NGC/CSTC 2009 Summers School, August 10, 2009

Physics of the UltimateTransistor:

an introduction to "Electronics from the Bottom Up"

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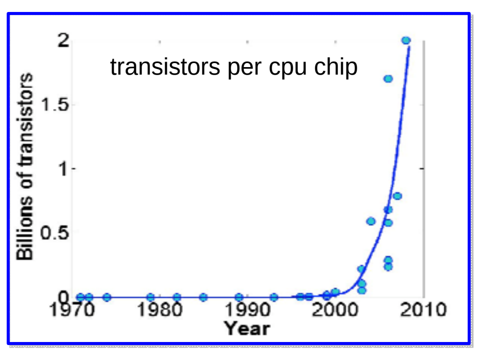
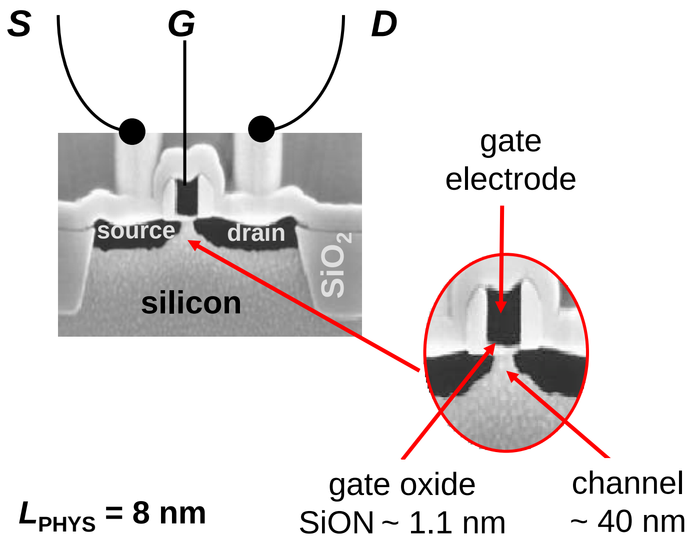
21st century nanoelectronics

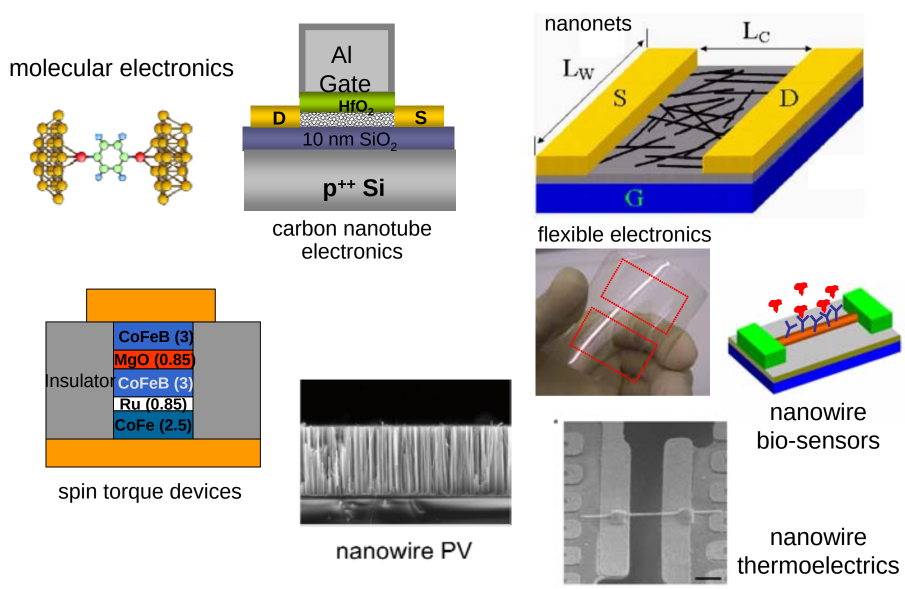


nanoscale MOSFETs

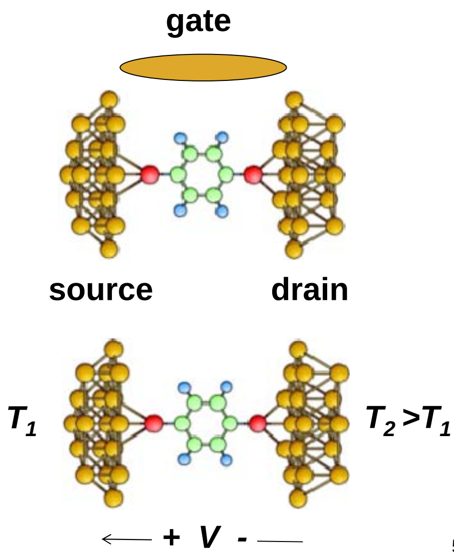


ITRS 2022: L_{PHYS} = 8 nm

21st century electronics



molecular transistors?



$$\vec{J} = nq\mu_n \vec{E} + qD_n \vec{\nabla} n \text{ ?}$$

$$\mu = \frac{q\tau}{m^*} \text{ ?}$$

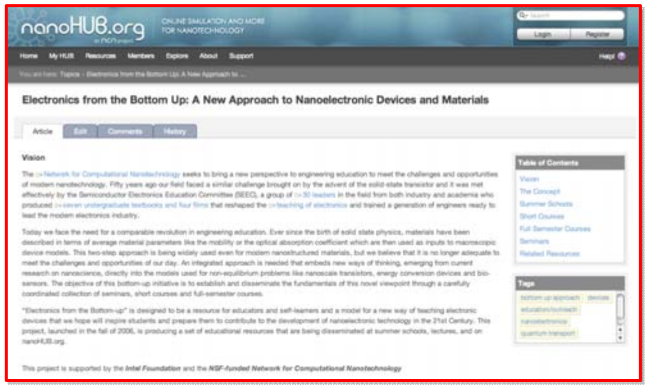
$$E(k)\text{?}$$

a new approach…

"Trying to explain things rigorously, but simply often requires new organizing principles and approaches."

Paul Penfield
class notes on 'Information'
www.mtl.mit.edu/Courses/6.050/2007/notes/preface.pdf

“Electronics from the Bottom Up”

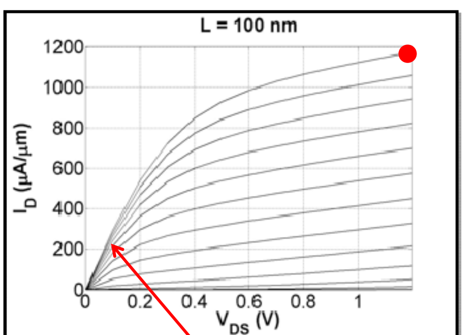


http://nanohub.org/topics/ElectronicsFromTheBottomUp
or Google “Electronics from the Bottom Up”

See “Physics of Nanoscale MOSFETS” by M. Lundstrom

nanoscale MOSFETs: questions

2007 N-MOSFET



(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)

2) maximum on-current?

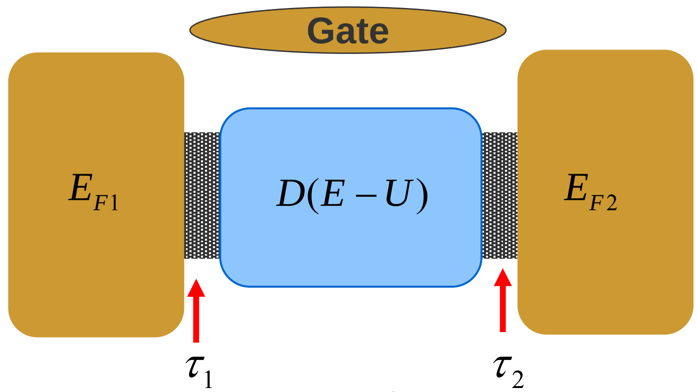
$$I_D = WC_{ox}\upsilon_{sat}\left(V_{GS} - V_T\right)$$

3) Ultimate limits and the role of quantum mechanics?

1) minimum channel resistance?

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

generic model of a nanodevice



$$\gamma = \hbar / \tau$$

S. Datta, *Quantum Transport: Atom to Transistor*, Cambridge, 2005
("Electronics from the Bottom Up" **nanoHUB.org**)

Landauer-Datta

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

or

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

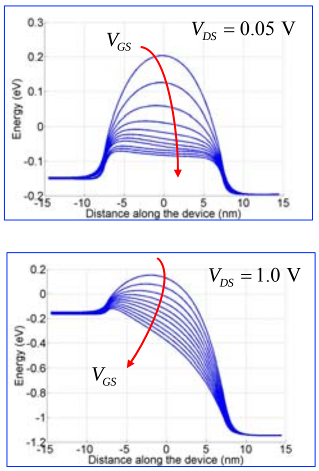
and MOS electrostatics:

$$Q = q\int \frac{D(E)}{2}\left(f_1 + f_2\right)dE \approx C_{ox}\left(V_{GS} - V_T\right)$$

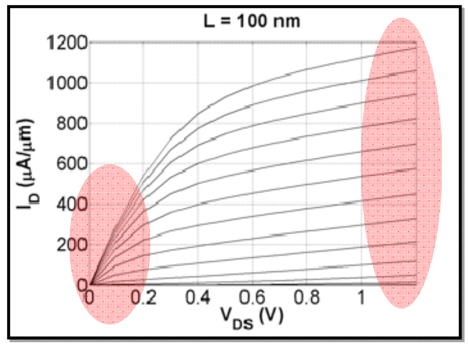
(ballistic)

how transistors work

electron energy vs. position



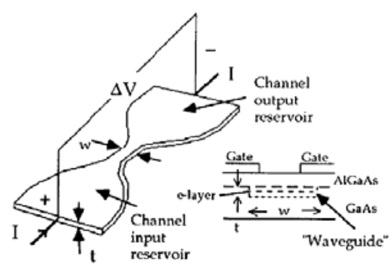
2007 N-MOSFET

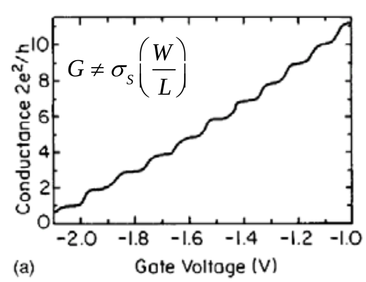


(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)

E.O. Johnson, "The IGFET: A Bipolar Transistor in Disguise," *RCA Review*, 1973

quantized resistance





W -->

B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, and C. T. Foxon, ''Quantized conductance of point contacts in a two-dimensional electron gas,'' *Phys. Rev. Lett.* **60**, 848–851,1988.

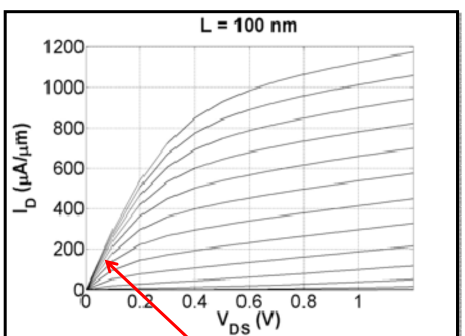
Conductance is quantized in units of $2q^2/h$ - it is not proportional to *W*.

The conductance is finite as *L* --> 0.

outline

ballistic channel resistance (Si MOSFET)

2007 N-MOSFET



(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)

1) minimum channel resistance?

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

$$G_B = 1/R_B = \frac{2q^2}{h}M \quad (T = 0\text{K})$$

$$M = g_V \frac{W}{\lambda_F/2} \qquad k_F = \frac{2\pi}{\lambda_F}$$

$$n_S = g_V \frac{k_F^2}{2\pi} = Q_i/q$$

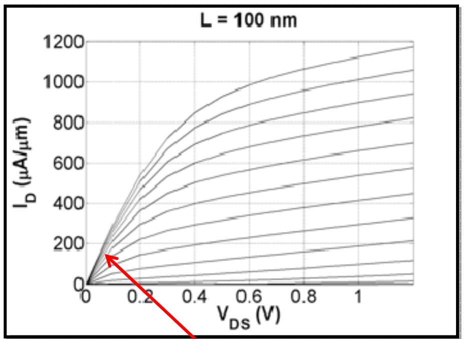
$$Q_i/q \approx 6.7\times10^{12}\ \text{cm}^{-2}$$

$$R_B \approx 44\ \Omega-\mu\text{m}$$

$$R_{ch} \approx 215\ \Omega-\mu\text{m} \approx 5\times \text{R}_\text{B}$$

diffusive channel resistance (Si MOSFET)

2007 N-MOSFET



(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)

1) minimum channel resistance?

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

$$G_{ch} = 1/R_{ch} = \frac{W}{L}\mu_{eff}Q_i$$

$$\mu_{eff} \approx 260 \text{ cm}^2/\text{V-s}$$

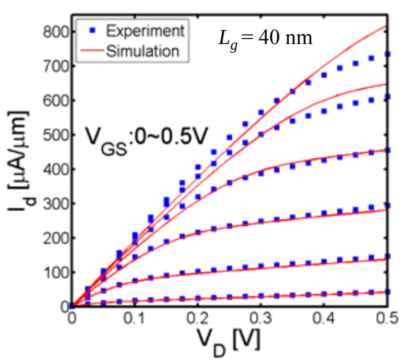
$$Q_i/q \approx 6.7\times 10^{12} \text{ cm}^{-2}$$

$$L \approx 60 \text{ nm}$$

$$R_{ch}\left(\text{diff}\right) \approx 215\ \Omega - \mu\text{m}$$

$$R_{ch}\left(\text{diff}\right) \approx R_{ch}\left(\text{meas}\right) >> R_B$$

channel resistance (InGaAs HEMT)



(courtesy, J.A. del Alamo, 2009)

$$G_B = 1/R_B = \frac{2q^2}{h}W\sqrt{\frac{2g_V n_S}{\pi}}\ \left(T = 0\text{K}\right)$$

$$n_S = Q_i/q \approx 1.9\times 10^{12} \text{ cm}^{-2}$$

$$R_B \approx 116\ \Omega - \mu\text{m}$$

$$G_{ch} = 1/R_{ch} = \frac{W}{L}\mu_{eff}Q_i$$

$$\mu_{eff} \approx 10{,}000 \text{ cm}^2/\text{V-s}$$

$$R_{ch}\left(\text{diff}\right) \approx 197\ \Omega - \mu\text{m}$$

$$R_{ch}\left(\text{diff}\right) \approx R_B$$

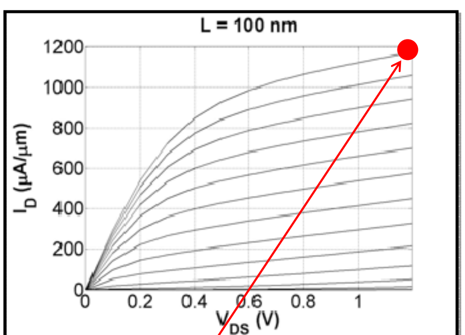
Si MOSFETs vs. InGaAs HEMTs

Under low drain bias, a Si MOSFET with ~ 60 nm channel length operates in the **diffusive** limit.

InGaAs HEMTs with comparable channel lengths operate in the **quasi-ballistic** limit.

ballistic on-current (Silicon MOSFET)

2007 N-MOSFET



(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)

2) maximum on-current?

$$I_D = W C_{ox} \upsilon_{sat} (V_{GS} - V_T)$$

$$I_{ON} = W Q_i \langle \upsilon(0) \rangle$$

$$Q_i / q \approx 6.7 \times 10^{12} \text{ cm}^{-2}$$

$$\langle \upsilon(0) \rangle \approx 1.1 \times 10^7 \text{ cm/s}$$

what is the maximum velocity?

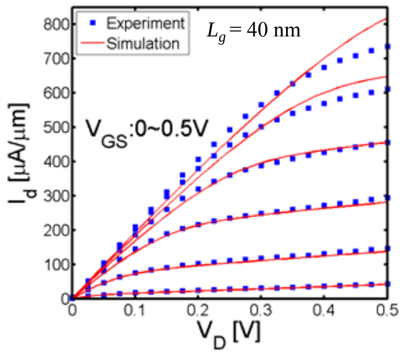
$$\upsilon_{ball} = \frac{4}{3\pi} \upsilon_F = \frac{8h}{3m^*} \sqrt{n_S / \pi}$$

$$\upsilon_{ball} \approx 2.8 \times 10^7 \text{ cm/s}$$

$$I_{ON} \approx 0.4 \times I_{ON}(\text{ball})$$

$$(T = 0\text{K})$$

ballistic on-current (InGaAs HEMT)



(courtesy, J.A. del Alamo, 2009)

$$I_{ON} = W\,Q_i \langle \upsilon(0) \rangle$$

$$Q_i/q \approx 1.6 \times 10^{12}\ \text{cm}^{-2}$$

$$\langle \upsilon(0) \rangle \approx 2.7 \times 10^{7}\ \text{cm/s}$$

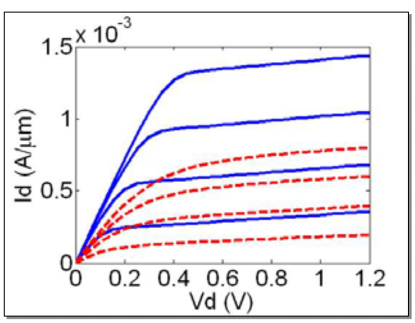
what is the maximum velocity?

$$\upsilon_{ball} \approx 2.9 \times 10^{7}\ \text{cm/s}$$

(numerical)

$$I_{ON} \approx 0.93 \times I_{ON}(\text{ball})$$

Si NMOS (ballistic vs. measured)



$L_G = 60$ nm

$$\frac{I_D(\text{meas})}{I_D(\text{ball})} \approx 0.20 \quad (\text{linear})$$

$$\frac{I_D(\text{meas})}{I_D(\text{ball})} \approx 0.56 \quad (\text{saturation})$$

C. Jeong, et al. “On Back-Scattering and Mobility in Nanoscale Silicon MOSFETs,” submitted (2009)

Si MOSFETs vs. InGaAs HEMTs

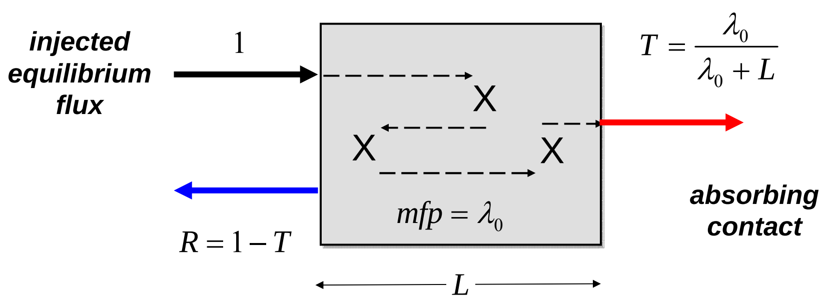
Under high drain bias, a Si MOSFET with ~ 60 nm channel length delivers about 50% of the ballistic current.

InGaAs HEMTs with comparable channel lengths deliver over 90% of the ballistic current.

Under high bias, when increased scattering is expected, both devices operate closer to the ballistic limit.

outline

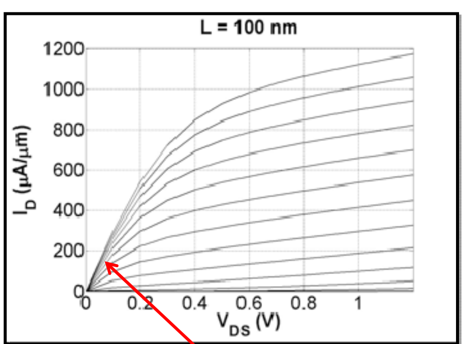
carrier scattering



λ_0 is the near-equilibrium 'mean-free-path for backscattering'

channel resistance (Si MOSFET)

2007 N-MOSFET



(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)

1) minimum channel resistance?

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

$$G_{ch} = 1/R_{ch} = \frac{2q^2}{h} T_{lin} M$$

$$\mu_{eff} = 260 \ \ \mathrm{cm^2/V\text{-}s}$$

$$\lambda_0 \approx 14 \ \mathrm{nm}$$

$$T_{lin} = \frac{\lambda_0}{\lambda_0 + L} \approx 0.19$$

$$T_{lin} = \frac{G_{ch}(\mathrm{meas})}{G_{ch}(\mathrm{ball})} \approx 0.20$$ 4

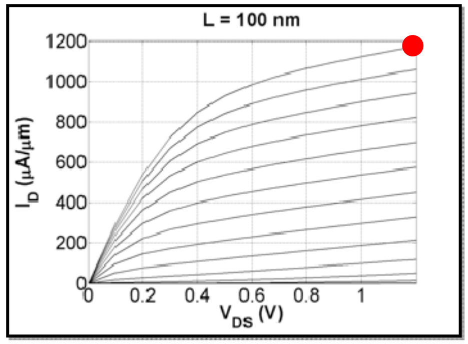
on-current and transmission

$$I_{ON} = T_{sat} I_{ON}(\text{ball})?$$

$$I_{ON} = \left(\frac{T_{sat}}{2 - T_{sat}}\right) I_{ON}(\text{ball})$$

$$Q_i(0) = q\left(n_S^+ + n_S^-\right)$$

2007 N-MOSFET



(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)

transmission under high V_{DS}

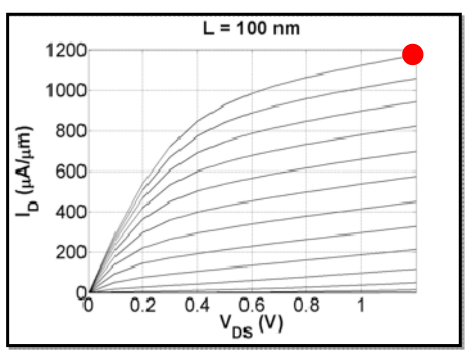
$$\frac{I_D(\text{meas})}{I_D(\text{ball})} \approx 0.56 \quad (\text{saturation})$$

$$I_{ON}(\text{meas}) \approx \left(\frac{T_{sat}}{2 - T_{sat}}\right) I_{BALL}$$

$$\rightarrow T_{sat} = 0.72$$

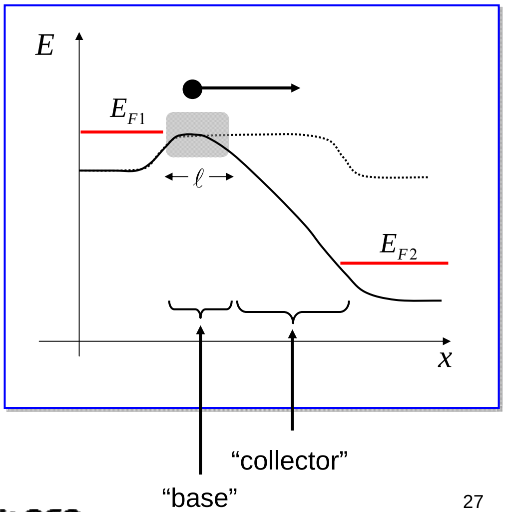
$$T_{sat} = 0.72 > T_{lin} = 0.20$$

2007 N-MOSFET



(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)

scattering under high V_{DS}



$$T_{lin} = \frac{\lambda_0}{\lambda_0 + L}$$

$$T_{sat} = \frac{\lambda_0}{\lambda_0 + \ell}$$

$$\ell << L$$

$T_{sat} > T_{lin}$ "explained"

critical length

$$\frac{I_{ON}(\text{meas})}{I_{ON}(\text{ball})} \approx \left(\frac{T_{sat}}{2 - T_{sat}}\right)$$

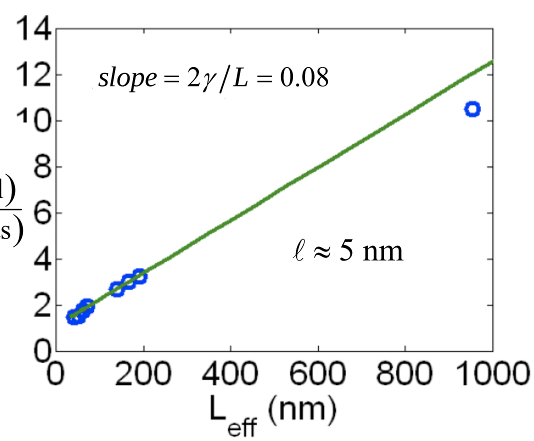
$$T_{sat} = \frac{\lambda_0}{\lambda_0 + \ell}$$

$$\ell \approx \gamma L$$

$$\frac{I_{ON}(\text{ball})}{I_{ON}(\text{meas})} = 1 + \frac{2\gamma}{\lambda_0} L$$

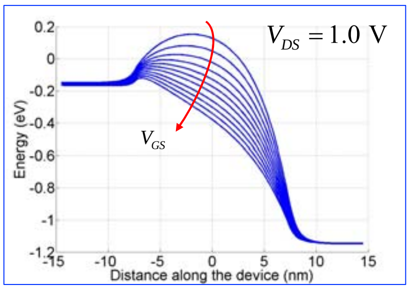
$\uparrow$

$$\frac{I_{ON}(\text{ball})}{I_{ON}(\text{meas})}$$



mobility and high V_{DS} transmission

electron energy vs. position



$\mu_{eff} = 260 \ \ \text{cm}^2/\text{V-s}$

$\lambda_0 \approx 14 \text{ nm} \qquad \ell \approx 5 \text{ nm}$

$$T_{sat} = \frac{\lambda_0}{\lambda_0 + \ell} \approx 0.74$$

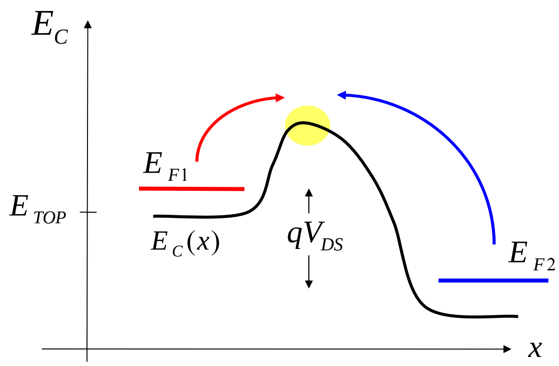
$$T_{sat} = \frac{2}{1 + I_{ON}(\text{ball})/I_{ON}(\text{meas})} \approx 0.72$$

4

outline

1) Introduction
2) Ballistic theory
3) Scattering in nano MOSFETs
4) **Discussion**
5) Summary

the ballistic MOSFET (MB statistics)



$$Q_i = q\left(n_S^+ + n_S^-\right)$$

$$I_D = q\left(n_S^+ \upsilon_T - n_S^- \upsilon_T\right)$$

$$n_S^- / n_S^+ = e^{-qV_{DS}/k_BT}$$

$$Q_i = C_{ox}\left(V_{GS} - V_T\right)$$

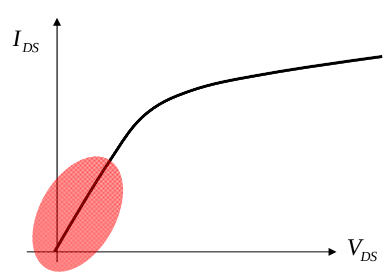
$$I_D = WC_{ox}\left(V_{GS} - V_T\right)\upsilon_T\left(\frac{1 - e^{qV_{DS}/k_BT}}{1 + e^{qV_{DS}/k_BT}}\right)$$

connection to traditional model (low V_{DS})

$$I_D = T_{lin}\left(WC_{ox}\left(V_{GS} - V_T\right)\frac{\upsilon_T}{\left(2k_BT_L/q\right)}\right)V_{DS}$$

$$T_{lin} = \frac{\lambda_0}{\lambda_0 + L}$$

$$D_n = \frac{\upsilon_T \lambda_0}{2}$$



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

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

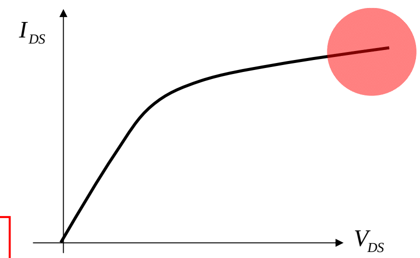
connection to traditional model (high V_{DS})

$$I_{ON} = WC_{ox}\left(V_{GS} - V_T\right)\upsilon_T\left(\frac{T_{sat}}{2 - T_{sat}}\right)$$

$$I_D = WC_{ox}\upsilon_{sat}\left(V_{GS} - V_T\right)$$

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

$$D_n = \frac{\upsilon_T \lambda_0}{2}$$

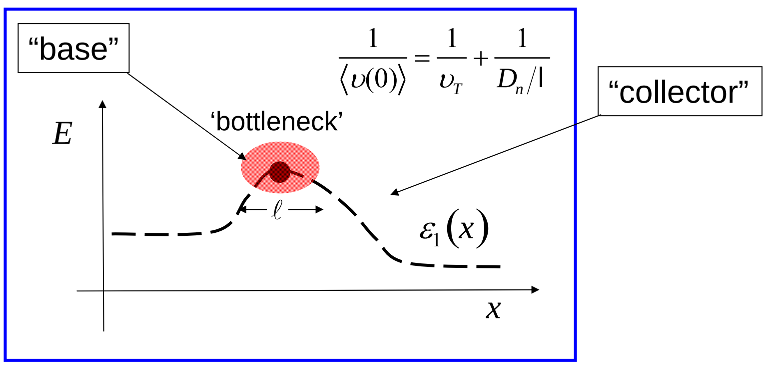


$$I_{ON} = W\left[\frac{1}{\upsilon_T} + \frac{1}{\left(D_n/l\right)}\right]^{-1} C_{ox}\left(V_{GS} - V_T\right)$$

the MOSFET as a BJT

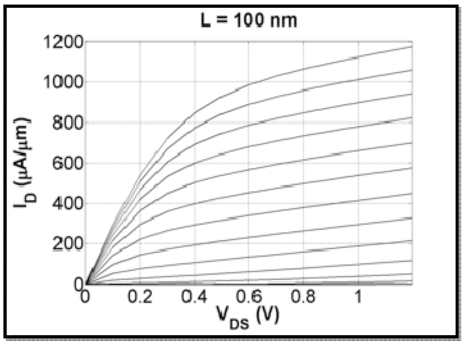
$$I_D = W\langle\upsilon(0)\rangle C_{ox}\left(V_{GS} - V_T\right)$$

$$\frac{1}{\langle\upsilon(0)\rangle} = \frac{1}{\upsilon_T} + \frac{1}{D_n/l}$$



nanoscale MOSFETs: questions

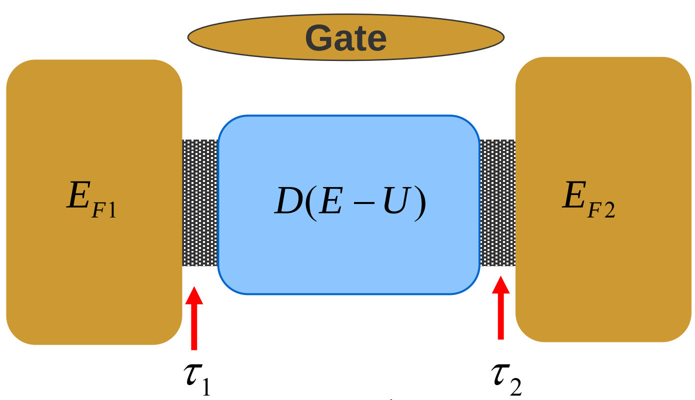
2007 N-MOSFET



(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)

3) Ultimate limits and the role of quantum mechanics?

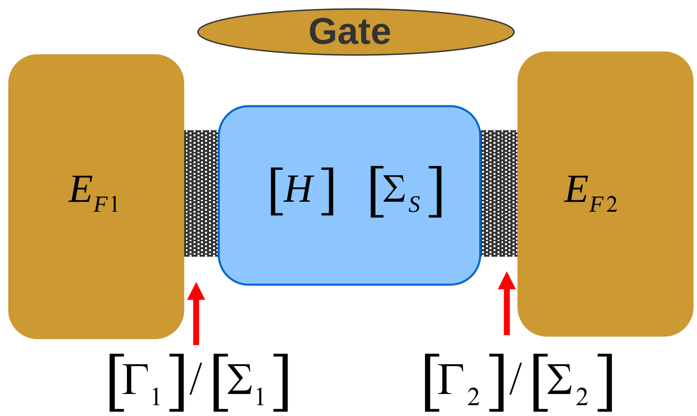
generic model of a nanodevice



$$\gamma = \hbar/\tau$$

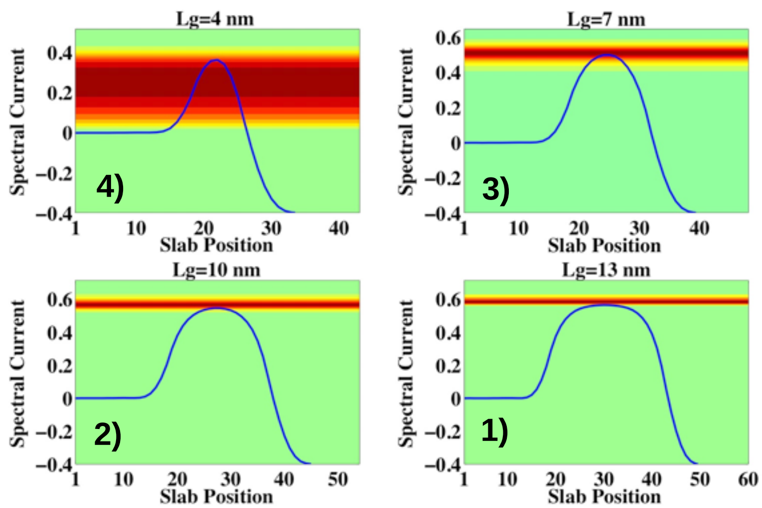
S. Datta, *Quantum Transport: Atom to Transistor*, Cambridge, 2005
(“Concepts of Quantum Transport” **nanohub.org**)

generic model ---> NEGF



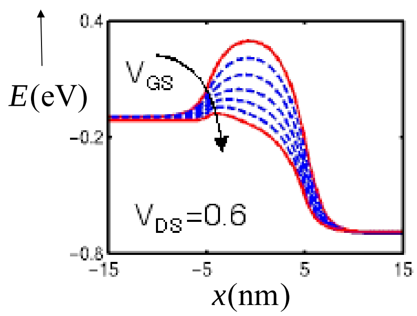
S. Datta, *Quantum Transport: Atom to Transistor*, Cambridge, 2005
("Concepts of Quantum Transport" **nanohub.org**)

quantum transport



from M. Luisier, ETH Zurich / Purdue

limits of transistors



Limits

$$E_S\big|_{min} = \ln(2)\, k_B T$$

$$L_{min} \approx \hbar \big/ \sqrt{2m\, E_S\big|_{min}}$$

$$\tau_{min} \approx \hbar \big/ E_S\big|_{min}$$

$$(\Delta p \Delta x = \hbar)$$

$$(\Delta E\, \Delta t = \hbar)$$

V.V. Zhirnov, R.K. Cavin, J.A. Hutchby, and G. Bourianoff, "Limits to Binary Logic Switch Scaling - A Gedankan Model," Proc. IEEE, Special Issue on Nanoelectronics and Nanoscale Processing, Nov. 2003.

45 nm technology vs. limits

Limits

$$E_S\big|_{min} = \ln(2)\, k_B T$$

$$L_{min} \approx \hbar \big/ \sqrt{2mE_{min}} = 1.5\,\text{nm}(300\text{K})$$

$$\tau_{min} \approx \hbar \big/ E_S\big|_{min} = 0.04\ \text{ps} \quad (300\text{K})$$

$$n_{max}(\text{at } 100\text{W/cm}^2) = 1.5\ \text{B/cm}^2$$

45 nm node
(ITRS 2006 ed.)

$$E_S \approx 5{,}000 \times E_S\big|_{min}$$

$$L \approx 20 \times L_{min}$$

$$\tau \approx 20 \times \tau_{min}$$

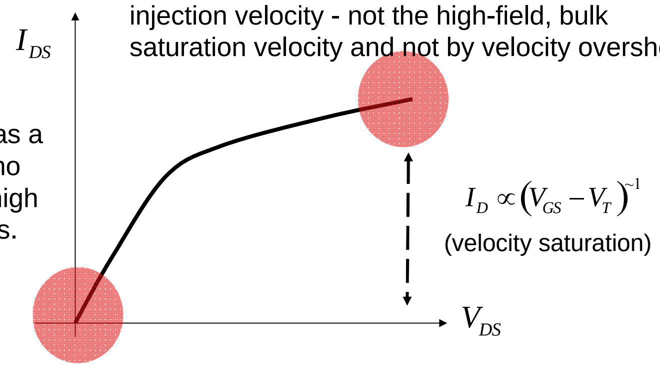
$$n \approx 1\ \text{B/cm}^2$$

outline

physics of nanoscale MOSFETs

3) The on-current is controlled by the ballistic injection velocity - not the high-field, bulk saturation velocity and not by velocity overshoot..

2) The channel resistance has a lower limit - no matter how high the mobility is.



1) Transistor-like I-V characteristics are a result of electrostatics.

questions

- How good is the connection to the source?
  (are states at the top-of-the-barrier filled according to Fermi levels?)
- What does scattering in the S/D extension do?
- Are the S/D contacts absorbing?
- How important are up- and down-stream effects?
  (is there a bottleneck?)
- What controls backscattering?
  (near-equilibrium transport?)
- What experimental tests can answer these questions?

conclusions

- In a well-tempered nanoscale MOSFET, the on-current is controlled by a short, bottleneck region the beginning of the channel.
- The backscattering that occurs in this bottleneck is controlled by low energy portions of the $E(k)$ and by low energy scattering processes.
- The amount of backscattering from the bottleneck region can be estimated surprisingly well from the near equilibrium mfp for backscattering as extracted from the near-equilibrium mobility.
- For well tempered MOSFETs, $Q_i(0) \approx C_G (V_{GS} - V_T)$.
- Up stream and down stream transport effects do not seem to control the performance of nanoscale MOSFETs.
- A very wide range of experimental data and experience can be described within this framework.

"Electronics from the Bottom Up"

http://nanohub.org/topics/ElectronicsFromTheBottomUp
or Google "Electronics from the Bottom Up"

See "Physics of Nanoscale MOSFETS" by M. Lundstrom