# Scaling of Resistance and Electron Mean Free Path of Single-Walled Carbon Nanotubes

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Journal Club Carbon Nanotube

Mai 9, 2007

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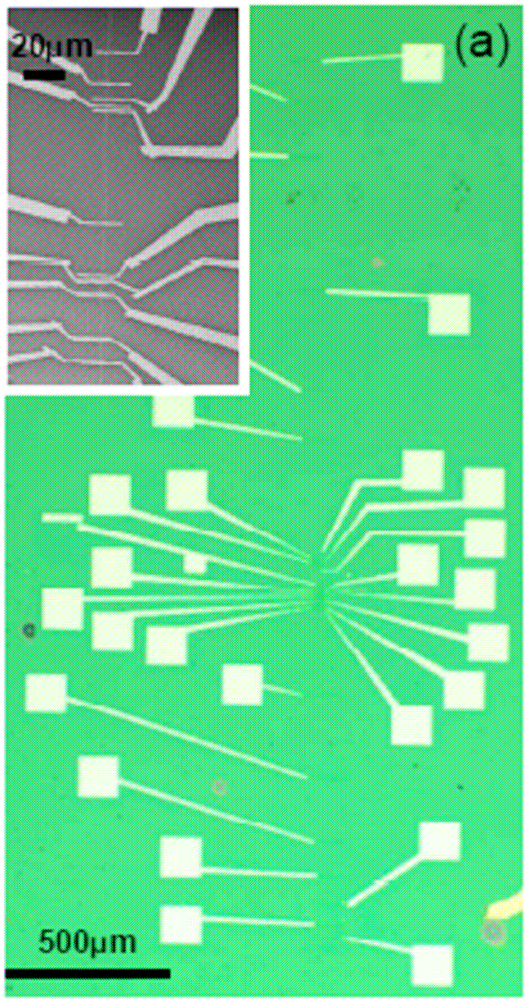
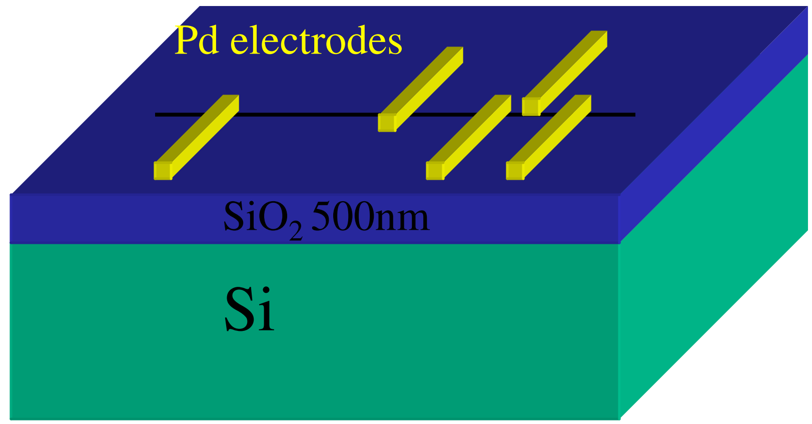
# Outline

- Sample setup
- Sample categorization
- Measurement of contact resistance and resistivity
- Determination of the mean free path
- The temperature dependent behavior of the mean free path
- Measurement with scanning gate microscopy – infuence of disorder
- The non-linear scaling of R(L)
- Summary

# Sample setup




•Length of nanotubes > 1mm

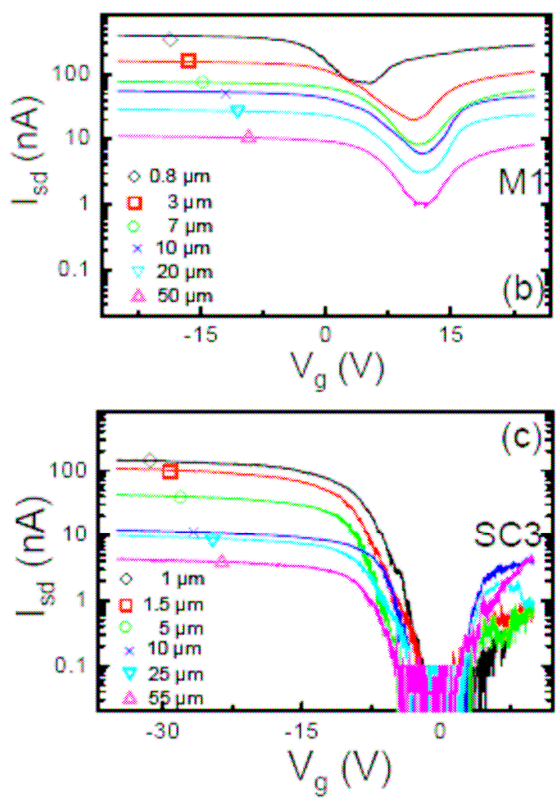
•Many pairs of contacts with different distance are fabricated

•Diameter < 2.5nm

•High bias saturation current < 30uA

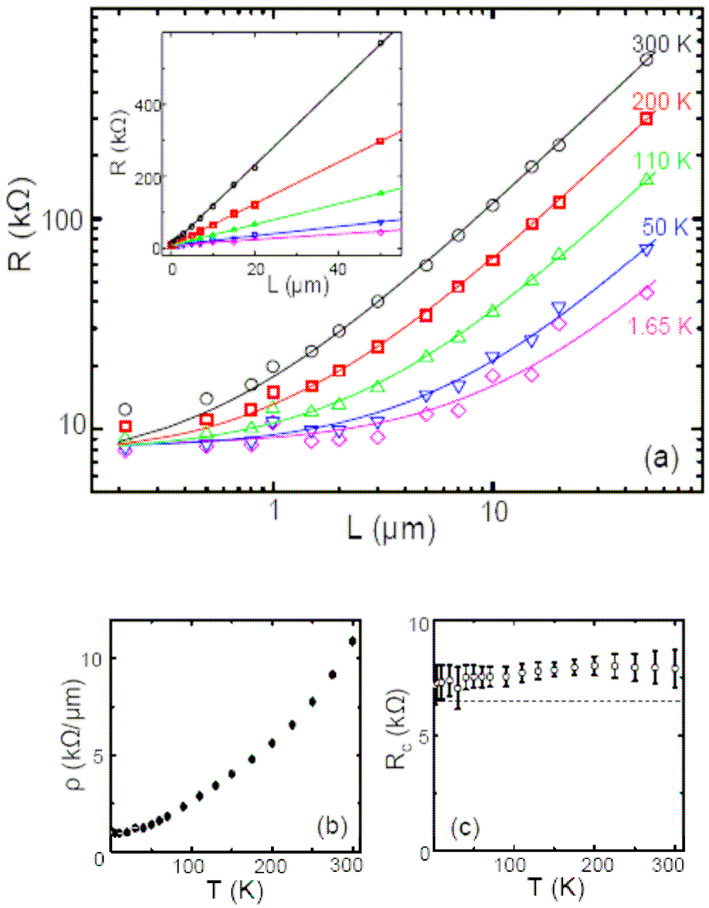
➔ Only singlewall carbon nanotubes are contacted

# Sample characterization




- $I_{SD}(V_g)$ is used to characterize the CNT as metallic or semiconducting
  - Metallic CNTs have small current suppression at Fermi- Level
  - In semiconducting CTNs current is strongly suppressed
- Different pairs of contacts are used to get the behavior depending on the intrinsic structure of the CNT;
  Not from local disorder

# Measurement of contact resistance and resitivity




- 2-point measurements of R(L) show linear behavior for all measured temperatures
- For small distances the resistance converges to a finite value
- The behavior can be described well with:

$$R(L) = \rho L + R_C$$

were ρ is the 1D resistivity
and $R_C$ is the contact resistance

- The contact resistance remains nearly constant for different temperatures
- The resistivity has metallic behavior
  - increases with increasing temperature
  - saturates to a value $R_{sat}$ at low temperatures

# Determination of the mean free path and the nontransparent contact resistance

The Landauer-Buttiker formula applied to SWCNTs:

$$R(L) = (h/(4e^2))(L/L_m + 1) + R_{nc}$$

$$R(L) = Lh/(4e^2 L_m) + h/(4e^2) + R_{nc}$$

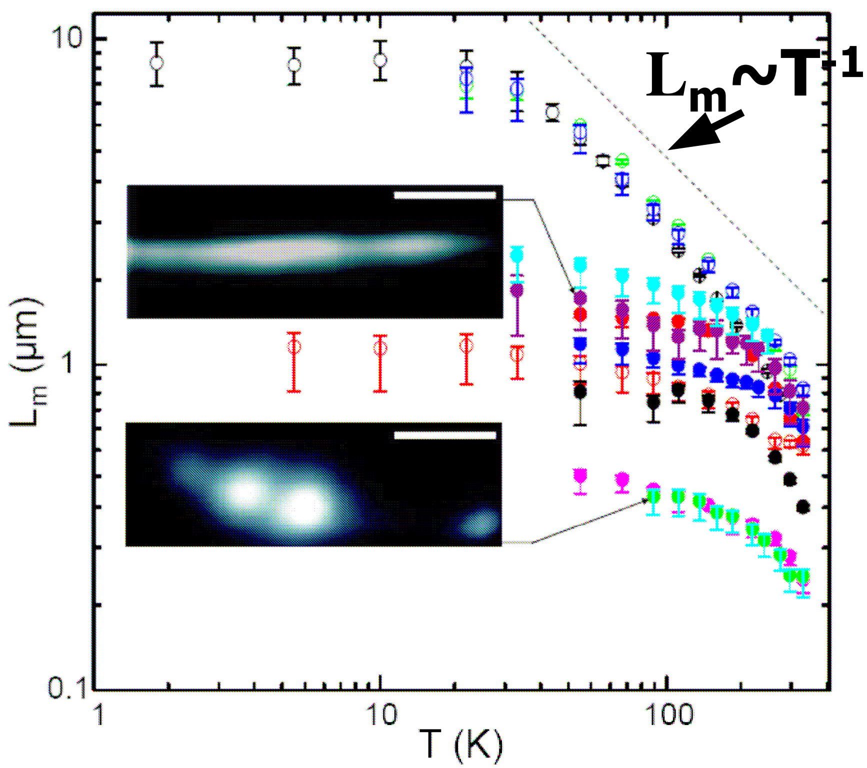
Compared to $R(L) = \rho L + R_C$

$$L_m = h/(4e^2 \rho(T))$$

$$R_{nc} = R_c - h/(4e^2)$$

| | M1 | M2 | M3 | M4 | SC1 | SC2 | SC3 | SC4 | SC5 | SC6 | SC7 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $d(nm)$ | $2.0 \pm .2$ | $1.3 \pm .4$ | $1.7 \pm .6$ | $1.6 \pm .4$ | $1.6 \pm .4$ | $1.8 \pm .6$ | $1.9 \pm .4$ | $2.1 \pm .2$ | $2.2 \pm .2$ | $2.0 \pm .6$ | $2.2 \pm .2$ |
| $R_c(k\Omega)$ | $7.9 \pm .8$ | $11.5 \pm 2.9$ | $8.3 \pm 2.5$ | $12.0 \pm 4.4$ | $10.2 \pm 4.5$ | $14.9 \pm 5.7$ | $10.4 \pm .9$ | $7.0 \pm 2.3$ | $25.4 \pm 4.2$ | $6.9 \pm 40$ | $21.8 \pm 14$ |
| $\rho_{sat}(k\Omega/\mu m)$ | $0.76 \pm .02$ | $0.87 \pm .02$ | $0.93 \pm .01$ | $6.5 \pm .08$ | $2.95 \pm .05$ | $3.61 \pm .05$ | $4.64 \pm .01$ | $5.91 \pm .12$ | $8.13 \pm .31$ | $14.1 \pm .19$ | $16.3 \pm .13$ |
| $L_m^{sat}(\mu m)$ | $8.56 \pm .23$ | $7.65 \pm .17$ | $7.07 \pm .08$ | $1.00 \pm .01$ | $2.24 \pm .04$ | $1.83 \pm .03$ | $1.40 \pm .01$ | $1.10 \pm .02$ | $0.80 \pm .03$ | $0.47 \pm .01$ | $0.40 \pm .01$ |

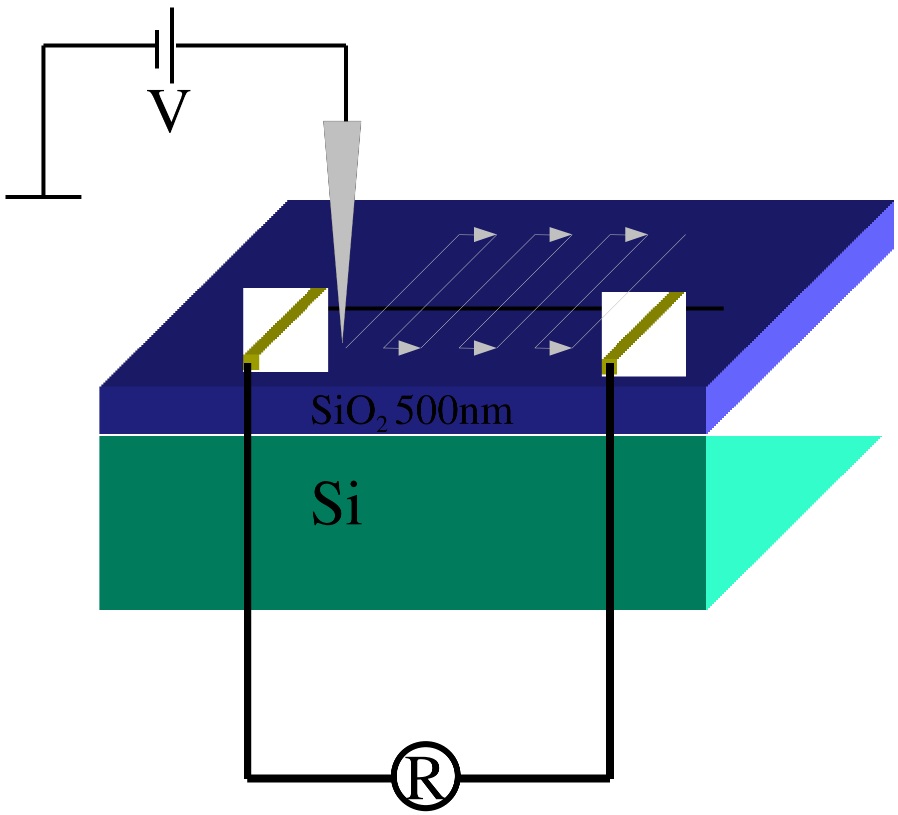
# Temperature dependent behavior of the mean free path




- Different behaviours in two regimes
- High temperature: $L_m \sim T^{-1}$ → inelastic scattering between electrons and acoustic phonons dominates
- Low temperature: $L_m$ saturates to the tube specific $L_m^{sat}$
- The lower $L_m^{sat}$ the higher the separation temparature

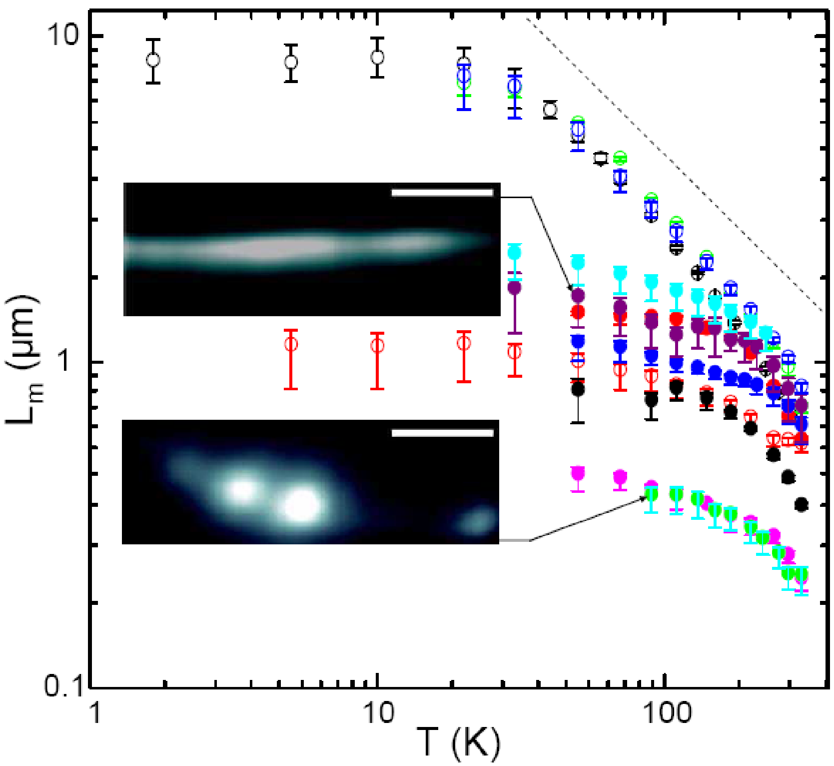
How is $L_m^{sat}$ defined?

# Overlook: scanning gate microscopy




- Scanning with a tip with a well defined potential above the sample (→ coducting AFM) usig it as local gate
- Measuring the resistance of the tube for the local gate above every point on the sample results in a SGM image (the lower the resistance the darker the color)
- At the locations that limit the current through the CNT, the local gate changes the whole resistance

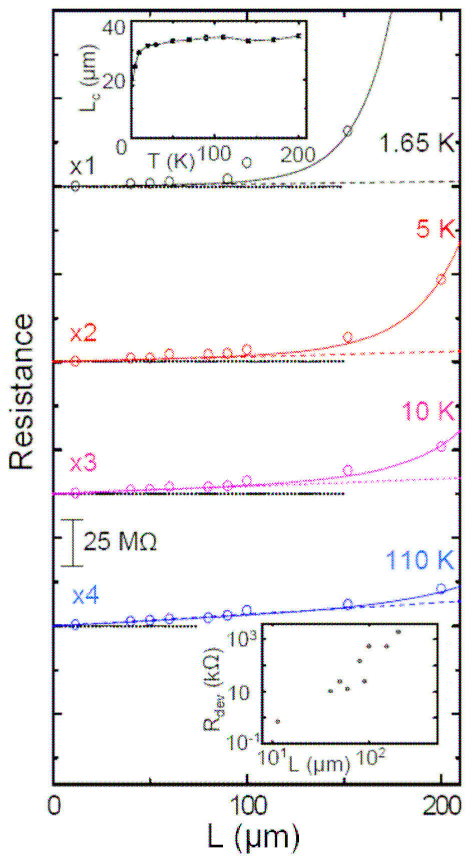
# Electron mean free path versus disorder



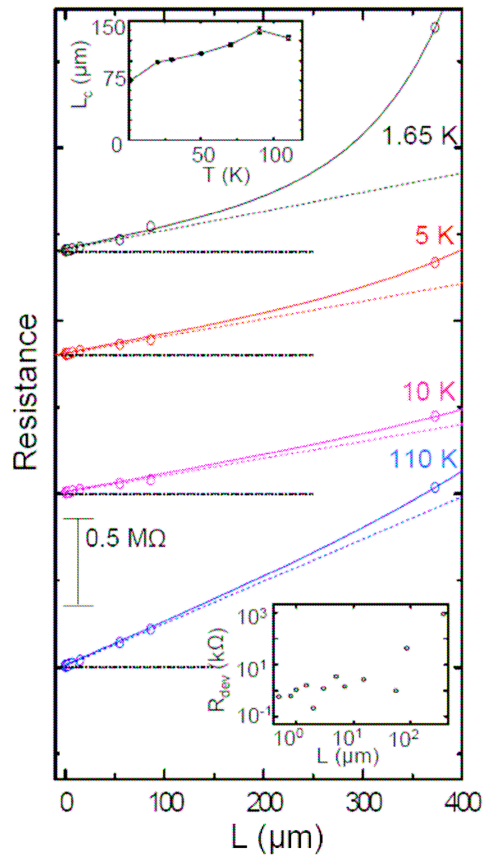

- $L_m$ is generally much higher for metallic CNTs (open circle) than that of semiconducting CNTs (closed circles) → scattering of electrons in metallic CNTs is strongly suppressed
- CNTs with lower $L_m^{sat}$ show much more disorder → $L_m^{sat}$ is defined by the disorder in the tubes

# The non-linear scaling of R(L)

semiconducting




metallic




- For longer lengthscales and low temperature there is a deviation from linear behavior
- For determining the critical lengthscale $L_c$ beyond which the non-linear behavior is dominant the following equation was used:

$$R(L) = R_c + R_Q\left(\frac{L}{L_m} + e^{\frac{L}{L_c}}\right)$$

- There was found that $L_c >> L_m$ for all temperature regimes
- $L_c$ increased with increasing T

➔ This behavior of $L_c$ shows that there is no strong localization

# Summary

- Contact resistance and resistivity can be derived from 2-point measurements of R(L)
- With the Landauer-Buttiker formula $L_m$ and $R_{nc}$ was calculated
- For high temperatures scattering with acoustic phonons is dominant
  For low temperatures $L_m$ saturates
- Measuerements with SGM show that $L_m^{sat}$ is determined by impurities
- Scattering of electrons is suppressed in metallic CNTs
- The non-linear scaling of R(L) shows that there is no strong localisation