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SPRING COLLEGE ON SCIENCE AT THE NANOSCALE
(24 May - 11 June 2004)

Nanoscale Transistors: Ultimate Silicon and Beyond

M. LUNDSTROM
School of Electrical & Computer Engineering, Purdue University
West Lafayette, IN, USA

These are preliminary lecture notes, intended only for distribution to participants.

Spring College on Science at the Nanoscale - Trieste, Italy, June 2004

Nanoscale Transistors:

Ultimate silicon and beyond

Mark Lundstrom
Purdue University
Network for Computational Nanotechnology
www.nanohub.org

I) Introduction
II) Theory
III) Nanowire MOSFETs
IV) Nano MOSFETs
V) Molecular MOSFETs?
VI) Conclusions

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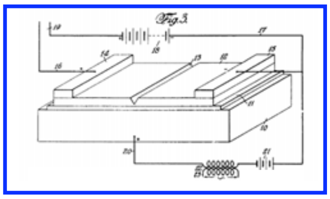
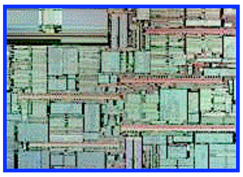
I) Introduction: FETs



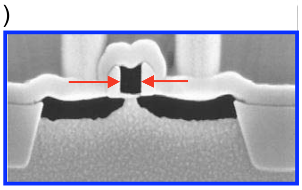
Lillienfield, 1925
Heil, 1935

- Si MOSFET, 1960
- PMOS IC's, 1963
- CMOS invented, 1963
- NMOS IC's, 1970

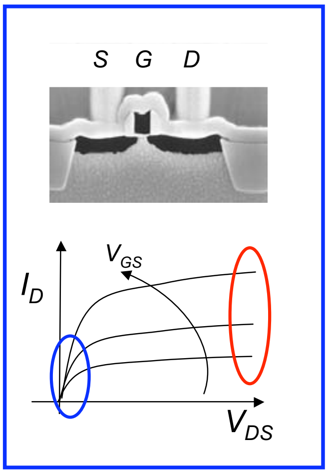


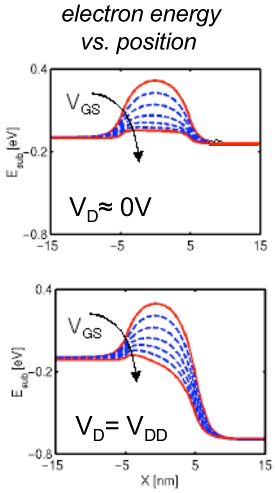
4004 Intel (Hoff, 1971)

50 nm (2003 production)
5 nm (2003 research)



I) Introduction: MOSFET as a BJT in disguise





E.O. Johnson, *RCA Review*, 1971

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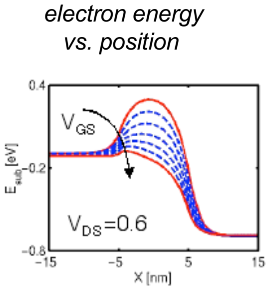
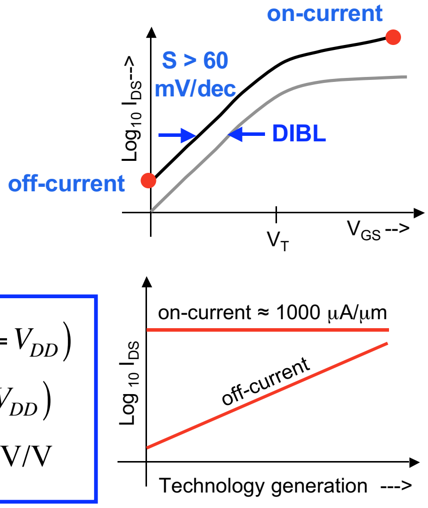
I) Introduction: device metrics





$$I_{ON} \equiv I_D(V_{GS} = V_{DD}, V_{DS} = V_{DD})$$

$$I_{OFF} \equiv I_D(V_{GS} = 0, V_{DS} = V_{DD})$$

S mV/decade $\quad$ $DIBL$ mV/V

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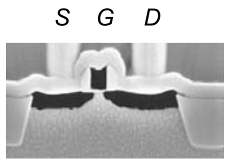
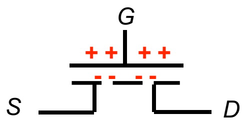
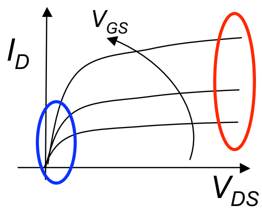
I) Introduction: traditional theory







$$I_D = W\, Q_n\, \upsilon_x$$
$$= W\, C_{ox}\left(V_{GS} - V_T\right)\mu_{eff}\, \mathcal{E}_x$$

i) low V_{DS}:

$$\mathcal{E}_x = V_{DS}/L$$
$$I_D = \left(\frac{W}{L}\right)\mu_{eff} C_{ox}\left(V_{GS} - V_T\right)V_{DS}$$

ii) high V_{DS}:

$$\mathcal{E}_x(0) \approx \left(V_{GS} - V_T\right)/2L$$
$$I_D = \frac{W}{2L}\mu_{eff} C_{ox}\left(V_{GS} - V_T\right)^2$$

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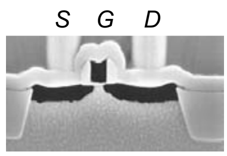
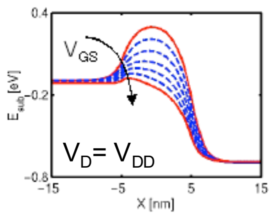
I) Introduction





$$I_D = Q(x=0)\langle \upsilon(x=0)\rangle$$

1) electrostatics:

$$Q(V_G, V_D)$$

2) transport:

$$\langle \upsilon(V_G, V_D)\rangle$$

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I) Introduction
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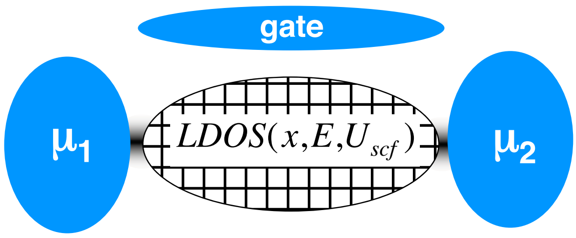
II) Theory

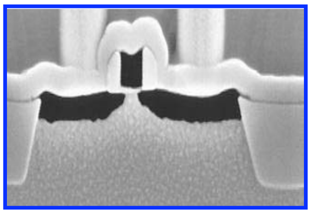


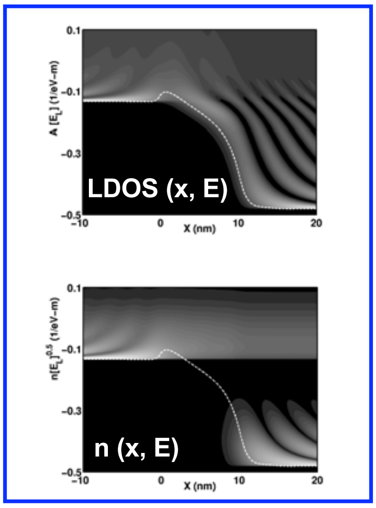
1) Electronic states in the device are controlled by the terminal voltages (**electrostatics**)

2) States in the device are filled from the two contacts according to their Fermi levels (**transport**)

S. Datta, IEDM Tech. Dig., 2002

II) Theory: ballistic quantum transport





(Ramesh Venugopal, TI)

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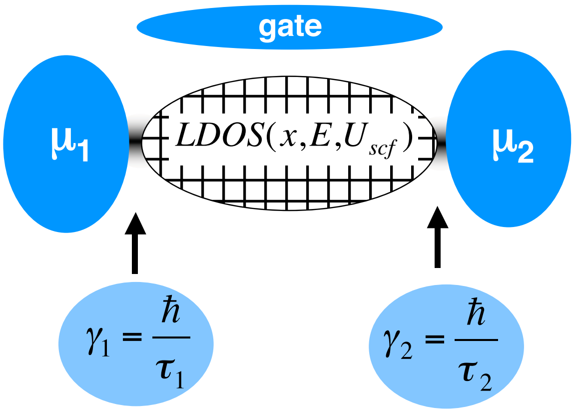
II) Theory: role of the contacts



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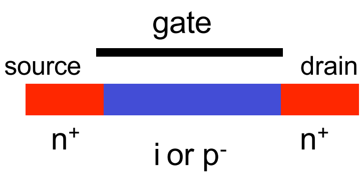
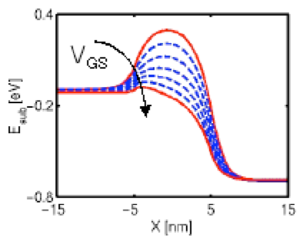
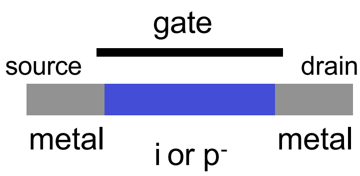
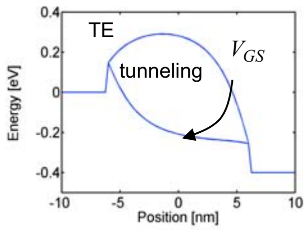
II) Theory: two kinds of transistors





MOSFET





SBFET

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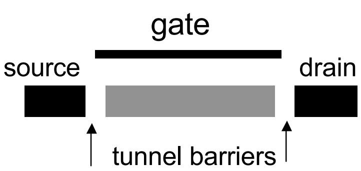
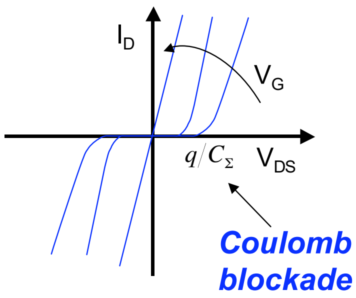
II) Theory: single electron transistors





$$\frac{q^2}{C_\Sigma} > k_B T$$

$$\gamma_1, \gamma_2 < k_B T$$

Requires a particle approach not a wave approach

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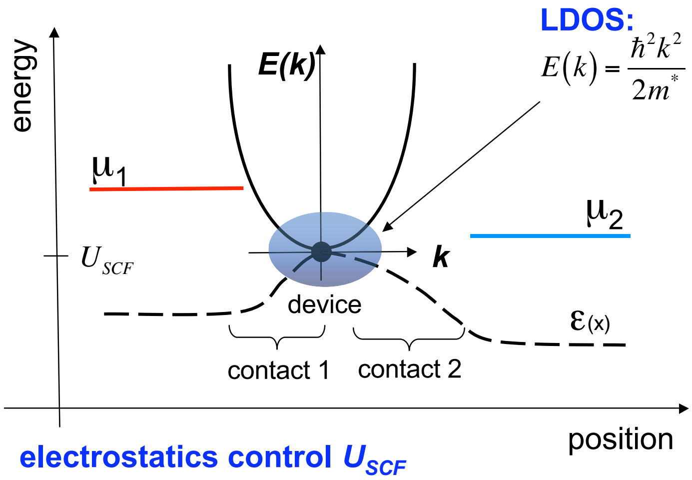
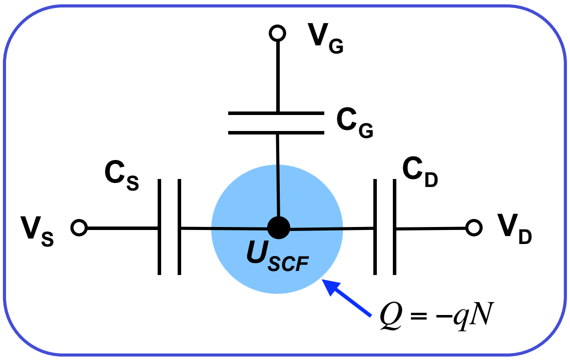
II) Theory: MOSFETs



electrostatics control U_{SCF}

---> raise and lower LDOS

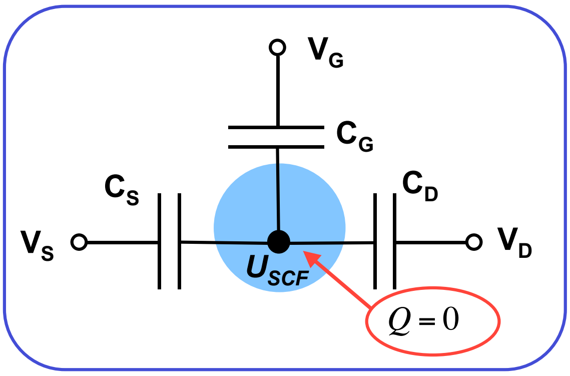
II) Theory: electrostatics



U_{SCF} is controlled by the gate, drain, and source voltages and by the charge in the device

A. Rahman, et al. *IEEE TED*, Sept., 2003

II) Theory: electrostatics



$$U_{Laplace} = -qV_G\left(\frac{C_G}{C_\Sigma}\right) - qV_D\left(\frac{C_D}{C_\Sigma}\right) - qV_S\left(\frac{C_S}{C_\Sigma}\right)$$

$$C_\Sigma = C_G + C_D + C_S$$

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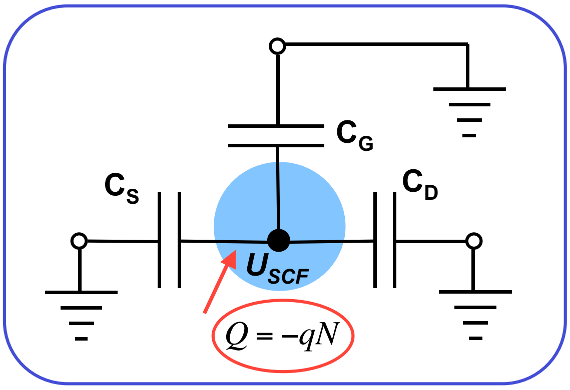
II) Theory: electrostatics



$$U_P = \frac{q^2 N}{C_\Sigma}$$

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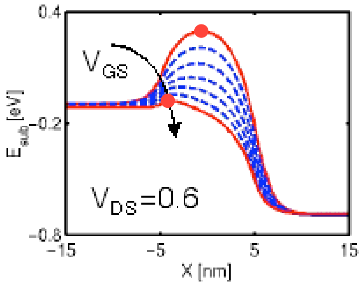
II) Theory



FETToy:

$$U_{SCF}(N) = -qV_G\left(\frac{C_G}{C_\Sigma}\right) - qV_D\left(\frac{C_D}{C_\Sigma}\right) - qV_S\left(\frac{C_S}{C_\Sigma}\right) + \frac{q^2N(U_{SCF})}{C_\Sigma}$$

well-tempered MOSFET:

$$qN = C_G(V_{GS} - V_T) \quad (V_{GS} > V_T)$$

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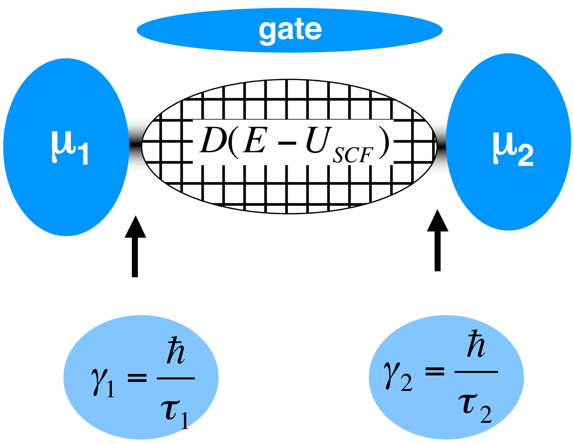
II) Theory: transport



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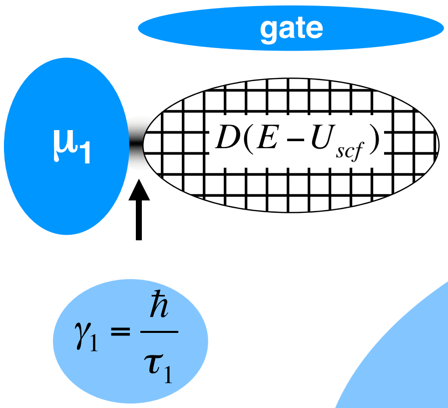
II) Theory: filling from the left contact…..

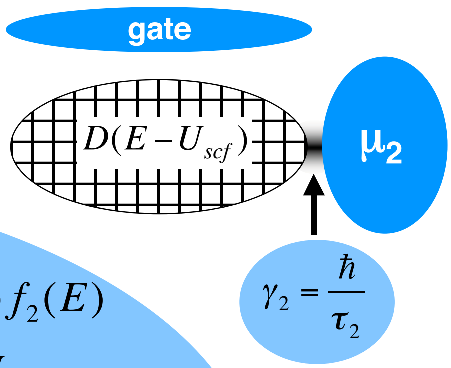


(ballistic)

$$N_1(E) = D(E - U_{scf})\, f_1(E)$$

$$\frac{dN(E)}{dt} = \frac{N_1(E) - N}{\tau_1}$$

II) Theory: filling from the right contact…..



$$N_2(E) = D(E - U_{scf})\, f_2(E)$$

$$\frac{dN(E)}{dt} = \frac{N_2(E) - N}{\tau_2}$$

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II) Theory:

$$\frac{dN(E)}{dt} = \frac{N_1 - N}{\tau_1} + \frac{N_2 - N}{\tau_2} = 0$$

(steady-state)

$$N = \int \left[A_1(E) f_1(E) + A_2(E) f_2(E) \right] \frac{dE}{2\pi}$$

$$A_1(E) = 2\pi \frac{\gamma_1}{\gamma_1 + \gamma_2} D\left(E - U_{scf}\right)$$

$$A_2(E) = 2\pi \frac{\gamma_2}{\gamma_1 + \gamma_2} D\left(E - U_{scf}\right)$$

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II) Theory: steady-state

$$I_D = \frac{N_1 - N}{\tau_1} = \frac{-\left(N_2 - N\right)}{\tau_2}$$

$$I_D = \frac{2q}{h} \int T(E) \left(f_1(E) - f_2(E) \right) dE$$

(Landauer)

$$T(E) = \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2} \pi D\left(E - U_{scf}\right)$$

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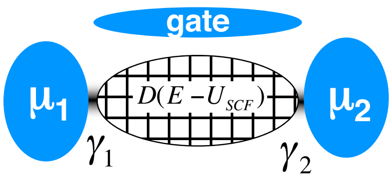
II) Theory: summary



FETToy

www.nanohub.org

Given:

Device structure (C_G, C_D, C_S, etc)

Contacts (γ_1, γ_2)

$D(E - U_{SCF})$

μ_1, μ_2

Compute:

$U_{SCF}(V_{GS}, V_{DS}, N)$
$N(U_{SCF}, V_{DS})$

$I_D(U_{SCF}, V_{DS})$

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Spring College on Science at the Nanoscale - Trieste, Italy, June 2004

- I) Introduction
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- **III) Nanowire MOSFETs**
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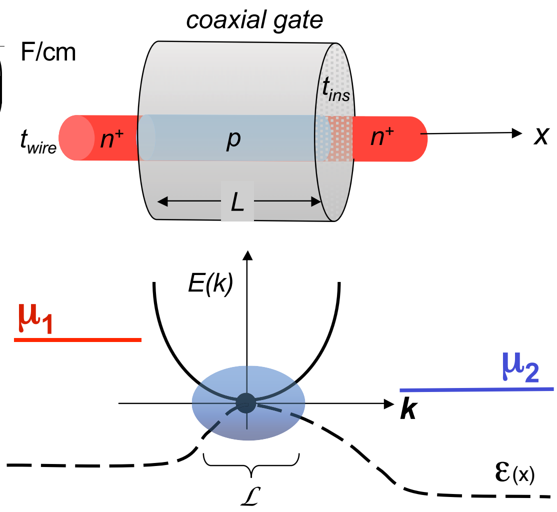
III) Nanowire MOSFETs

$$C_{ins} = \frac{2\pi\kappa\varepsilon_0}{\ln\left(\frac{2t_{ins}+t_{wire}}{t_{wire}}\right)} \text{ F/cm}$$



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III) Nanowire MOSFETs

steady-state electron number:

$$N = \int \left[A_1(E) f_1(E) + A_2(E) f_2(E) \right] \frac{dE}{2\pi}$$

$$\frac{A_1(E)}{2\pi} = \frac{\gamma_1}{\gamma_1+\gamma_2} D\left(E - U_{scf}\right) = \frac{\mathcal{L}}{2\pi\hbar}\sqrt{\frac{2m^*}{E-\varepsilon}} H\left(E - U_{scf} - \varepsilon\right)$$

$$N = N^+(\mu_1) + N^-(\mu_2) = \frac{N_{1D}\mathcal{L}}{2}\mathcal{F}_{-1/2}(\eta_F) + \frac{N_{1D}\mathcal{L}}{2}\mathcal{F}_{-1/2}(\eta_F - U_D)$$

$$\left\{ N_{1D} = \sqrt{\frac{2m^* k_B T}{\pi\hbar^2}} \qquad \begin{matrix} \eta_F = \left(\mu_1 - \varepsilon_0 - U_{SCF}\right)/k_B T \\ U_D = qV_D / k_B T \end{matrix} \right\}$$

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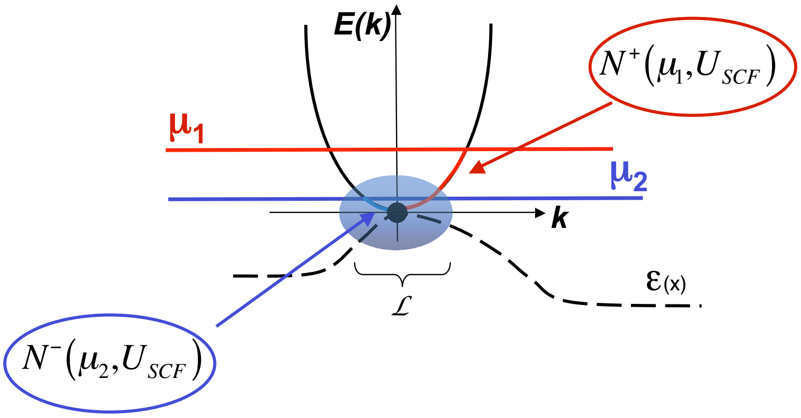
III) Nanowire MOSFETs



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III) Nanowire MOSFETs: electrostatics

$$\begin{cases} U_{SCF}(N) = -qV_G\left(\frac{C_G}{C_\Sigma}\right) - qV_D\left(\frac{C_D}{C_\Sigma}\right) - qV_S\left(\frac{C_S}{C_\Sigma}\right) + \frac{q^2 N(U_{SCF})}{C_\Sigma} \\ N(U_{SCF}, \mu_1, \mu_2) = N^+ + N^- = \frac{N_{1D}\mathcal{L}}{2}\mathcal{F}_{-1/2}(\eta_F) + \frac{N_{1D}\mathcal{L}}{2}\mathcal{F}_{-1/2}(\eta_F - U_D) \\ \eta_F = (\mu_1 - \varepsilon_0 - U_{SCF})/k_B T \end{cases}$$

"well-tempered MOSFET"

$$\frac{N}{\mathcal{L}} = \frac{C_{ins}}{q}(V_{GS} - V_T) = \frac{N_{1D}}{2}\mathcal{F}_{-1/2}(\eta_F) + \frac{N_{1D}}{2}\mathcal{F}_{-1/2}(\eta_F - U_D)$$

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III) Nanowire MOSFETs: I_D

$$I_D = \frac{2q}{h}\int T(E)\left(f_1(E) - f_2(E)\right)dE$$

$$T(E) = \frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2}\pi D\left(E - U_{scf}\right) = 1$$

$$\gamma_1 = \gamma_2 = \frac{\hbar}{\tau} = \hbar\frac{\upsilon_k}{\mathcal{L}} \qquad D(E) = \frac{2}{\pi}\frac{\mathcal{L}}{\hbar\upsilon_k}$$

$$I_D = \frac{2qk_BT}{h}\left\{\mathcal{F}_0(\eta_F) - \mathcal{F}_0(\eta_F - U_D)\right\}$$

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III) Nanowire MOSFETs

$$\frac{C_{ins}}{q}\left(V_{GS}-V_T\right) = \frac{N_{1D}}{2}\mathcal{F}_{-1/2}(\eta_F) + \frac{N_{1D}}{2}\mathcal{F}_{-1/2}(\eta_F - U_D) \qquad (1)$$

$$I_D = \frac{2qk_BT}{h}\left\{\mathcal{F}_0(\eta_F) - \mathcal{F}_0(\eta_F - U_D)\right\} \qquad (2)$$

$$I_D = C_{ins}\left(V_{GS}-V_T\right)\tilde{\upsilon}_T\left\{\frac{1-\mathcal{F}_0(\eta_F)/\mathcal{F}_0(\eta_F-U_D)}{1+\mathcal{F}_{-1/2}(\eta_F)/\mathcal{F}_{-1/2}(\eta_F-U_D)}\right\}$$

$$\tilde{\upsilon}_T = \sqrt{\frac{2k_BT}{\pi m^*}}\left(\frac{\mathcal{F}_0(\eta_F)}{\mathcal{F}_{-1/2}(\eta_F)}\right)$$ "injection velocity"

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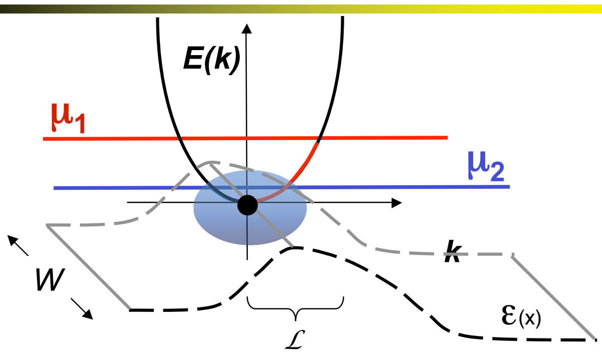
IV) The nano-MOSFET



$$N(\mu_1,\mu_2,U_{SCF}) = \int \frac{D(E-U_{SCF})}{2}\left[f_1(E)+f_2(E)\right]dE = N^+ + N^-$$

$$D(E-U_{SCF}) = W\mathcal{L}\left(\frac{m^*}{2\pi\hbar}\right)H(E-\varepsilon-U_{SCF})$$

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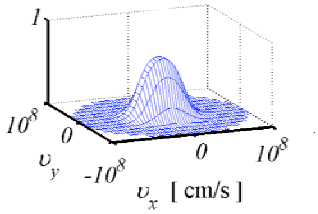
IV) The nano-MOSFET: filling the states

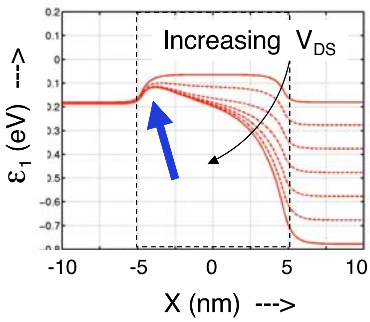
$$f_0 = \frac{1}{1+e^{(E-E_F)/k_BT}} \approx e^{(E_F-E)/k_BT} = e^{(E_F-E_C)/k_BT} \times e^{m^* \upsilon^2/2k_BT}$$

$$f_0 \propto e^{m^*(\upsilon_x^2+\upsilon_y^2)/2k_BT}$$

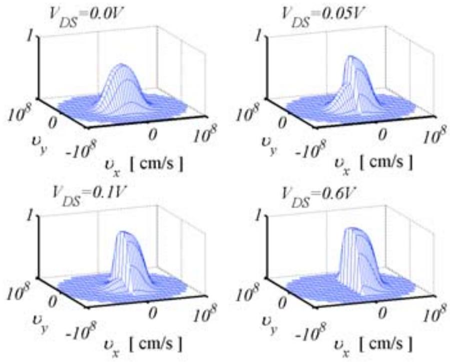


IV) The nano-MOSFET: filling the states

ε_1 vs. x for V_{GS} = 0.5V

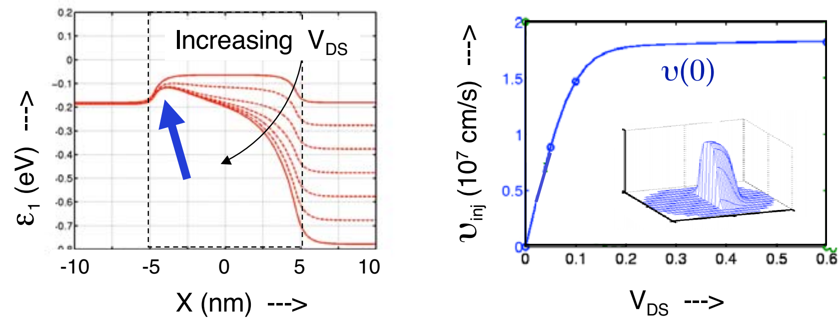


$f(k_x, k_y)$



electrostatics: ***$qN = C_G(V_{GS} - V_T)$***

IV) The nano-MOSFET: velocity saturation



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

$$\tilde{\upsilon}_T = \sqrt{\frac{2k_BT}{\pi m^*}}\left(\frac{\mathcal{F}_{1/2}(\eta_F)}{\mathcal{F}_0(\eta_F)}\right)$$

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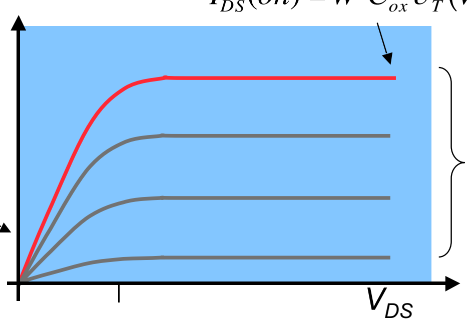
IV) The nano-MOSFET

$$I_{DS} = W C_{ox}(V_{GS} - V_T)\tilde{\upsilon}_T \times \left\{\frac{1 - \frac{\mathcal{F}_{1/2}(\eta_F - U_{DS})}{\mathcal{F}_{1/2}(\eta_F)}}{1 + \frac{\mathcal{F}_0(\eta_F - U_{DS})}{\mathcal{F}_0(\eta_F)}}\right\}$$

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

quantum conductance

$$\approx M\frac{2q^2}{h}$$



$$(V_G - V_T)^\alpha$$

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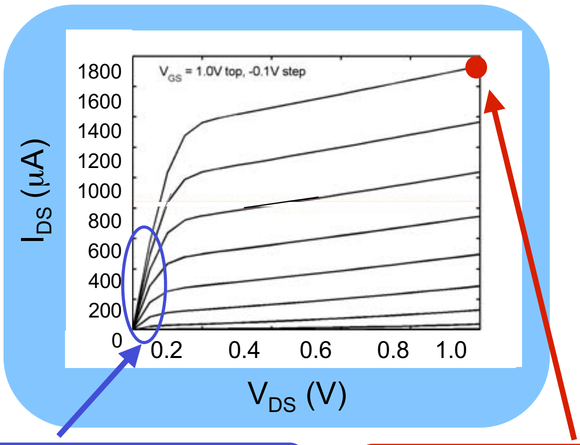
K. Natori, *JAP*, **76**, 4879, 1994.

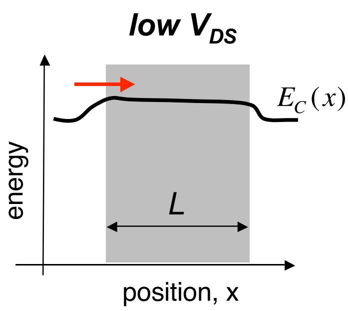
IV) The nano-MOSFET



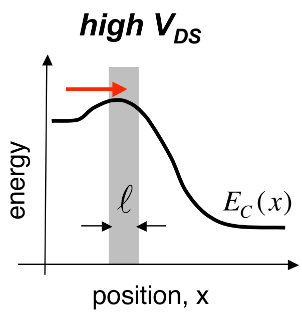
measured channel conductance
~10% of ballistic limit

measured on-current
~50% of ballistic limit

IV) The nano-MOSFET: scattering



$$T \approx \frac{\lambda_o}{L + \lambda_o} \approx 0.10$$



$$T \approx \frac{\lambda_o}{\ell + \lambda_o} \approx 0.50$$

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Spring College on Science at the Nanoscale - Trieste, Italy, June 2004

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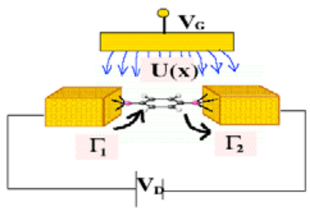
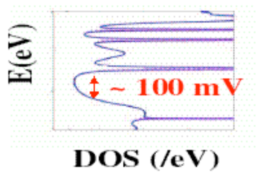
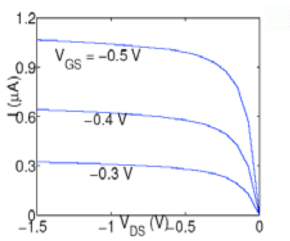
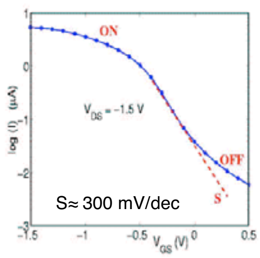
V) Molecular MOSFETs? Organic Molecular FETs









L≈ 1 nm

$t_{ox} << L$

$t_{ox} \approx$ 1-2Å !!

temperature-independent MIGS

S. Datta, A. Ghosh, P. Damle, T. Rakshit

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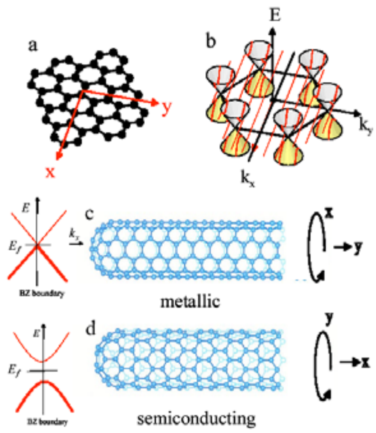
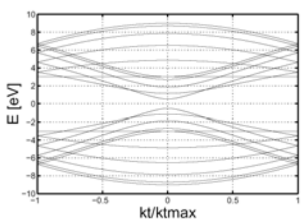
V) Molecular MOSFETs? CNTFETs





$$E_G \approx 0.8eV/d(\text{nm})$$

$$E(k) = \pm\left(\frac{E_G}{2}\right)\sqrt{1+(3kd/2)^2}$$

McEuen et al., *IEEE Trans. Nanotech.*, 1 , 78, 2002.

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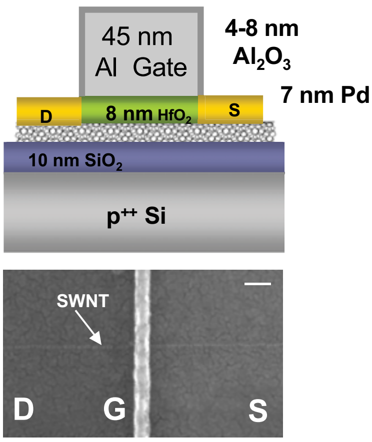
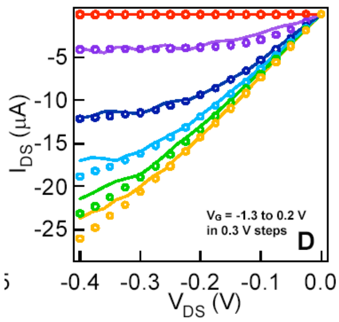
V) Molecular MOSFETs?: CNTFETs





$I(\text{on}) \approx 12\ \mu A$

$S \approx 110$ mV/dec

$G_D \approx 0.4\, G_0$

Hongjie Dai Group, Stanford

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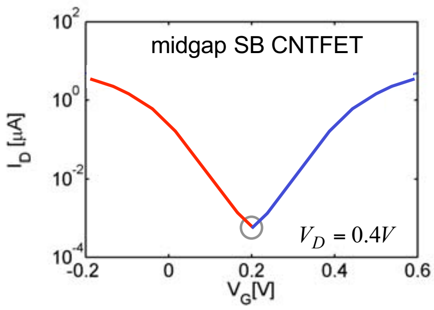
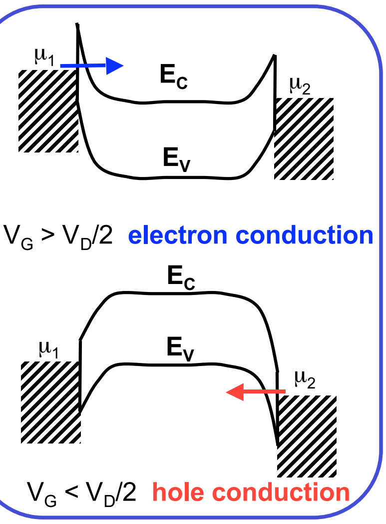
V) Molecular MOSFETs? ambipolar conduction



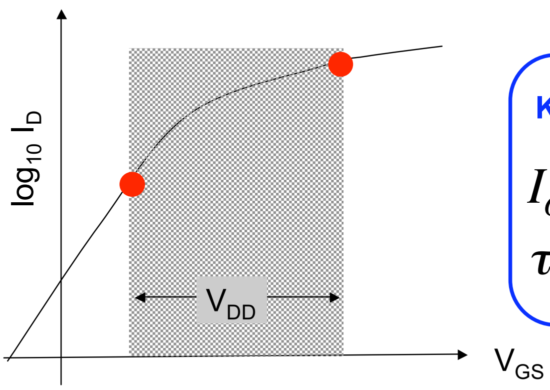
$V_G < V_D/2$ **hole conduction**

$V_G > V_D/2$ **electron conduction**



Guo, Datta, and Lundstrom, *IEEE TED*, Jan. 2004

V) Molecular MOSFETs? CNTFETs vs. MOSFETs



Key device metrics:

$$I_{ON}/I_{OFF}$$

$$\tau = C_G V_{DD}/I_{ON}$$

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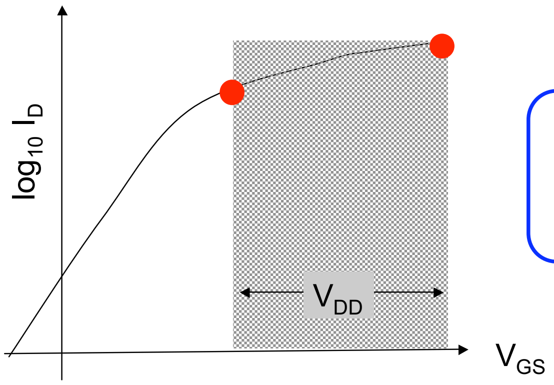
V) Molecular MOSFETs? CNTFETs vs. MOSFETs



good τ

poor I_{ON} / I_{OFF}

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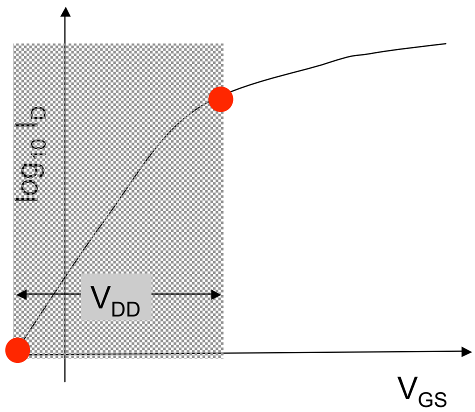
V) Molecular MOSFETs? CNTFETs vs. MOSFETs



poor τ

good I_{ON} / I_{OFF}

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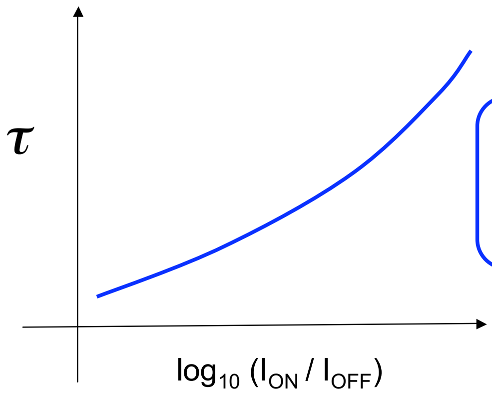
V) Molecular MOSFETs? CNTFETs vs. MOSFETs



The τ vs. I_{ON}/I_{OFF} characteristic can be used to compare technologies.

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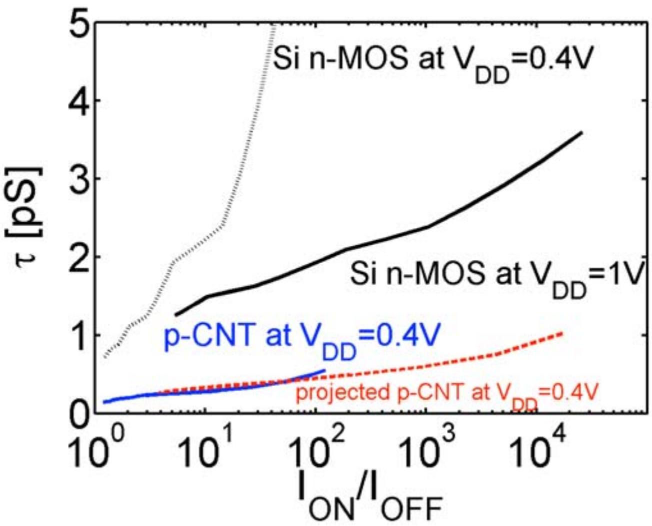
V) Molecular MOSFETs? CNTFETs vs. MOSFETs



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VI) Conclusions

1) Ballistic nano-MOSFETs are easy to understand

2) Present-day MOSFETs operate at ~ 50% of the ballistic limit.

3) Carbon nanotubes promise improved performance, but….

4) At the end of the ITRS, the Si MOSFET will operate close to fundamental limits.

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