Four-point resistance of individual single-wall carbon nanotubes

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We have studied the resistance of single-wall carbon nanotubes measured in a four-point configuration with noninvasive voltage electrodes. The voltage drop is detected using multiwalled carbon nanotubes while the current is injected through nanofabricated Au electrodes. The resistance at room temperature is shown to be linear with the length as expected for a classical resistor. This changes at cryogenic temperature; the four-point resistance then depends on the resistance at the Au-tube interfaces and can even become negative due to quantum-interference effects.

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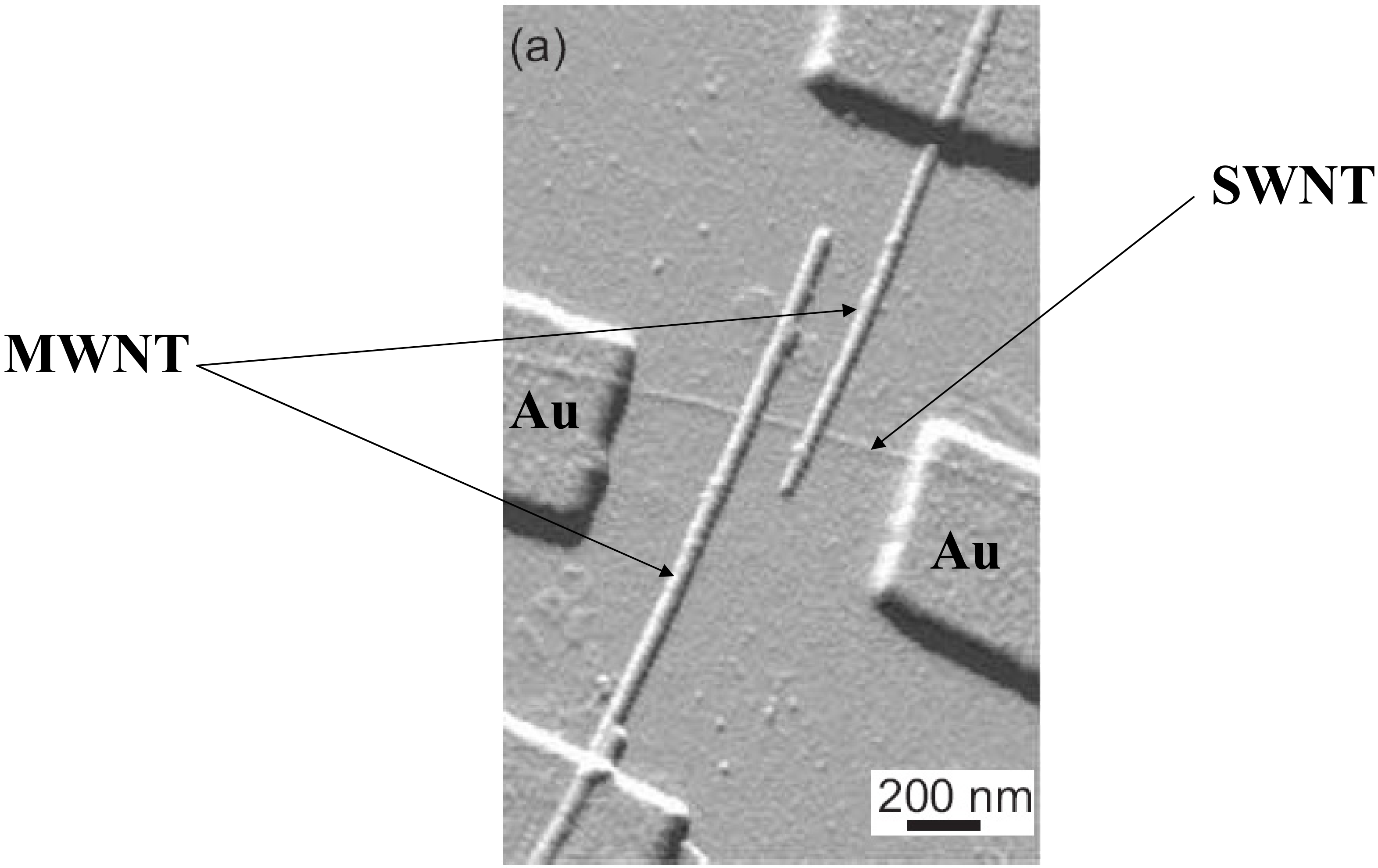
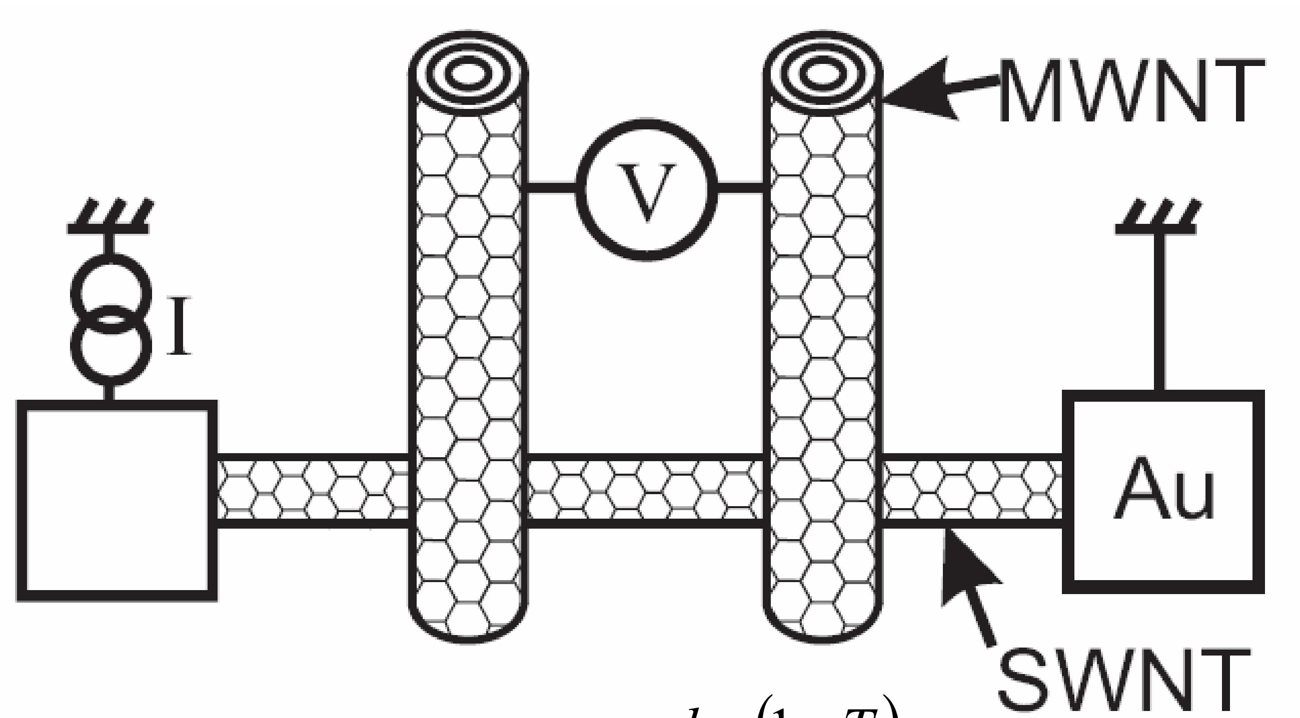
Context and Motivation

- Transport measurements are a powerful technique to investigate electronic properties of molecular systems.
- Two-point experiments do not allow the determination of the intrinsic resistance (scattering processes involving e.g. phonons, disorder).
- To eliminate the contribution of contacts, use of scanning probe microscopy technique in **four-point measurement in molecular systems:**
  - **But the electrodes used so far have been invasive.**
    - ➢ **Nanotubes divided into multiple quantum dots!**
  - **SWNT are remarquably good one-dimensional conductors :**
    - R as low as 1.5 kΩ for a 95 nm long section
    - Linear dependence with length at RT,
    - At low T, R can be negative.
    - ➢ **Four-point measurements can be described by the Landauer-Büttiker formalism**

Four-Point resistance measurements on C-SWNT using C-MWNT



Basic Physics of Four-Point measurements



$$R_{4pt} = \frac{h}{4e^2}\frac{L}{l_e}$$

From Landauer Formula: $\frac{h}{4e^2}\frac{(1-T)}{T}$ with the transmission $T = \frac{l_e}{L+l_e}$

With l_e: the elastic mean-free path

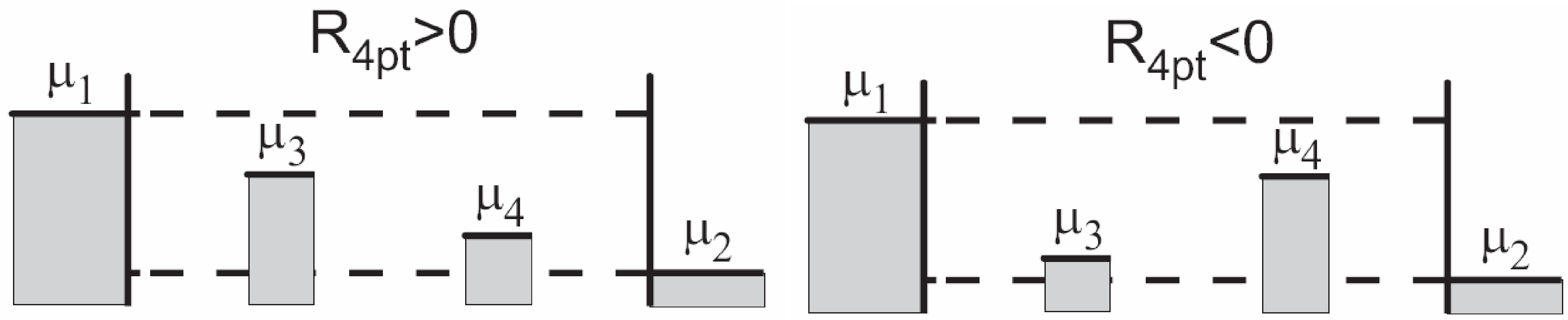
L: the separation between the voltage electrode

Basic Physics of Four-Point measurements

The current I_α in each electrode is related to the electrochemical potential μ_β of the other electrodes by

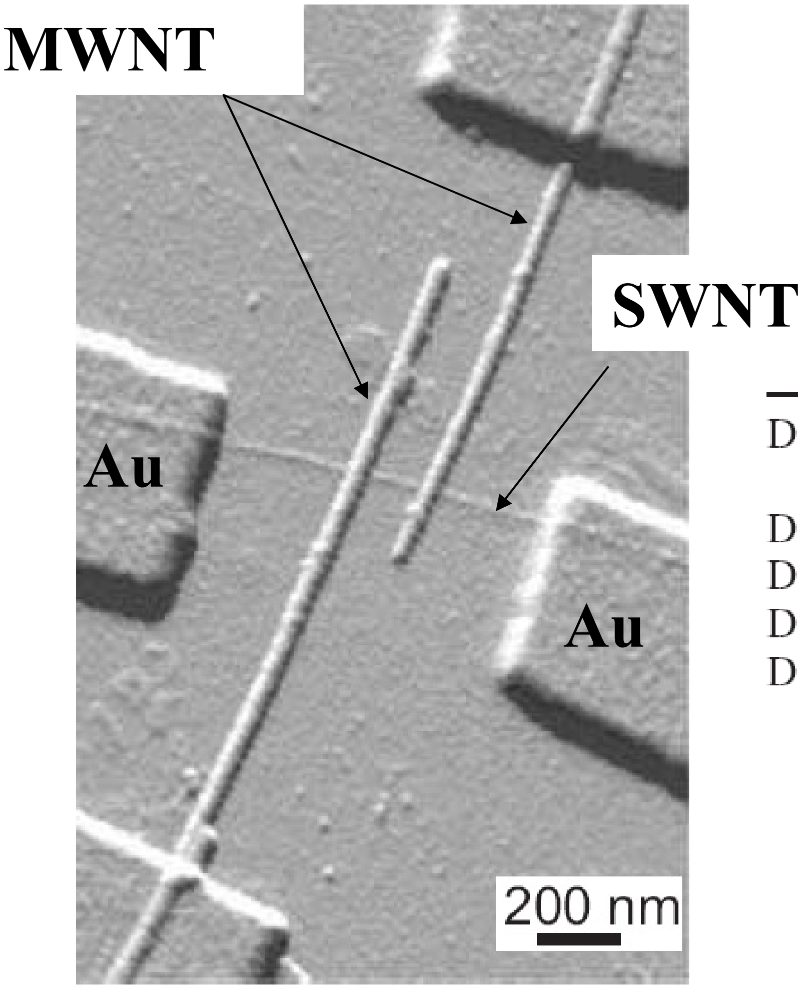
$$I_\alpha = \frac{4e^2}{h}\sum_\beta T_{\beta\alpha}\mu_\alpha - T_{\alpha\beta}\mu_\beta$$

With $T_{\alpha\beta}$ the total transmission between α and the β electrodes



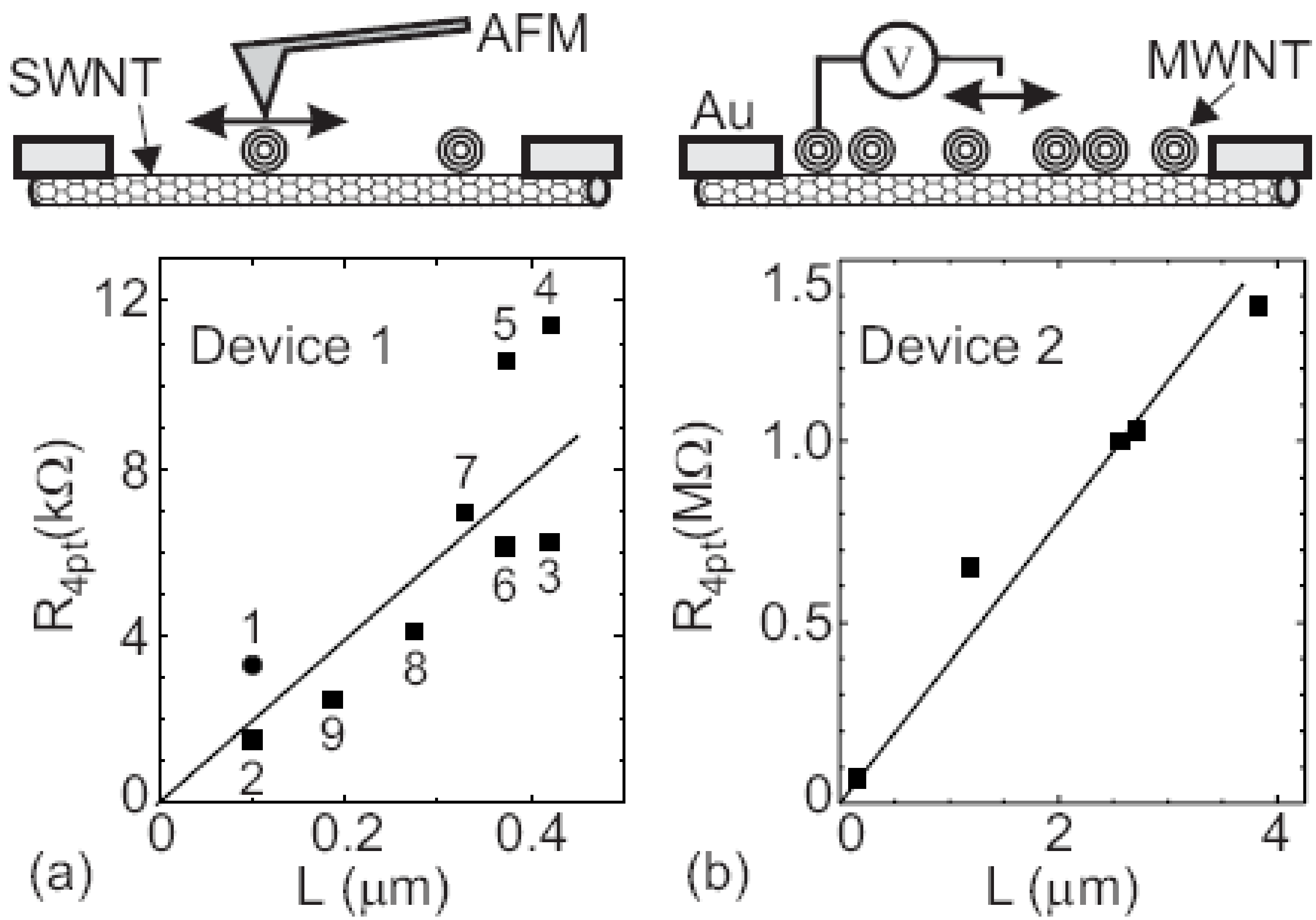
$$R_{2pt} = \frac{(\mu_1 - \mu_2)}{I} \quad R_{4pt} = \frac{(\mu_3 - \mu_4)}{I} \Rightarrow -R_{2pt} \le R_{4pt} \le R_{2pt}$$

Four-Point resistance measurements on C-SWNT using C-MWNT



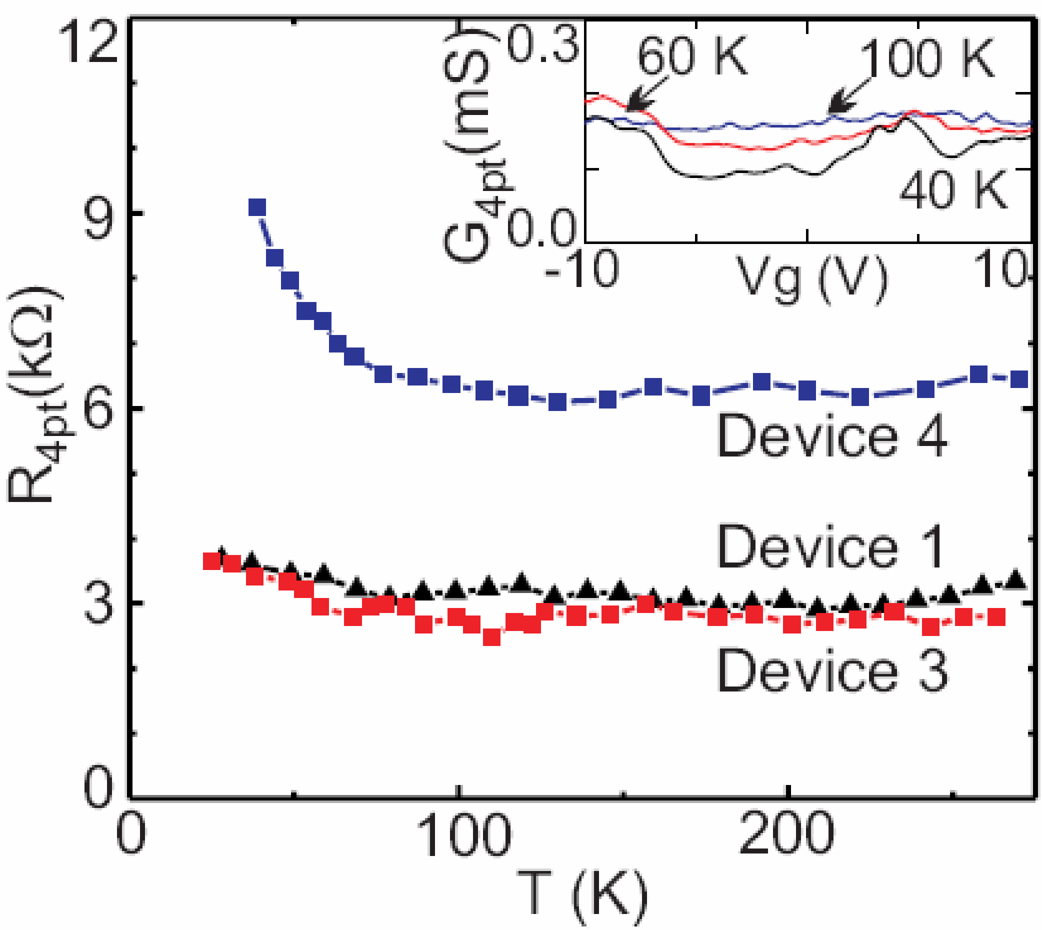
	R_{4pt} (kΩ)	L (nm)	l_e (nm)	T^* (K)	L_T (nm)	
Device 1	3.3	95	185	~40	~150	CVD
	1.5	95	408			CVD
Device 2	37.0	100	17			LA
Device 3	2.7	150	358	~30	~200	CVD
Device 4	6.3	140	143	~60	~100	LA
Device 5	12.7	590	300	~30	~200	LA

Length dependence of R_{4pt} at RT and $V_g = 0$



First direct measurement of intrinsic resistance of a NT

Temperature dependence of R_{4pt} at $V_g = 0$



Possible origin of the fluctuations

❑ ***Low transmission barriers*** created by :

✓the MWNTs

✓or some static disorder that form quantum dots along the nanotube

➢Transport dominated by Coulomb blockade

$$G = G_0\left(1 - \frac{1}{3} E_c / kT\right)$$

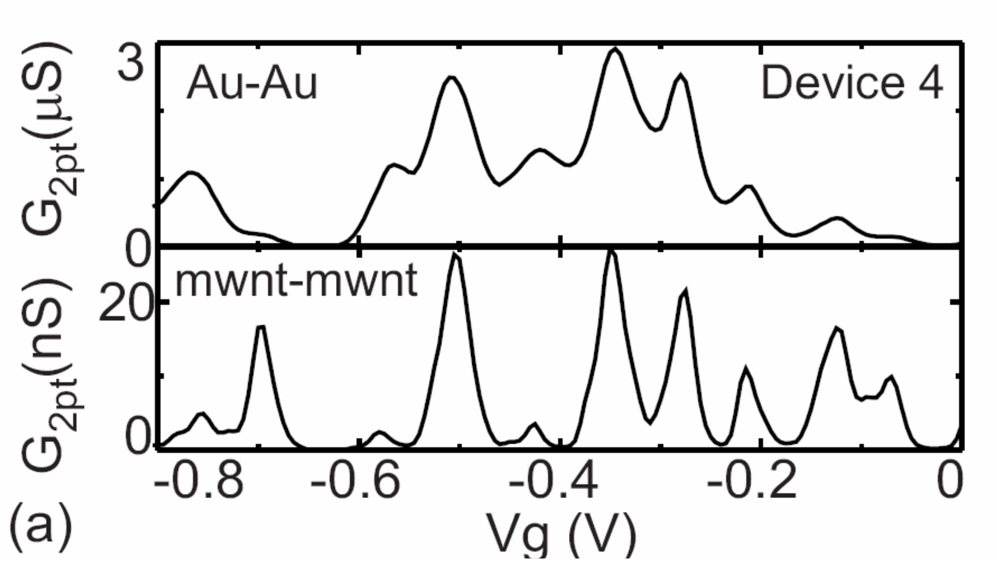
But conduction constant with T above $T^* \sim 60$ K

≠ Coulomb Blockade theory

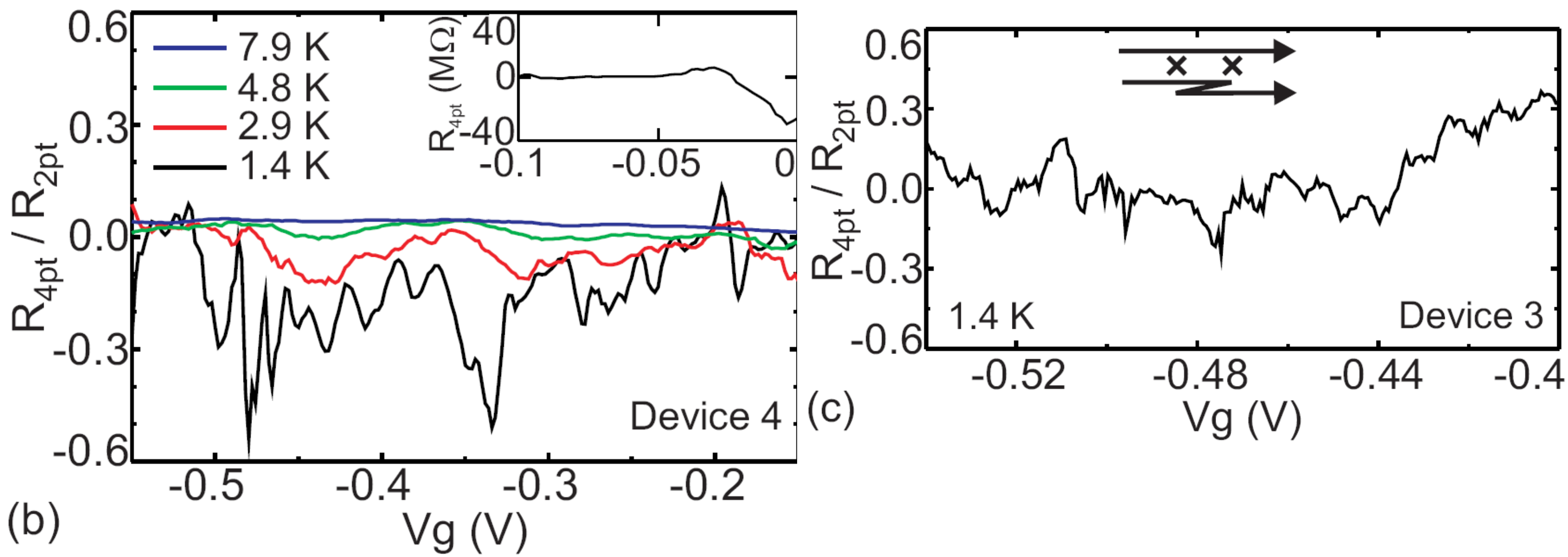
❑ ***Presence of disorder*** generates a complicated interference pattern along the tube that should vary with the Fermi level:

$$\left.\begin{array}{c} L_T = \hbar \upsilon_F / kT \\ L_\varphi \end{array}\right\} \gg \ell_e$$

Negative four-point resistance at low temperature



$$E_c \approx \frac{5meV}{L[\mu m]}$$



Origin of the negative four-point resistance R_{4pt}

- **Voltage electrodes**

  ↘ but this classical effect should persist at high T

  ⌧ R_{4pt} is only positive at T≥ 10 K

- $$\frac{R_{4pt}}{R_{2pt}} = \frac{T_{31}T_{42} - T_{32}T_{41}}{(T_{31}+T_{32})(T_{41}+T_{42})}$$

  ↘Coulomb blockade leads to oscillations in T_{ij} transmissions

  ↘Disorder in the SWNT

- R_{4pt}/R_{2pt} goes to zero when T ⇗ to 5 K
- $L_T = \left(\hbar \upsilon_F l_e / kT\right)^{1/2}$

Conclusions

✓ Dramatic modulation of R_{4pt} of SWNTs by quantum interference effects

➘ R_{4pt} becomes negative when L_T is longer than the dimension of the system

✓ L_T = 20 nm at RT

✓ Inclusion of these quantum-mechanical interference effects will ultimately be required in the design of practical multi-thermal intramolecular devices!