, $G_0 = 2e^2/h$

• *Ab initio* calculations predict contact resistivities $\geq 24.2 \text{k}\Omega\cdot\text{nm}^2$ for a side-contacted graphene layer*

• For near-ballistic transport and optimum metal-CNT interfaces, contact resistance can be minimized for device functionalization

DFT/Green’s Function

Tunneling

Schottky barrier (metal-semiconducting SWCNT)


Tunneling barrier (metal-MWCNT)

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Conductive – Atomic Force Microscopy (C-AFM)

Scanner

Sensor

Scan

TEOS SiO$_2$

Nanotube

Metal

SiO$_2$

$+$

$-$

$I$

Santa Clara University
Center for Nanostructures
C-AFM Results

- Current through every single CNT sensed for fixed $V$
- Locate precisely individual CNT and measure electrical characteristics
- Position tip for $I-V$ sweeps
Scanning Spreading Resistance AFM

M. Fayolle et al., Microelectronic Engineering 88, 833 (2011)
In Situ Nanoprobing inside SEM

Tip radius $\leq 50$nm

Tungsten probe tip

Typical $I$-$V$ for single CNT
Nanoprobing Measurements

(c) Constant current through outer probes

(d) 4PP resistance remains constant
Contact Resistance Extraction

Current\(\mu A\)

Voltages [mV]

\[2\text{PP: 4.39 k\Omega}\]

\[4\text{PP: 3.90 k\Omega}\]

\(R_C = 0.49\) k\Omega
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Contact Engineering

• Contact Geometry consideration
  – End contact vs. side contact

• Joule Heating

• E-beam Treatment

• Contact Encapsulation
  – Electrode contact deposition
  – Contact area

• As-grown interface vs. metal deposition
End vs. Side Contacts

- Chemical bonding at end contact
  - Saturated C-bonds
  - Conduction modes of graphitic structure is unaffected
  - Interface with concentric walls

- Van der Waals bonding at side contact
  - Larger interfacial separation
  - C-bonds remain unsaturated, inhibiting conduction
  - Interface with outermost wall only
E-beam Irradiation

- Results in a-C depo
  - Non-conductive
- 4PP unaffected by exposure
- Does not affect CNT

E-beam Fused Contacts

Contact Area Enhancement

$R_C$ appears to be area independent for contact longer some characteristic length

Tunneling

Tunneling barrier (metal-MWCNT)

Joule Heating

- I-V nonlinearity reduced by stress current
- Interfacial gap remains large
- Contact resistance ~ few kΩ
- CNTs exhibit high contact resistance
- CNT contact resistance can be reduced with metal deposition on contacts
Resistance with & without W-deposited contacts
Work Function and Wettability

Lim et al., Appl. Phys. Lett. 95, 264103 (2009)
Metal-CNT Contact Encapsulation

Metal-CNT Contact Encapsulation

Metal-CNT Contact Encapsulation

EBID-C + Joule heating

Total resistance reduced from 300 kΩ to 116 Ω

Contact Engineering

- Contact Geometry consideration
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- Contact Encapsulation
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  - Contact area
- As-grown interface vs. metal deposition
Contact Engineering

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As-grown Interface

Grainy substrate

Smooth substrate
Measurement Setup

\[ R_{\text{Total}} = (R_{\text{bundle}} + R_{\text{CNT/m}} + R_{p/CNT} + R_m) + R_{\text{CNT}}(L) \]

\[ R_{\text{CNT}} = \frac{4\rho L_{\text{CNT}}}{\pi D_{\text{CNT}}^2} \]

\[ R_{\text{C}} + R_{\text{CNT}}(L) \]
Resistance vs. Length

Ni/Ti (grainy substrate)

$R_{Total} = R_C + R_{CNT} = R_C + \frac{4 \rho}{\pi D_{CNT}^2} L_{CNT}$

$\rho$ (Ω-cm) | $R_C$ (Ω)
--- | ---
1.66 - 1.85 x 10^{-4} | 825

Diameter range of probed samples: 90 – 100 nm
Resistance vs. Length

Diameter of probed samples: ~50 nm

\[ R_{Total} = R_C + R_{CNT} = R_C + \frac{4\rho}{\pi D_{CNT}^2} L_{CNT} \]

<table>
<thead>
<tr>
<th>( \rho ) (( \Omega )-cm)</th>
<th>( R_C ) (( \Omega ))</th>
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<tbody>
<tr>
<td>2.4 ( \times ) 10^{-4}</td>
<td>388</td>
</tr>
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Resistance measurements for CNT via

Nihei et al., (ICS/CT), 541-543 (2008)
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Summary

• Metal-CNT contact resistance critically affects device performance, but can be engineered to yield desirable outcomes
• End-contacted vertical structures typically result in lower contact resistance due to strong bonding between edge carbon and surface metal atoms
• Contact engineering can result in sub-kΩ contact resistance values, which still need to decrease considerably before device functionalization
• Contact resistance can be drastically reduced by Joule heating and contact metallization using selection criteria governed by wettability metal-CNT work-function difference.
• As-grown interface between CNT and underlayer metal can yield very low contact resistance under the best growth conditions, such as catalyst and underlayer metal depositions without ambient adsorbates trapped at the interfaces
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Landauer (quantum limit)

- 2-D surface to 1-D conduction
  \[ G = \frac{2e^2}{h} MT \]
  - Materials and engineering independent
  - \( \lambda_{\text{MFP}} \geq L \)

- Conservation of momentum (Bloch symmetry) violation
  - Conduction through surface scattering
  - Van der Waals?

Tersoff, APL 74, 2122 (1998)