Journal club presentation

by Norbert Nemec

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PHYSICAL REVIEW B **70**, 195408 (2004)

Observation of Fano resonances in single-wall carbon nanotubes

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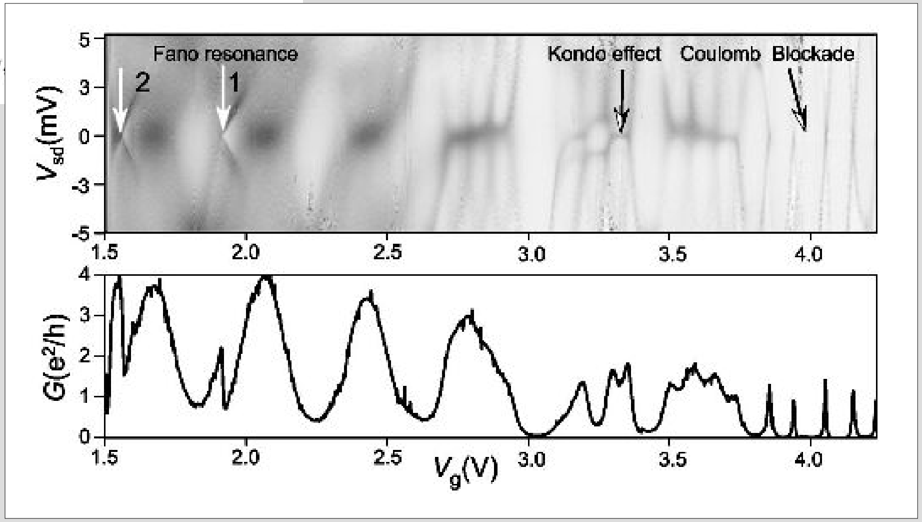
(Received 23 June 2004; published 10 November 2004)

We have explored the low-temperature linear and nonlinear electrical conductance G of metallic carbon nanotubes (CNT's), which were grown by the chemical-vapor deposition method. The high transparency of the contacts allows to study these two-terminal devices in the high conductance regime. We observe the expected four-fold shell pattern together with Kondo physics at intermediate transparency $G \lesssim 2e^2/h$ and a transition to the open regime in which the maximum conductance is doubled and bound by $G_{max}=4e^2/h$. In the high-G regime, at the transition from a quantum dot to a weak link, the CNT levels are strongly broadened. Nonetheless, sharp resonances appear superimposed on the background which varies slowly with gate voltage. The resonances are identified by their lineshape as Fano resonances. The origin of Fano resonances is discussed along the modeling.

DOI: 10.1103/PhysRevB.70.195408 PACS number(s): 73.63.Fg, 73.63.Kv,



Experimental setup

- SWCNT grown from catalyst islands by CVD on Si/SiO_2
- Si used as backgate (SiO_2 400nm thick)
- 2P-contacts patterned by electron beam lithography
- low-Ohmic metallic tubes selected
  by G — V_g dependence at room temperature

➔ found that palladium contacts make excellent contacts
  ($G > e^2/h$ for most samples without post-growth treatment)

- measurements done at 300 mK in ^3He system
- measured $I(V_g,V_b)$, determined dI/dV numerically
  (linear response measured at V_b=40µV)

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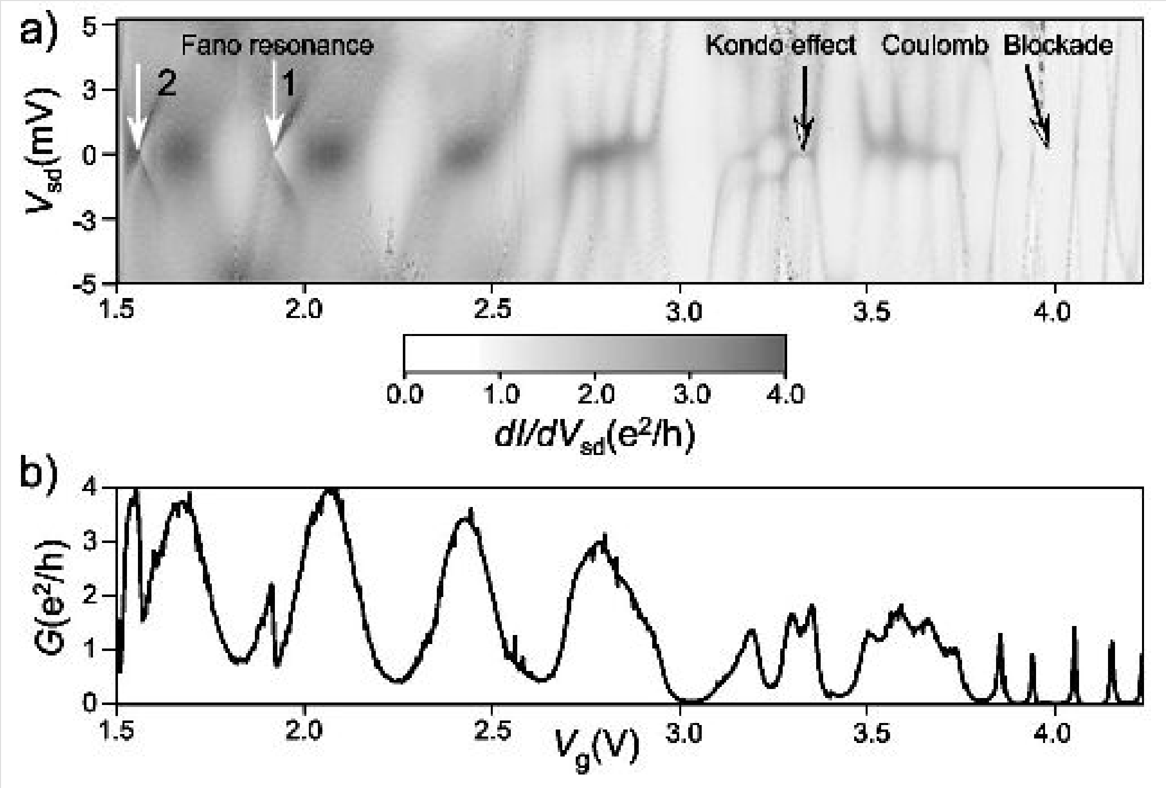
General observations

weak coupling:
- Coulomb Regime
  (four-fold degeneracy)

medium coupling:
- Kondo-effect

strong coupling:
- open wire
- Fabry-Perot interference
- Fano resonances



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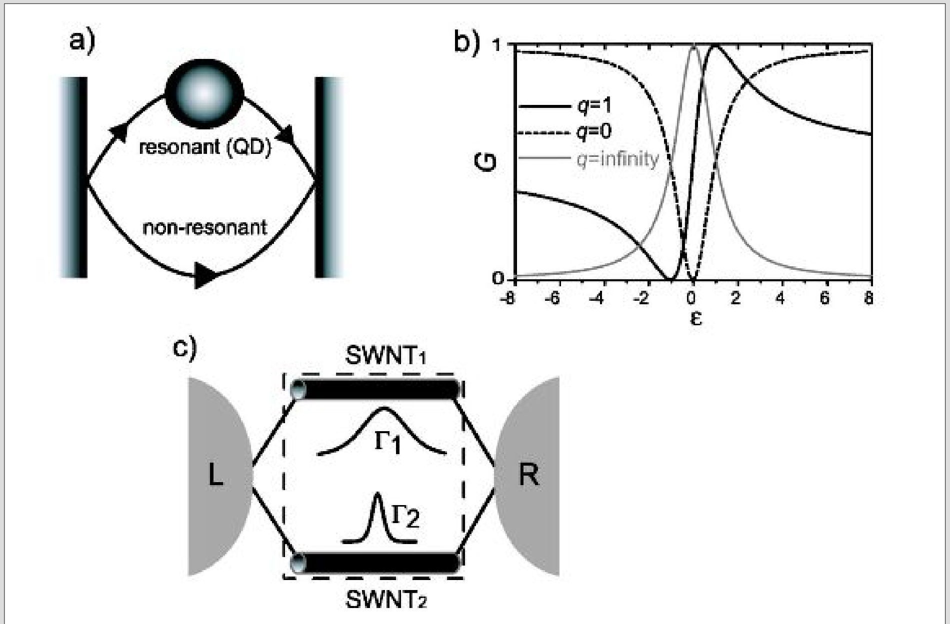
Fano resonances



$$G(\epsilon) = G_{\mathrm{nonres}} + G_{\mathrm{res}} \frac{(\epsilon + q)^2}{\epsilon^2 + 1},$$

$$\epsilon \equiv 2(E - E_0)/\Gamma$$

Universal feature

(e.g. atom/molecule spectroscopy, electron/neutron/Raman scattering)

Interference between
resonant channel (QD)
and
non-resonant channel

U. Fano, Phys Rev. **124**, 1866 (1961)

Γ – width of resonant state

q – assymetry parameter (~ ratio between transmission of two channels)

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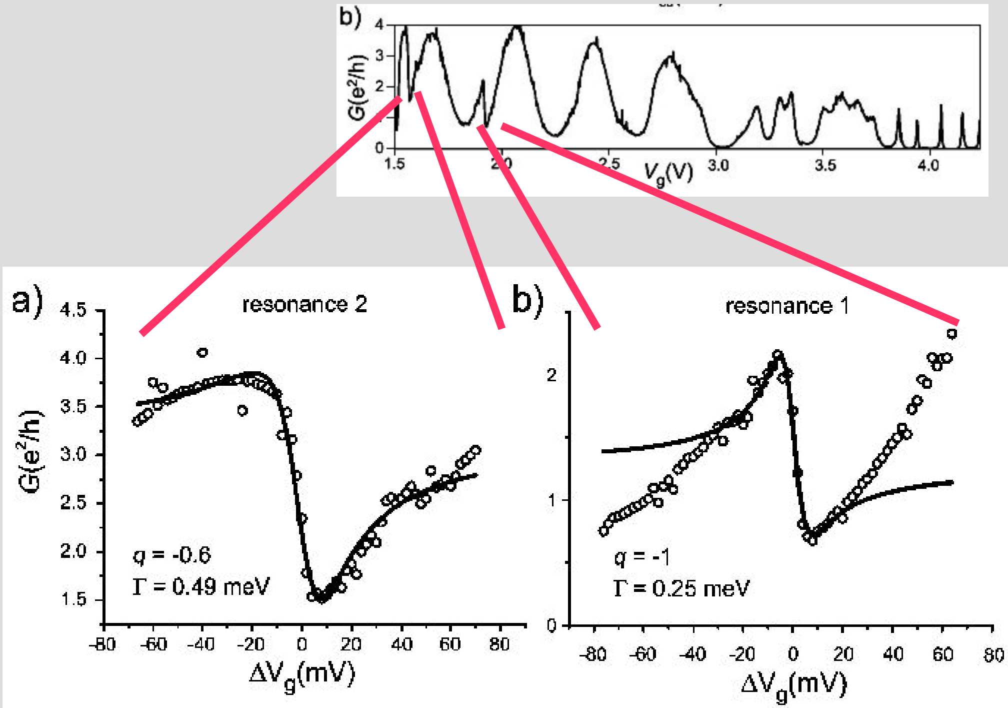
Examination of Fano-resonances



Fitted by:

$$G(\epsilon) = G_{\text{nonres}} + G_{\text{res}} \frac{(\epsilon + q)^2}{\epsilon^2 + 1},$$

$$\epsilon \equiv 2(E - E_0)/\Gamma$$

compare
broadening of levels
in cotunneling regime

$$\Gamma_{\text{cotunneling}} = 2.0 \text{ meV}$$

(even bigger in open wire regime!)

➔ broadening of non-resonant levels much smaller

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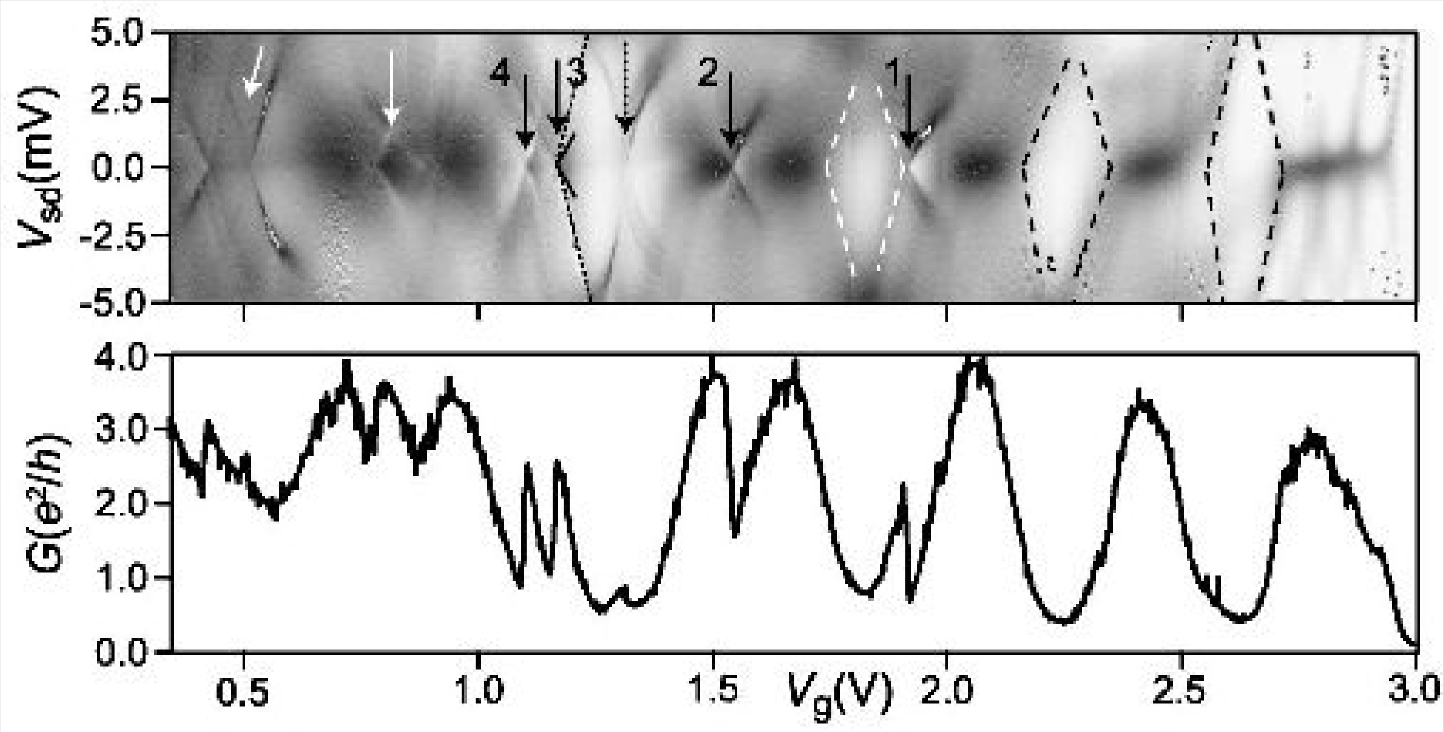
Further measurements

Same sample at lower V_g:



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Discussion

Former results:

Fano resonance in crossed MWCNT

Kim et al., PRL **90** 166403 (2003)

➔ localized states at crossing...

Fano resonances in isolated MWCNT

Yi, Lu, Hi, Pan and Xie, PRL **91**, 076801 (2003)

➔ resonant states in one of the shells...

➔ localized states at defects...

Now:

Fano resonances in isolated SWCNT

all four channels are coupled with similar strength

➔ **"ghost" Fano resonances?**

(i.e.: two resonant states recombining to one resonant and one non-resontant state)

Ladrón *et al.*, PRB **64**, 155311 (2001)

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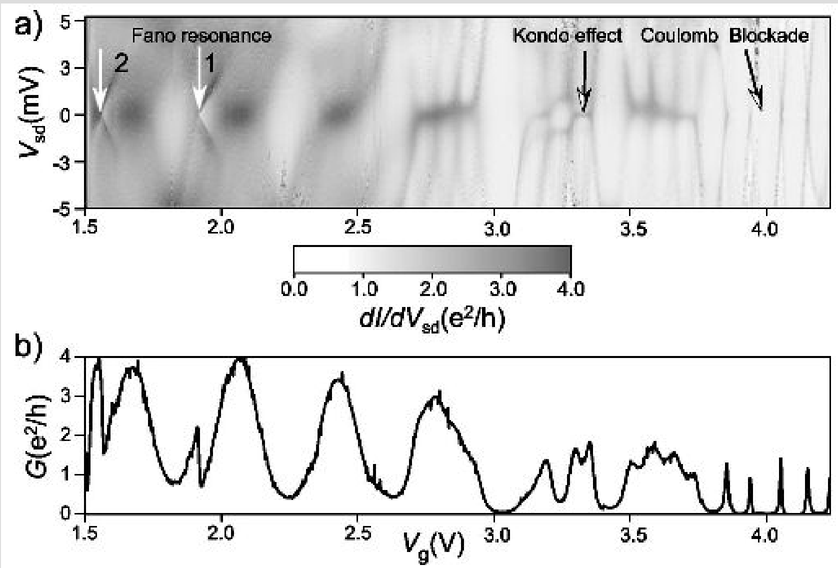
Gate dependence of contacts

Not discussed further in paper by Babić and Schönenberger



Thought:

Schottky-barriers in contacts

Carbon Nanotubes as Schottky Barrier Transistors

S. Heinze, J. Tersoff,* R. Martel, V. Derycke, J. Appenzeller, and Ph. Avouris†

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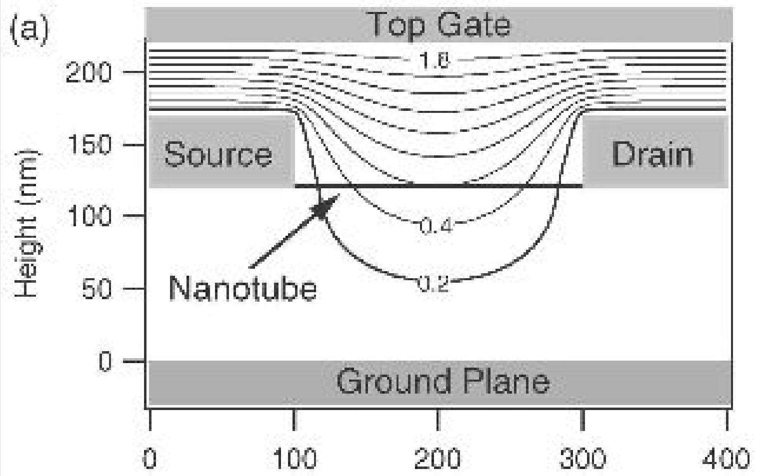
(Received 16 March 2002; published 15 August 2002)

We show that carbon nanotube transistors operate as unconventional "Schottky barrier transistors," in which transistor action occurs primarily by varying the contact resistance rather than the channel conductance. Transistor characteristics are calculated for both idealized and realistic geometries, and scaling behavior is demonstrated. Our results explain a variety of experimental observations, including the quite different effects of doping and adsorbed gases. The electrode geometry is shown to be crucial for good device performance.

DOI: 10.1103/PhysRevLett.89.106801 PACS numbers: 73.63.Fg, 73.40.Cg

Schottky barrier CNT-metal contact

From Heinze *et al.:*



semiconducting CNT:
gate-dependent Schottky barriers

↓

CNT-Transistor

Babić & Schönenberger?

metallic CNT:
gate-dependent band-bending
(i.e. partial reflection)

→

Gate-dependent contact quality

Why isn't it observed more commonly?

Palladium as contact material

Work in progress - preliminary results

A) Closely matching work function ($\Delta E \approx 0.4$ eV)

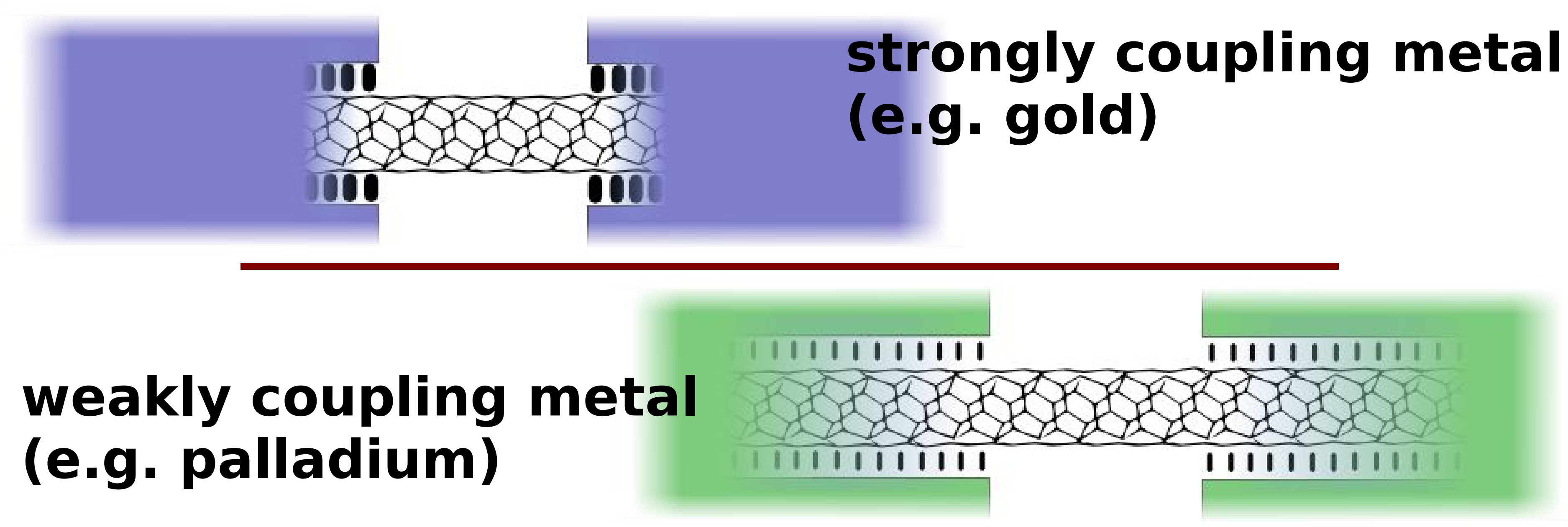
(i.e. small charge transfer at contact surface)

B) Weak hybridization near Fermi level

(i.e. electronic structure of CNT is not perturbed by coating)

C) Small hopping between Pd and CNT

(i.e. electrons can travel along coated CNT without dissipating into Pd)



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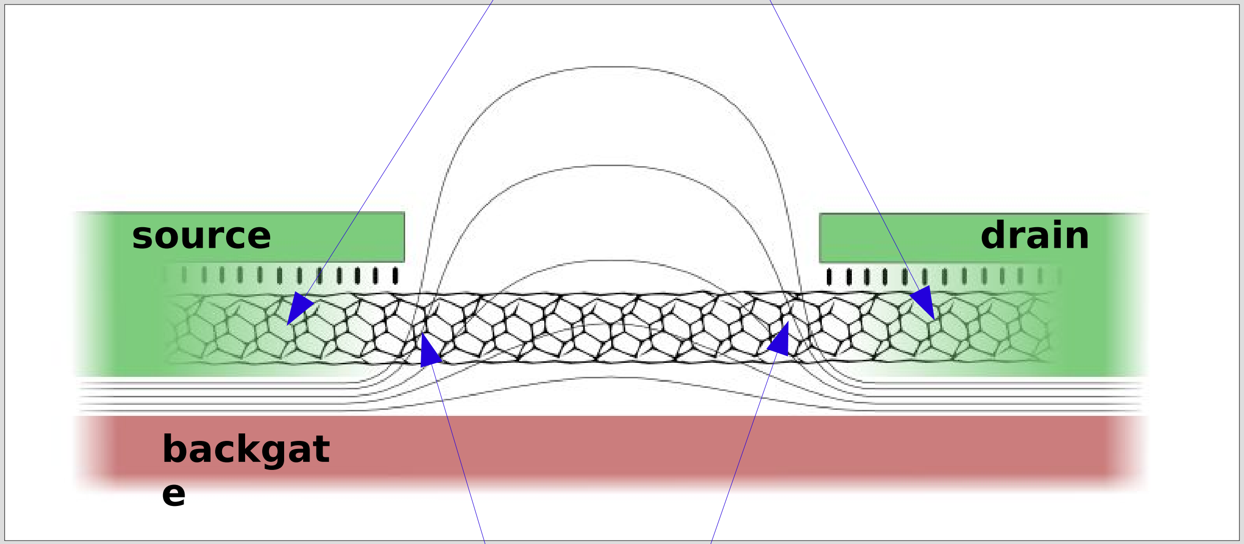
Gate dependence of Pd contacts

metal-CNT contact: smooth and transparent



weakest point: potential steps (dependent on V_g)

➔ **V_g defines quality of contact**

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single-wall nanotubes
different regimes as a function of gate voltage

open dot ($R \sim R_Q$)
blurred CB diamonds
Fabry-Perot, Kondo physics

closed dot ($R >> R_Q$)
sharp CB diamonds
spectroscopy