Physics of Nanoscale Transistors: Lecture 1:
A Review of MOSFET Fundamentals

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1) Introduction
2) MOSFET theory
3) Device performance metrics
4) The barrier model of a MOSFET
5) Carrier transport in MOSFETs
6) Summary
transistors

physical structure

S G D

(Texas Instruments, 1997)

gate

source

drain

circuit schematic

“The transistor was probably the most important invention of the 20th century,” Ira Flatow, Transistorized!  www.pbs.org/transistor
MOSFETs

For representative dimensions and parameters of current and future MOSFETs, see:

International Technology Roadmap for Semiconductors (ITRS)

especially the chapter:

PIDS: Process Integration and Device Sciences.

http://public.itrs.net
IV characteristics

circuit symbol

 gate-voltage controlled resistor

$V_{GS}$ $V_{DS}$ $I_{DS}$

gate-voltage controlled current source

$V_{GS}$ $V_{DS}$ $I_{DS}$ $V_{DSAT}$ $V_{T}$

$I_D \sim 0$ for $V_{GS} < V_{T}$
IV characteristic: real

(Courtesy, Shuji Ikeda, ATDF, Dec. 2007)
MOSFET technology evolution

\[ \log L \]

1975 → 2005

5 \( \mu m \) → 5 nm

\[ 10^3 \] → \[ 10^9 \]

see: http://www.intel.com/technology/mooreslaw/index.htm
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MOSFET IV: low $V_{DS}$

$I_D = W Q_i(x) v_x(x)$

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

$\mathcal{E}_x = \frac{V_{DS}}{L}$

$I_D = \frac{W}{L} \mu_{eff} C_{ox} (V_{GS} - V_T) V_{DS}$
MOSFET IV: ‘pinch-off’ at high $V_{DS}$

\[ Q_i(x) = -C_{ox} \left( V_{GS} - V_T - V(x) \right) \]

\[ V(x) = (V_{GS} - V_T) \]

\[ Q_i(x) \approx 0 \]
MOSFET IV: high $V_{DS}$

$V(x) = (V_{GS} - V_T)$

$Q_i(x) = -C_{ox}(V_{GS} - V_T - V(x))$

$I_D = W Q_i(x) \nu_x(x) = W Q_i(0) \nu_x(0)$

$I_D = W C_{ox}(V_{GS} - V_T) \mu_{eff} \mathcal{E}_x(0)$

$\mathcal{E}_x(0) \approx \frac{V_{GS} - V_T}{L}$

$I_D = \frac{W}{2L} \mu_{eff} C_{ox}(V_{GS} - V_T)^2$
velocity saturation

\[ \frac{V_{DS}}{L} = \frac{1.0 \text{ V}}{100 \text{ nm}} \approx 1 \times 10^5 \text{ V/cm} \]

\[ \nu = \nu_{sat} \]

\[ \nu = \mu \mathcal{E} \]

\[ \text{velocity cm/s } \rightarrow \]

\[ 1 \times 10^7 \]

\[ 10^4 \quad 10^5 \]

\[ \text{electric field V/cm } \rightarrow \]
MOSFET IV: velocity saturation

\[ I_D = W Q_i(x) \nu_x(x) \]

\[ I_D = W C_{ox} (V_{GS} - V_T) \nu_{sat} \]

\[ I_D = W C_{ox} \nu_{sat} (V_{GS} - V_T) \]

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common source characteristics

1) ground source \( (V_S = 0) \)
2) set \( V_G \)
3) sweep \( V_D \) from 0 to \( V_{DD} \)
4) step \( V_G \) from 0 to \( V_{DD} \)
common source characteristics

\[ V_{DS} \ll V_{DSAT} \]

‘linear region of operation’

\[ V_{DS} = V_{DSAT} \]

'on-current'

\[ I_{DS}(V_{GS} = V_{DD}, V_{DS} = V_{DD}) \]

\[ I_{DSAT} : (V_{GS} - V_{T})^{\alpha} \]

\[ \alpha = 2 \text{ (‘square law’)} \]

\[ \alpha = 1 \text{ (‘velocity saturated’)} \]

\[ V_{DS} \gg V_{DSAT} \]

‘saturation region’

(‘beyond pinch-off’)
common source characteristics

currents typically quoted per micrometer of MOSFET width, \( W \)

\[ R_{TOT} = \frac{V_{DS}}{I_{DS}} \left( \Omega - \mu m \right) \]

\[ R_o = \frac{\Delta V_{DS}}{\Delta I_{DS}} \left( \Omega - \mu m \right) \]

\[ I_{ON} (\mu A/\mu m) \]

\[ V_{GS} \approx V_T \]
transfer characteristics

1) ground source
2) set $V_D$
3) sweep $V_G$ from 0 to $V_{DD}$

$L = 100$ nm
measuring $V_T$

$L = 100 \text{ nm}$

intercept gives $V_T(\text{sat}) < V_T(\text{lin})$

intercept gives $V_T(\text{lin})$
slope is related to the effective mobility
transconductance

\[ g_{m\text{MAX}} = 1225 \, \mu \text{S/\mu m} \]

\[ g_m \equiv \frac{\partial I_{DS}}{\partial V_{GS}} \bigg|_{V_{DS}} \]
1) ground source
2) set $V_D = V_{DD}$
3) sweep $V_G$ from 0 to $V_{DD}$

$log_{10} I_D$ vs. $V_{GS}$

$G$ \[ \begin{array}{c} \text{D} \\ \text{V} \end{array} \]

$L = 100 \text{ nm}$

high $V_D$

low $V_D$

more current

$\log I_D (\mu A/\mu m)$

$V_{GS} (V)$

shift to left
another way to ‘measure’ $V_T$

1) ground source
2) set $V_D = V_{DD}$
3) sweep $V_G$ from 0 to $V_{DD}$
$\log_{10} I_D$ vs. $V_{GS}$

$L = 100$ nm

$V_D = 1.2V$
$V_D = 0.05V$

Off current $V_{GS} = 0$ $V_{DS} = V_{DD}$

On current $V_{GS} = V_{DS} = V_{DD}$

Subthreshold swing $S > 60$ mV/decade

$S$ is the number of millivolts required to increase $V_G$ to produce a factor of 10 increase in $I_D$ (in the sub-threshold region).
DIBL (drain-induced barrier lowering)

DIBL is the horizontal shift in the subthreshold characteristic (in millivolts) divided by the change in $V_D$ (in volts).

$V_T(V_D = 1.2V) < V_T(V_D = 0.05V)$
long channel vs. short channel

$L = 100\text{nm}$

$L = 10\ \mu\text{m} (10,000\ \text{nm})$

\[ I_{DSAT} : (V_{GS} - V_T)^\alpha \]
long channel vs. short channel

$L = 100\, \text{nm}$

$L = 10\, \mu\text{m} (10000\, \text{nm})$
device performance metrics summary

You should now be familiar with the following terms:

1) On-current
2) Off-current
3) Channel resistance
4) Output resistance
5) Threshold voltage
6) Drain saturation voltage
7) Subthreshold swing $S$ (mV/dec)
8) Drain Induced Barrier Lowering DIBL (mV/V)
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energy vs. position

source gate drain

physical structure

equilibrium E-band diagram

\[ E(x) \]

\[ E_F \]
controlling current with energy barriers

\[ E = -qV \]
low $V_{DS}$

$I^+ - I^- \propto V_{DS}$
high $V_{DS}$

$I^+$ $\propto$ $I^-$

$I_{DS}$

$V_{DS} = 1.0$ V

$V_{GS}$

$I_{DS} \propto I^+$
MOSFET IV: pinch-off at high \( V_{DS} \)

\[
Q_i(x) = -C_{ox} \left( V_{GS} - V_T - V(x) \right)
\]

\[
V(x) = (V_{GS} - V_T)
\]

\[
Q_i(x) \approx 0
\]
pinch off in a MOSFET

The electron velocity is very high in the pinch-off region. High velocity implies low inversion layer density (because $I_D$ is constant). In the textbook model, we say $Q_i \approx 0$, but it is not really zero - just very small.

**pinch-off point:** where the electric field along the channel becomes very large. Note that electrons are simply swept across the high-field (pinched-off) portion at very high velocity.
barrier-controlled vs. charge controlled view

\[ Q_i(x) = -C_{ox}(V_{GS} - V_T - V(x)) \]

\[ Q_i(x) \approx -C_{ox}(V_{GS} - V_T) \]
barrier-controlled vs. charge controlled view

\[ Q_i(x) = -C_{ox}(V_{GS} - V_T - V(x)) \]

\[ E_{F2} = E_{F1} - qV_{DS} \]
IV characteristic for high $V_{DS}$

$I_D \approx I^+$

$V_{DS} = 1.0 \text{ V}$

$\log_{10} I_D \sim (V_{GS} - V_T)$

$\sim e^{q(V_{GS}-V_T)/m k_B T}$
IV characteristic for high $V_{DS}$ (below threshold)

\[ I^+ \approx I^+ \quad I^- \]

\[ V_{DS} = 1.0 \text{ V} \]

\[ I_D \approx I^+ \sim e^{-\Delta E/k_BT} \]

\[ \Delta E = \Delta E_{FB} - q\psi_S \]

\[ I_D \sim e^{q\psi_S/k_BT} \]

\[ \psi_S = V_{GS}/m \]

\[ I_D \sim e^{qV_{GS}/mk_BT} \]
IV characteristic for high $V_{DS}$ (above threshold)

$I_D \propto I^+$

$V_{DS} = 1.0 \text{ V}$

$E.O. \text{ Johnson, } RCA \text{ Review, 1971}$

$Q_I \sim e^{q\psi_S/k_BT}$

$|Q_I| = C_{ox} (V_{GS} - V_T)$

$\psi_S \sim \ln(V_{GS} - V_T)$

$I_D \sim (V_{GS} - V_T)$
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drift-diffusion transport

\[ J_n = nq\mu_n E_x + qD_n \frac{dn}{dx} \]

above threshold, drift dominates

below threshold, diffusion dominates
velocity saturation

\[ J_n = nq\mu_n E_x \Rightarrow \langle \nu_x \rangle = -\mu_n (E) E_x \]

\[ \nu = \mu E \]

velocity cm/s --->

10^7

10^4

electric field V/cm --->

\[ \nu = \nu_{sat} \]
velocity overshoot in sub-micron MOSFETs

Frank, Laux, and Fischetti, IEDM Tech. Dig., p. 553, 1992

\[ V_D = 0.8V \]
\[ V_{G-T} = 0.5V \]
diffusive vs. ballistic transport

1) diffusive:
\[ R = \rho_s \left( \frac{L}{W} \right) \quad \rho_s = \frac{1}{n_s q \mu_n} \quad \langle v_x \rangle = -\mu_n E_x = \mu_n \left( \frac{V}{L} \right) \]

2) ballistic:
\[ R = \left( M \frac{2q^2}{h} \right)^{-1} \quad \text{("quantum contact resistance" } T = 0 \text{ K)} \]
diffusive transport in a MOSFET

$L \gg \lambda$

$E_C(x)$

energy

position

$NCN$
ballistic transport in a MOSFET

\[ L \ll \lambda \]

\[ \langle KE \rangle = \frac{1}{2} m^* \nu^2 \]

\[ E_C(x) \]
velocity overshoot in sub-micron MOSFETs

Frank, Laux, and Fischetti, IEDM Tech. Dig., p. 553, 1992
quantum transport in a nano MOSFET

$L = 10 \text{ nm}$

$n(x, E)$

nanoMOS (www.nanoHUB.org)
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summary

1) Traditional MOSFET theory is based on drift-diffusion and MOS electrostatics.

2) MOSFETs are ‘barrier controlled devices.’

3) A few key device metrics characterize performance.

4) Modern MOSFETs operate between the diffusive and ballistic limits.
‘Barrier controlled transport’ is responsible for the shape of the MOSFET IV characteristic.

\[ I_D = W C_{ox} \nu_{sat} (V_{GS} - V_T) \]

\[ I_D = \frac{W}{L} \mu_{eff} C_{ox} (V_{GS} - V_T) V_{DS} \]

The specific transport model determines the magnitude of the current.
A good reference for this lecture is:


You may also wish to consult the online lectures:

*Nanoscale Transistors*, by Mark Lundstrom, https://www.nanohub.org/courses/nanoscale_transistors

These references discuss the physics of DIBL, subthreshold swing, etc.