Physics of Nanoscale Transistors

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additional information at: www.ece.purdue.edu/celab

Acknowledgements

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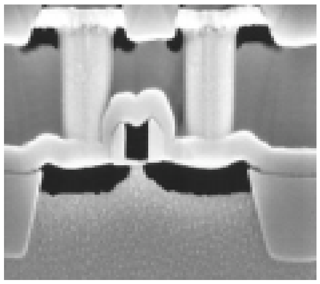
sponsors: NSF, SRC
MARCO Focus Center on Materials, Devices Structures
ARO DURINT
Indiana 21st Century Research and Technology Fund

1. Introduction

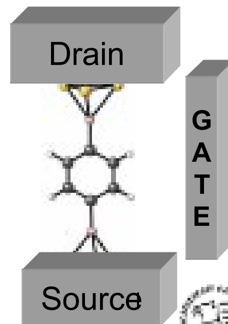


MOSFET

CNTFET

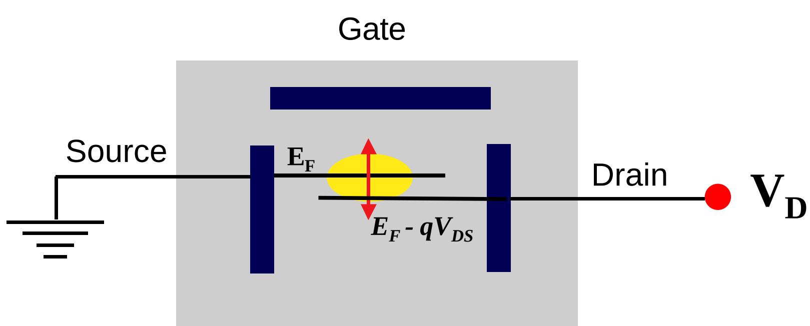
Bachtold, et al., *Science*, Nov. 2001

Molecular FETs?



Lundstrom

1. Introduction

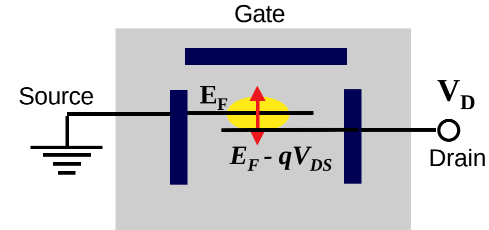


1) self-consistent electrostatics

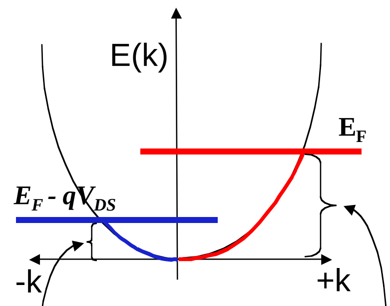
2) transport

Lundstrom

1. Introduction



$$Q = Q^+(E_F) + Q^-(E_F - qV_{DS})$$
$$I_D = I^+(E_F) - I^-(E_F - qV_{DS})$$



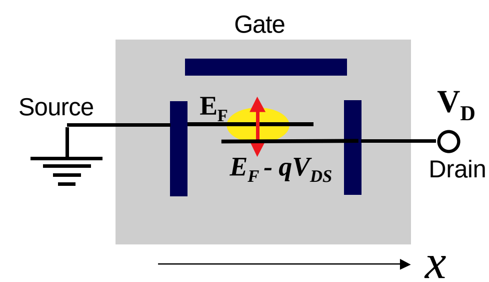
$$Q = C_{GS}V_{GS} + C_{DS}V_{DS}$$

(electrostatics)

$Q^-(E_F - qV_{DS})$
$I^-(E_F - qV_{DS})$

$Q^+(E_F - qV_{DS})$
$I^+(E_F - qV_{DS})$

1. Introduction



$$Q(x)$$

at $x = 0$.....

$$Q(0) \approx C_{GS}V_{GS} + C_{GD}V_{GD}$$

$C_{GS} \approx C_{ox}$ (constant)

$C_{DS} << C_{GS}$

$$Q(0) \approx C_{ox}(V_{GS} - V_T)$$

1) Compute $Q(V_{GS}, V_{DS})$ 2) Determine E_F 3) Compute I_D

1. Introduction

Now……

let's see how these ideas work out for MOSFETs

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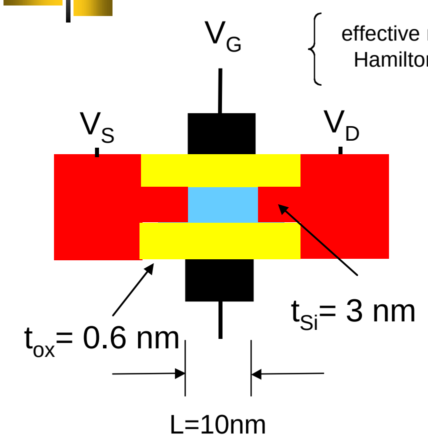
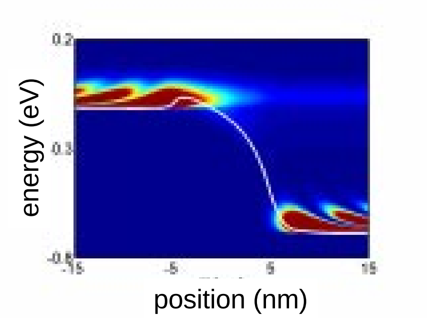
1. Introduction

nanoMOS simulations

effective mass Hamiltonian



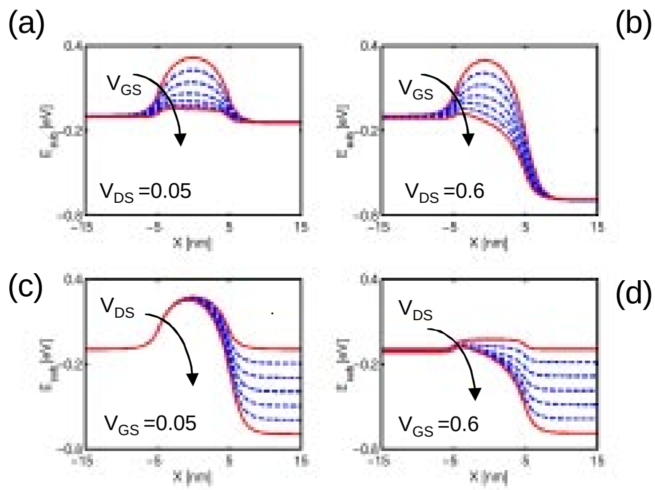


Z. Ren, R. Venugopal, S. Datta, and M. Lundstrom, IEDM, 2001

Lundstrom

1. Introduction

energy band diagrams



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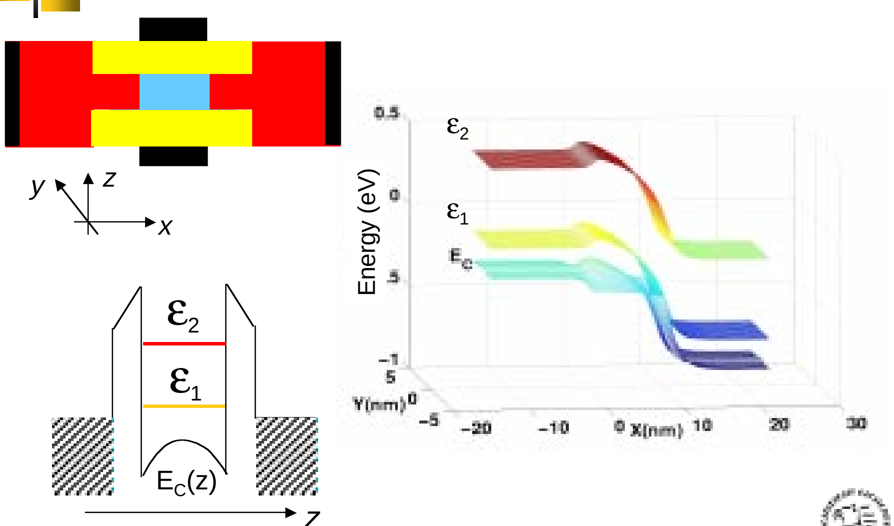
1. Introduction

energy band diagrams



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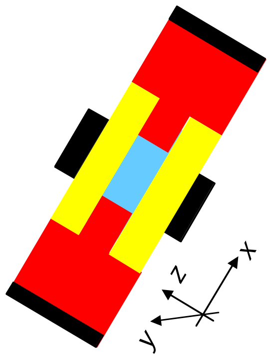
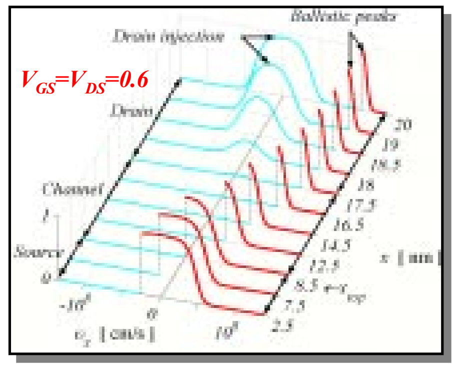
1. Introduction

transport





- *2D Electrostatics*
- *Strong off-equilibrium transport*
- *Scattering*

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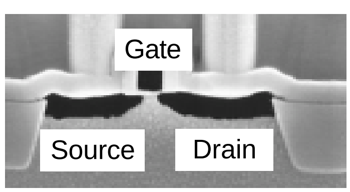
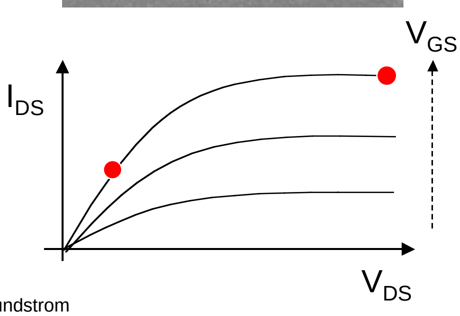
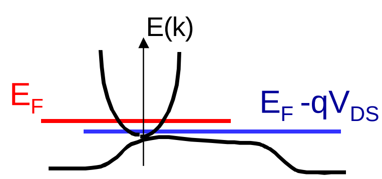
2. The Ballistic MOSFET

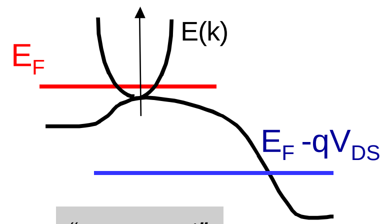
Natori's theory







linear current



"on-current"

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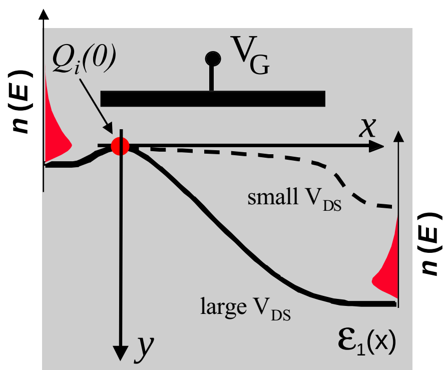
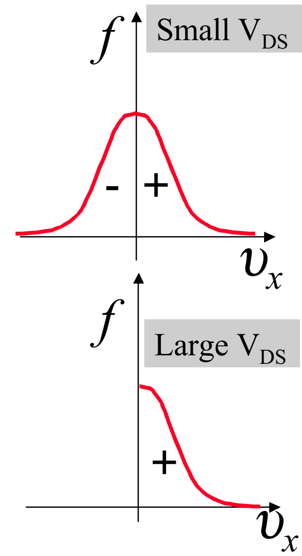
2. The Ballistic MOSFET..... *thermionic emission*





$$f_o = e^{-E/k_BT} \sim e^{-m^* \upsilon_x^2 / 2k_BT}$$

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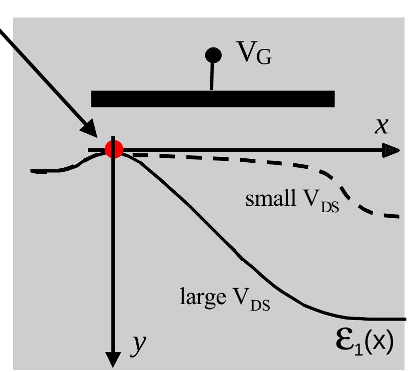
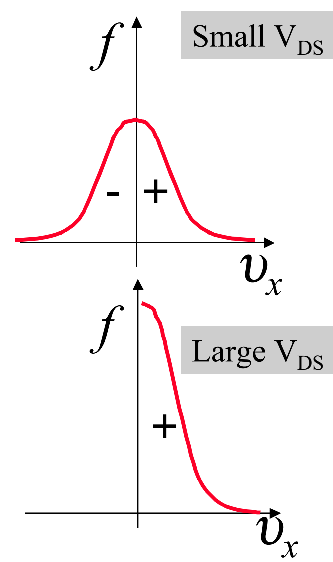
2. The Ballistic MOSFET.... *charge control in a "well-tempered MOSFET"*

$Q_i(0) \approx C_{ox}\,(V_{GS} - V_T)$





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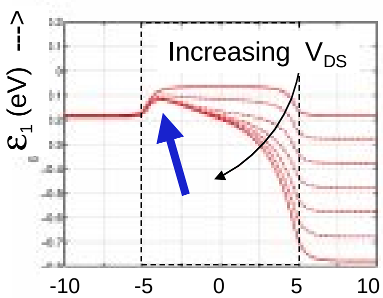
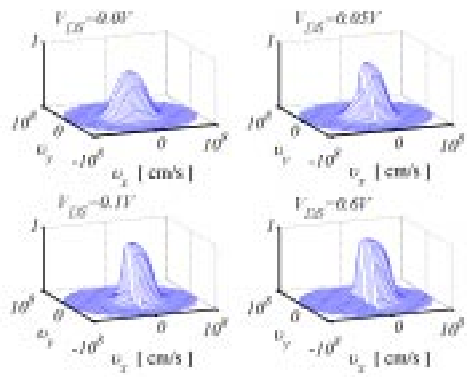
2. The Ballistic MOSFET.....

numerical solution of the ballistic BTE

$\mathcal{E}_1$ vs. x for V_{GS} = 0.5V



$f(k_x, k_y)$

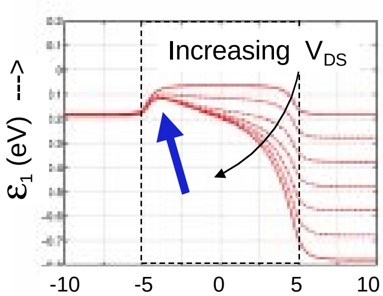


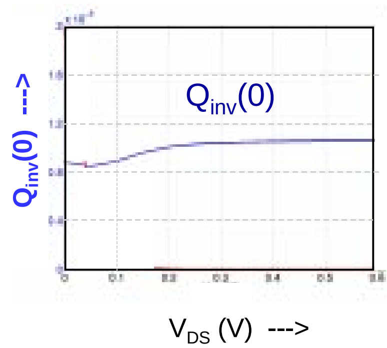
J.-H. Rhew, Purdue University

2. The Ballistic MOSFET.....

charge control

$\mathcal{E}_1$ vs. x for V_{GS} = 0.5V



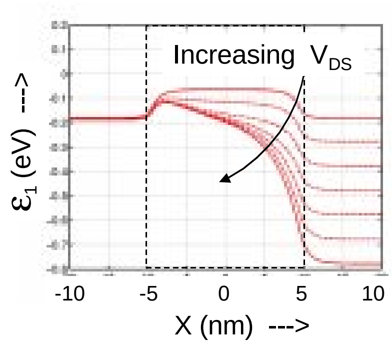


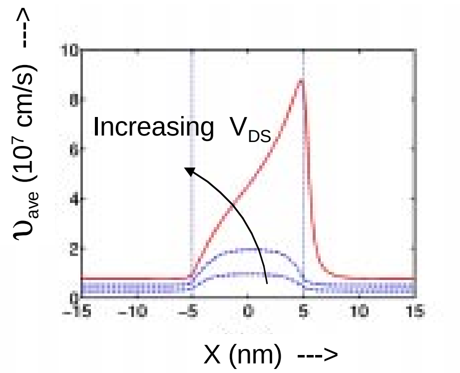
i) $Q_i(0) \approx$ constant

2. The Ballistic MOSFET.....

$\mathcal{E}_1$ vs. x for V_{GS} = 0.5V

i) $Q_i(0) \approx$ constant
ii) <υ(0)> --> υ_T





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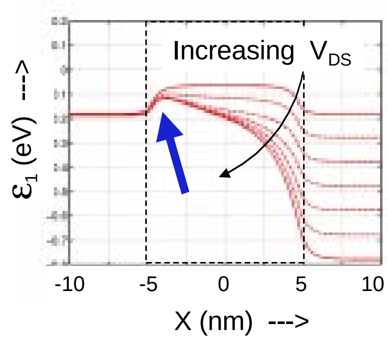
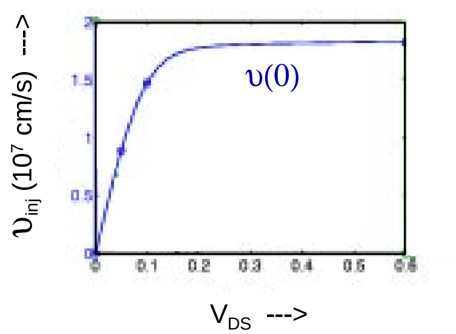
2. The Ballistic MOSFET..... *velocity saturation in a ballistic FET*

$\mathcal{E}_1$ vs. x for V_{GS} = 0.5V

i) $Q_i(0) \approx$ constant
ii) <υ(0)> --> υ_T





$$\upsilon(0) \rightarrow \tilde{\upsilon}_T$$

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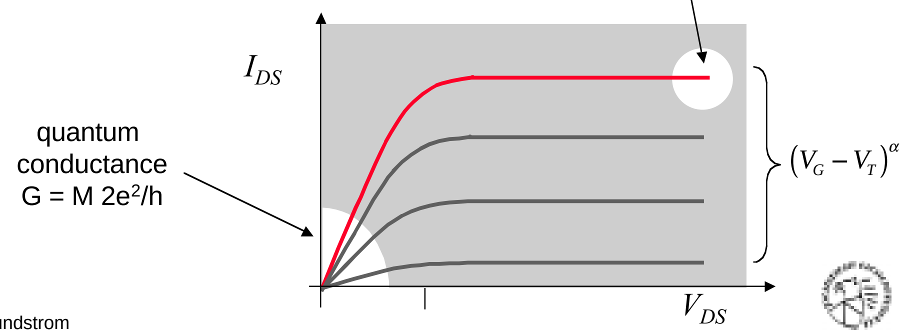
2. The Ballistic MOSFET.....

$$I_{DS} = W Q_i(V_{GS})\tilde{\upsilon}_T \times \left\{ \frac{1 - \dfrac{F_{1/2}(\eta_F - U_{DS})}{F_{1/2}(\eta_F)}}{1 + \dfrac{F_0(\eta_F - U_{DS})}{F_0(\eta_F)}} \right\}$$

$$I_{DS}(on) = W\, C_{ox}\, \tilde{\upsilon}_T (V_{GS} - V_T)$$



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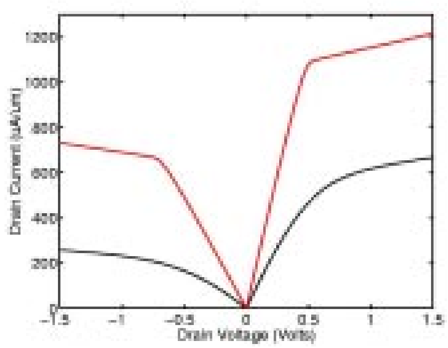
2. The Ballistic MOSFET..... *comparison with measurements.....*

L_{eff} = 115/125 nm technology



measured

ballistic
(with measured Rs)

NMOS: ~ 50% of limit

PMOS: ~ 33% of limit

- F. Assad, et al. (1999 IEDM)
- G. Timp, J. Bude, et al., (1999 IEDM)
- D. Rumsey (TECHON 2000)
- A. Lochtefeld, D. Antoniadis (EDL, Feb 2001)

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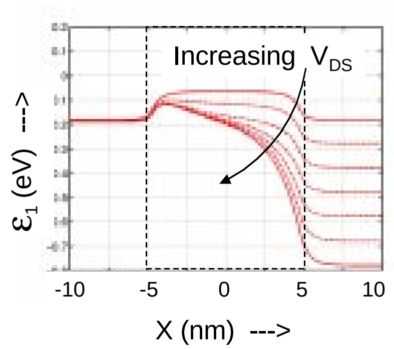
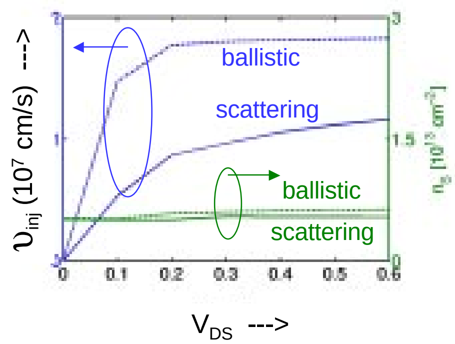
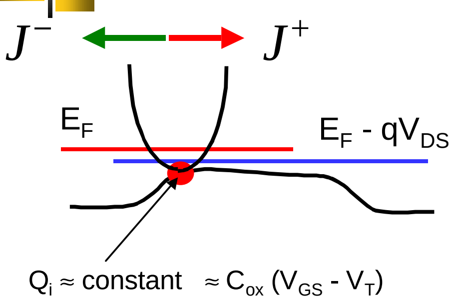
3. Scattering Theory of the MOSFET.....





3. Scattering Theory of the MOSFET.....



$$J^+ = n^+ \tilde{\upsilon}_T^+$$

$$J^- = (1-T)J^+ + TJ^-_{ball}$$

$$I_D = Wq\left(J^+ - J^-\right)$$

$$Q_i(V_{GS}) = \frac{q\left(J^+ + J^-\right)}{\tilde{\upsilon}_T^+}$$

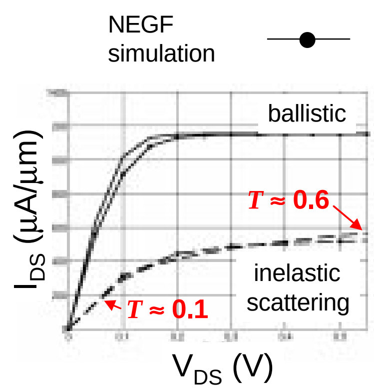
$$I_{DS} = WQ_i(V_{GS})\tilde{\upsilon}_T\left(\frac{T}{2-T}\right)\times\left\{\frac{1-\dfrac{F_{1/2}(\eta_F - U_{DS})}{F_{1/2}(\eta_F)}}{1+\left(\dfrac{T}{2-T}\right)\dfrac{F_0(\eta_F - U_{DS})}{F_0(\eta_F)}}\right\}$$

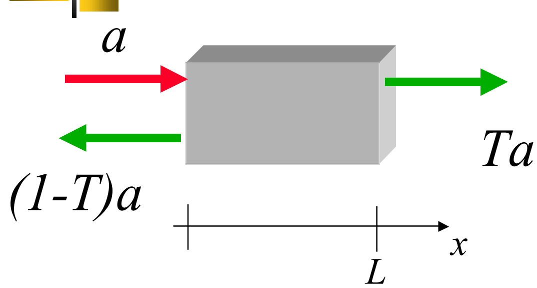
Landauer/McKelvey model

$$I_{DS} = W C_{ox}\left(V_{GS} - V_T\right)\tilde{\upsilon}_T\left(\frac{T}{2-T}\right)\times$$

$$\frac{F_{1/2}(\eta_F)}{\ln(1+e^{\eta_F})}\times\left\{\frac{1-\dfrac{F_{1/2}(\eta_F - U_{DS})}{F_{1/2}(\eta_F)}}{1+\left(\dfrac{T}{2-T}\right)\dfrac{\ln(1+e^{\eta_F - U_{DS}})}{\ln(1+e^{\eta_F})}}\right\}$$

$$T(V_{GS}, V_{DS})$$

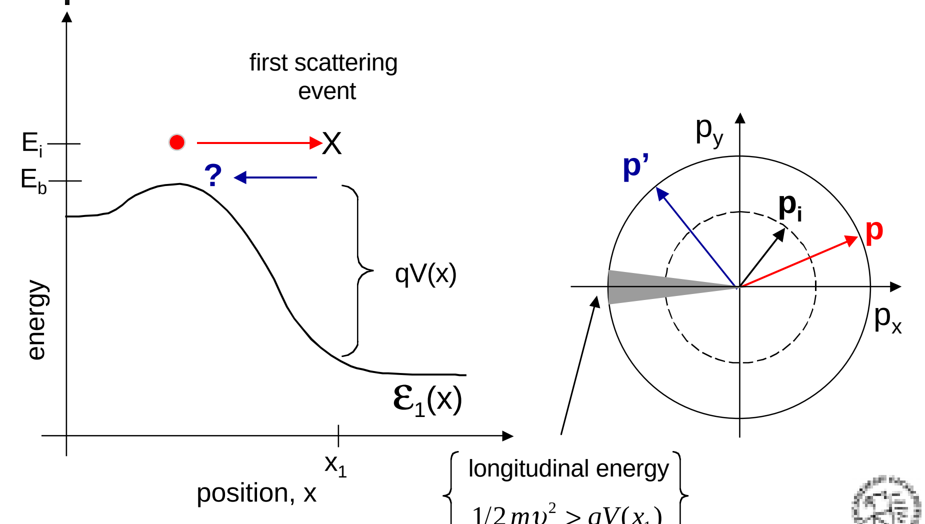


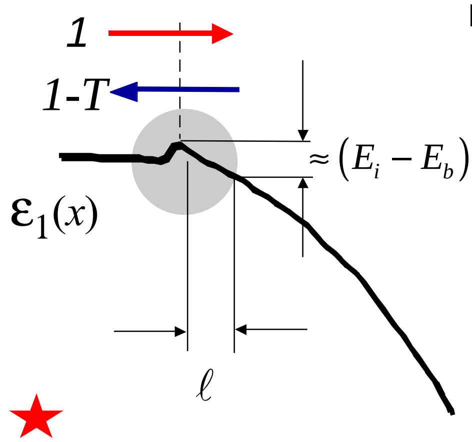


$$T = \frac{\lambda_0}{L + \lambda_0}$$

$$I_{DS} = W C_{ox}\left(\frac{\upsilon_T}{k_B T / q}\right) T\left(V_{GS} - V_T\right) V_{DS}$$

$$I_{DS} = \mu_{eff} C_{ox}\left(\frac{W}{L + \lambda_0}\right)\left(V_{GS} - V_T\right) V_{DS}$$





$P(x_1)$: probability of returning to the source after scattering first at x_1

$x_1 < \ell$ $P(x_1)$ large

$x_1 > \ell$ $P(x_1)$ small

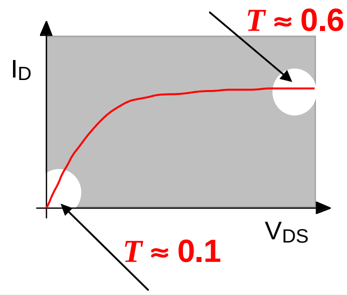
$$qV(\ell) \approx (E_i - E_b)$$

$$T \approx \frac{\lambda_o}{\ell + \lambda_o}$$

★ mobility is important for nanoscale FETs

3. Scattering Theory of the MOSFET..... *Landauer/McKelvey model*

$$I_D = W C_{ox} \upsilon_T \left(\frac{T}{2-T} \right) (V_{GS} - V_T)$$



$$I_D = W C_{ox} \left(\frac{\upsilon_T / 2}{k_B T / q} \right) T \left(V_{GS} - V_T \right) V_{DS}$$

$$I_{DS} = W C_{ox} (V_{GS} - V_T) \tilde{\upsilon}_T \left(\frac{T}{2-T} \right) \times \left\{ \frac{1 - \dfrac{F_{1/2}(\eta_F - U_{DS})}{F_{1/2}(\eta_F)}}{1 + \left(\dfrac{T}{2-T} \right) \dfrac{\ln(1 + e^{\eta_F - U_{DS}})}{\ln(1 + e^{\eta_F})}} \right\}$$

$$T = \frac{\lambda_o}{\ell + \lambda_o}$$

- transmission theory provides a clear picture of MOSFETs at the scaling limit:

  -source velocity is limited by thermal injection

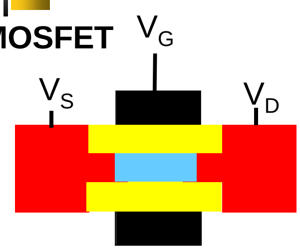
  -velocity saturation occurs at the source

  -the scattering that matters occurs near the source

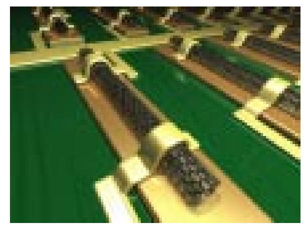
  -"mobility" is relevant to nanoscale MOSFETs

4. Beyond the Si MOSFET.....

1) MOSFET

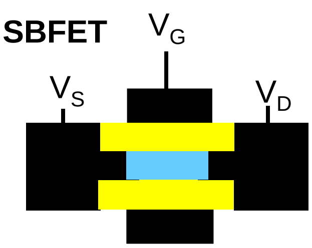


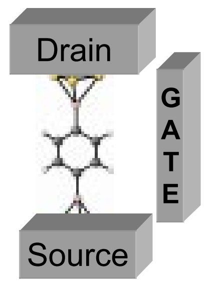
3) CNTFET



Bachtold, et al., Science, Nov. 2001

2) SBFET

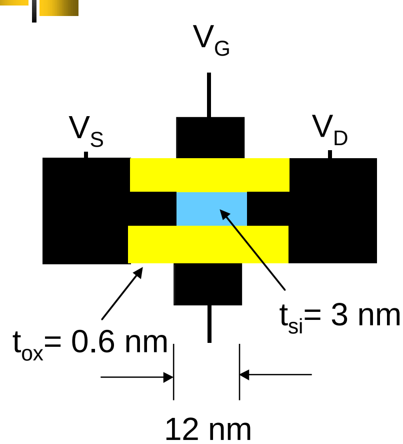




4) Molecular FETs?

4. Beyond the Si MOSFET.....

the Schottky barrier MOSFET



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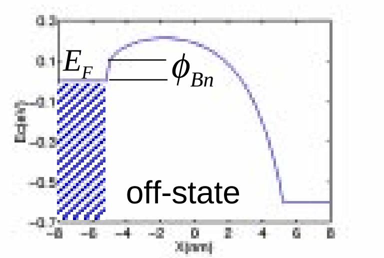
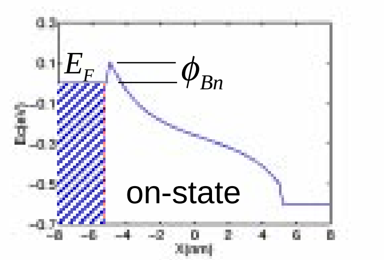
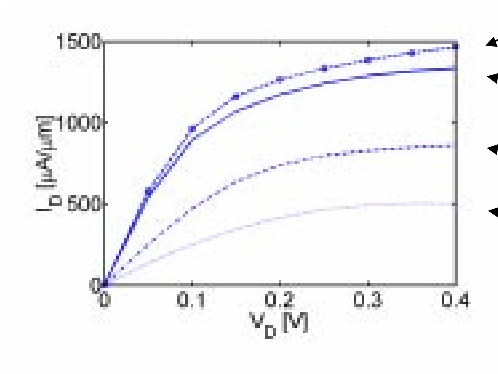




4. Beyond the Si MOSFET.....

the Schottky barrier MOSFET



equivalent MOSFET

$\phi_{Bn} = -0.25$ eV

$\phi_{Bn} = \;\; 0.0$ eV

$\phi_{Bn} = \;\; 0.1$ eV

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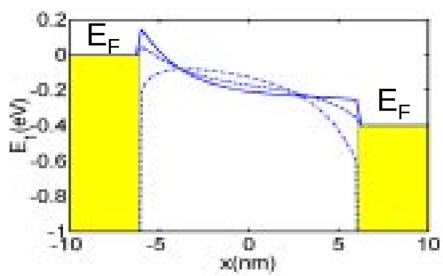
4. Beyond the Si MOSFET.....

the Schottky barrier MOSFET



MOSFET

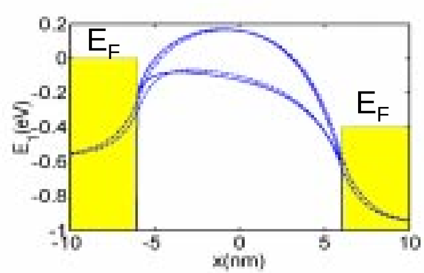
SBFET

$(\phi_{Bn} = -0.25 \text{ eV})$

$\phi_{Bn} = 0.1$ eV

$\phi_{Bn} = 0.0$ eV

$\phi_{Bn} = -0.25$ eV



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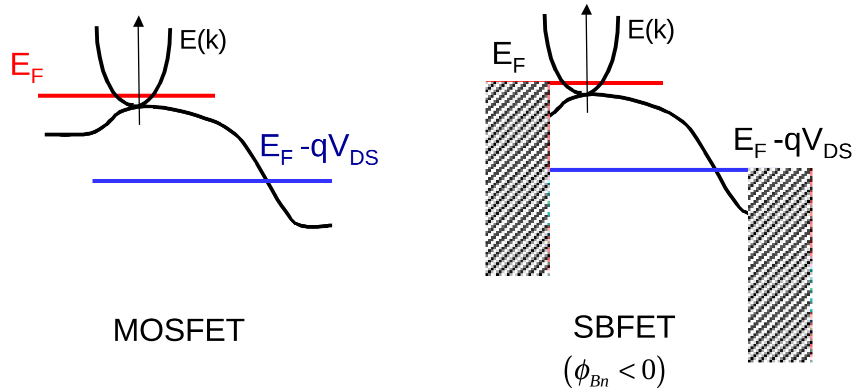
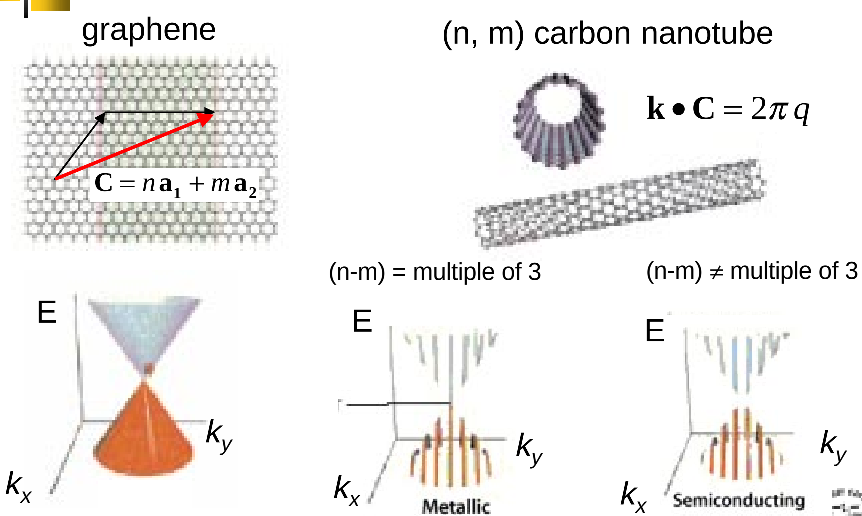
4. Beyond the Si MOSFET….. *the Schottky barrier MOSFET*

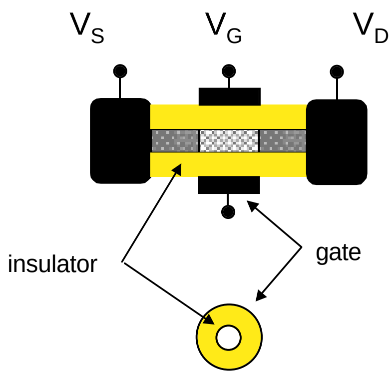


4. Beyond the Si MOSFET….. *the CNTFET*

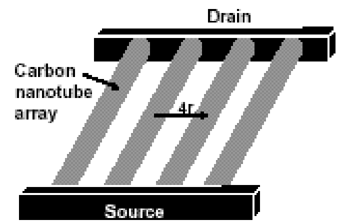


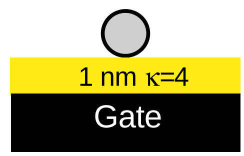
4. Beyond the Si MOSFET..... *the CNTFET*

coaxial geometry



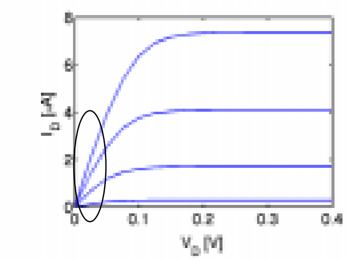
planar geometry CNTFET

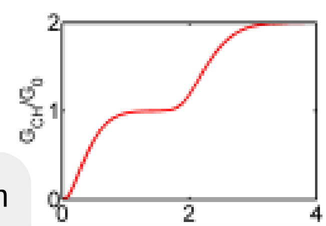




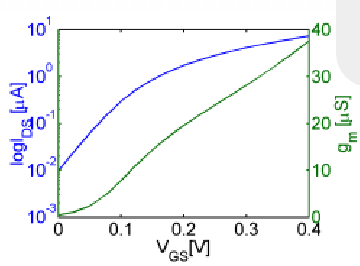
Lundstrom

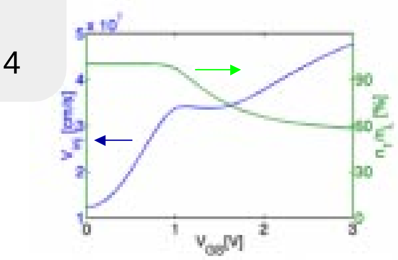
4. Beyond the Si MOSFET..... *the CNTFET*





D = 1 nm
t_{ins} = 1 nm
κ_{ins} = 4
V_{DD} = 0.4





5. Summary

- Essential physics of nanoscale transistors is controlled by:
  - *-electrostatics*
  - *-state filling*
  - *-transmission*

- Transmission theory provides insights into nanoscale MOSFET physics
  - -velocity saturation at the source
  - -importance of scattering near the source
  - -relevance of mobility

- The performance of transistors based on charge control is largely material-independent