ESE370: Circuit-Level Modeling, Design, and Optimization for Digital Systems

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Lec 8: September 22, 2021

MOS Transistor Operating Regions

Part 2

Today

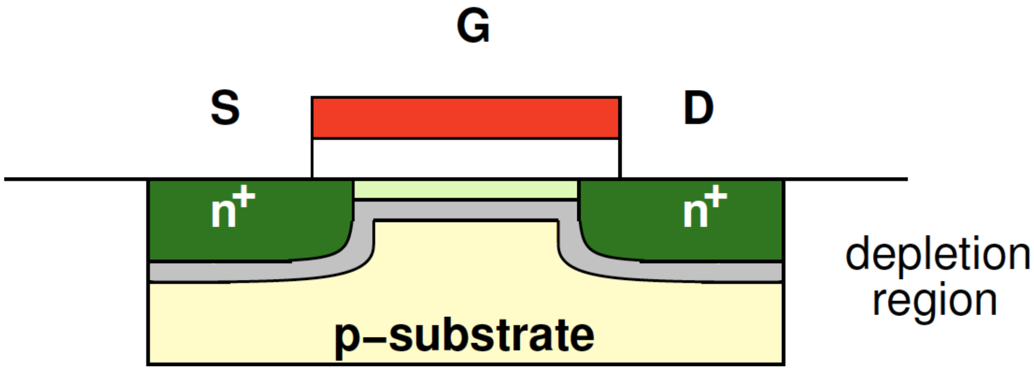
- Operating Regions (continued)
  - Resistive
  - Saturation
  - Subthreshold
  - Velocity Saturation
- Short Channel Effects
  - V_{th}
  - Drain Induced Barrier Lowering

Last Time…

Above Threshold

Linear Region

- $V_{GS} > V_{th}$ and V_{DS} small



$$C_{OX} = \frac{\varepsilon_{OX}}{t_{OX}}$$

$$\boxed{I_{DS} = \mu_n C_{OX}\left(\frac{W}{L}\right)\left[\left(V_{GS} - V_{th}\right)V_{DS} - \frac{V_{DS}^2}{2}\right]}$$

Saturation

- In saturation, $V_{DS\text{-effective}} = V_x = V_{GS} - V_T$

$$I_{DS} = \mu_n C_{OX}\left(\frac{W}{L}\right)\left[\left(V_{GS} - V_T\right)V_{DS} - \frac{V_{DS}^2}{2}\right]$$

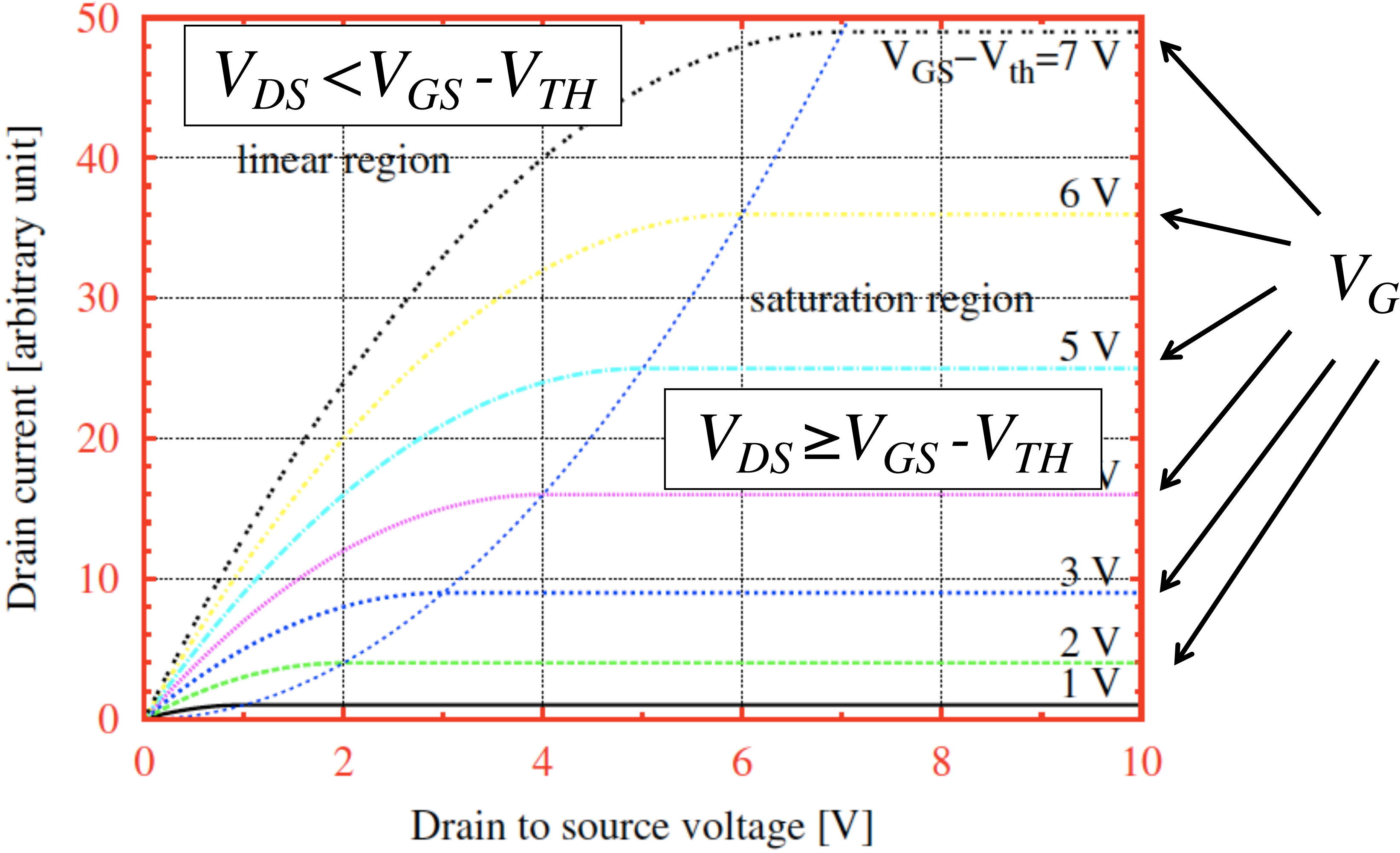
- Becomes:

$$I_{DS} = \mu_n C_{OX}\left(\frac{W}{L}\right)\left[\left(V_{GS} - V_T\right)^2 - \frac{\left(V_{GS} - V_T\right)^2}{2}\right]$$

$$\boxed{I_{DS} = \frac{\mu_n C_{OX}}{2}\left(\frac{W}{L}\right)\left[\left(V_{GS} - V_T\right)^2\right]}$$

MOSFET – IV Characteristics

I_{DS}



$V_{DS} < V_{GS} - V_{TH}$

$V_{DS} \geq V_{GS} - V_{TH}$

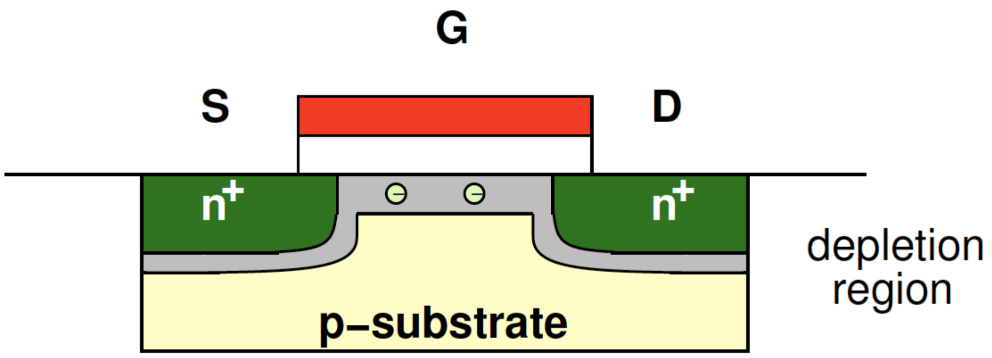
$V_{GS} - V_{th}$

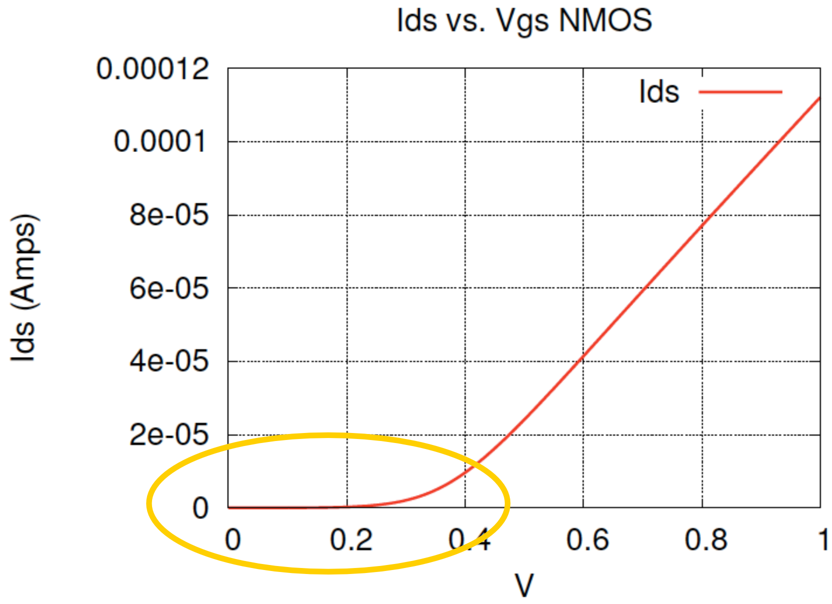
V_{DS}

Subthreshold

Below Threshold

- Transition from insulating to conducting is non-linear, but not abrupt
- Current does flow
  - But exponentially dependent on V_{GS}





Below Threshold

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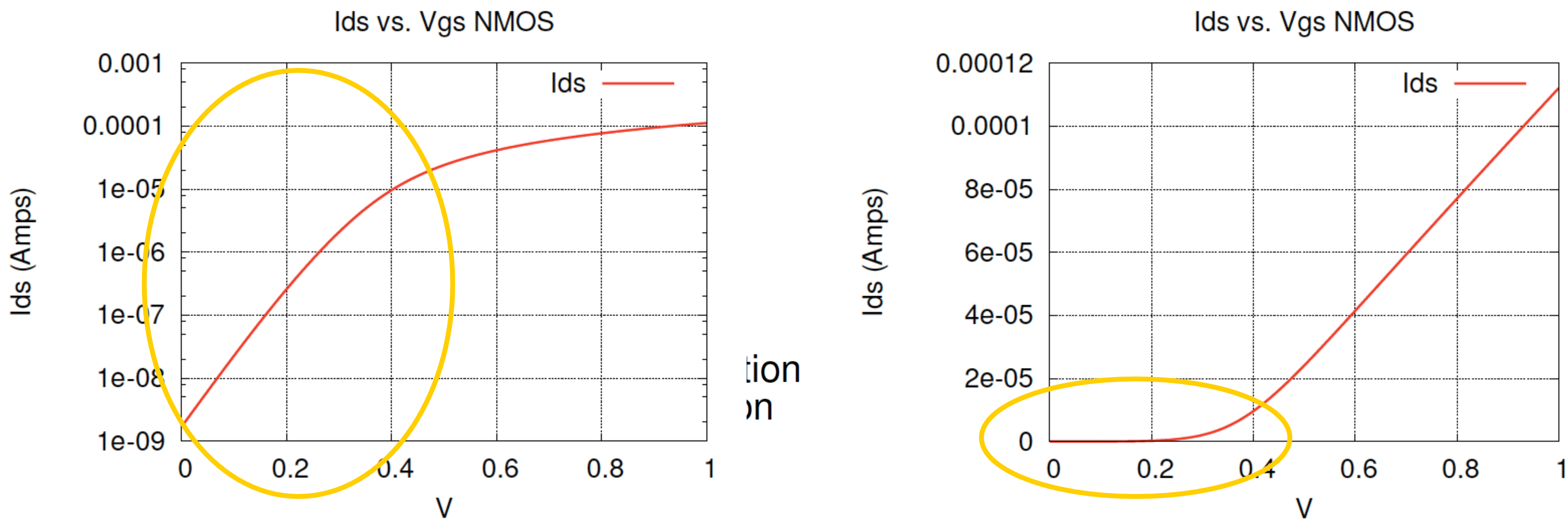
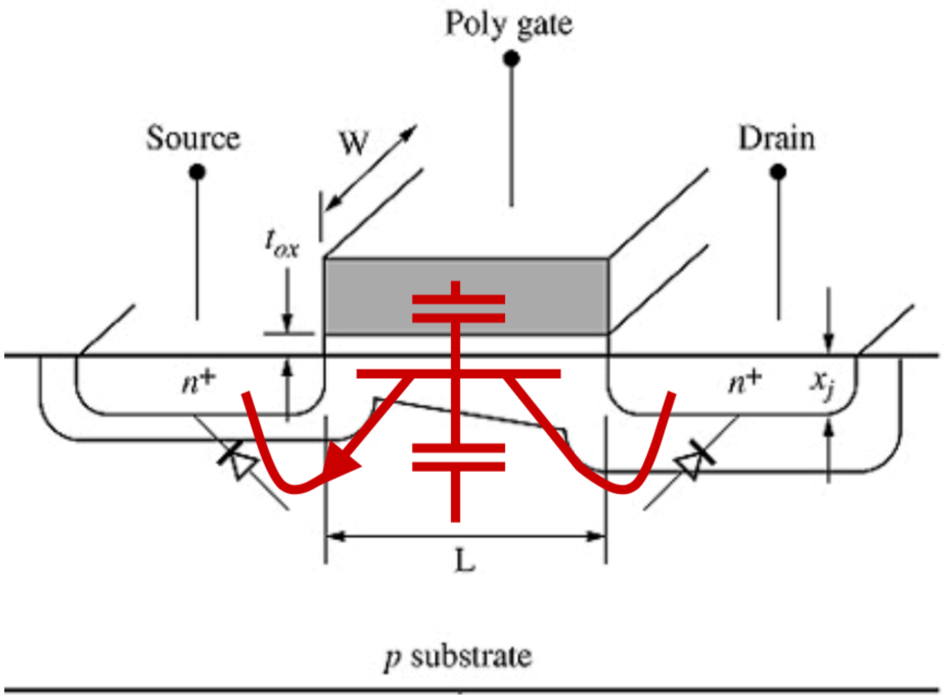


Parasitic NPN BJT

- We have an NPN sandwich, mobile minority carriers in the P region
- This is a BJT!
  - Except that the base potential is here controlled through a capacitive divider, and not directly an electrode



Subthreshold

$$\text{If} \quad V_{GS} < V_{th},$$

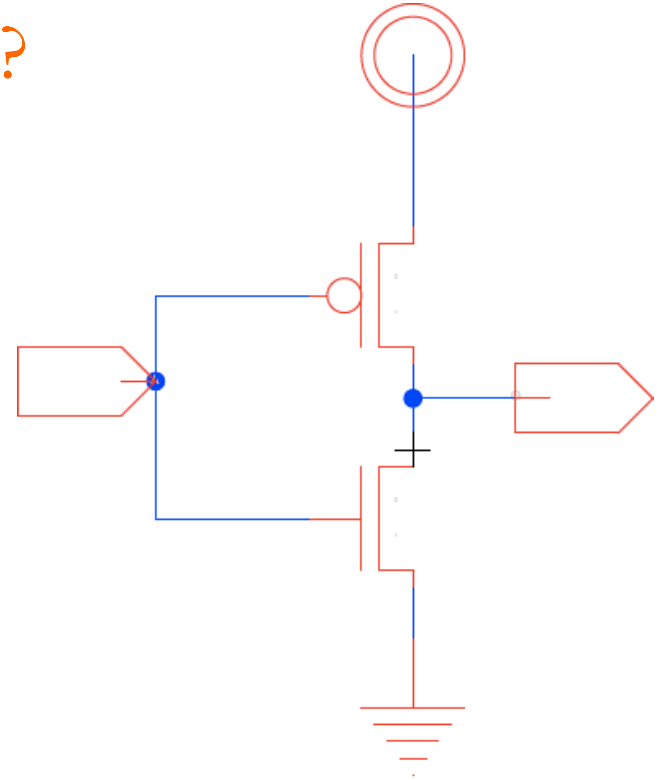
$$I_{DS} = I_S \left(\frac{W}{L}\right) e^{\left(\frac{V_{GS} - V_{th}}{nkT/q}\right)}$$

- Current is from the parasitic NPN BJT transistor when gate is below threshold and there is no conducting channel
  - n is the capacitive divider between parasitic capacitances
  - Typically 1 < n < 1.5

$$n = \frac{C_{js} + C_{ox}}{C_{ox}}$$

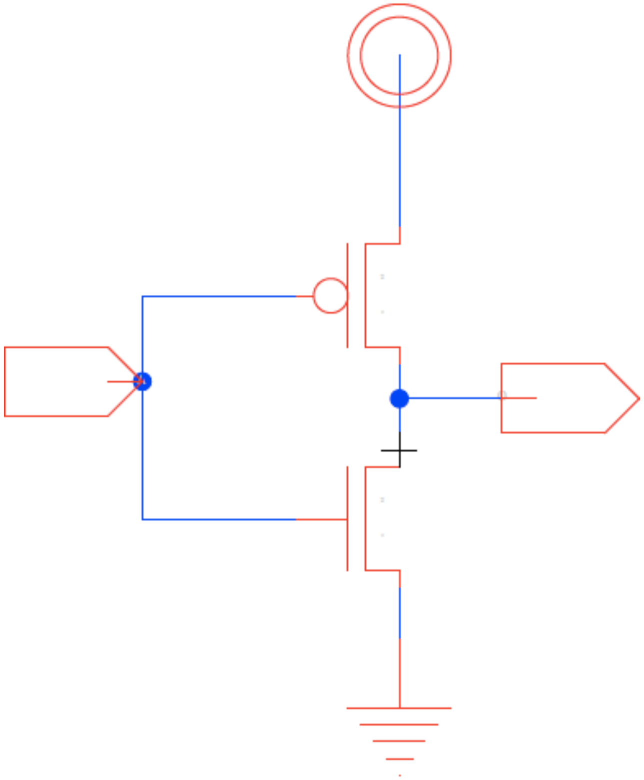
Steady State (Preclass 1)

- What current flows in steady state?
- What causes (and determines) the magnitude of current flow?
- Which device?



Leakage

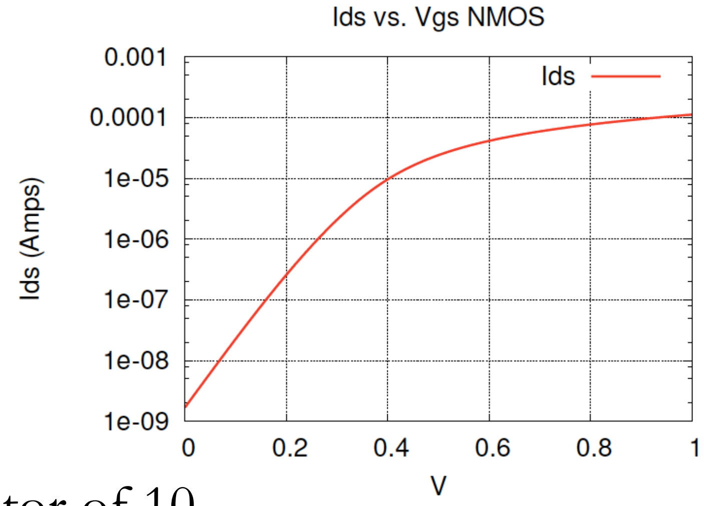
- Call this steady-state current flow leakage
  - $I_{ds,leakage}$



Subthreshold Slope Factor

- Exponent in V_{GS} determines how steep the turnon is

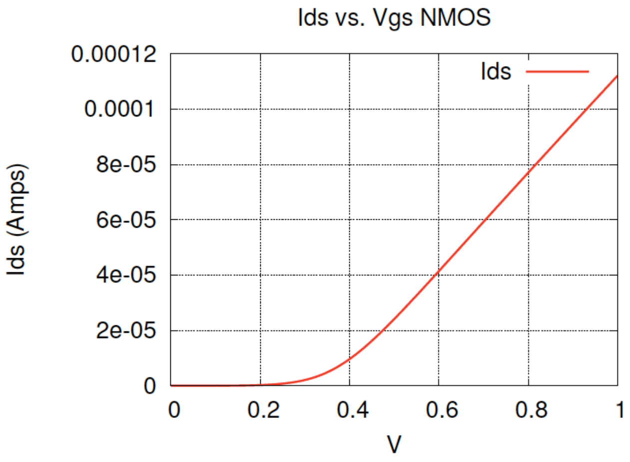
$$S = n\left(\frac{kT}{q}\right)\ln(10)$$

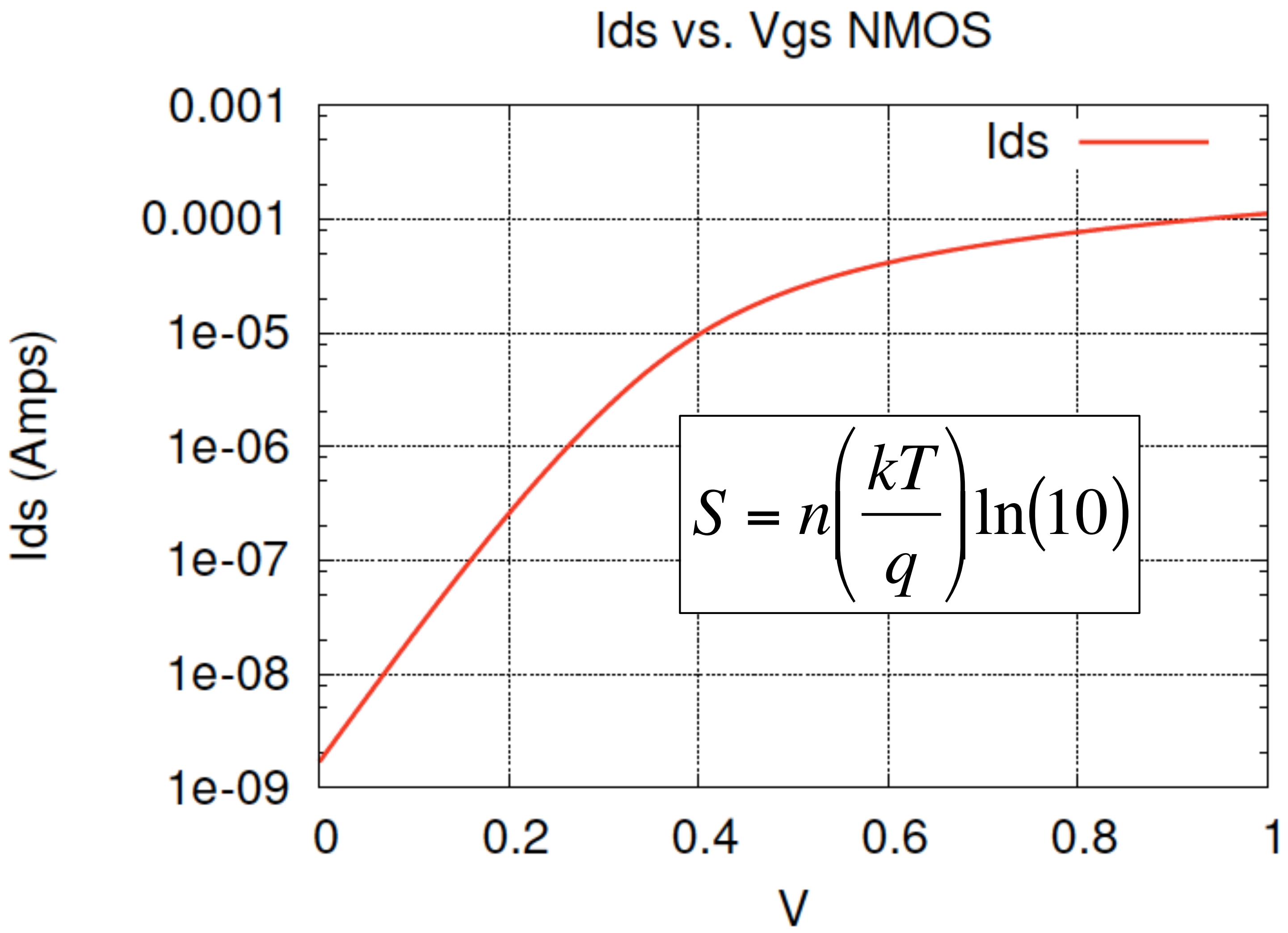


  - Units: V/decade
    - Every S Volts, I_{DS} is scaled by factor of 10

$$I_{DS} = I_S\left(\frac{W}{L}\right)e^{\left(\frac{V_{GS}-V_{th}}{nkT/q}\right)}$$

I_{DS} vs. V_{GS}





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

(Logscale)

Subthreshold Slope Factor

- Exponent in V_{GS} determines how steep the turnon is

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

  - Units: V/dec
  - Every S Volts, I_{DS} is scaled by factor of 10

- n – depends on parasitic capacitance divider

$$\boxed{n = \frac{C_{js} + C_{ox}}{C_{ox}}}$$

  - n=1 → S=60mV at Room Temp. (ideal)
  - n=1.5 → S=90mV
  - Single gate structure showing S=90-110mV

Subthreshold Slope Factor (Preclass 2)

- If S=100mV and V_{th}=300mV, what is Ids(Vgs=300mV)/Ids(Vgs=0V) ?
- What if S=60mV?

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

Velocity Saturation

Carrier Velocity

- Model assumes carrier velocity increases with field
  - Increases with voltage proportionally to mobility

$$v = \mu_n \cdot \frac{V_{DS}}{L_{eff}} = \left(\frac{\mu_n}{L_{eff}}\right) V_{DS}$$

Carrier Velocity

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$$v = \mu_n \cdot \frac{V_{DS}}{L_{eff}} = \left(\frac{\mu_n}{L_{eff}}\right) V_{DS}$$

($3\text{x}10^8$ m/sec)

Preclass 3

- (a) What is the electrical field in the channel?

$$L_{eff} = 25nm, V_{DS} = 1V$$

$$\text{Uniform Field} = \frac{V_{DS}}{L_{eff}}$$

- Velocity:

$$v = F \cdot \mu_n$$

- Electron mobility: $\mu_n = 500 cm^2 / (V \cdot s)$
- (b) What is the electron velocity?

Moving Charge

$$I = \left(\frac{1}{R}\right)V$$

- I increases
  linearly in V
- What's I?

Moving Charge

$$I = \left(\frac{1}{R}\right)V$$

- I increases

  linearly in V

- What's I?
  - ΔQ/Δt
  - Speed at which charge moves

Moving Charge

$$I = \left(\frac{1}{R}\right)V$$

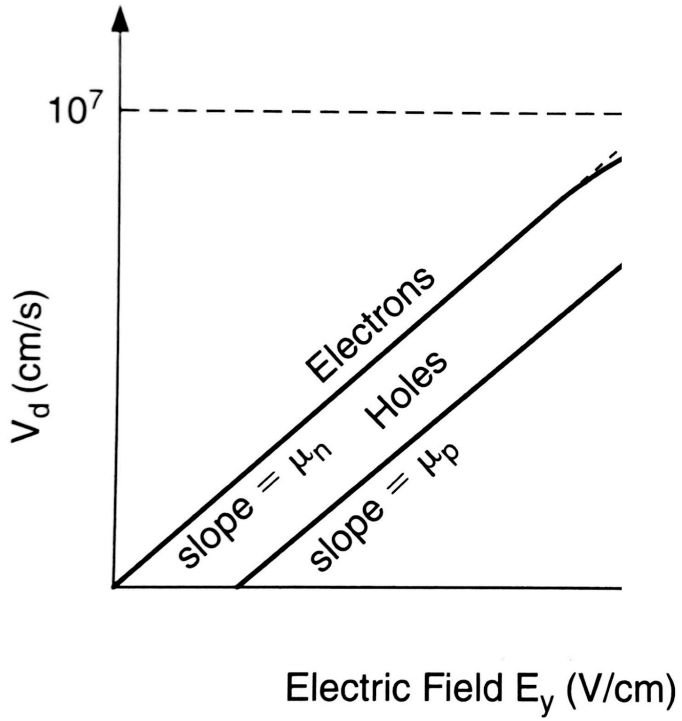
$$Field = \frac{V_{DS}}{L_{eff}}, v = \mu_n \cdot F$$

$$v = \mu_n \cdot \frac{V_{DS}}{L_{eff}} = \left(\frac{\mu_n}{L_{eff}}\right)V_{DS}$$

- I increases linearly in V
- What's I?
  - ΔQ/Δt
  - Speed at which charge moves

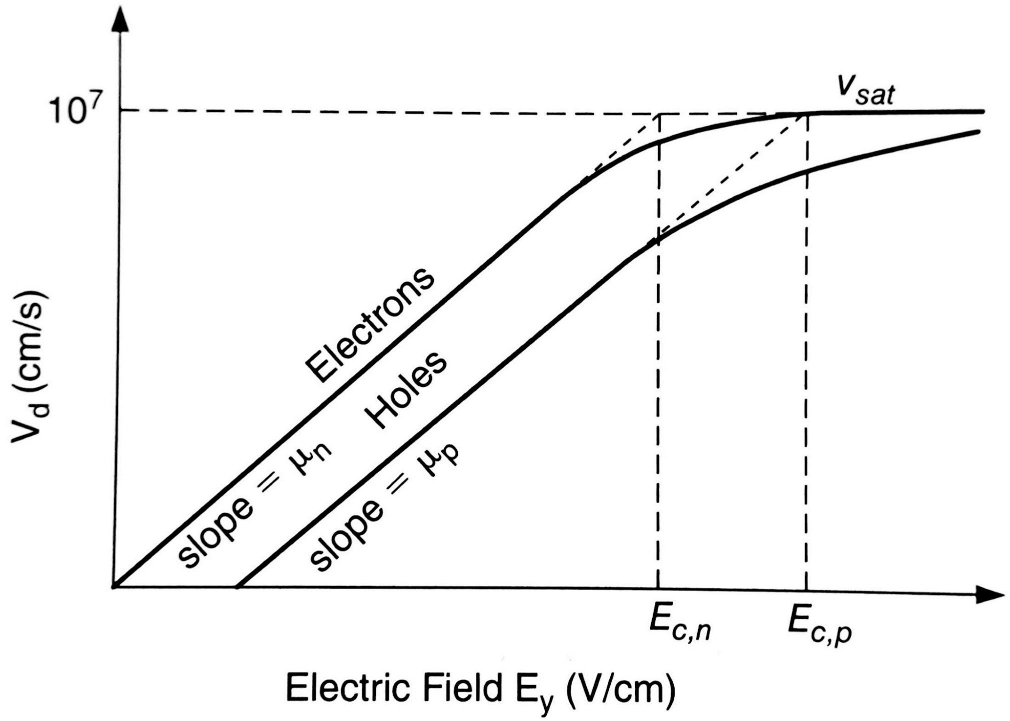
- Velocity increases linearly in V
- What's a moving electron?

Carrier Velocity



- Velocity –
  - increases for increasing field with slope of mobility

Carrier Velocity



- Velocity –
  - increases for increasing field with slope of mobility
  - saturates for increasing field
    - More likely to hit the critical field in short channel

Short Channel

- Model assumes carrier velocity increases with field
  - Increases with voltage proportionally to mobility
- There is a limit to how fast carriers can move
  - Limited by scattering effects
    - ~ 10^5m/s
- Encounter *velocity saturation* when channel short
  - Modern processes, L is short enough to reach this region of operation

Velocity Saturation (Preclass 3)

- (c) At what voltage do we hit the speed limit 10^5m/s?
  - L_{eff}=25nm, V_{ds}=1V
  - V_{DSAT} = voltage at which velocity (current) saturates

Velocity Saturation

- Our current model equation:

$$I_{DS} = \mu_n C_{OX} \left(\frac{W}{L}\right)\left[\left(V_{GS} - V_{th}\right)V_{DS} - \frac{V_{DS}^2}{2}\right]$$

- Once velocity saturates:

Velocity Saturation

- Our current model equation:

$$I_{DS} = \mu_n C_{OX}\left(\frac{W}{L}\right)\left[\left(V_{GS} - V_{th}\right)V_{DS} - \frac{V_{DS}^2}{2}\right]$$

- Once velocity saturates:

$$V_{DS} = V_{DSAT} \Rightarrow I_{DS} = \mu_n C_{OX}\left(\frac{W}{L}\right)\left[\left(V_{GS} - V_{th}\right)V_{DSAT} - \frac{V_{DSAT}^2}{2}\right]$$

Velocity Saturation

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$$I_{DS} = \left(\mu_n \frac{V_{DSAT}}{L}\right)C_{OX}W\left[\left(V_{GS} - V_{th}\right) - \frac{V_{DSAT}}{2}\right]$$

Velocity Saturation

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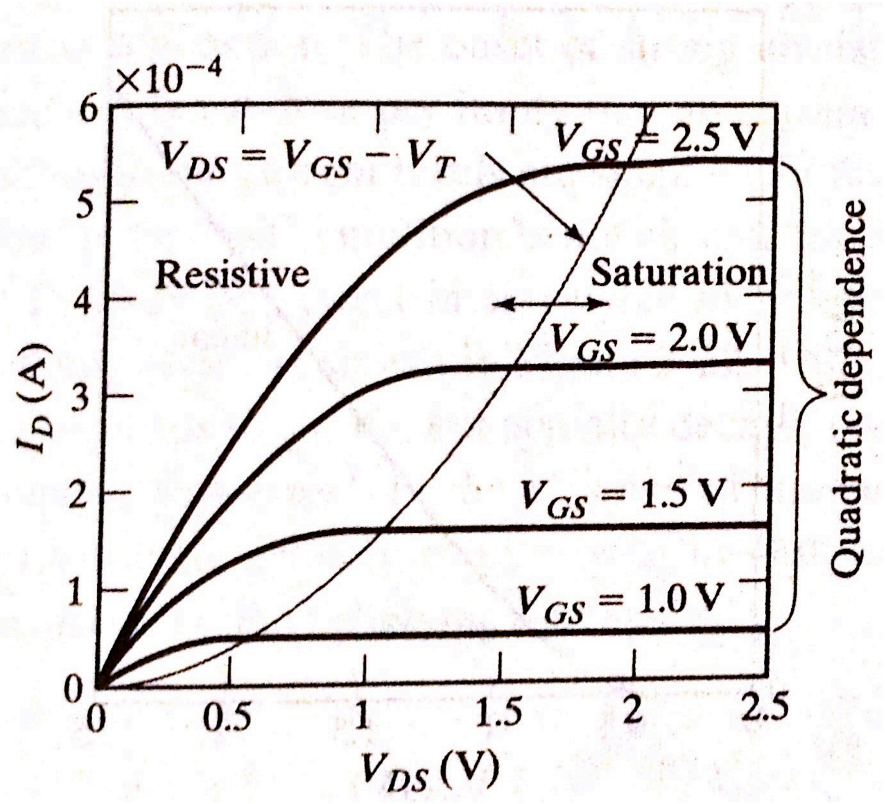
$$I_{DS} = \left(\mu_n \frac{V_{DSAT}}{L}\right)C_{OX}W\left[\left(V_{GS} - V_{th}\right) - \frac{V_{DSAT}}{2}\right]$$

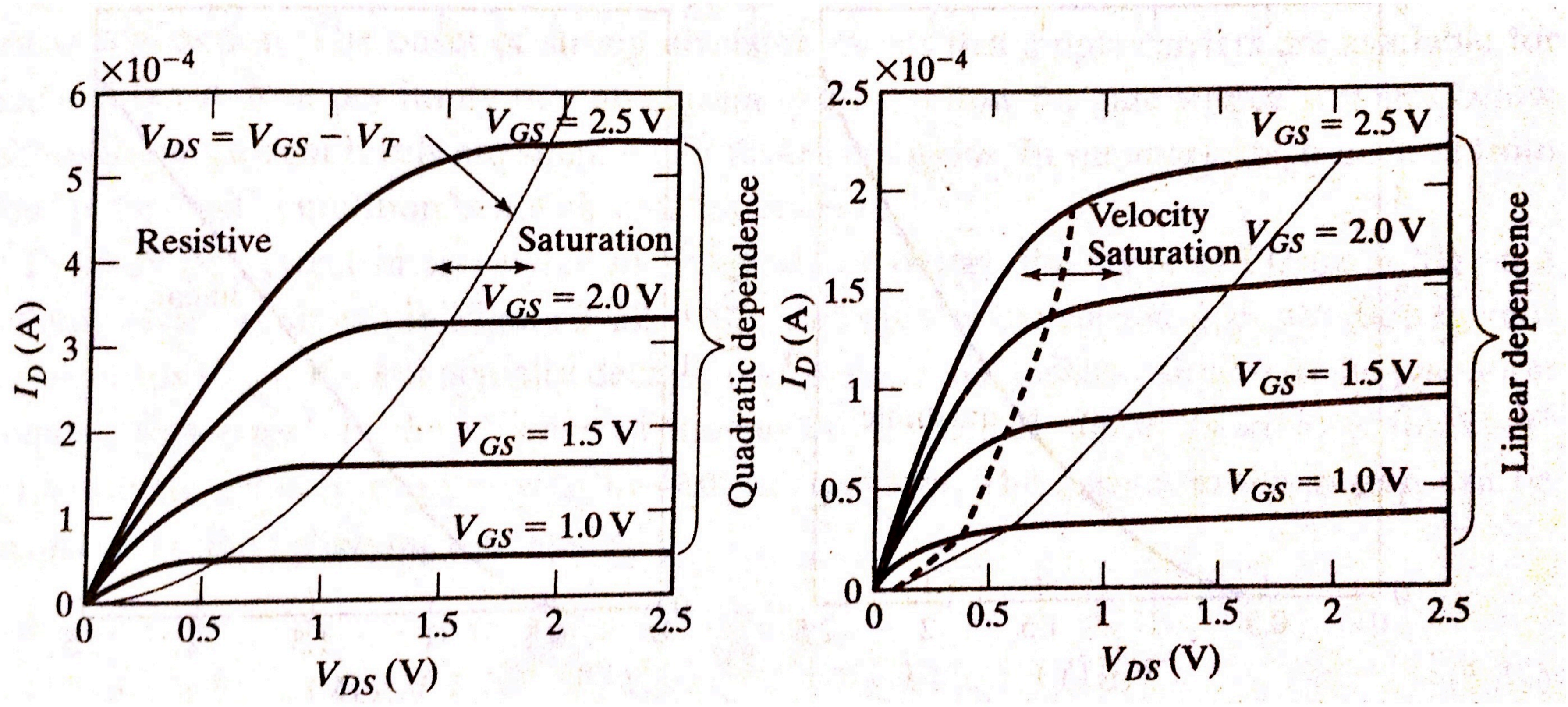
$$I_{DS} \approx v_{sat} C_{OX} W\left[\left(V_{GS} - V_{th}\right) - \frac{V_{DSAT}}{2}\right]$$

Velocity Saturation



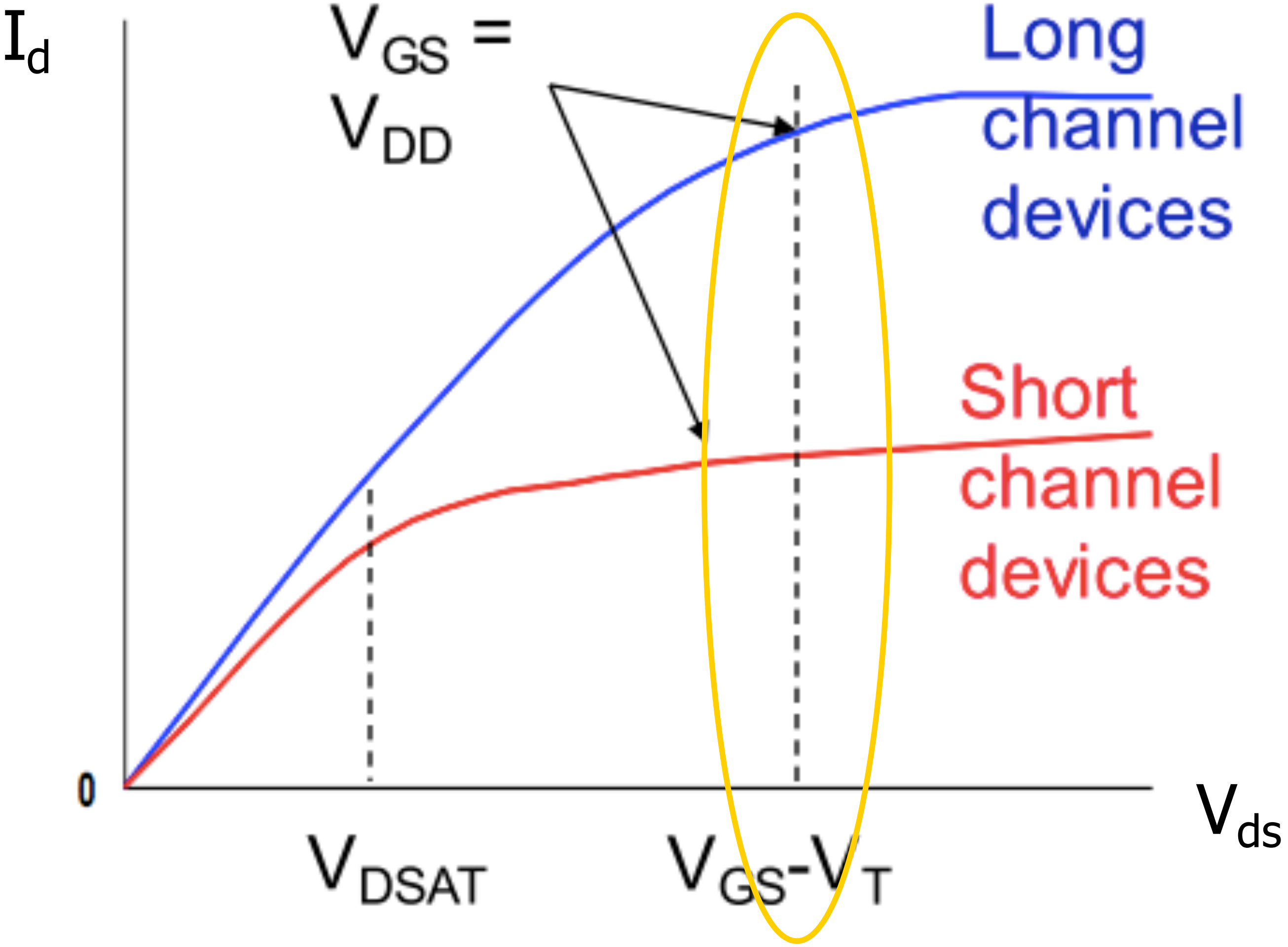
- Long Channel

Velocity Saturation



- ❑ Long Channel
- ❑ Short Channel

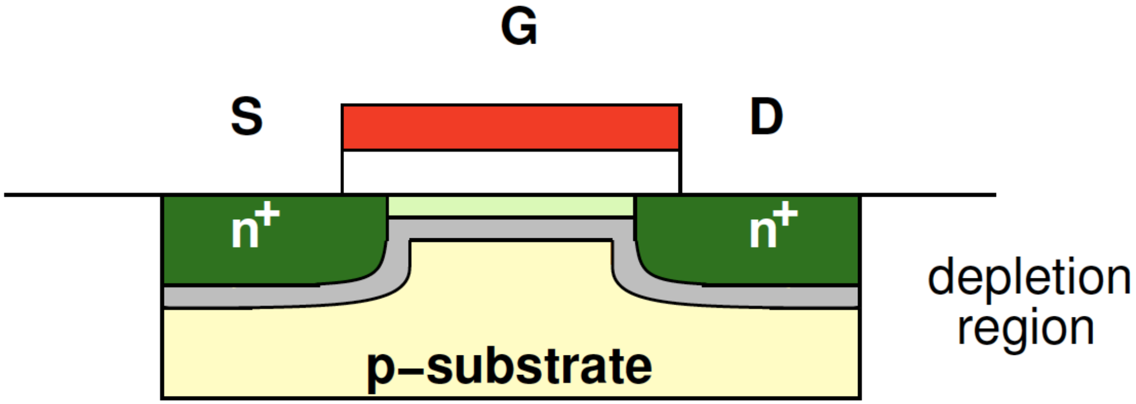
Velocity Saturation



Velocity Saturation

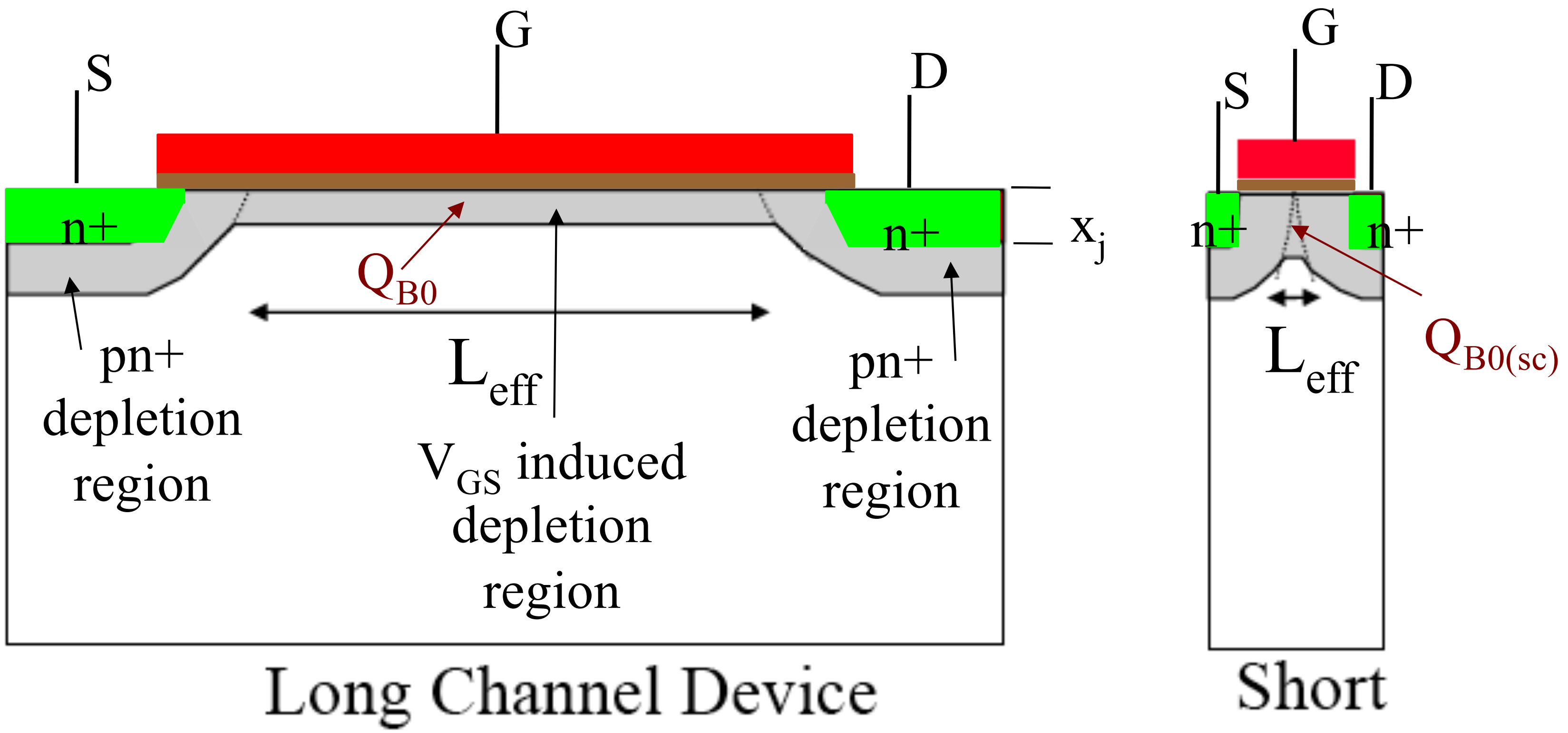
- Once velocity saturates we can still increase current with parallelism
  - Effectively make a wider device

$$I_{DS} \approx v_{sat} C_{OX} W \left[\left(V_{GS} - V_{th} \right) - \frac{V_{DSAT}}{2} \right]$$



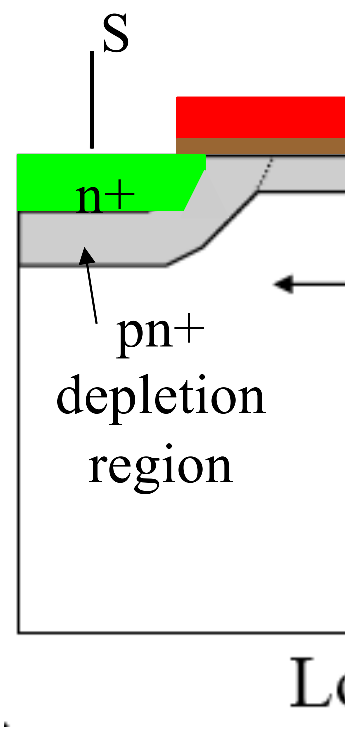
Threshold

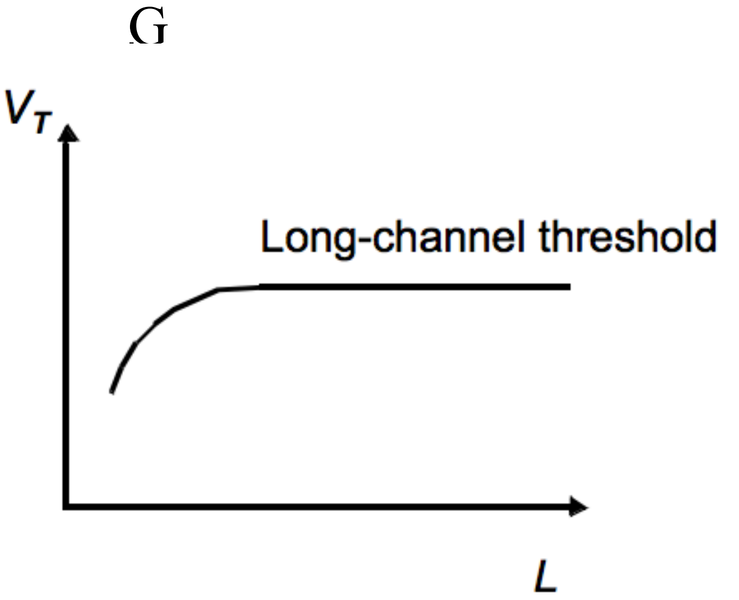
Short Channel Effects – V_T Reduction



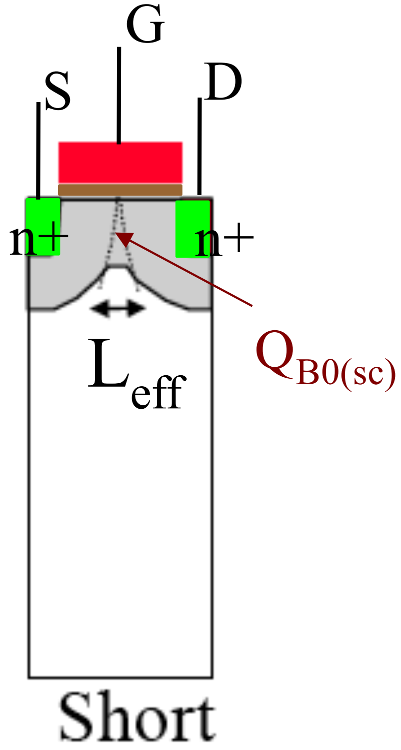
V_{T0} (short channel) = $V_{T0} - \Delta V_{T0}$

Short Channel Effects – V_T Reduction





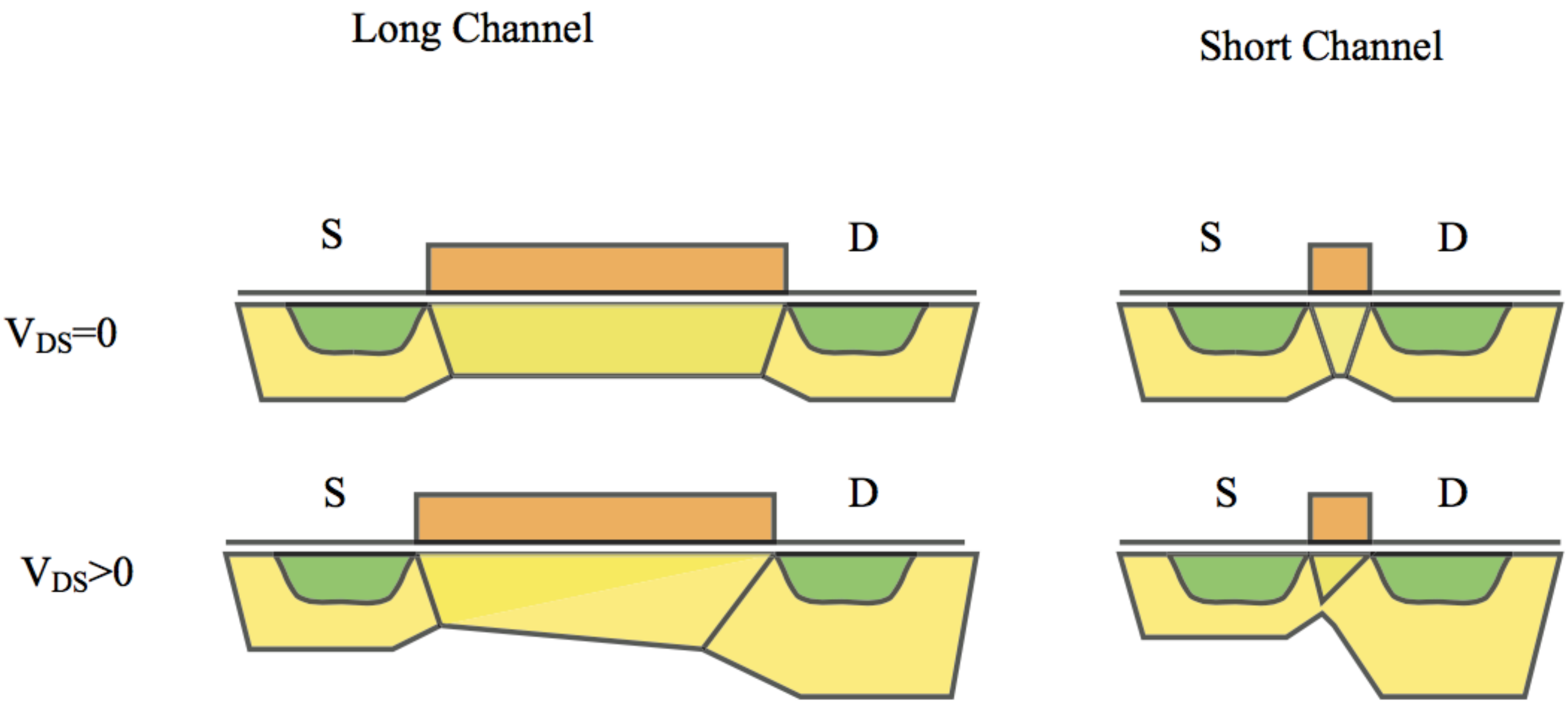
Threshold as a function of the length (for low V_{DS})



V_{T0} (short channel) $= V_{T0} - \Delta V_{T0}$

Short Channel Effects - DIBL

- Drain Induced Barrier Lowering
  - V_T Reduction with Drain Bias



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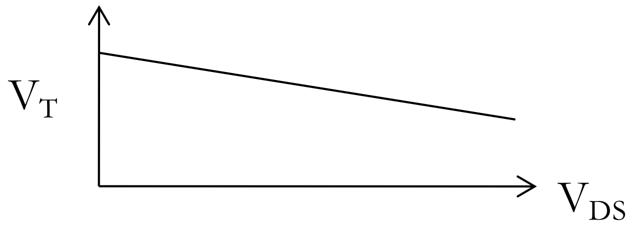
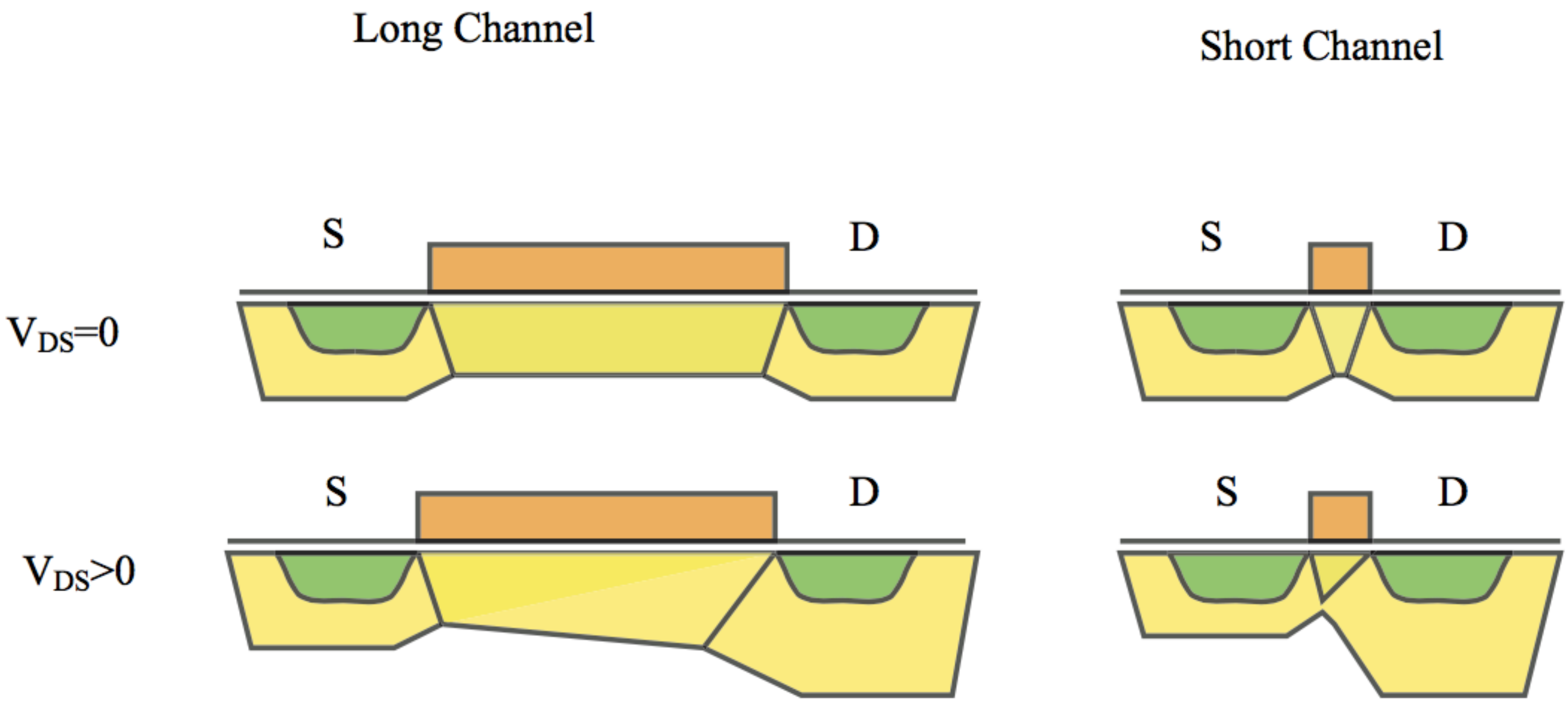
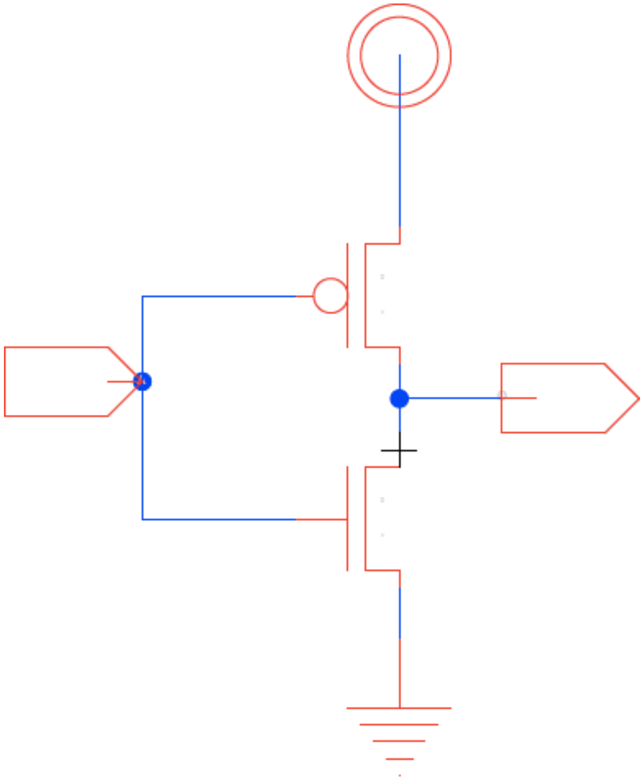




Threshold Reduction Impact

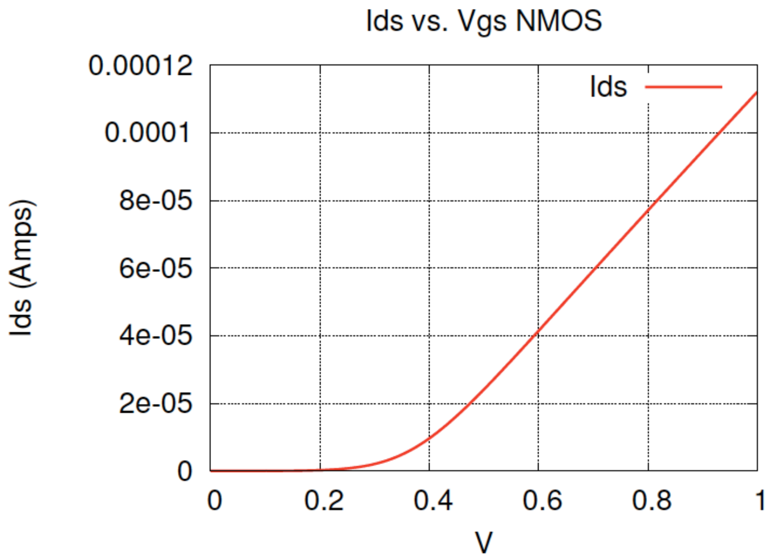
In a Gate?

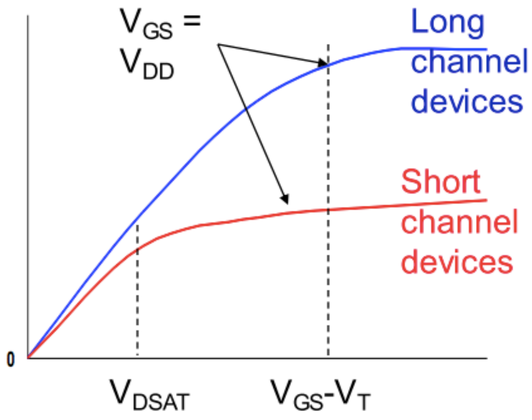
- What does it impact most?
  - Which device, has large V_{ds}?
  - How does this effect operation?
    - Speed of switching?
    - Leakage?

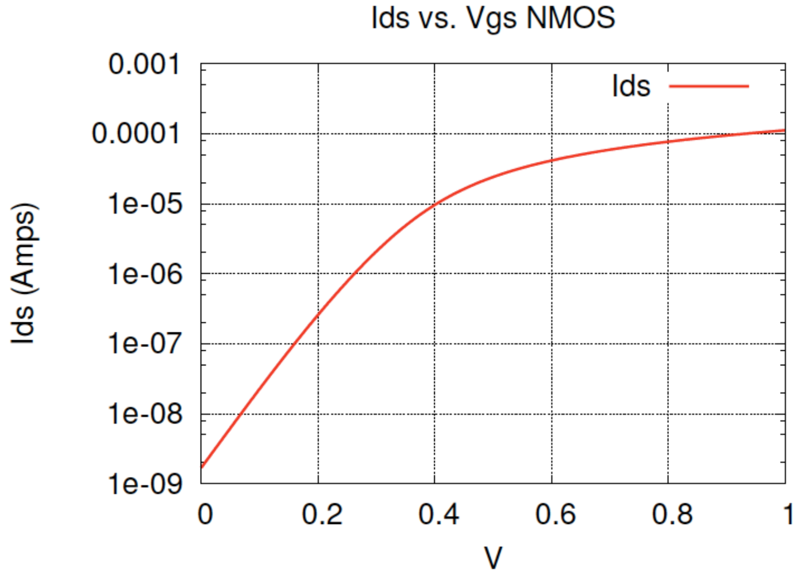


Big Idea

- 3+ Regions of operation for MOSFET
  - Subthreshold
  - Linear
  - Saturation
    - Pinch Off
  - Velocity Saturation, DIBL
    - Short channel







Admin

- HW3 due Monday
  - Takes time! Learning curve for how to debug
  - Don't forget the demo/video of SPICE workflow
- Midterm 1 Review session
- Midterm 1 Friday 10/1 (next week)
  - 7-9pm in Towne 309
  - No Lecture, virtual office hours
    - (use my OH link on Piazza)
  - Midterms from 2010-2019
    - All online with and without answers
    - Suggest start without answers
  - Conflicts must let me know ASAP