Digital Integrated Circuits – EECS 312

http://robertdick.org/eecs312/

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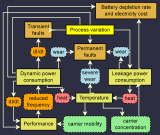
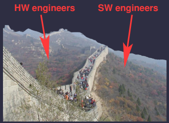
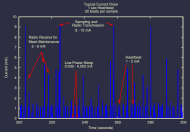
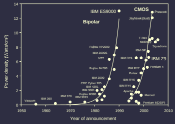








Writing, drop box

Writing

1. Organization.
2. Get to the point.
3. Show, don't tell.
4. Keep it relatively formal.
5. This is awesome: William Strunk Jr. and E. B. White. *The Elements of Style*.
   Macmillan Publishing Co., Inc., 2000.

In–out box

EECS 2417, in the jungle to the back-right of the room.

Homework 1 tips

- Problem 1: Use equations in textbook or lecture notes packet 4.
- Problem 2: See lecture notes packet 2 and use reasoning. Can explain/justify assumptions you make, e.g., frequency is closely related to number of operations per second. Can also use other sources, but cite them.
- Problem 4: Use cited equation in lecture notes packet 2.
- Problems 5 and 6: Learned these in lecture and lab assignment 1.
- Problems 7 and 8: Learned these in lecture.
- Problem 10: This is an extension from lab assignment 1 and what we learned about PMOSFETs in lectures 2 and 3.
- Problems 11 and 12: We learned these in lecture 4.

Midterm exam time

- Our original midterm exam time conflicted with many classes.
- Now shifted to 7:00–8:30 on 8 October in 1670 BBB.

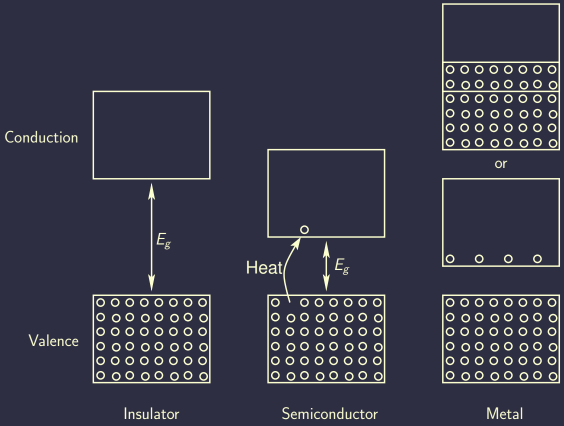
Special topics talks

- I read all of your areas of interest and boiled this down to general topics you might give special topics talks on.
- Shengshuo posted a Google document, which you used to select topics.
- I added dates to all topics.
- Talks will be given in the middle of lecture: 5–7 minutes.
- First one is 24 Sep on fabrication. It might be good to talk with or exchange email with me about the details on this.
- If your talk topic looks similar to something in the course overview document, it is best to send me an outline of your talk a week or two ahead of time so I can warn you if we might be covering the same material.
- If you will use slides, send me a PDF by midnight of the previous day at the latest. I will project using my laptop, and will post the slides to the website.

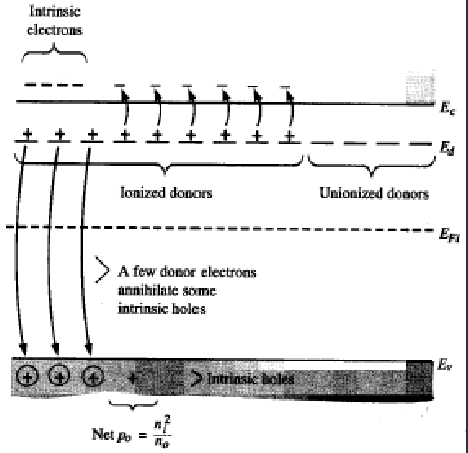
Review of semiconductor basics and diodes

- Electrons and holes.
- Intrinsic charge carriers and doping.
- Diffusion and drift.
- Built-in potential.
- I–V curve for diodes.
- Avalanche breakdown.

Material properties



Dopant influence on energy band diagram

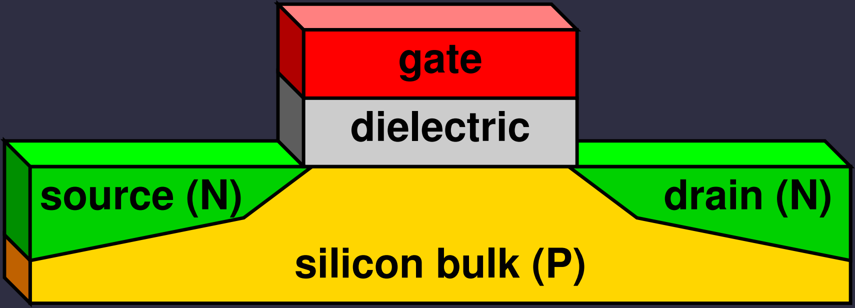


From Sameh Rehan.

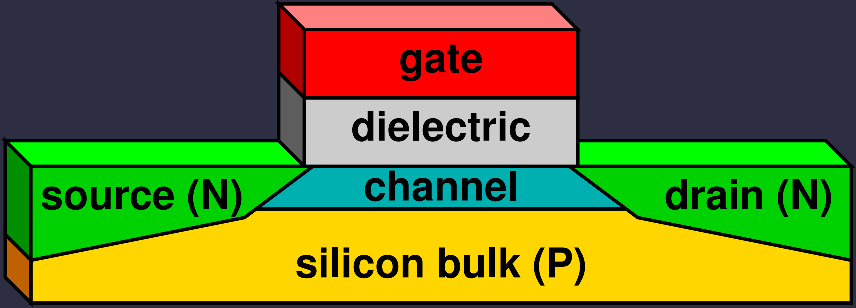
Lecture plan

1. MOSFET threshold voltage
2. MOSFET operating regions
3. MOSFET short channel effects
4. Homework

NMOSFET



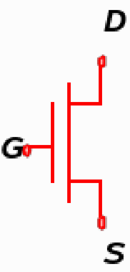
NMOSFET



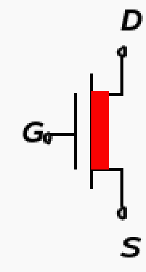
MOSFET properties

1. Voltage-controlled current.
2. Very little steady-state I_{GS} and I_{GD}.
3. When on, channel sandwiched between insulator and depletion region.
4. Bulk bias can be changed.
5. Generally made minimal-length: Why?

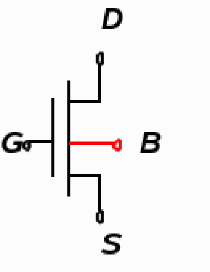
MOSFET symbols



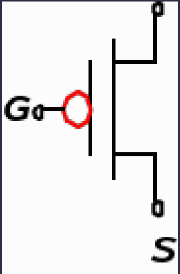
NMOSFET



Depletion mode NMOSFET



NMOSFET w. bulk contact



PMOSFET

Physics-based threshold voltage expression

$$V_T = \Phi_{ms} - 2\Phi_F - \left(\frac{Q_B}{C_{ox}} + \frac{Q_{SS}}{C_{ox}} + \frac{Q_I}{C_{ox}}\right)$$

- $\Phi_{ms} = \Phi_m - \Phi_s$: Gate work function, point at which charge transfer due to differing work functions stops.
- $\Phi_F = \Phi_T \ln\left(\frac{N_A}{n_i}\right)$: Fermi potential.
- $\Phi_T = \frac{kT}{q}$.
- $\frac{Q_B}{C_{ox}}$: Voltage due to depletion layer charge.
- $\frac{Q_{SS}}{C_{ox}}$: Voltage due to surface charge.
- $\frac{Q_I}{C_{ox}}$: Voltage due to implants.

$$Q_B = \sqrt{2qN_A\epsilon_{Si}\left(|-2\Phi_F + V_{SB}|\right)}$$

Precisely determining these parameters is challenging.

Empirical threshold voltage expression

$$V_T = V_{T0} + \gamma \left(\sqrt{|-2\Phi_F + V_{SB}|} - \sqrt{|2\Phi_F|} \right)$$

$$V_{T0} = \Phi_{ms} - 2\Phi_F - \left(\frac{Q_{B0}}{C_{ox}} + \frac{Q_{SS}}{C_{ox}} + \frac{Q_I}{C_{ox}} \right)$$

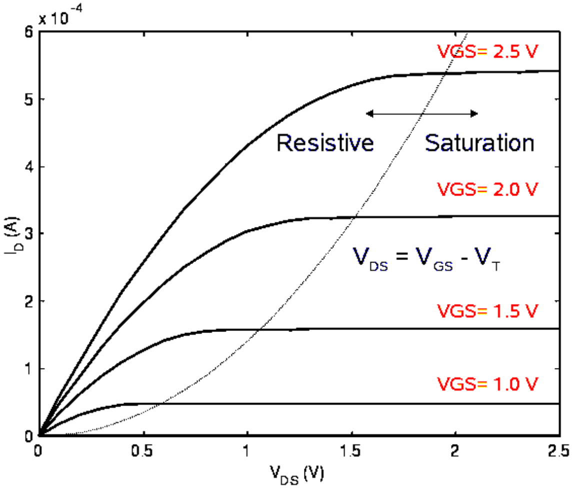
$$\gamma = \frac{\sqrt{2q\epsilon_{Si}N_A}}{C_{ox}}$$

- V_{T0}: V_T at $V_{SB} = 0$. Usually measured directly.
- Q_{B0}: Depletion layer charge when $V_{SB} = 0$.
- γ: Body-effect coefficient expressing impact of ΔV_{SB}.

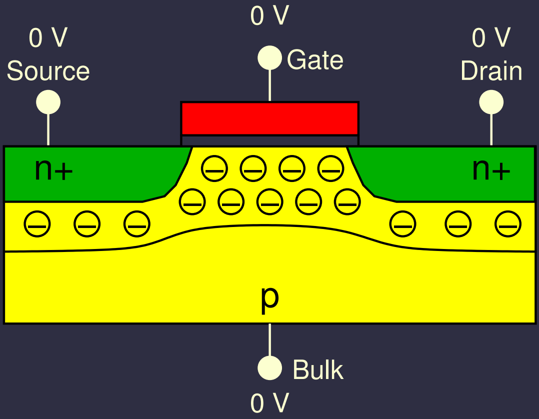
Lecture plan

1. MOSFET threshold voltage
2. MOSFET operating regions
3. MOSFET short channel effects
4. Homework

I–V relationship

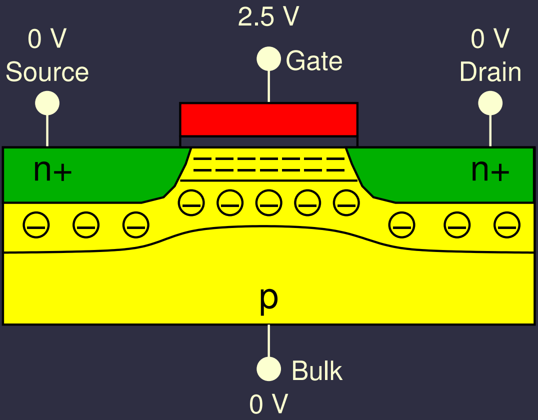


Unbiased



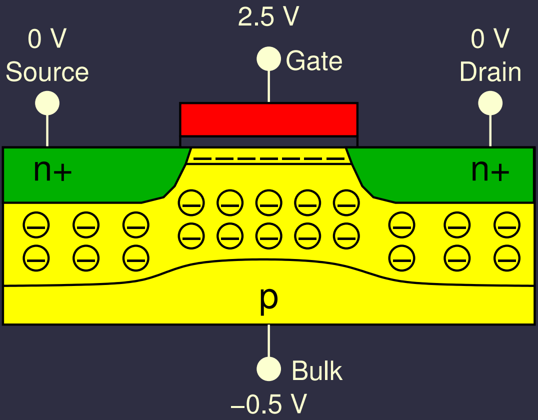
- Depletion regions at P–N junctions.

V_{GS} high



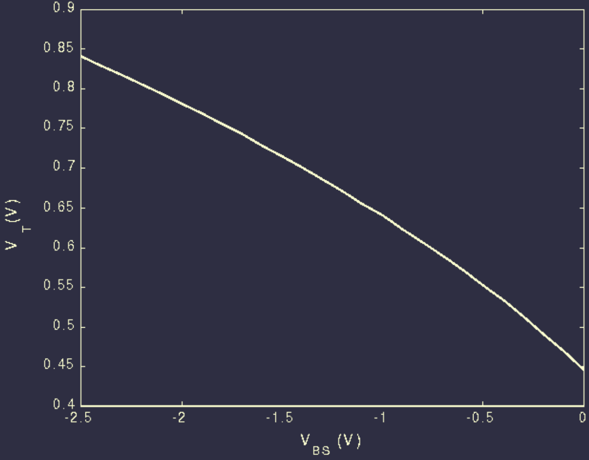
- Inversion in thin channel under gate.

Body bias: V_{BS} low

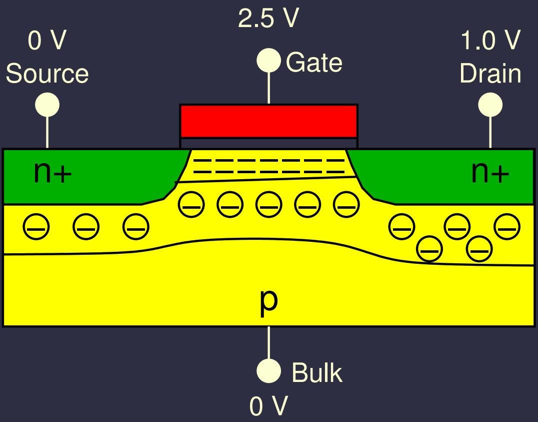


- Depletion region widens.
- Carriers in channel repelled to source.

Body effect as a function of V_{BS}



Linear region: V_{GS} high and V_{DS} moderately high



- Slight deformation of channel due to widening depletion region around reverse-biased P–N junction.

Linear mode current–voltage relationship for long-channel device

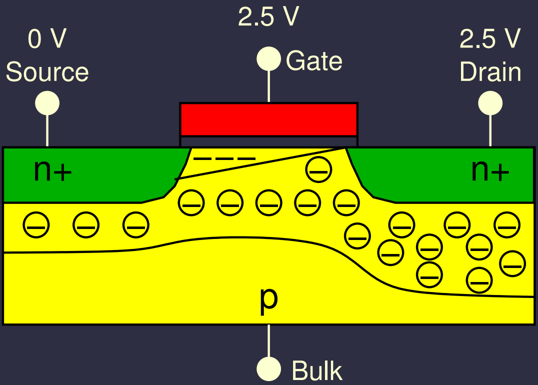
$$\text{Given: } V_{DS} \leq V_{GS} - V_T$$

$$I_D = k_n' \frac{W}{L} \left((V_{GS} - V_T) V_{DS} - \frac{{V_{DS}}^2}{2} \right)$$

$$k_n' = \mu_n C_{ox} = \frac{\mu_n \epsilon_{ox}}{t_{ox}}$$

- k_n': Process transconductance.
- C_{ox}: Oxide capacitance.
- μ: Carrier mobility.
- W: Transistor width.
- L: Transistor length.
- ϵ_{Si}: Permittivity.
- t_{ox}: Oxide thickness.

Saturation: V_{GS} high and V_{DS} very high



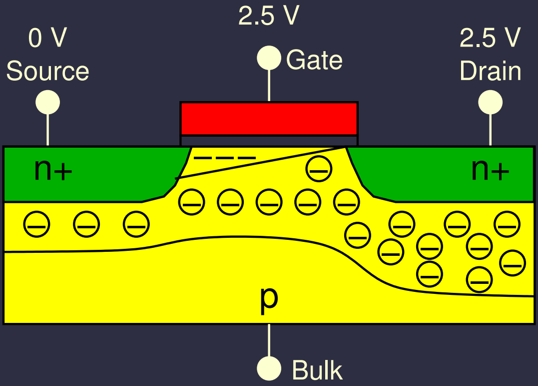
- Pinch-off due to widening depletion region around reverse-biased P–N junction.

Saturation mode current–voltage relationship for long-channel device

Given: $V_{DS} \geq V_{GS} - V_T$

$$I_D = \frac{k_n'}{2}\frac{W}{L}\left(V_{GS} - V_T\right)^2$$

Saturation: V_{GS} high and V_{DS} very high



- Pinch-off due to widening depletion region around reverse-biased P–N junction.
- Decreased channel length → some increase in current.

Saturation mode current–voltage relationship for long-channel device considering channel length modulation

$$
\begin{aligned}
\text{Given: } & V_{DS} \geq V_{GS} - V_T \\
I_D &= \frac{k_n'}{2}\frac{W}{L}\left(V_{GS} - V_T\right)^2 \\
I_D &= \frac{k_n'}{2}\frac{W}{L}\left(V_{GS} - V_T\right)^2\left(1 + \lambda V_{DS}\right)
\end{aligned}
$$

- Channel length decreases with high V_{DS} due to expanding depletion region.
- λ: Empirical constant inversely related to channel length.

Lecture plan

1. MOSFET threshold voltage
2. MOSFET operating regions
3. MOSFET short channel effects
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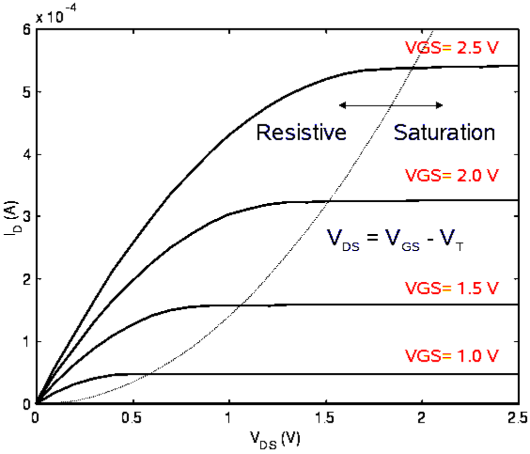
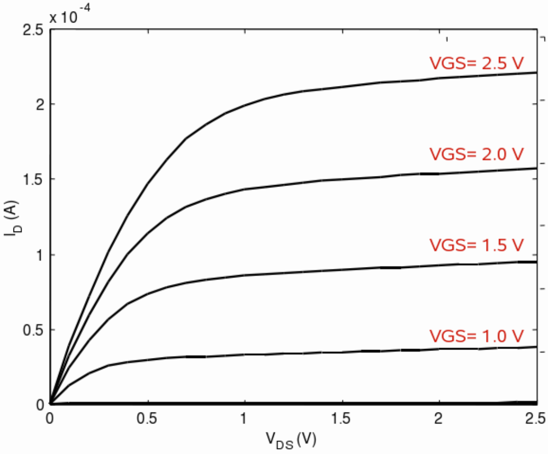
Current–voltage relationship for long-channel devices



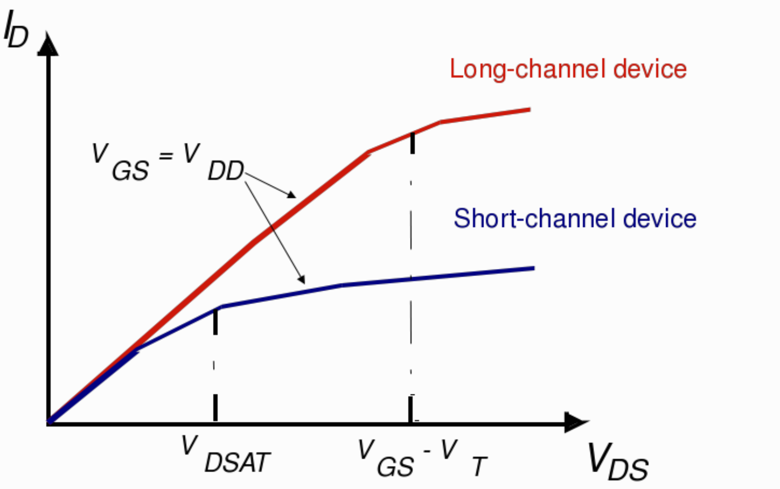
Quadratic dependence on V_{GS}.

Current–voltage relationship for short-channel devices

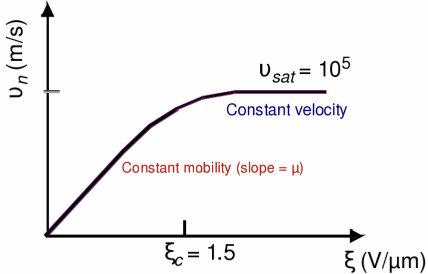


Linear dependence on V_{GS}.

Current–voltage relationship for long- and short-channel devices

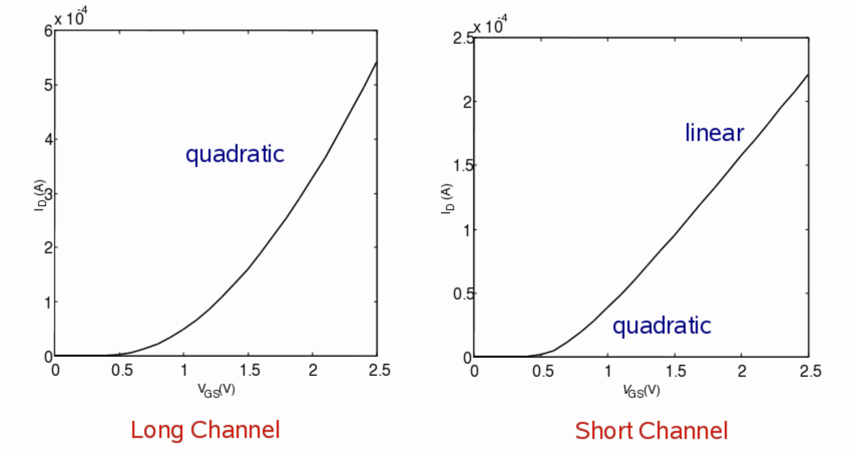


Velocity saturation

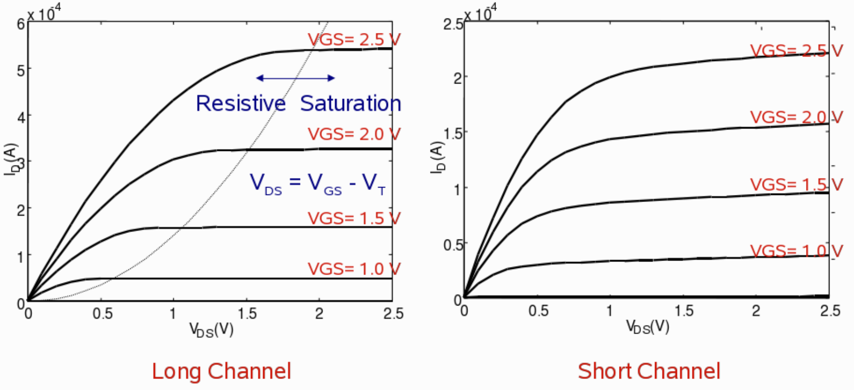


- Charge carriers move randomly, with a net drift velocity.
- What happens when drift velocity approaches particle velocity?

V_{GS} dependence for long- and short-channel devices



V_{DS} dependence for long- and short-channel devices



Unified model

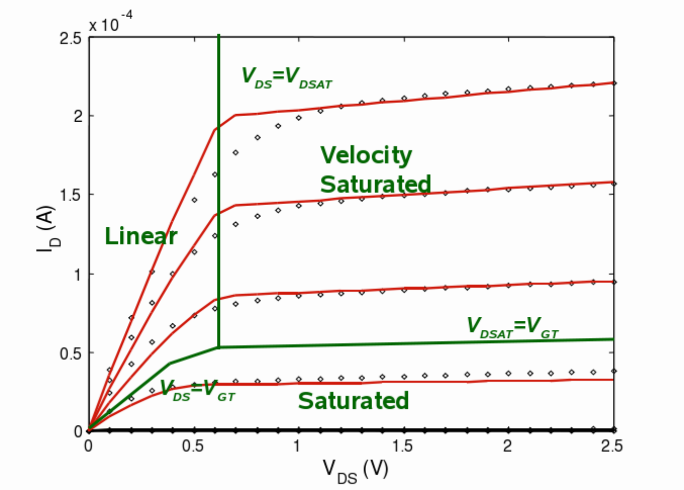
$$I_D = \begin{cases} 0 & \text{if } V_{GT} \leq 0 \text{ and} \\ k' \frac{W}{L} \left(V_{GT} V_{min} - \frac{{V_{min}}^2}{2} \right) (1 + \lambda V_{DS}) & \text{if } V_{GT} \geq 0. \end{cases}$$

$$V_{min} = \min \left(V_{GT}, V_{DS}, V_{DSAT} \right)$$

$$V_{GT} = V_{GS} - V_T$$

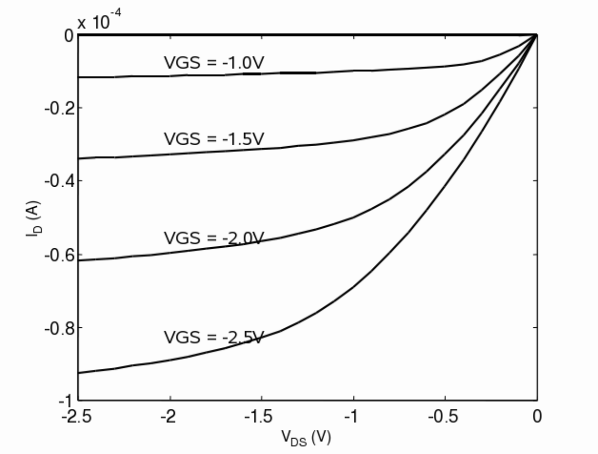
$$V_T = V_{T0} + \gamma \left(\sqrt{\left|-2\Phi_F + V_{SB}\right|} - \sqrt{\left|2\Phi_F\right|} \right)$$

Quality of unified model



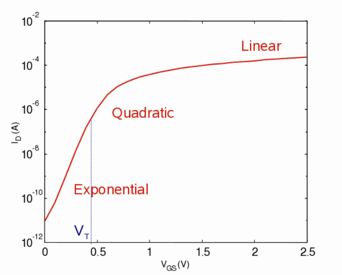
Dots are from detailed simulation, line is for unified model.

Generalization for PMOSFETs



Negate all variables.

Near-threshold and subthreshold operation



$$I_D = I_S e^{\frac{V_{GS}}{nkT/q}} \left(1 - e^{-\frac{V_{DS}}{kT/q}}\right)(1 + \lambda V_{DS})$$

- I_S: Empirical current normalization parameter.
- n (≈ 1.5): Empirical temperature dependence parameter.

Subthreshold slope

- I_D clearly depends exponentially on V_{GS}.
- Define the slope factor, S, as the change in V_{GS} for I_D to change by 10×.
- From the subthreshold current expression, can solve for S.

$$S = n\left(\frac{kT}{q}\right)\ln\left(10\right)$$

Simplified resistance-based model

- Sometimes, static behavior is sufficient.
- Can model on device as resistor.
- Off devices with ∞ resistance.

MOSFET operating regions summary

- Sub-threshold
    - Weak inversion.
    - $V_{GS} \leq V_T$.
    - I_D exponential in V_{GS}.
    - I_D linear in V_{DS}.
- Linear or resistive: Strong inversion.
    - $V_{GS} \geq V_T$.
    - $V_{DS} \leq V_{DSAT}$.
- Saturated: Strong inversion but pinch-off or velocity saturation.
    - $V_{GS} \geq V_T$.
    - $V_{DS} \geq V_{DSAT}$.
    - Approximately constant current.

Summary

1. Physics allows understanding of MOSFET channel inversion and other behaviors.
2. Some physical parameters can be difficult to directly measure, so empirical model often used.
3. Threshold voltage is important, and can be statically and dynamically varied.
4. MOSFETs have regions of operation decided by V_{DS}.
5. Behaviors vary from long-channel to short-channel devices.
6. For manual analysis, a region-based model can be used.
7. Subthreshold operation can enable very low power consumption, at cost of low performance.

Upcoming topics

- Fabrication.
- Transistor dynamic behavior.
- Interconnect.

Announcement: ECE Faculty Candidate Seminar

- Professor Leung Tsang, Department of Electrical Engineering, University of Washington
- Electromagnetic Simulations of Signal Integrity in Interconnects: Effects of Multiple Vias and Surface Roughness
- Wednesday, September 18, 2013
- 9:30–10:30
- Johnson Rooms 3rd floor Lurie

Lecture plan

1. MOSFET threshold voltage
2. MOSFET operating regions
3. MOSFET short channel effects
4. Homework

Homework assignment

- 24 September: Read Section 2.1, 2.2, and 1.3.1 in J. Rabaey, A. Chandrakasan, and B. Nikolic. *Digital Integrated Circuits: A Design Perspective*.
  Prentice-Hall, second edition, 2003. Really! You will be confused on Tuesday, otherwise.
- 24 September: Homework 1.