Analytical Theory of the Ballistic Carbon Nanotube Field-Effect Transistor

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Introduction
Gate electrostatics
I-V characteristics
Conclusions

Introduction: a promising device

µ(max) ~ 2,000-20,000 cm^2/V-s

I_{on} ~ 10 µA at V_{DD}~1V

McEuen et al., to be published.

Analytical $Q(V_G)$ and $C(V_G)$

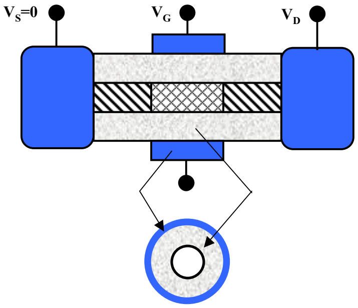
Analytical $I_D(V_G,V_D)$

Understand device physics

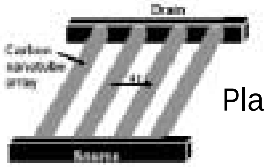
Explore design approaches

Modeled Device Structures

Coaxial



Planar

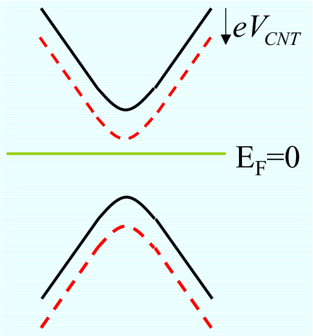


Planar array

Single tube

Gate Electrostatics:*Approach*

Semiclassical model



1) Charge density vs. CNT potential

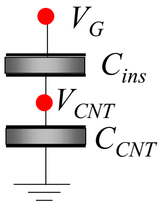
$$Q_{CNT}(V_{CNT}) = e \cdot \int dE\,\mathrm{sgn}(E) D(E) f\{\mathrm{sgn}(E)(E - eV_{CNT})\}$$

2) CNT potential vs. gate vltage

$$V_G^{'} = V_G - V_{fb} = V_{CNT} - \frac{Q_{CNT}(V_{CNT})}{C_{ins}}$$

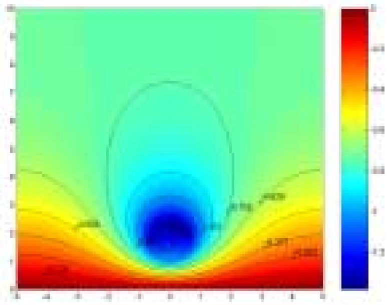
J. Guo et al., submitted for publication

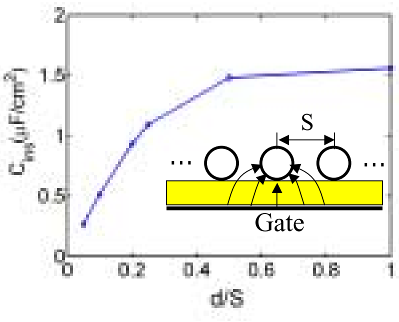
Gate Electrostatics:C_{ins}



$$\frac{1}{C_G} = \frac{1}{C_{ins}} + \frac{1}{C_{CNT}}$$

Gate Electrostatics: C_{ins}:

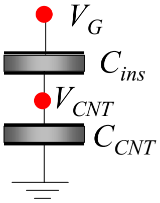




Planar: Numerical Poisson

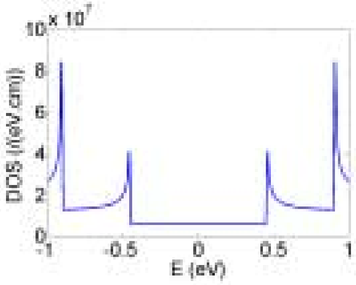
Coaxial: $C_{ins} = \dfrac{2\pi\kappa\varepsilon}{\ln(R_G / R_{CNT})}$

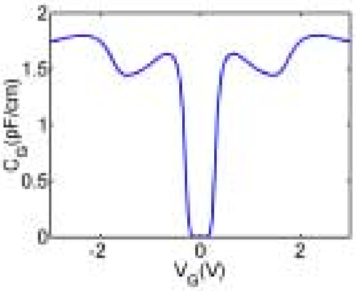
Gate Electrostatics: C_{CNT}



$$\frac{1}{C_G} = \frac{1}{C_{ins}} + \frac{1}{C_{CNT}}$$

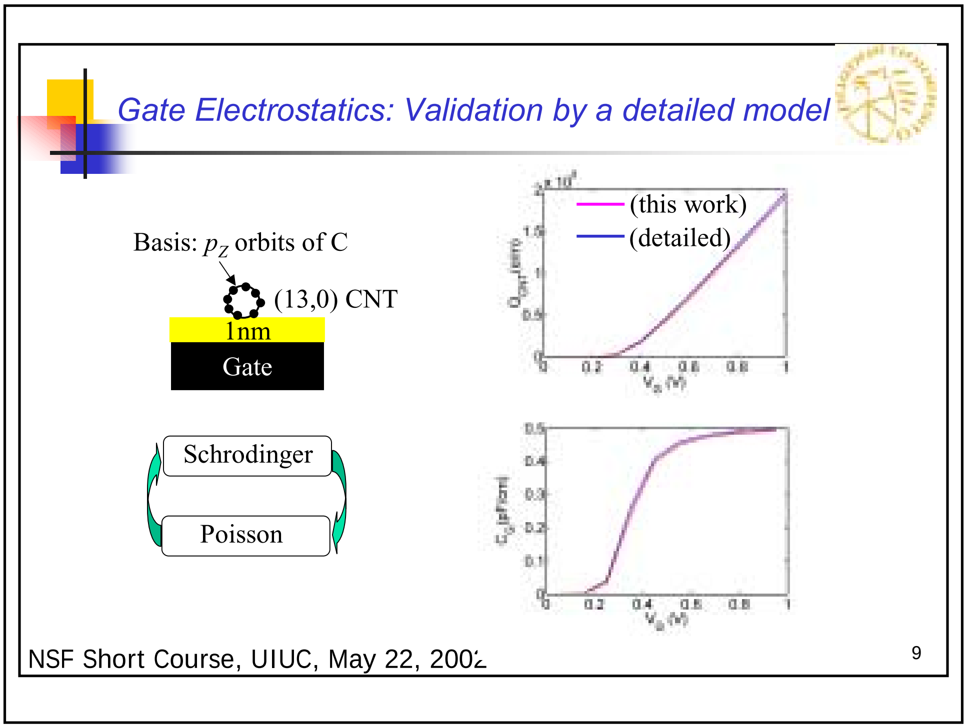
Gate Electrostatics: *C-V Reflects 1D DOS*





$$C_{CNT}(V_{CNT}) = e^2 D(eV_{CNT})$$
$$at\, T = 0K$$

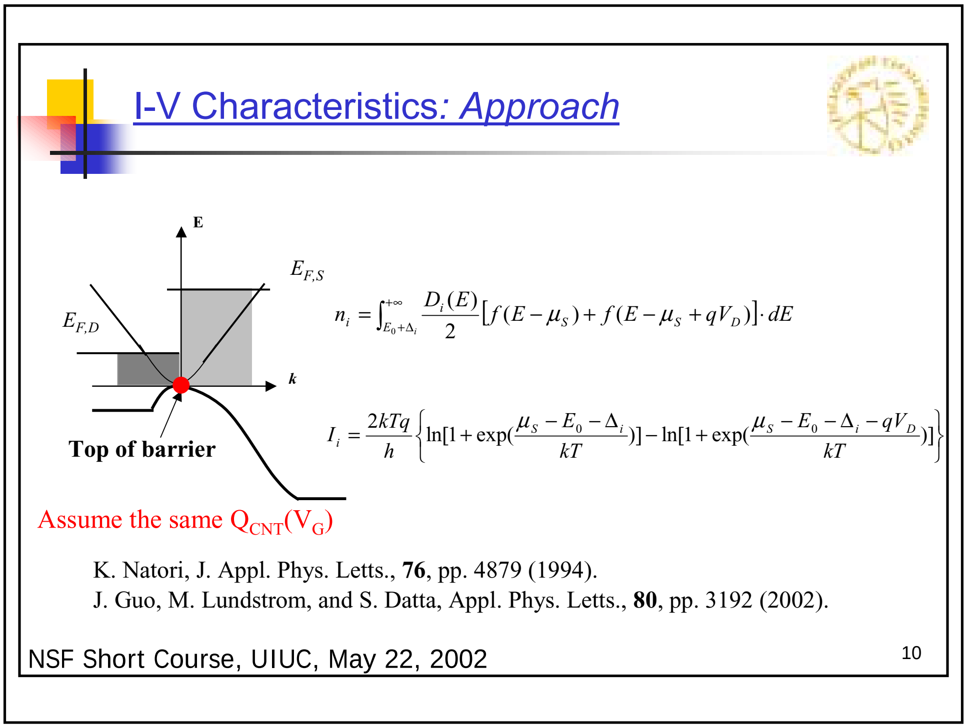
$$\frac{1}{C_G} = \frac{1}{C_{ins}} + \frac{1}{C_{CNT}}$$



Gate Electrostatics: Validation by a detailed model

Basis: p_Z orbits of C

(13,0) CNT



I-V Characteristics: *Approach*

$$n_i = \int_{E_0+\Delta_i}^{+\infty} \frac{D_i(E)}{2}\left[f(E-\mu_S)+f(E-\mu_S+qV_D)\right]\cdot dE$$

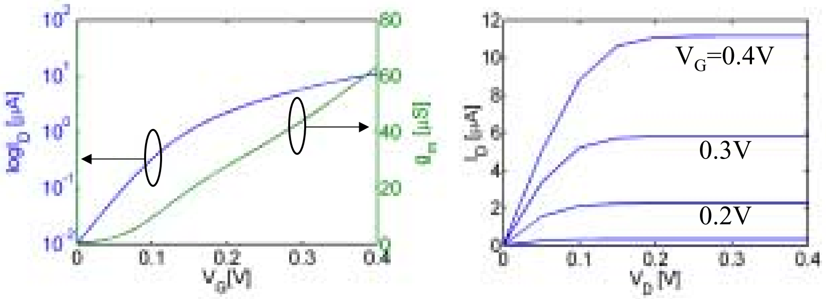
$$I_i = \frac{2kTq}{h}\left\{\ln[1+\exp(\frac{\mu_S-E_0-\Delta_i}{kT})]-\ln[1+\exp(\frac{\mu_S-E_0-\Delta_i-qV_D}{kT})]\right\}$$

Assume the same $Q_{CNT}(V_G)$

K. Natori, J. Appl. Phys. Letts., **76**, pp. 4879 (1994).
J. Guo, M. Lundstrom, and S. Datta, Appl. Phys. Letts., **80**, pp. 3192 (2002).

I-V Characteristics:

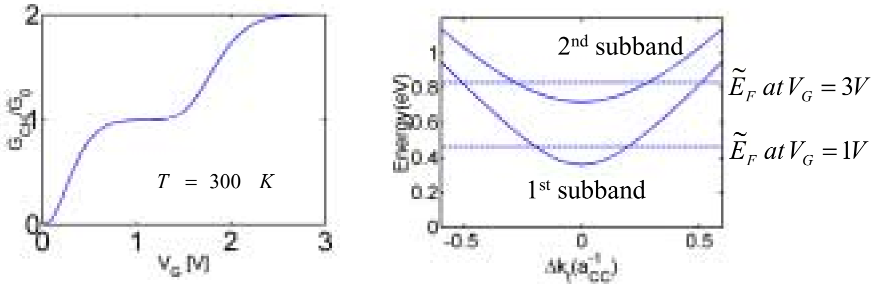
Ballistic CNTFET performance projection (upper limit)



Coaxially gated: t_{ins}=1nm, K =4

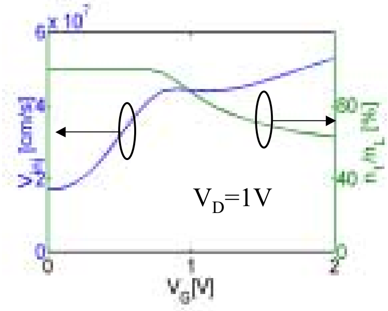
Quantized Channel Conductance:

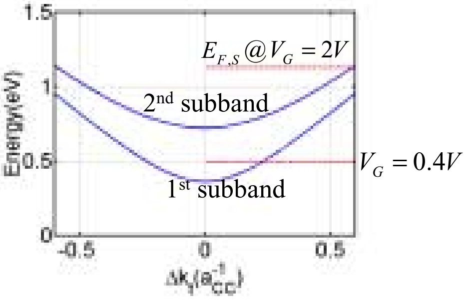
Coaxially gated: t_{ins}=1nm, $\kappa = 4$



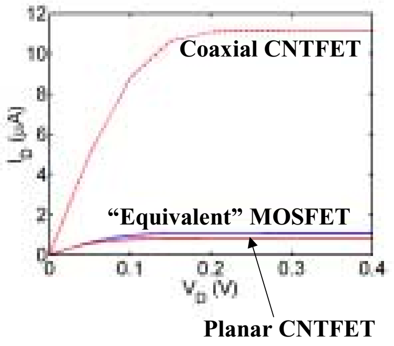
The Injection Velocity and Subband Occupancy

Coaxially gated: t$_{ins}$=1nm, $\kappa = 4$





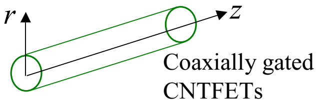
Comparison to silicon MOSFETs



- The electrostatic design is important for large I$_{on}$ at low power supply voltage.

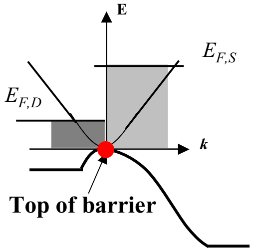
I-V characteristics: *Validation by a detailed model*

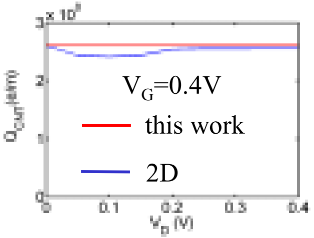
2D:

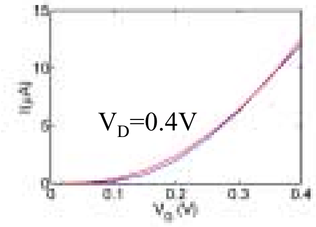


$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V}{\partial r}\right)+\frac{\partial^2 V}{\partial z^2}=-\frac{\rho}{\varepsilon}$$

1D:







NSF Short Course, UIUC, May 22, 2002

Conclusions:

- 1D analytical theory of silicon MOSFETs was adapted to CNTFETs and verified by detailed simulations.
- C-V of nanotube MIS capacitors is influenced by 1D DOS
- Quantized channel conductance due to 1D nature
- Careful electrostatic design will be important for CNTFETs

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