Journal club presentation

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Regensburg, Nov 24, 2004

VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

Determination of the Intershell Conductance in Multiwalled Carbon Nanotubes

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(Received 4 June 2004; published 21 October 2004)

We report on the intershell electron transport in multiwalled carbon nanotubes (MWNTs). To do this, local and nonlocal four-point measurements are used to study the current path through the different shells of a MWNT. For short electrode separations $\lesssim 1\ \mu$m the current mainly flows through the two outer shells, described by a resistive transmission line with an intershell conductance per length of $\sim(10\ \mathrm{k}\Omega)^{-1}/\mu$m. The intershell transport is tunnel type and the transmission is consistent with the estimate based on the overlap between π orbitals of neighboring shells.

DOI: 10.1103/PhysRevLett.93.176806 PACS numbers: 73.63.Fg, 72.80.Rj, 73.23.–b, 73.40.Gk

Goal of experiment

Measure the intershell conductance of multiwall carbon nanotubes

Previously known:

from experiment:
- interlayer restistivity of **graphite** varies greatly, depending on material quality: $10^{-3}..10^{-5}\ \Omega m$

from theory:
- **infinite perfect tubes** have zero intershell transport, due to conservation of Bloch vector and energy
- intershell transmission is large for injected **localized wave-packets** (attenuation length: $\sim 10\ nm$)

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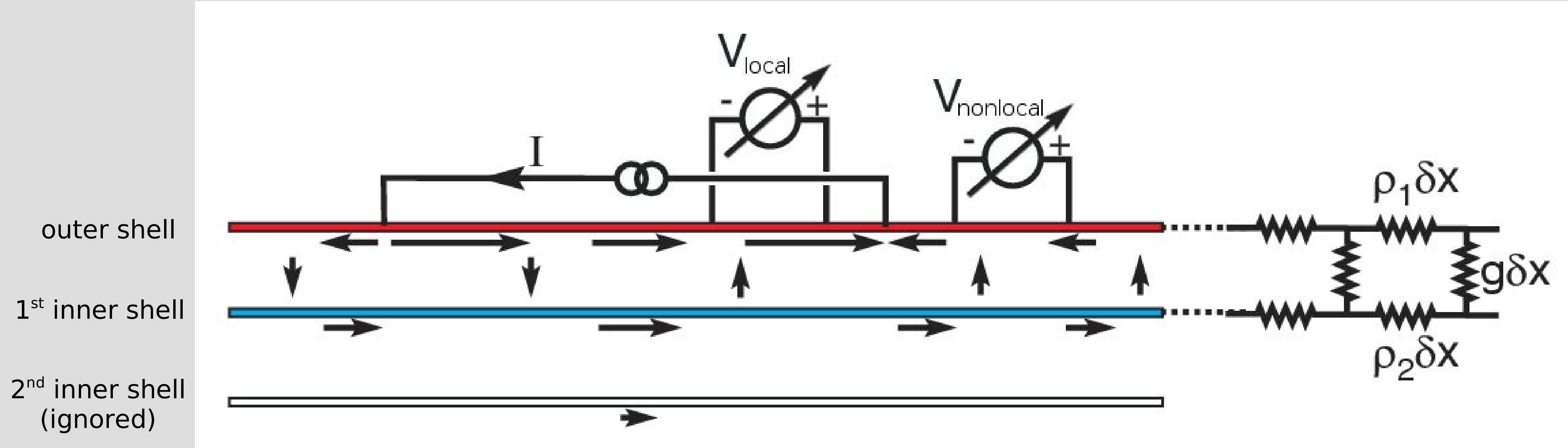
Basic idea behind the experiment

Model of current flow



- outermost shell is contacted in different positions
- current is fixed, voltage is measured
- intershell current paths cause $V_{nonlocal} \neq 0$

three unknown parameters enter the calculation

- ρ_1 and ρ_2: intrashell-resistance per length
- g: intershell-conductance per length

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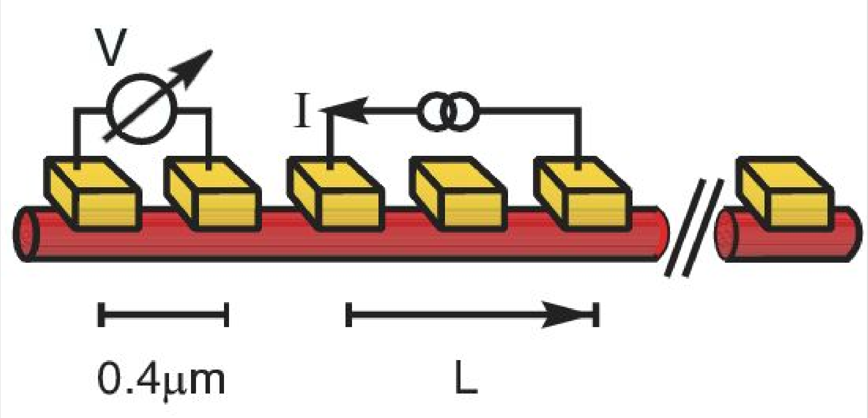
Experimental setup

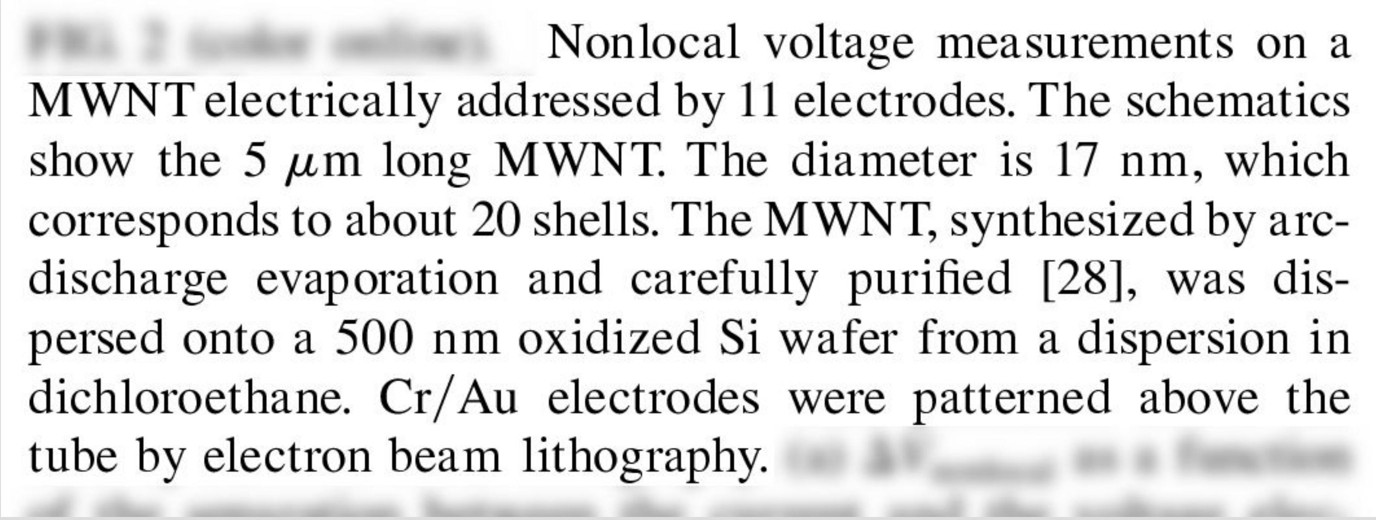
T=250 K

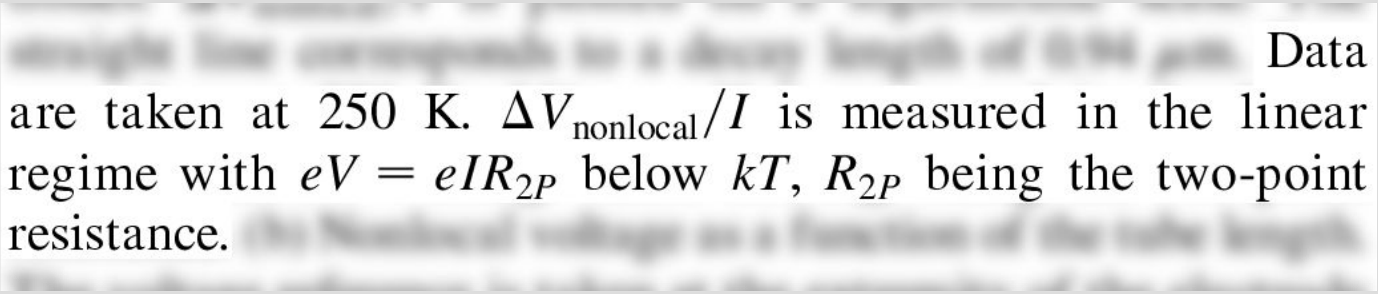
eV << kT



17 nm (20 shells)

UHV?
room pressure?


Nonlocal voltage measurements on a MWNT electrically addressed by 11 electrodes. The schematics show the 5 μm long MWNT. The diameter is 17 nm, which corresponds to about 20 shells. The MWNT, synthesized by arc-discharge evaporation and carefully purified [28], was dispersed onto a 500 nm oxidized Si wafer from a dispersion in dichloroethane. Cr/Au electrodes were patterned above the tube by electron beam lithography.


Data are taken at 250 K. $\Delta V_{\mathrm{nonlocal}}/I$ is measured in the linear regime with $eV = eIR_{2P}$ below kT, R_{2P} being the two-point resistance.

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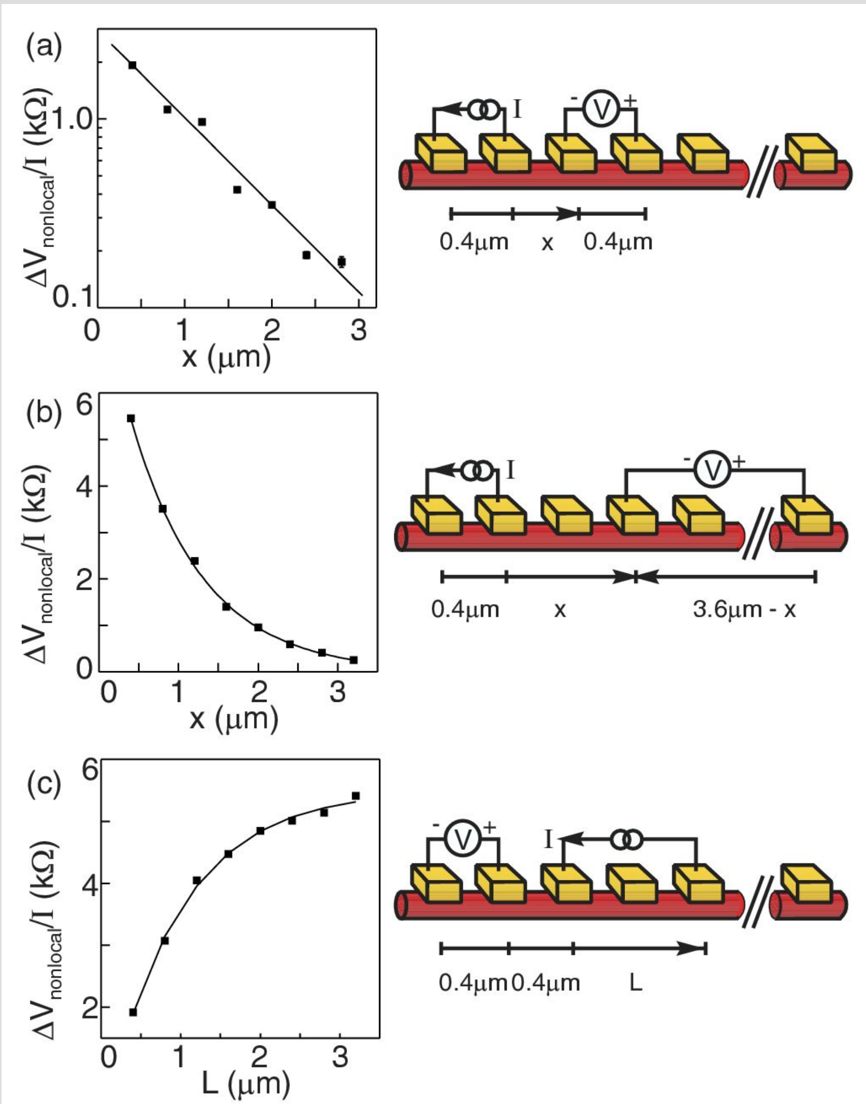
Voltage measurements

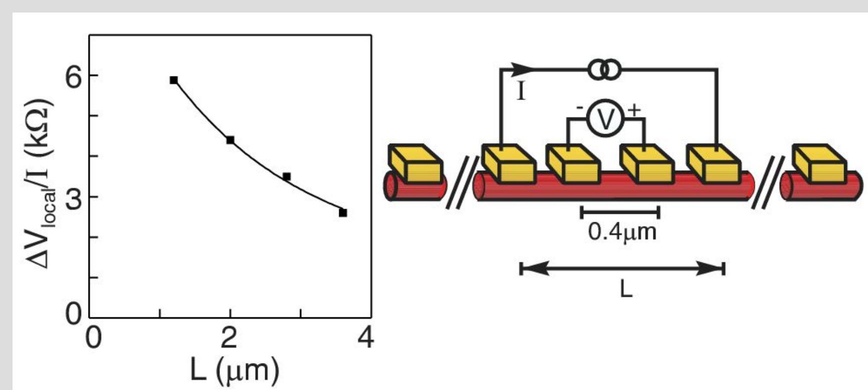


$V_{nonlocal}$

(a) decay length 0.94 μm
(b) decay length 0.92 μm
(c) prop. to $1\text{-}exp(\text{-}L/L_a)$ with $L_a = 0.94\mu m$

V_{local}

decay length 2 μm



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Further measurements

Dependence on type of MWCNT?

➔ all 40 measured samples show comparable behavior

Dependence on fabrication process?

➔ alternative configuration (MWCNT on top of contacts) gives similar results

Dependence on contact spacing?

➔ leaving out unused contacts does not change results

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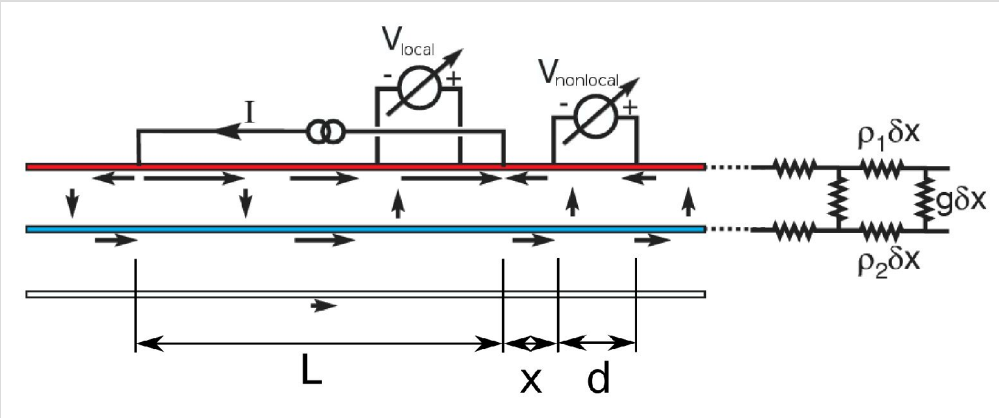
Theoretical model



L,*d*,*x*: given by setup
L_a, $V_{(non)local}$: measured
ρ_1,ρ_2, *g*: to be determined

Model based on infinite transmission line:

$$\frac{\Delta V_{\mathrm{nonlocal}}}{I} = \frac{g\rho_1^2 L_a^3}{2}\exp\left(\frac{-x}{L_a}\right)\left[1-\exp\left(\frac{-d}{L_a}\right)\right] \times \left[1-\exp\left(\frac{-L}{L_a}\right)\right], \quad (1)$$

$$\frac{\Delta V_{\mathrm{local}}}{I} = g\rho_1 L_a^3\left[\frac{\rho_2 d}{L_a} + 2\rho_1 \mathrm{sh}\left(\frac{d}{2L_a}\right)\exp\left(\frac{-L}{2L_a}\right)\right], \quad (2)$$

with $L_a^{-1} = \sqrt{g(\rho_1 + \rho_2)}$.

- agrees with qualitative behavior of measurements

Evaluation of results

Quantitiative evaluation based on

- $L_a = 0.93\ \mu m$
- $x = L = d = 0.4 \mu m$ (for $V_{nonlocal}$)
- $d = L/3 = 0.4 \mu m$ (for V_{local})
- average over eight independent measurements, translated along the tube, to avoid dependency on position (imperfections, finite size effects, ...)

Result for one specific sample:

$\rho_1 \sim 22\ k\Omega/\mu m$ $\rho_2 \sim 1\ k\Omega/\mu m$ $g \sim (20\ k\Omega)^{-1}/\mu m$

Result for eight samples ($6..23\ nm$ thick):

$\rho_1 \sim 6 ... 25\ k\Omega/\mu m$ $\rho_2 \sim 0.05 ... 2\ \rho_1$ $g \sim (3.7 ... 20\ k\Omega)^{-1}/\mu m$

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Further results

assuming $\rho_3=\rho_2$: contribution of third shell only 10%
(for length shorter than 5 µm)

ρ_1 often higher than ρ_2
-> higher diffusion in outermost shell?

intershell conductivity larger than
most theoretical expectations

weak temperature dependency from 8 to 280 K
-> intershell transmission unlikely to be thermally activated

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