Journal Club, 15.12.2004

Fabry-Perot interference in a nanotube electron waveguide

*W. Liang et al.**

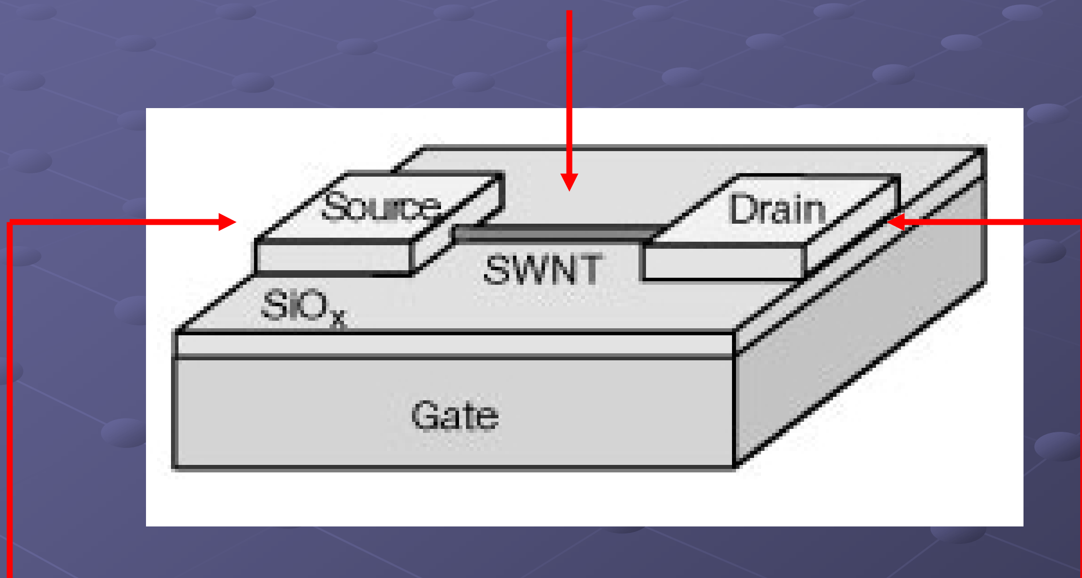
(Nature, Vol 411, June 2001)

presented by
Nils Meyer

*Department of Chemistry and Chemical Biology and Department of Physics, Harvard University, Cambridge, Massachusetts

Experimental Setup

SWCNT synthesized on degenerately doped silicon wafer with 1-µm oxide layer by chemical vapour deposition



Nanotube devices were fabricated by defining two Au/Cr electrodes on top of SWCNT by electron beam lithography

Carbon nanotube classification

- SWCNTs were classified by their resistance versus gate voltage (V_g) behaviour

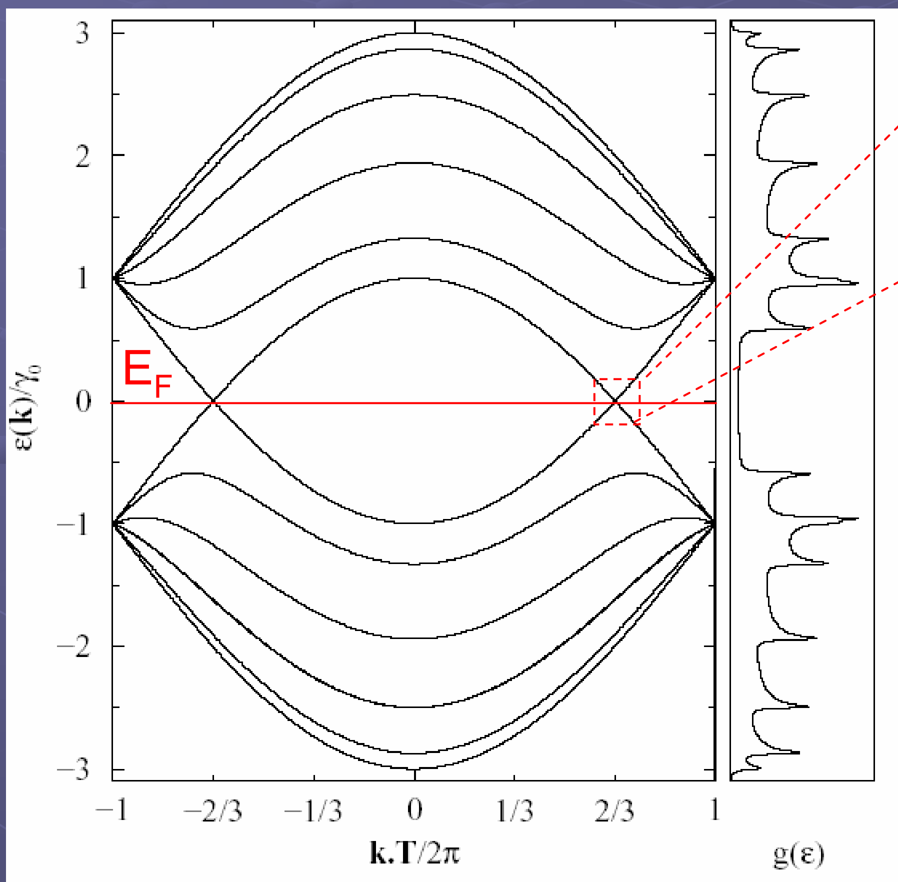
- Only metallic tubes with room-temperature resistances ≤ 15 kΩ have been used

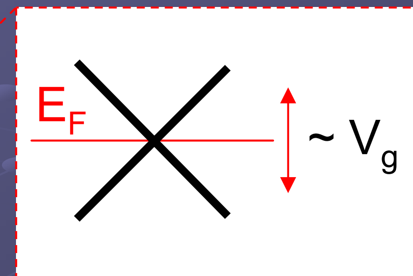
- Lowest resistances were around 7 kΩ
  Theoretical value: $2 * 2\ h/e^2 = 6.5\ k\Omega$

Almost perfect ohmic contacts
Little reflection

Band structure & density of states

Metallic SWCNT (5,5)



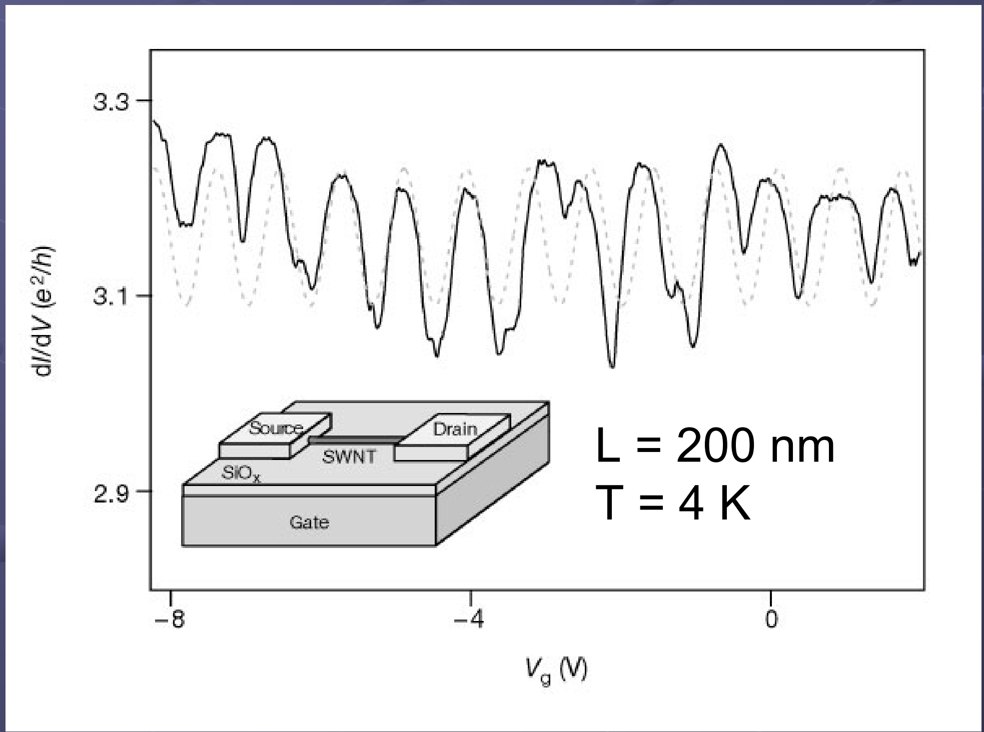


Current is carried by two spin-degenerate one-dimensional transport modes with linear dispersion for small gate voltages V_g

Maximum $\partial I/\partial V$ of 4 e^2/h

Zero-bias differential conductance

- Below T = 10 K oscillations in ∂I/∂V which are quasi-periodic in V_g due to resonant tunneling
- Average differential conductance around 3.2 e²/h

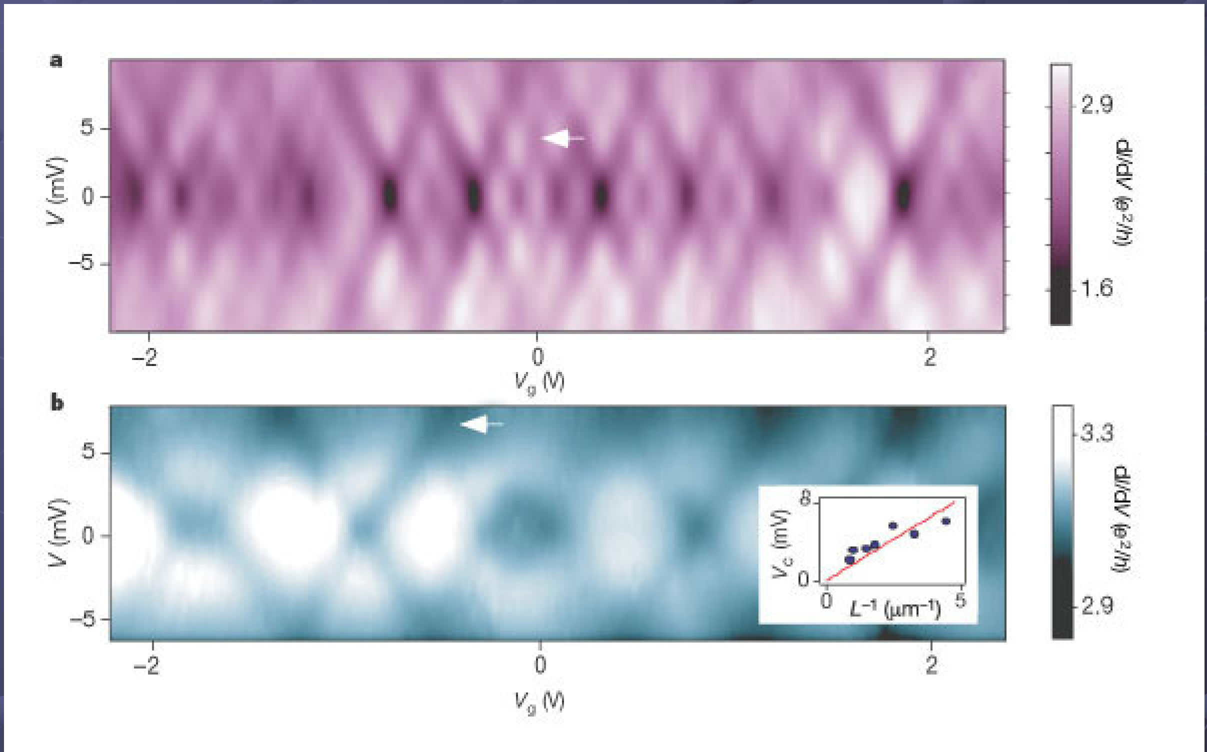


∂I/∂V – V – V_g patterns (I)

- Smooth mesh of crisscrossing dark lines due to interference
- Average differential conductance 2-3 e^2/h for all devices
- Non-zero ∂I/∂V indicates difference to Coulomb-diamonds

L = 530 nm

L = 220 nm



∂I/∂V – V – V_g patterns (II)

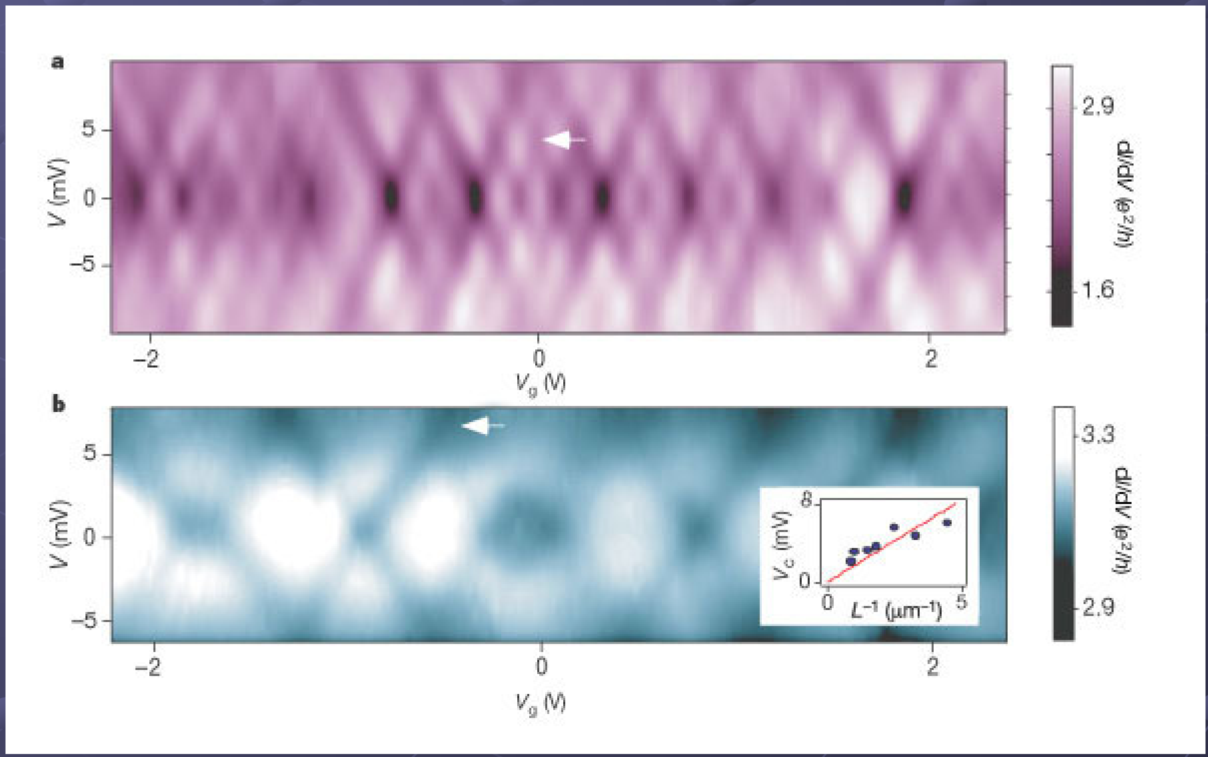
- First crossing of slopes at voltage V_c (indicated by ←) is proportional to inverse length L

V_c ~ 1/L (inset)

- electron scattering occurs mostly at the nanotube-metal interface (ballistic transport in the tube)

L = 530 nm
V_c = 3.5 meV

L = 220 nm
V_c = 6.5 meV



About the paper title …

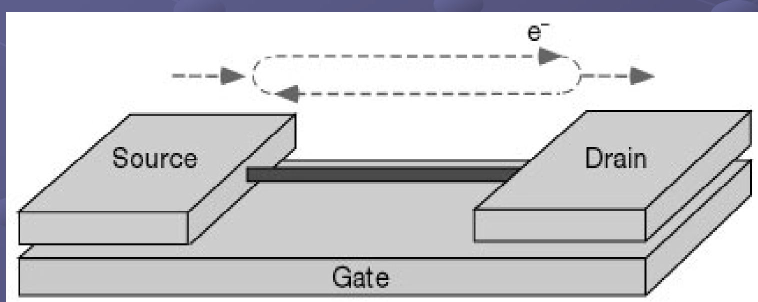
Ballistic transport
+ Scattering

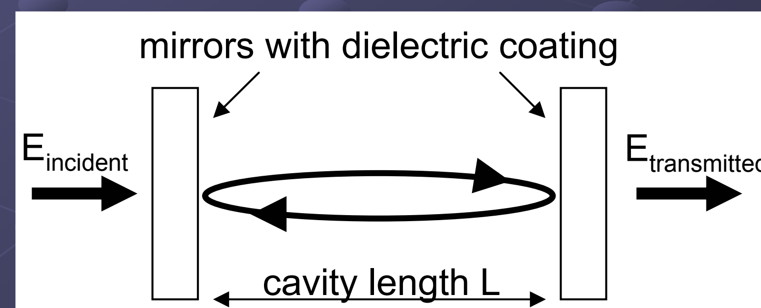
Analogous

Fabry-Perot-Cavity

Quantum interference between multiply reflected electron waves

Light interference in cavity between multiply reflected light waves



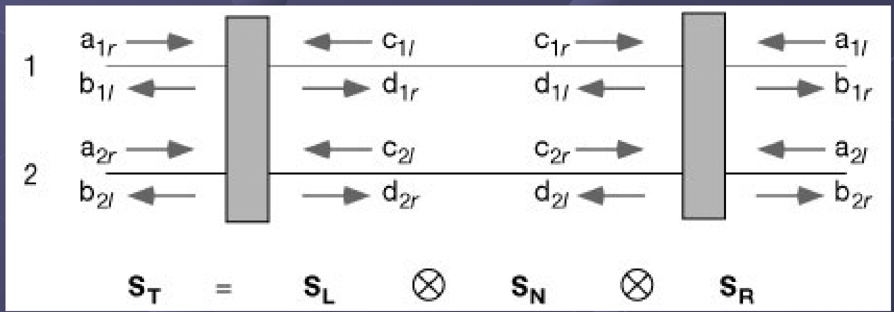


device characteristics

transmitted intensity

Theoretical model (I)

- Based on multichannel Landauer-Büttiker formalism
- The nanotube is considered as a coherent waveguide with two propagating modes
- Electron scattering modelled by 4x4 scattering matrices
  S_L, S_R (for interfaces) and
  S_N (energy depending phase accumulation)



Theoretical model (II)

- The current through the nanotube can be calculated by

$$I = \frac{2e}{h}\int_{-eV/2}^{eV/2}\sum_{i,j=1,2}|\, t_{il,jr}\left(\frac{E}{\hbar v_F}+\frac{\pi}{4}\frac{LC_L V_g}{e}\right)|^2 \; dE$$

- The differential conductance is hence given by

$$\frac{\partial I}{\partial V} = \frac{2e^2}{h}\left[\sum_{i,j=1,2}|\, t_{il,jr}\left(\frac{eV}{2\hbar v_F}+\frac{\pi}{4}\frac{C_L V_g}{e}\right)|^2 + \sum_{i,j=1,2}|\, t_{il,jr}\left(\frac{-eV}{2\hbar v_F}+\frac{\pi}{4}\frac{C_L V_g}{e}\right)|^2\right]$$

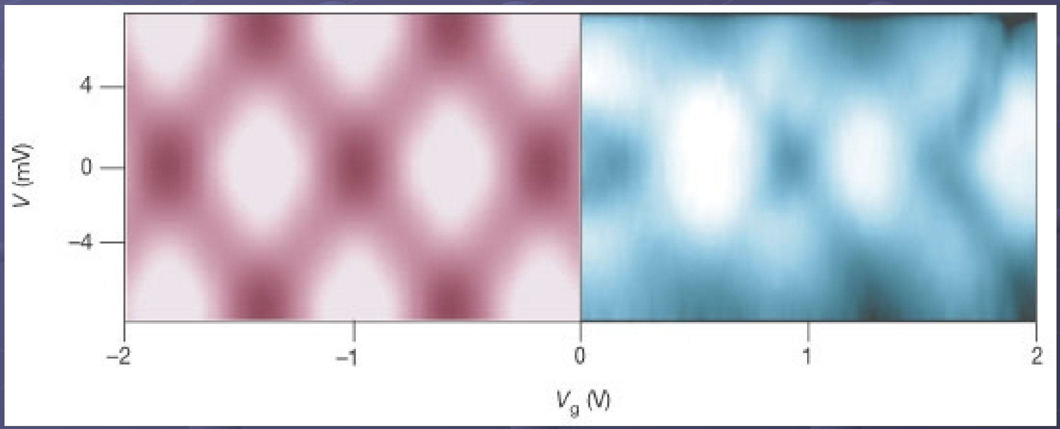
with C_L = 20 electrons / V µm — Capacitance per unit length

$v_F = 8*10^5$ m / s — Fermi velocity

Theoretical model (III)

- Good agreement between theoretical and experimental data

SWCNT of 220 nm length



- *But: Several features unexplained by theory*
  - magnitudes of ∂I/∂V – dips show variations
  - superstructures in 2d-plot which are not periodic in V_g
  - occurence of heating or dephasing when electron energy deviates from equilibrium

Interference effects in electronic transport through metallic single walled carbon nanotube

Phys. Rev. B, vol. 66, 073412

S. Krompiewski, J. Martinek and J. Barnas

presented by

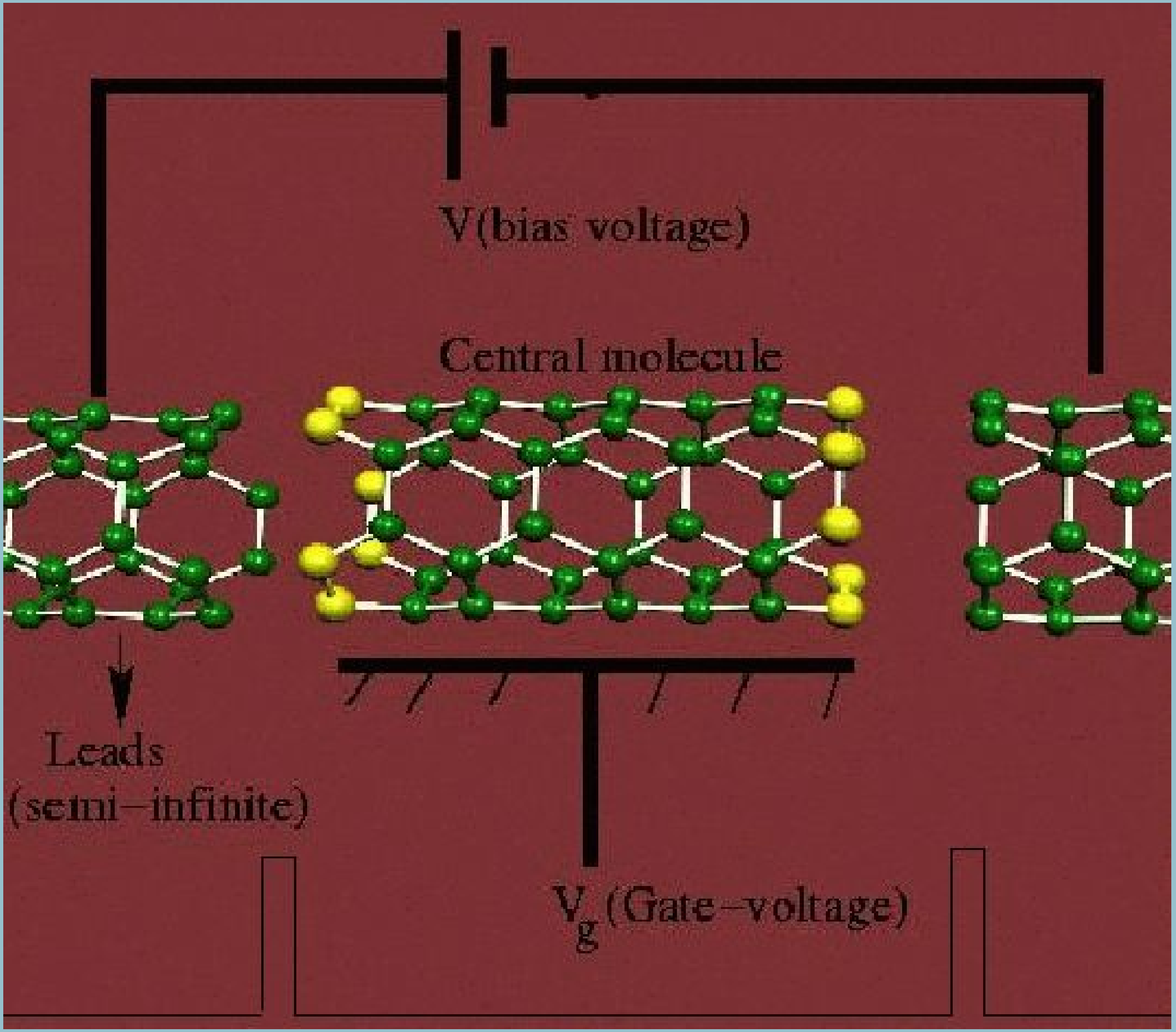
Nitesh Ranjan
MCG, Uni-Regensburg

Experimental Details

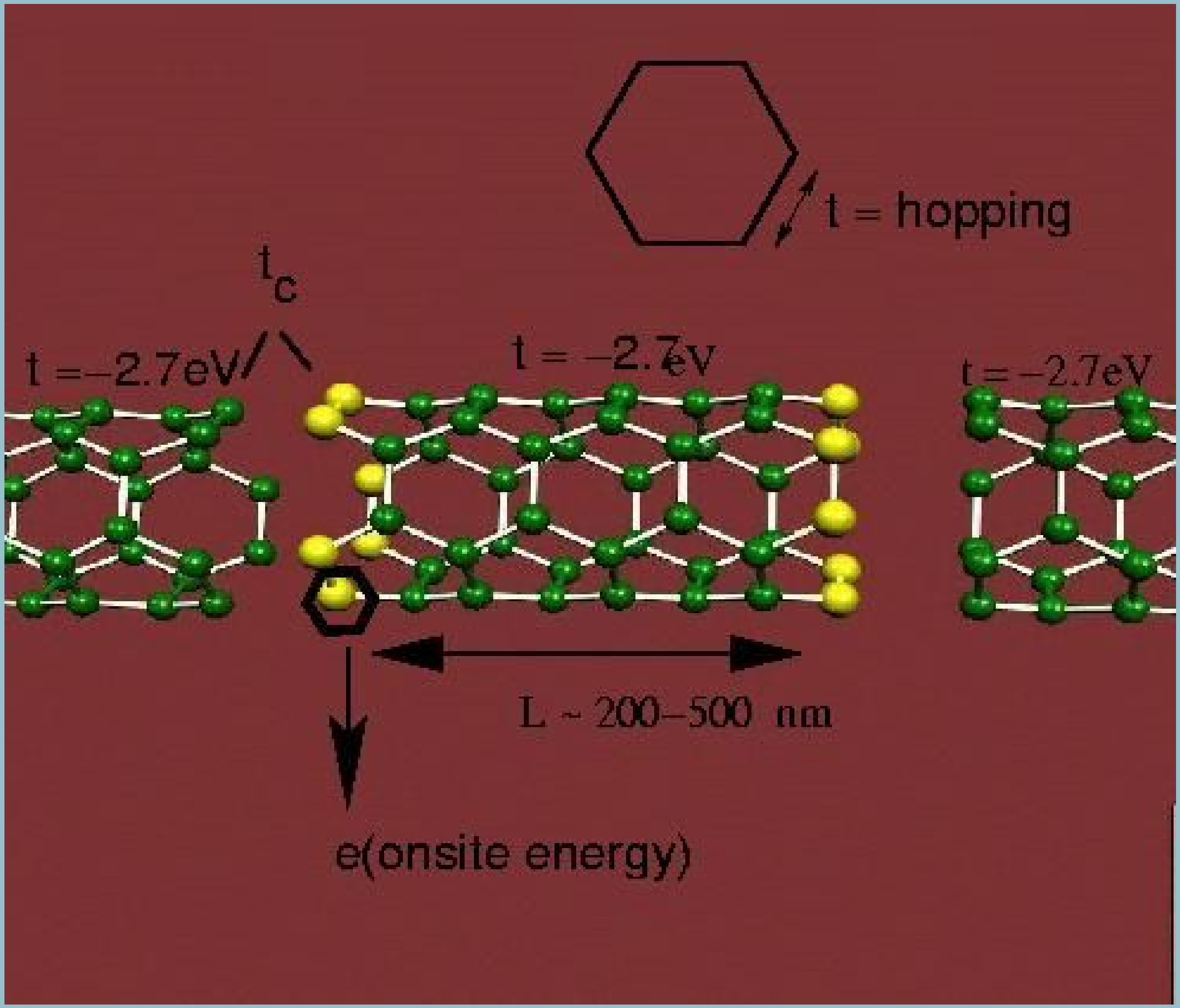
Liang. *et al*, Nature 411, 665 (2001)

- Metallic CNT strongly coupled to leads(Au/Cr).
- CNT behave as coherent molecular wave guides.
- Conductance show interference effects.
  - Multiple reflection from the boundaries.
- Color scale plot revealed characteristic diamond structures

Visualization of theoretical model



Our Parameters



* (3,3) CNT

* 884uc ~ 220nm

* 2129uc ~ 530nm

Theory

Block Hamiltonian

$$\begin{pmatrix} G_L & G_{LM} & G_{LR} \\ G_{ML} & \boxed{G_M} & G_{MR} \\ G_{RM} & G_{RM} & G_R \end{pmatrix} = \begin{pmatrix} E - H_L & -H_{LM} & 0 \\ -H_{ML} & \boxed{E - H_M} & -H_{MR} \\ 0 & -H_{RM} & E - H_R \end{pmatrix}^{-1}$$

- Solving the equation for the molecule we get $G_M = [E - H_M - \Sigma_L - \Sigma_R]^{-1}$ **Dyson's Equation**

  $\Sigma_{L/R}$ are the self energies given by :

  $\Sigma_\alpha = H_{M\alpha} g_\alpha^S H_{\alpha M}, \ \alpha = L/R$

- g_α^S is the surface green function of the contact(Right/Left) obtained by iterative calculation of transfer matrices.

Transmission

$$T_{LR}(E) = Tr(\Gamma_L G_M \Gamma_R G_M^\dagger) \quad \textbf{Landauer formula}$$

$$\Gamma_\alpha = i(\Sigma_\alpha - \Sigma_\alpha^\dagger) \quad \alpha = L/R$$

Differential conductance

Temperature = 0 K

$$I(V) = \frac{2e}{h} \int_{-\infty}^{\infty} [f(E - \frac{eV}{2}) - f(E + \frac{ev}{2})] T(E, \phi) dE$$

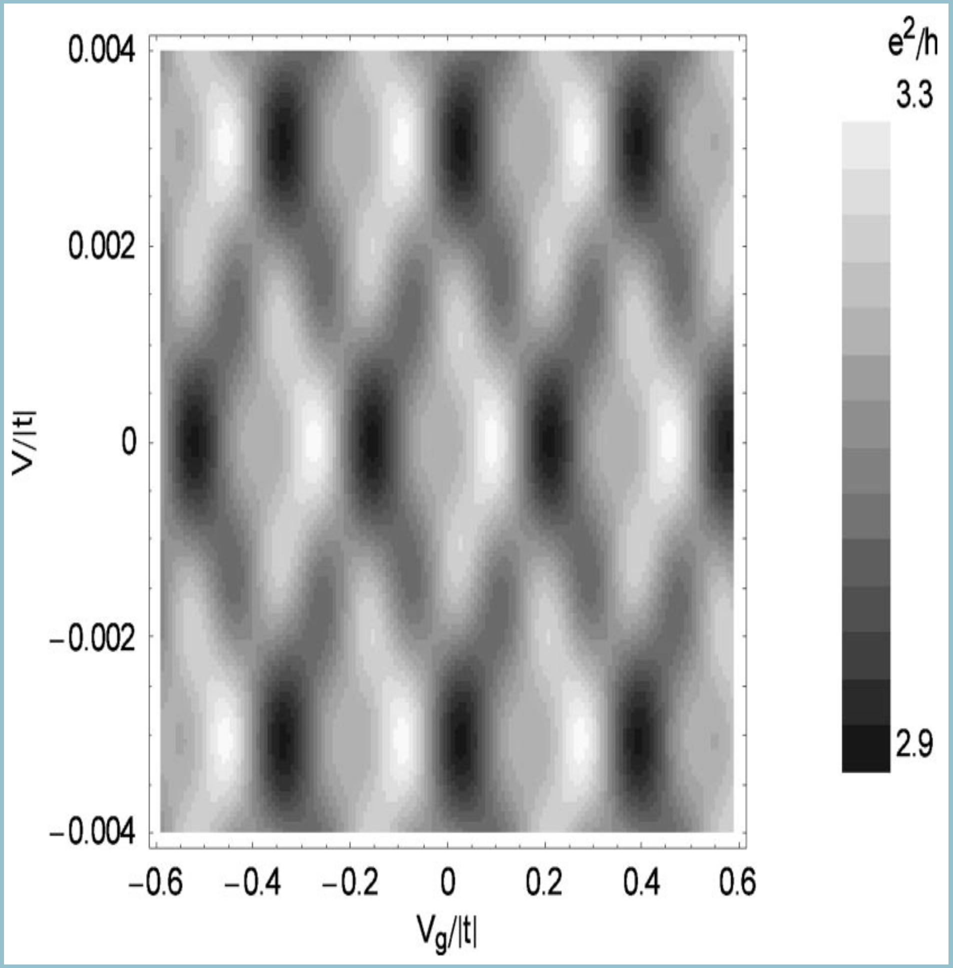
$$\frac{\partial I(V)}{\partial V} = \frac{e^2}{h} [T(E_F + \frac{eV}{2}, \phi) + T(E_F - \frac{eV}{2}, \phi)]$$

V = applied bias

ϕ = average potential energy due to applied gate voltage

Results

<u>Length of CNT = 220nm</u>

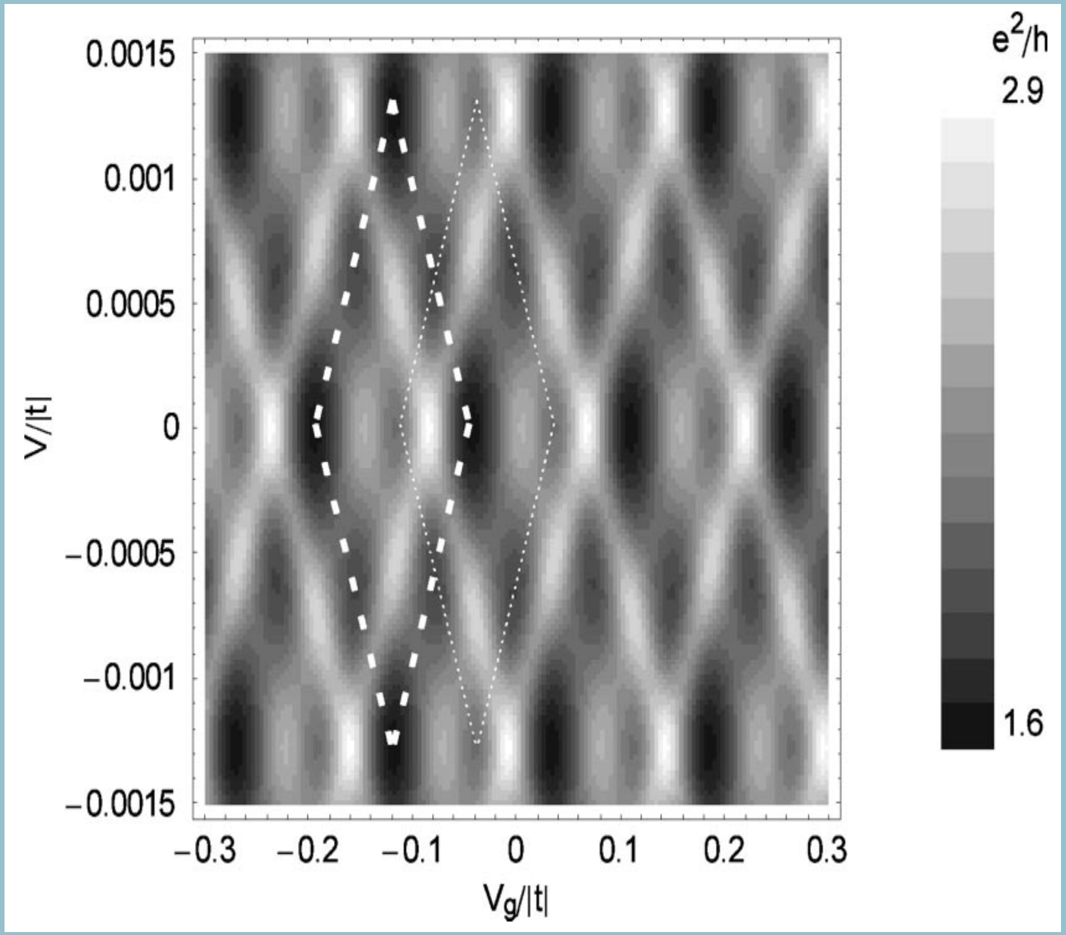


* Period in V = 16.7mV; from figure
* Estimated value = 15.2mV
* From experiment = 13mV

**t_C = -1.971eV ; ε = 0.189eV

Results(II)

Length = 530nm



* Period in V = 6.78mV (from Figure)
* Estimated value = 6.8mV
* From experiments = 7mV

**t_C = -1.62 , ε = 0.945
** double-diamond structures; observed when difference between t_C & t increases.

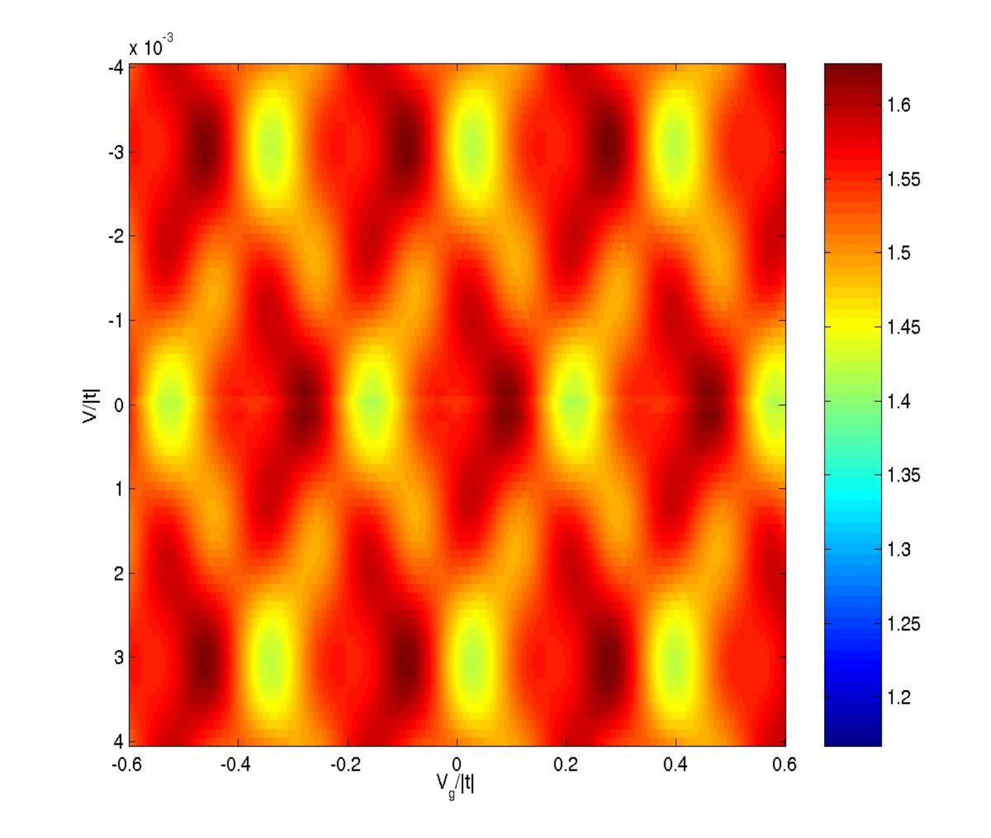
Results(III)

- Periods in V and V_g α 1/L
- t_c determine coupling of the leads(strong coupling or weak confinement)
- Onsite energy acts as additional reflecting factor.
- These two defects acting together gives satisfactory results.

Our Calculations,
To motivate some discussion !!

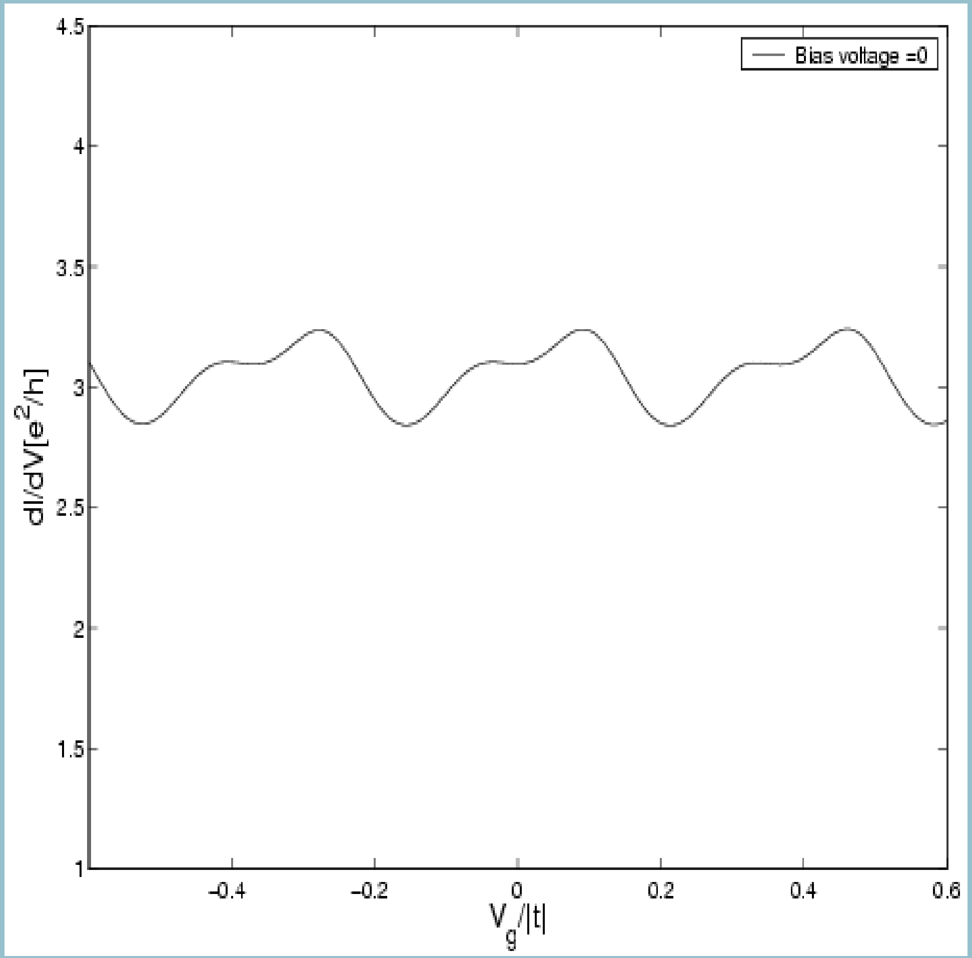
(3,3)CNT, 884 uc ~ 220nm

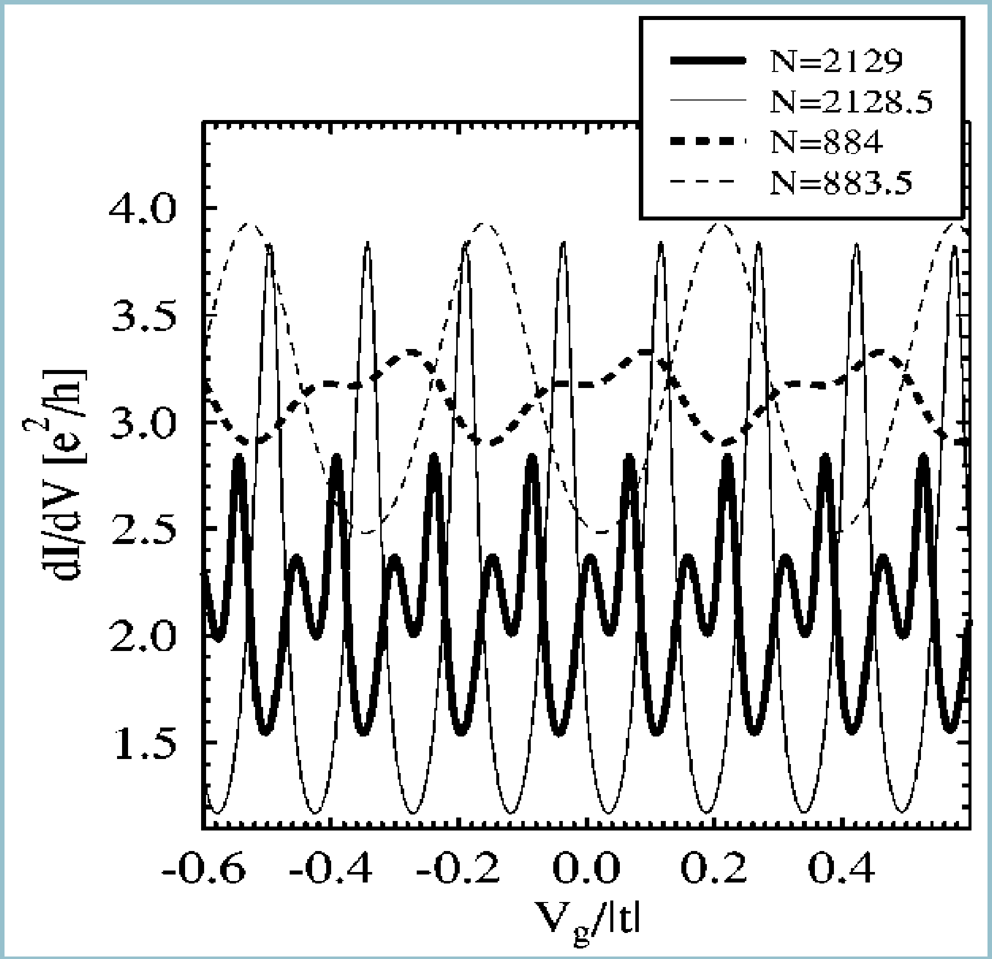
$t_c = -1.971$, $\varepsilon = 0.189$



Our Calculations(II)

Differential Conductance





Discussion !!

Some ideas to incorporate in the model !!