Electronic Devices and Analog Circuits

- Lecture 3
  - Diodes and LEDs
  - Semiconductors
  - MOSFETs

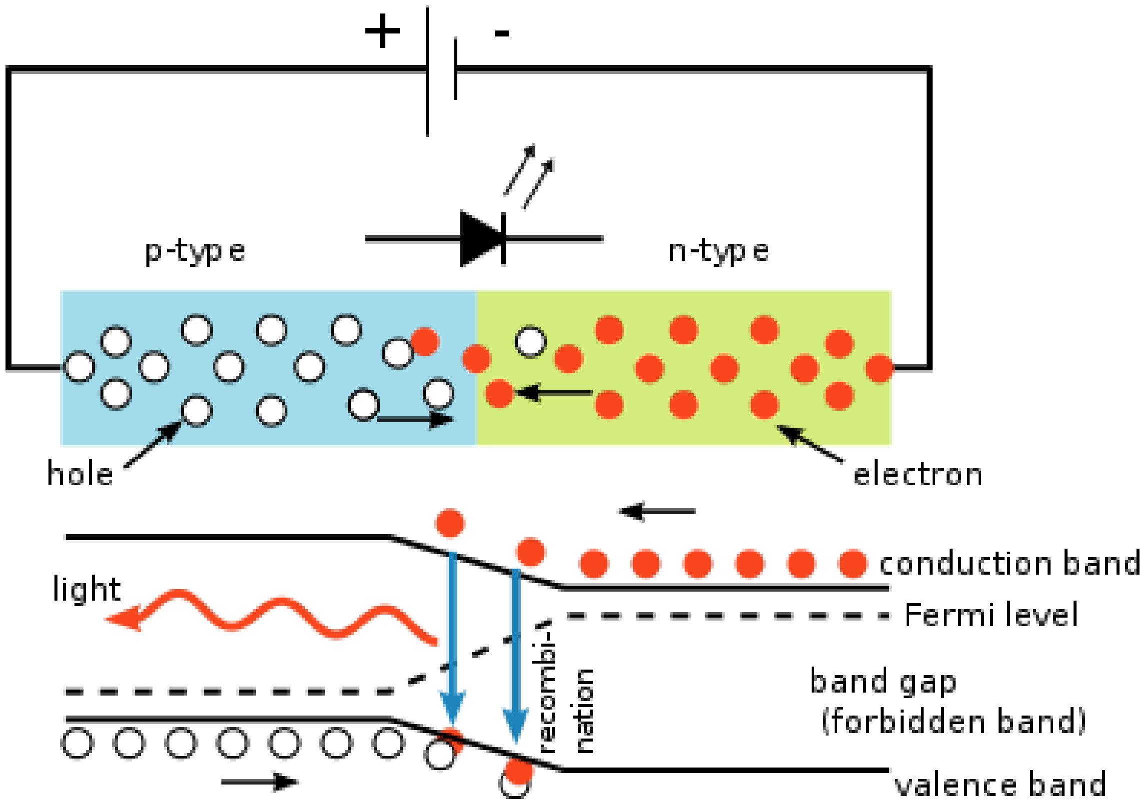
- Reading:
  - Sections 4.1-4.3
  - Sections 6.1-6.3, 7.1-7.3

Objectives of this Lecture

- Describe difference between linear and nonlinear circuit elements
- Introduce diodes and LEDs
  - Including models and how to use them
- Introduce MOSFETs
  - Just a start, since you'll see much more throughout the course
- Example diode problem

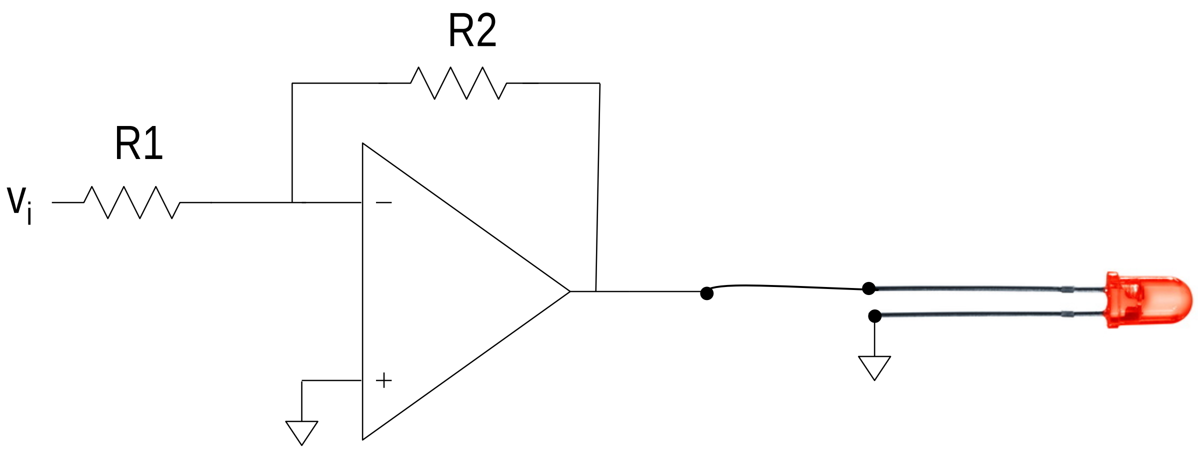
Semiconductor Diode

- Semiconductors can be P and N type
- The junction between P and N type silicon forms an energy barrier and creates a diode



Diodes and LEDs

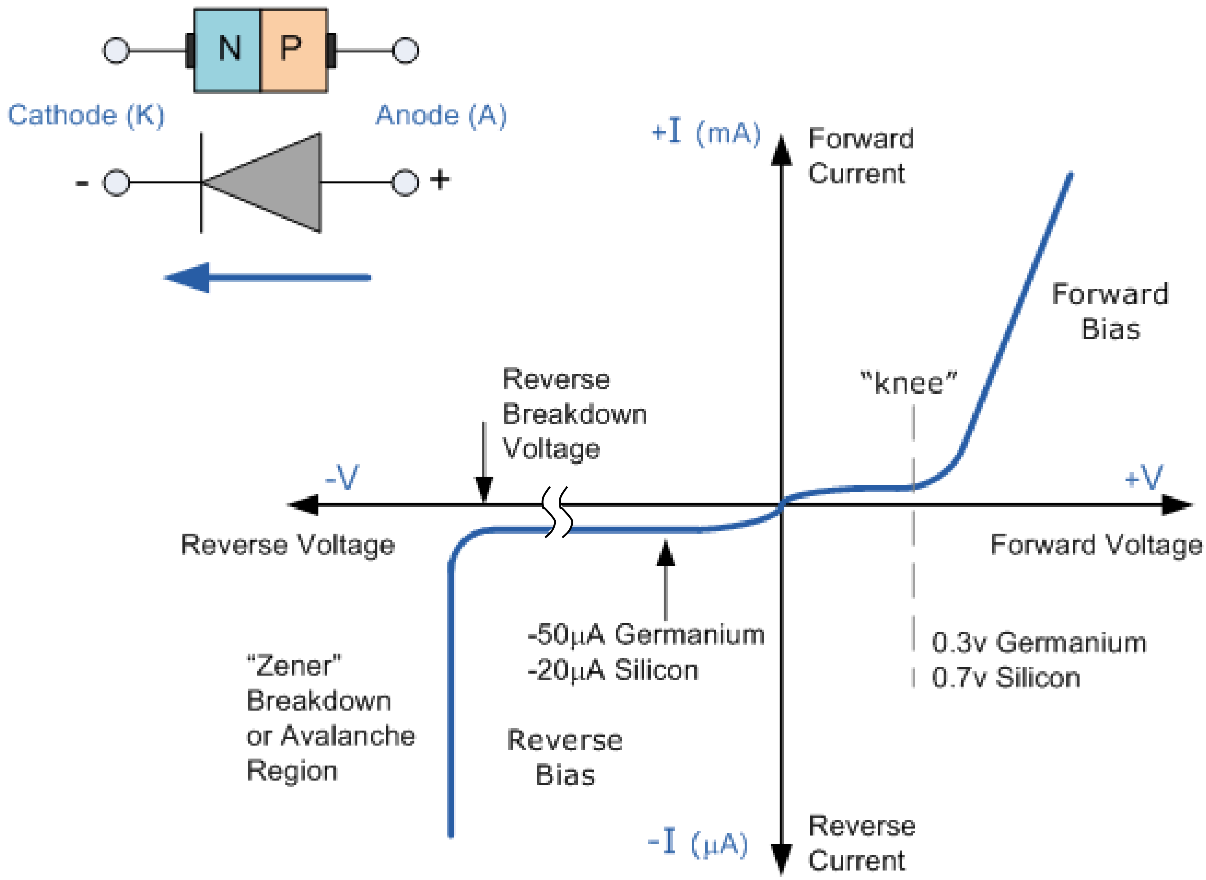
- We don't need to model all of the detailed physics to use diodes
- Just choose the modeling abstraction that is required for our design



- We have a model for the opamp
- Choose a model for the nonlinear LED based on how much precision we need

Diode Models

- Diodes are characterized by *nonlinear* behavior
- LEDs have the same I-V characteristic, but a diode model does not capture the photon emissions



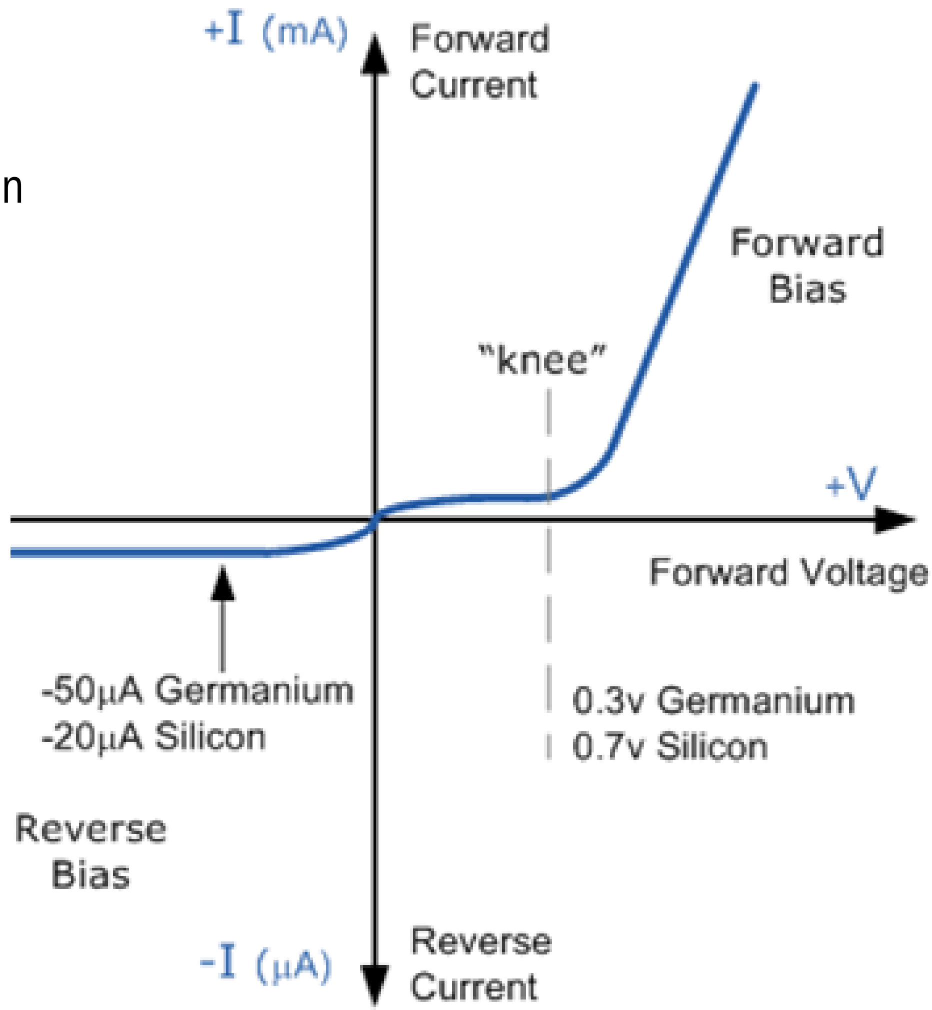
Diode Models

- Current-voltage relationship follows an *exponential* behavior in the *forward* bias range

$$i_D = I_S\left(e^{v_D / V_T} - 1\right)$$ Diode eqn

Forward current region

$$i_D \approx I_S e^{v_D / V_T} \qquad v_D > 0$$



Terminology Difference

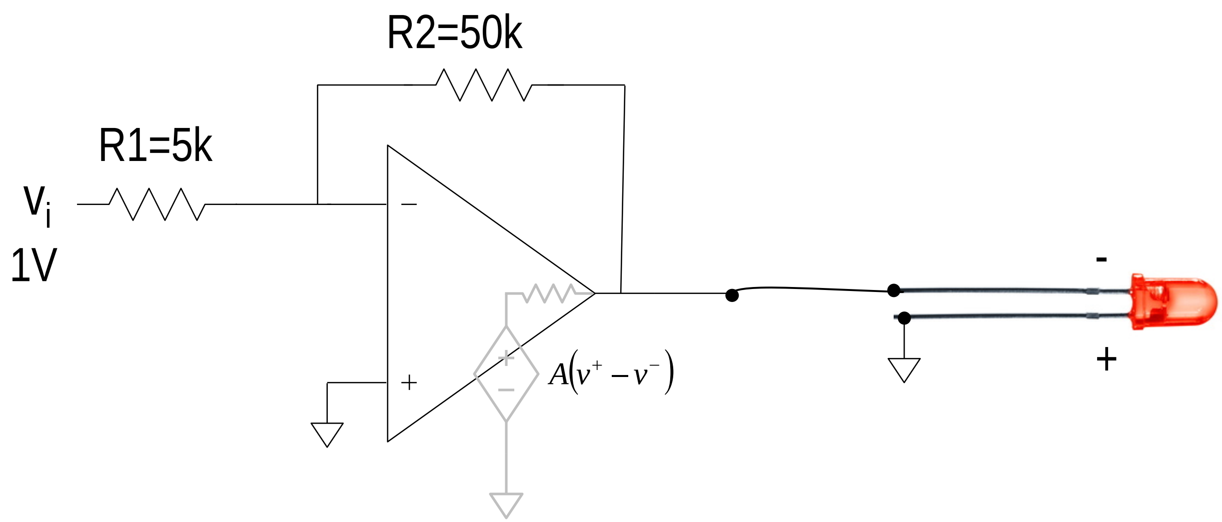
- Note that I am representing the thermal voltage as V_T
- The book refers to it as V_{TH}

$$i_D = I_S\left(e^{v_D/V_T} - 1\right) \qquad V_T = \frac{KT}{q}$$

- Relationship between current and potential voltage across a p-n junction depends on the thermal voltage
  - q is the charge on the electron – 1.602×10^{-19} C
  - k is Boltzmann's constant – 1.3806×10^{-23} J/K
  - At room temperature (≈ 300 K) the thermal voltage is ~26 mV

Diodes and LEDs

- If the opamp output resistance is really small, there is nothing to limit the diode current and voltage
- What would happen to it?

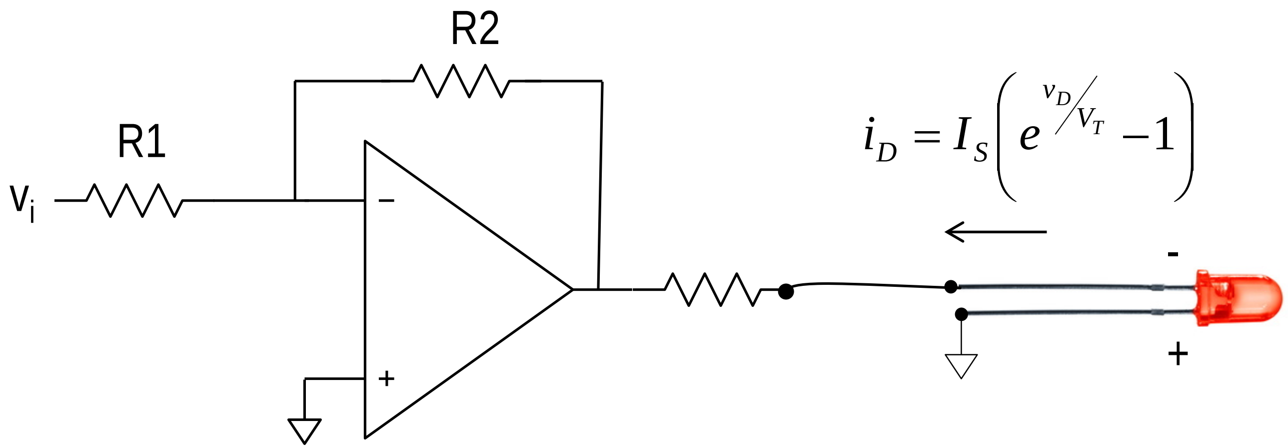


- For the nonideal opamp, v^- becomes whatever value it needs to be so that

$$-Av^- \approx 10v_i$$

Limiting Current

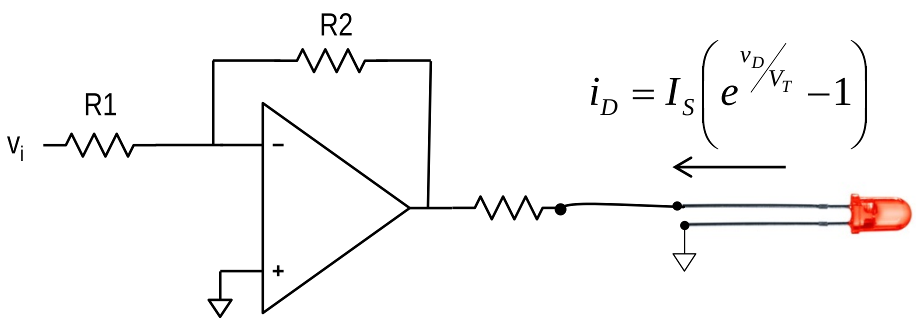
- In the lab we would want to add a series resistor to limit the current



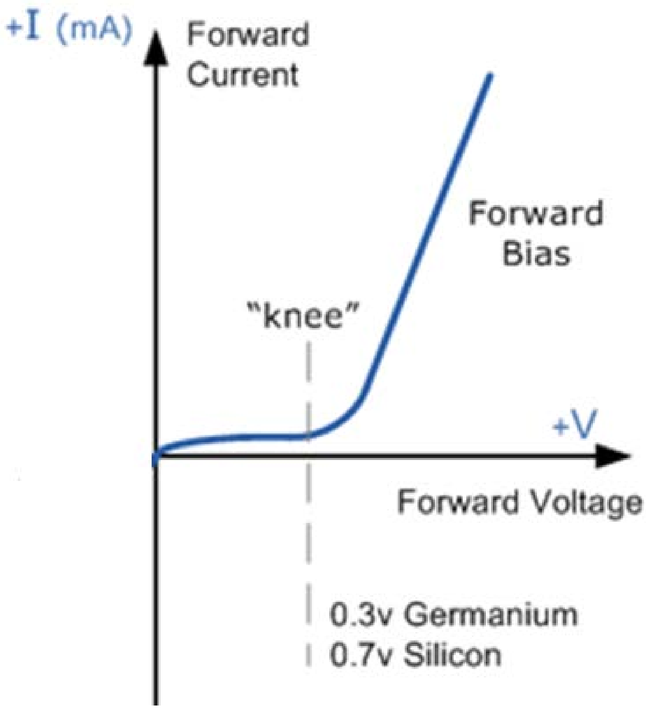
$$i_D = I_S\left(e^{v_D / V_T} - 1\right)$$

Engineering Approximations

- Can approximate the diode voltage as the "knee" voltage



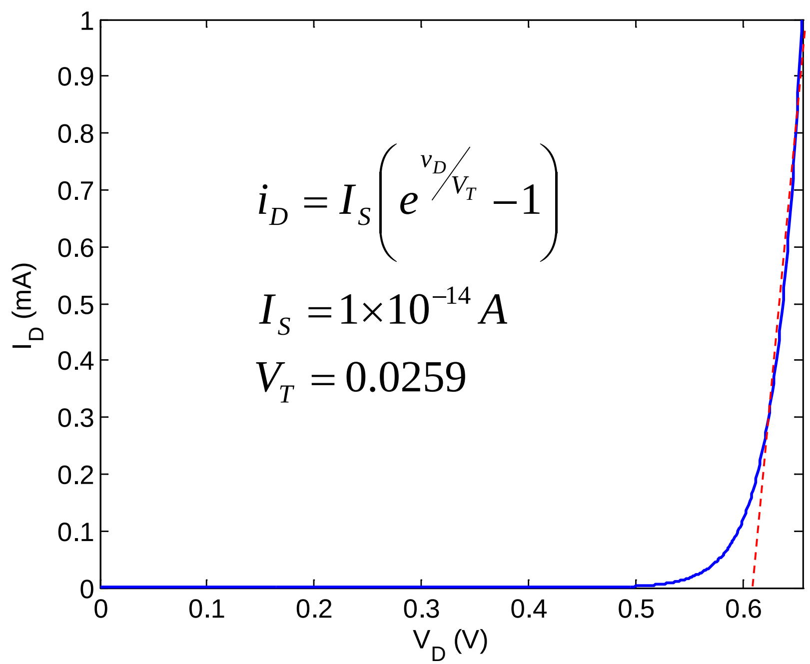
$$i_D = I_S\left(e^{v_D/V_T} - 1\right)$$

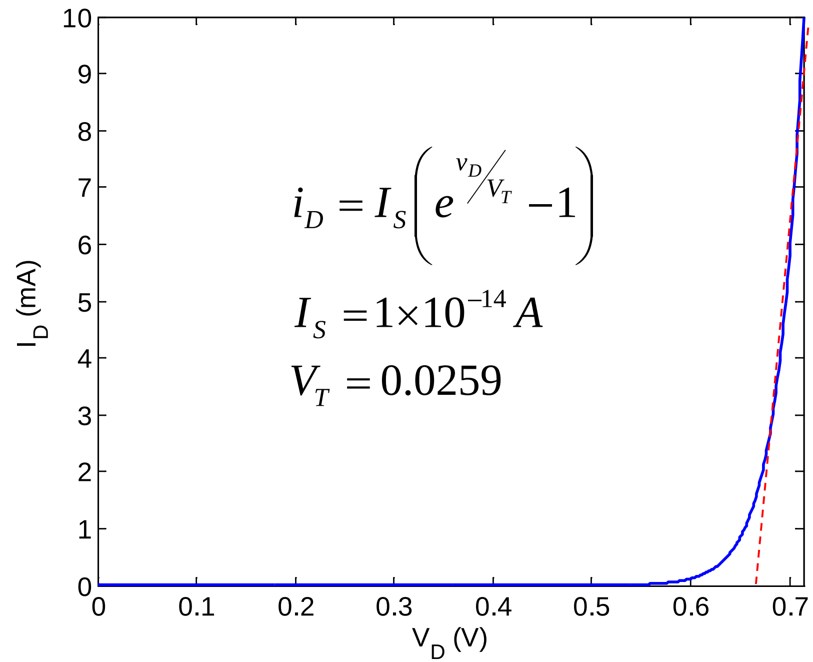


- NOTE: the value of the knee voltage depends on the *current range* for which you are using the diode

“Knee Voltage” or “On Voltage”

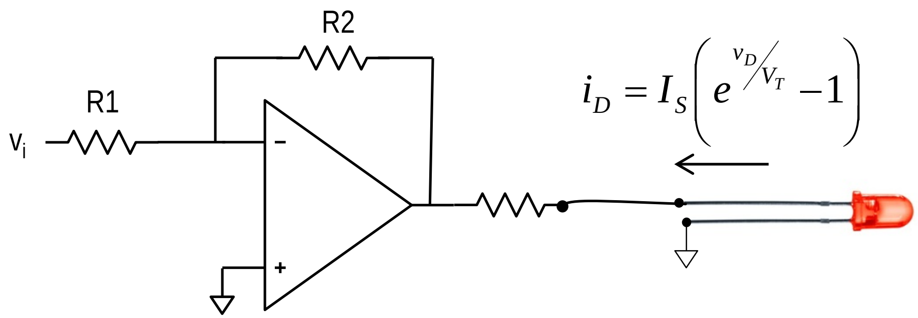
- Exponential function looks like the same shape when plotted over any current range
- Changing diode plot to cover a larger current range corresponds to a larger “knee voltage”



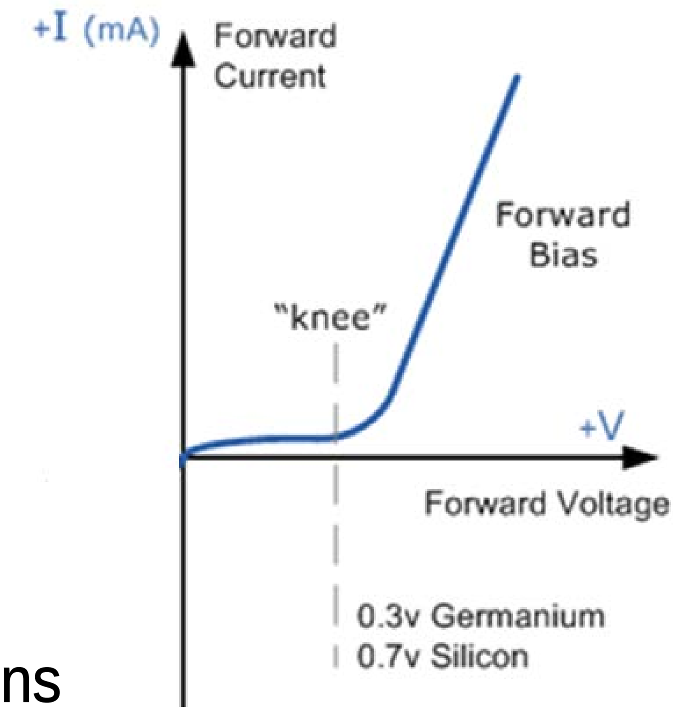


Engineering Approximations

- How do we solve nonlinear circuits?



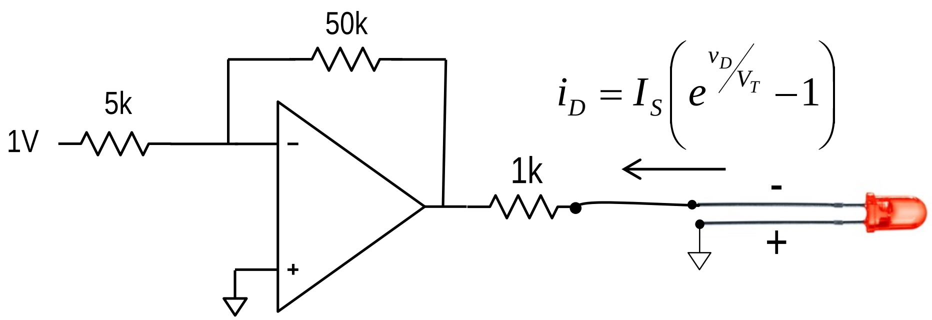
$$i_D = I_S\left(e^{v_D/V_T} - 1\right)$$



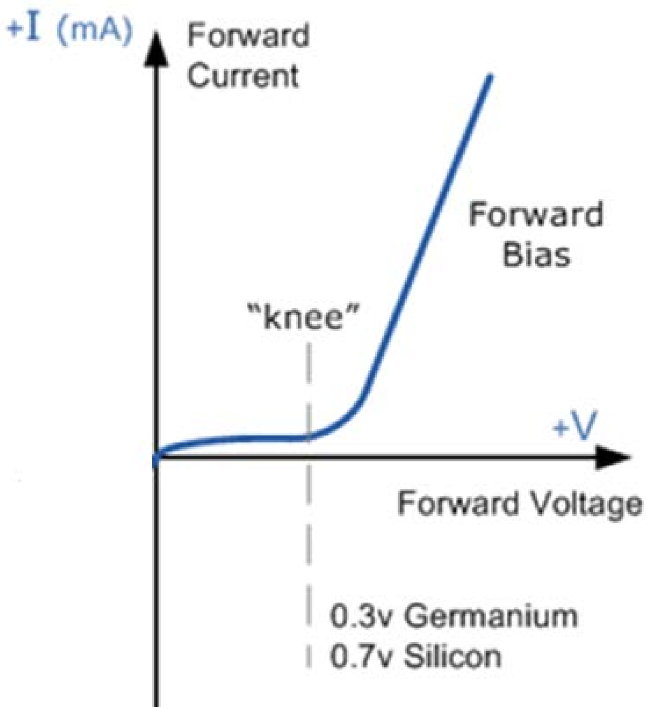
- Do we need to solve nonlinear equations for what we are trying to do?
  - Iterative solutions can be done as via Newton Method, etc.
  - Is our model precise enough to warrant that?
  - Does our design require such precision?

Engineering Approximations

- For our simple LED driver, does our design change significantly if the diode voltage is 0.6 or 0.7 volts?



$$i_D = I_S\left(e^{v_D/V_T} - 1\right)$$



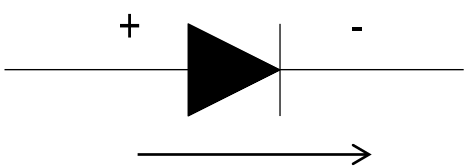
EXERCISE:

- Assume knee voltage is 0.7V, and solve for current
- Next do the same with a knee voltage of 0.6V and compare the values

Diode Model

- All diode models follow reference directions for current and voltage

$$i_D = I_S\left(e^{v_D/V_T} - 1\right)$$

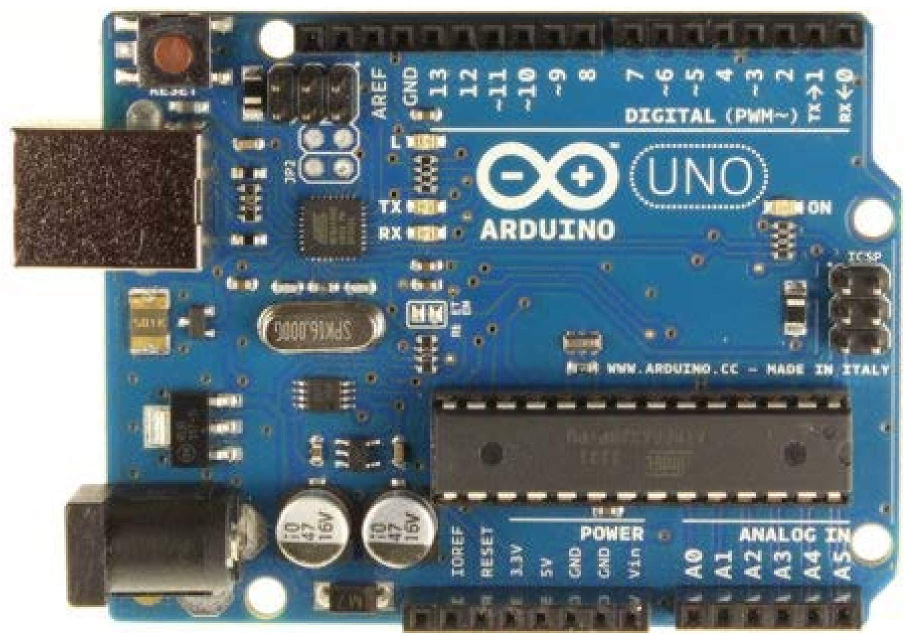


- They are *passive elements* that can only *dissipate or absorb power*
  - Voltage direction establishes current direction

- For an LED, the illumination intensity is proportional to I

Diodes

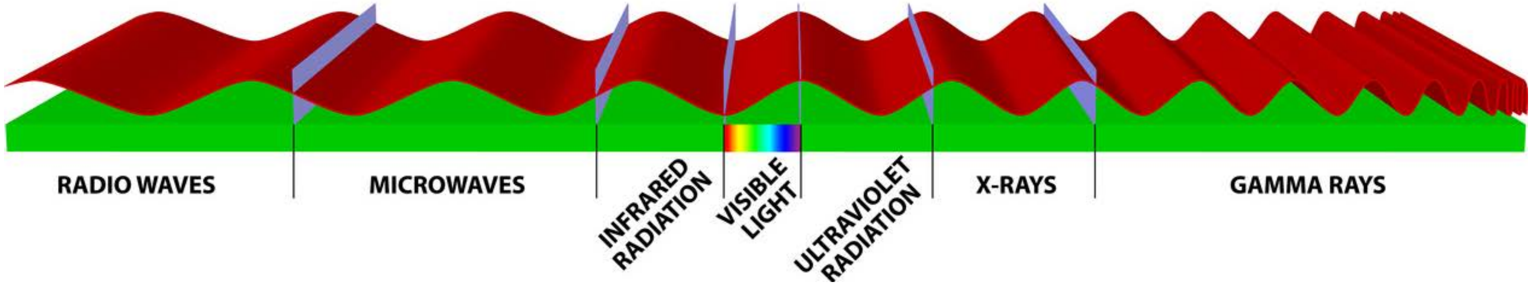
- In Lab 1 you will use an Arduino board and an IR diode to build a TV jammer remote controller



IR diode

Infrared Light

- Visible light
  - Wavelengths from ~390 to 750 nm, or 400–790 THz
- Ultraviolet (UV) light
  - Electromagnetic radiation with a wavelength shorter than that of visible light
  - 10 nm to 400 nm, 790 THz - 30 PHz
- Infrared (IR) light
  - Electromagnetic radiation with longer wavelengths than those of visible light
  - From the edge of the visible spectrum at 740 nm to 1 mm
  - ~300 GHz - 400 THz, and includes thermal radiation
  - Emitted or absorbed by molecules when they change their rotational-vibrational movements

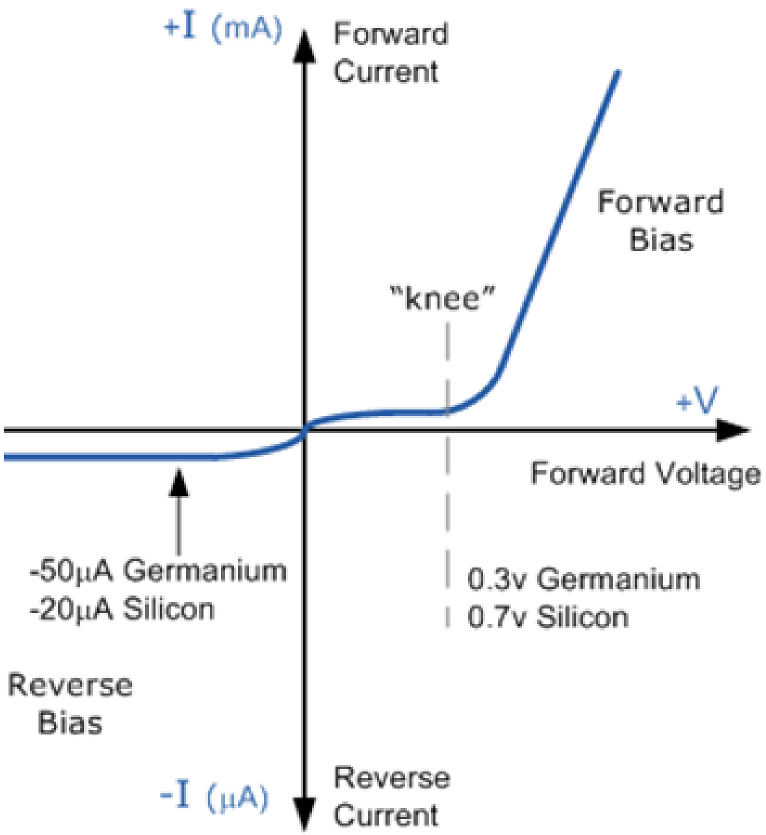


IR Light

- Human eyes have evolved to filter colors to see red, green and blue
  - Needed to recognize danger (poisonous plants), or human emotions (blushing), etc.
- Humans cannot see IR light due to our filtering, but we use IR cameras to see in the dark
- Some animals have adapted to be more sensitive to IR light
  - Pit vipers use it to detect warm bodies of prey
  - Some insects, such as moths and mosquitos are drawn to IR light

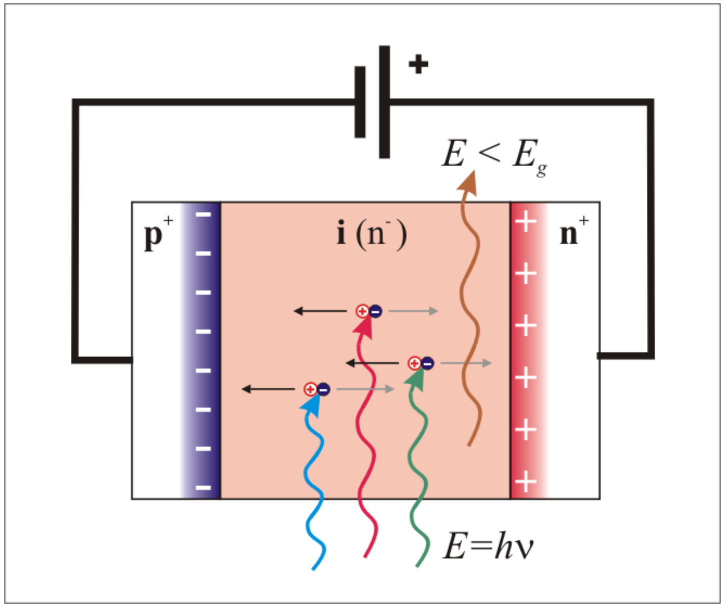
Photodiodes

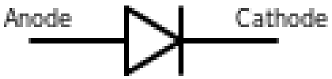
- Remote control transmits IR signals, and TV has an IR sensor to receive them
- Photodiodes work the same as IR LEDs – but in reverse
- IR diode is reverse-biased so that the electrons are swept out by a strong electric field
- Produces a small, but measurable current that can be converted to a voltage, amplified, filtered, etc.



Photodiodes

- Solar cells are large photodiodes
- Electrons freed when a photon with energy greater than or equal to bandgap strikes the photodiode
- PIN diode has an intrinsic lightly doped inner layer where light energy excites an electron and creates a free electron

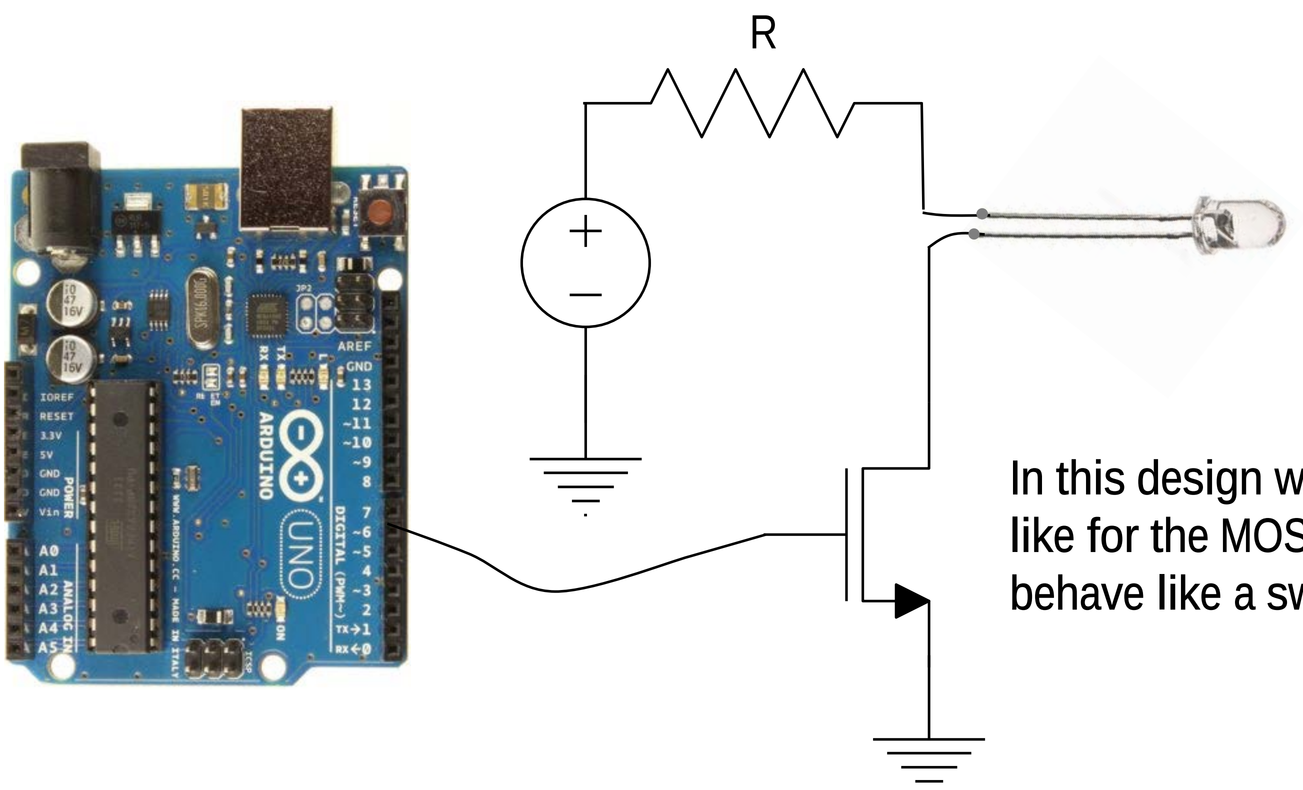




- You'll use photodiodes in some of the lab assignments

Lab 1

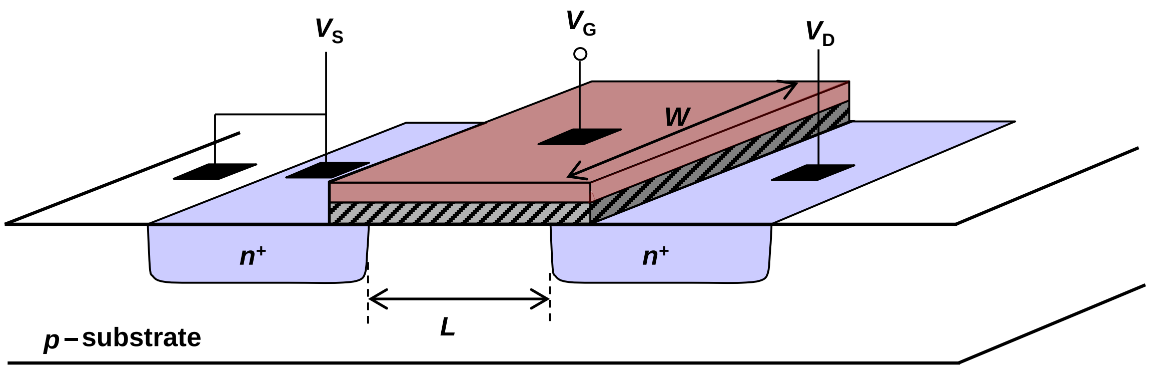
- Output drivers on Arduino provide limited current
- You are going to use MOSFETs to drive more current through the IR diode for longer range

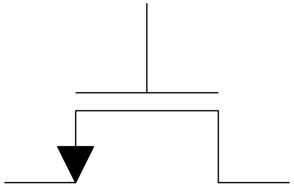


In this design we would like for the MOSFET to behave like a switch

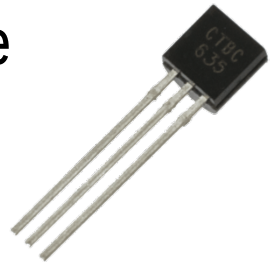
MOSFETs

- Transistors are more complex nonlinear models than diodes
- Three terminal MOSFETs are often used *when the substrate is connected to the source*



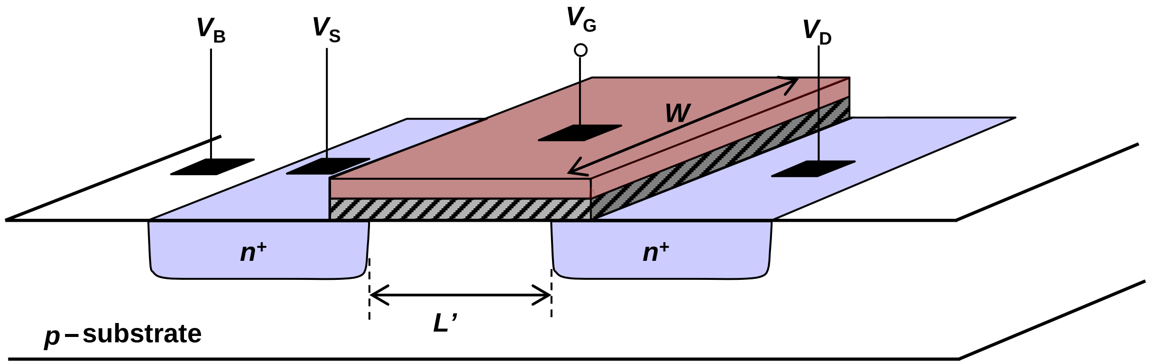


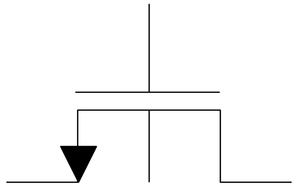
- Discrete transistor parts generally have source connected to bulk



Nonlinear Models

- But bulk substrate MOSFETs introduce a 4-th node in general

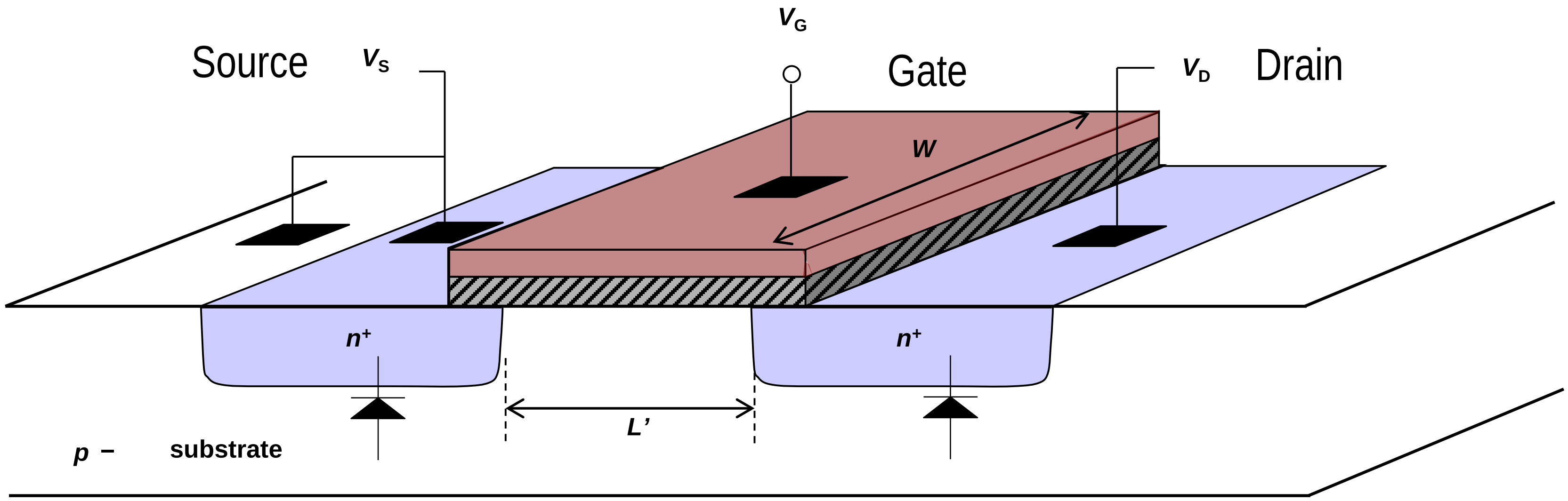




- Most integrated circuit transistors require you to properly configure all four terminals
- But modern Silicon on Insulator (SOI) transistors on an IC have no body connection since the substrate is a floating node

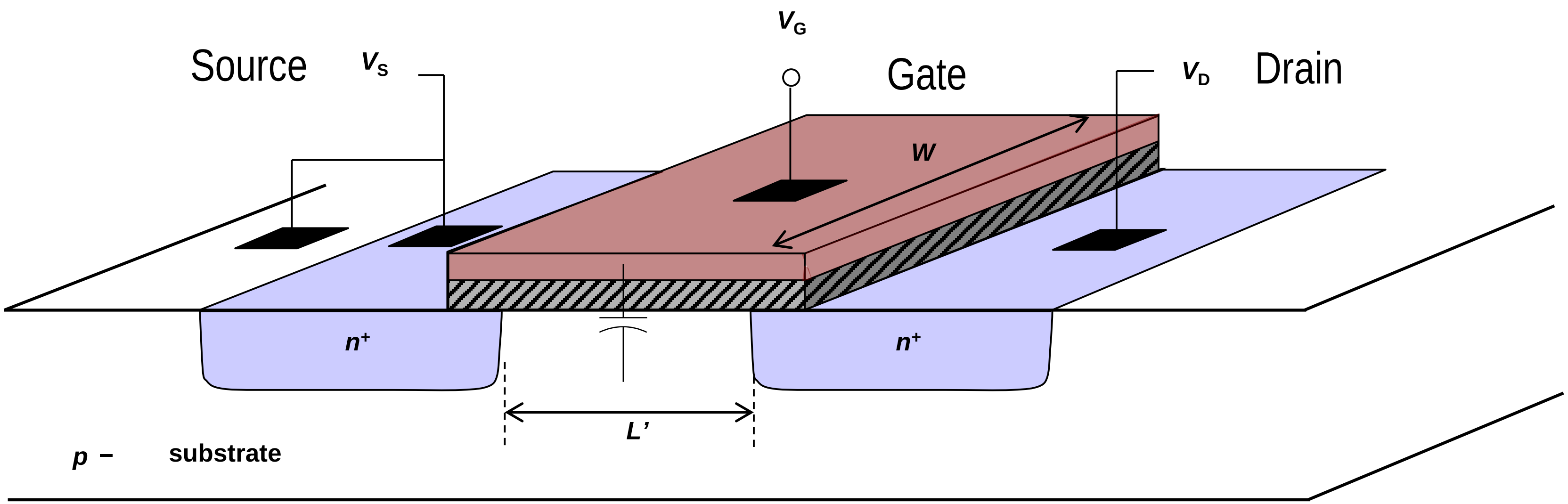
Brief Overview MOSFET Physics

- p-n junctions form unwanted diodes, so they must be biased to never become forward active (turn "on")



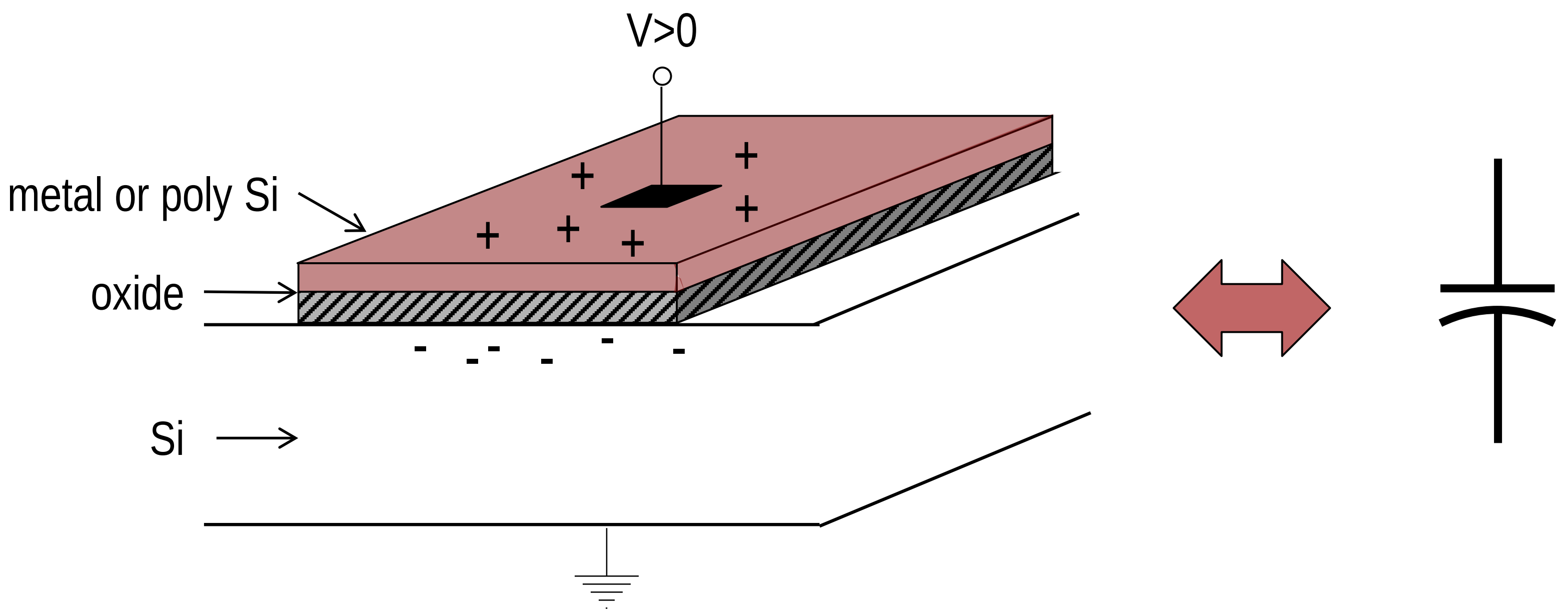
MOSFETs

- Electrical insulating layer between gate and channel creates a capacitor between gate and channel
- The channel is not an electrical node, but it is connected to the source and drain nodes



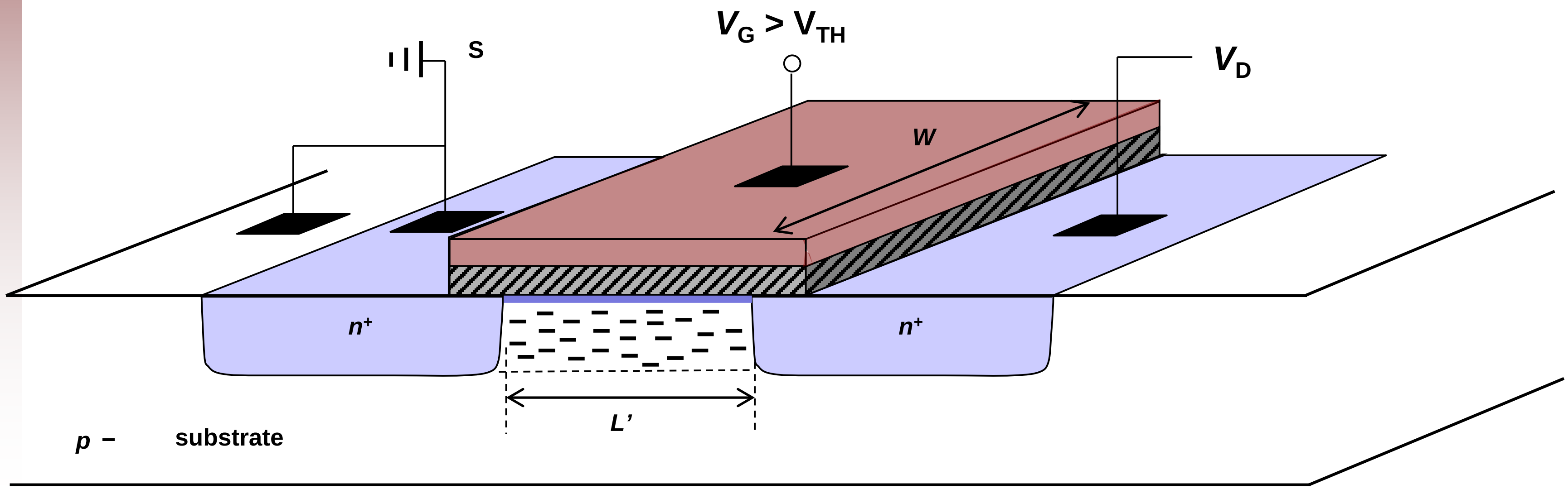
Capacitance

- Physics II will cover parallel plate capacitance



MOSFETs

- After the gate voltage exceeds the threshold voltage, the negative charge in the channel forms a conducting layer



- Current now flows from drain (higher voltage) to source
- Or, electrons flow from source and end up in drain
- Channel forms a resistance between drain and source

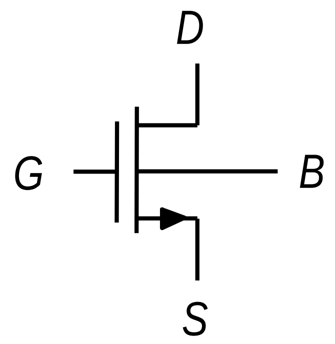
MOSFET Abstraction

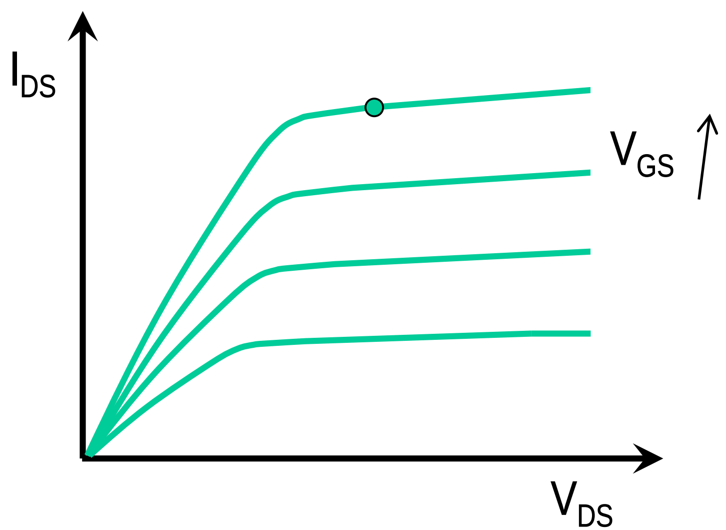
$I_D \cong 0$ cutoff : $V_{GS} < V_{TH}$ Subthreshold (leakage) current

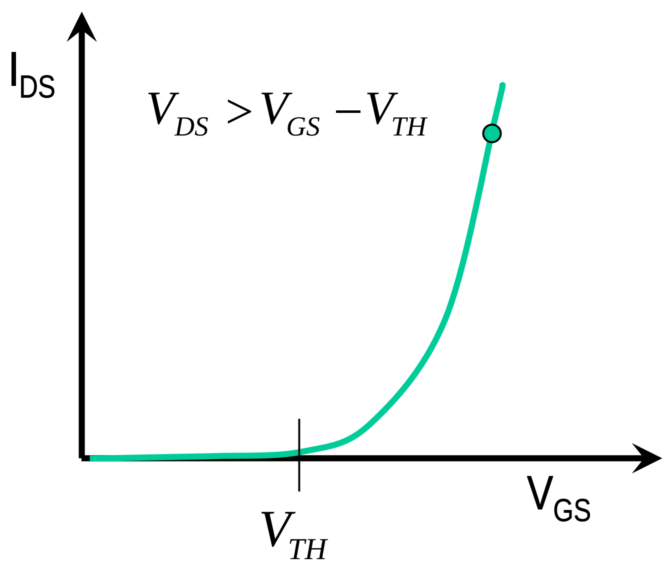
$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L'}(V_{GS} - V_{TH})^2 \quad \text{saturation} : V_{DS} > V_{GS} - V_{TH}$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L'}\left[2(V_{GS} - V_{TH})V_{DS} - V_{DS}{}^2\right] \quad \text{triode} : V_{DS} < V_{GS} - V_{TH}$$

$$\text{where} \quad V_{TH} = V_{TH0} + \gamma\left(\sqrt{2\phi_F - V_{BS}} - \sqrt{2\phi_F}\right)$$

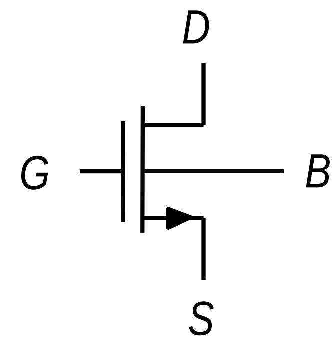


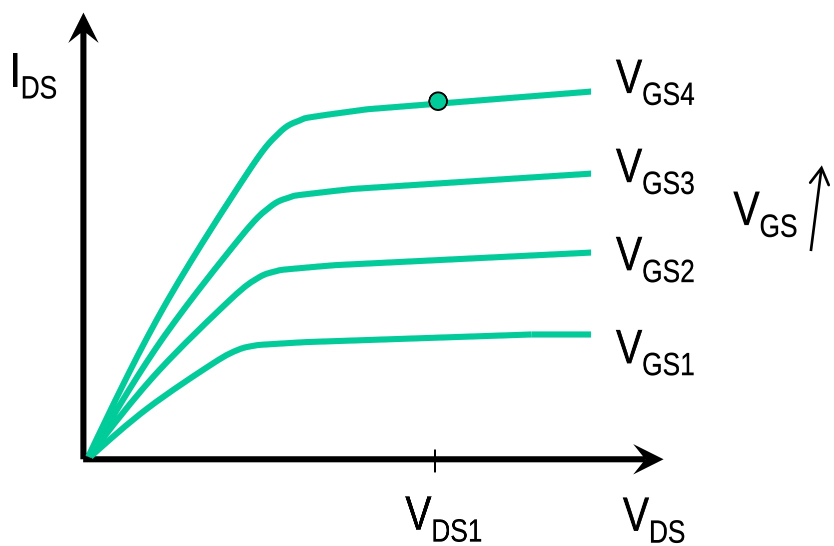


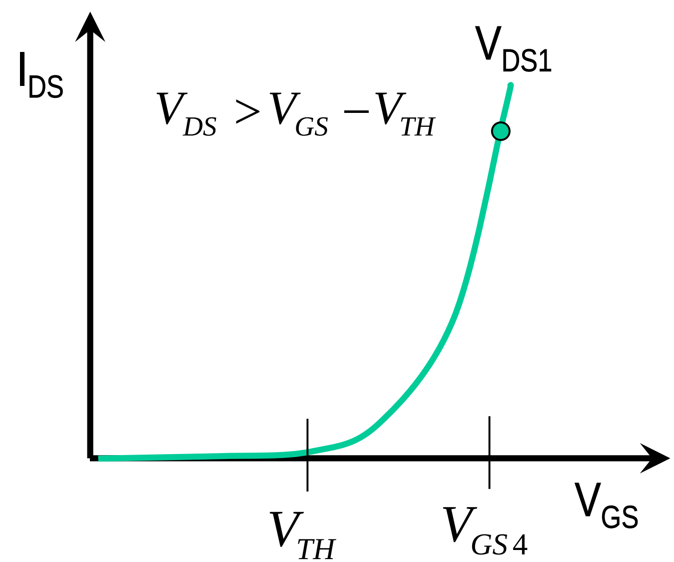


MOSFET Voltages

- Note that voltages are *between* two nodes
- Gate voltage (relative to the source) controls the current flow in the channel (turns on/off)
- Source and Drain nodes are defined by voltages
- MOSFET turns "on" when V_{GS} exceeds threshold voltage



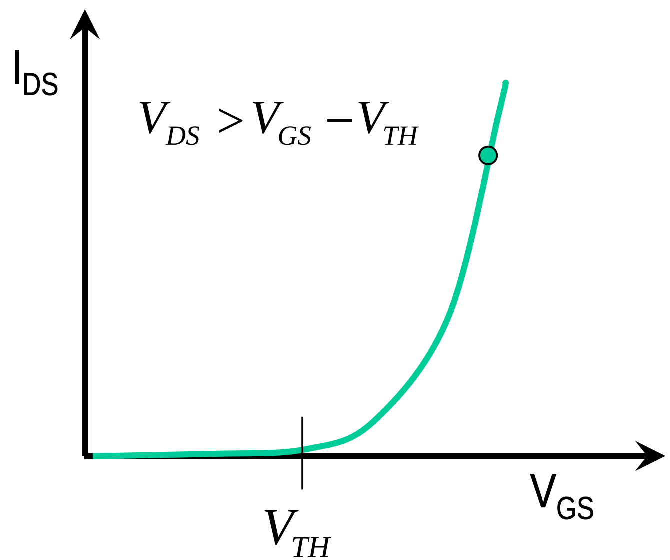




Terminology Difference

- Note that I am representing the threshold voltage as V_{TH}
- The book refers to it as V_T

- It represents the gate-to-source voltage for which the channel becomes strongly conducting



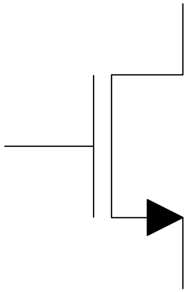
MOSFET Equations

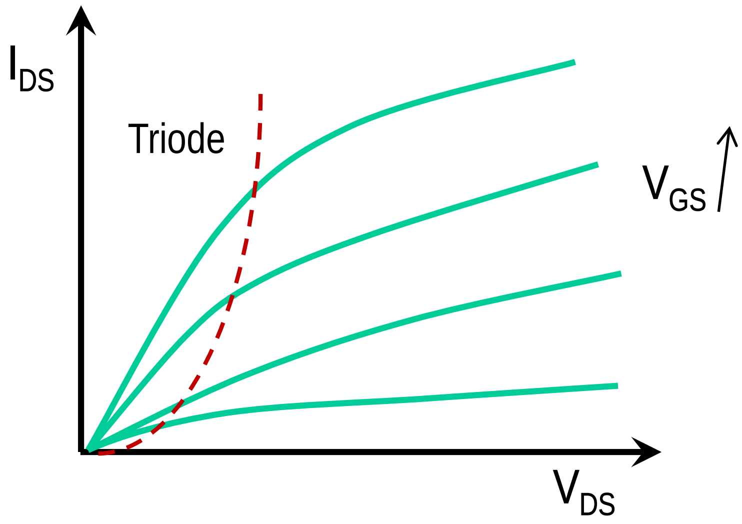
- MOSFET channel is a nonlinear resistance

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

$$I_D = \frac{K}{2}\left[2(V_{GS} - V_{TH})V_{DS} - V_{DS}{}^2\right]$$

$$K = \mu_n C_{ox} \frac{W}{L'}$$



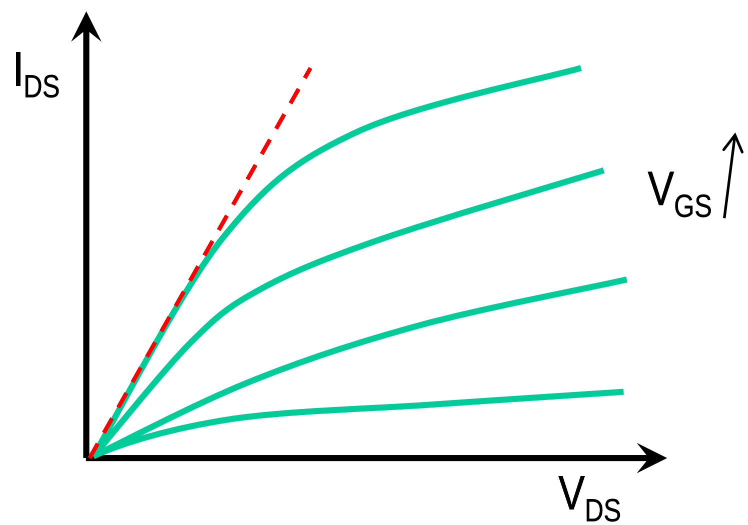


Linear or Triode Region of Operation

- For small drain to source voltage the MOSFET channel behaves like a voltage controlled resistor

Triode or linear region:

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L'}\left[2(V_{GS}-V_{TH})V_{DS}-V_{DS}^{\ 2}\right] \approx \frac{1}{2}\mu_n C_{ox}\frac{W}{L'}\left[2(V_{GS}-V_{TH})\right]\cdot V_{DS}$$



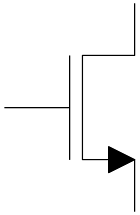
MOSFET Equations

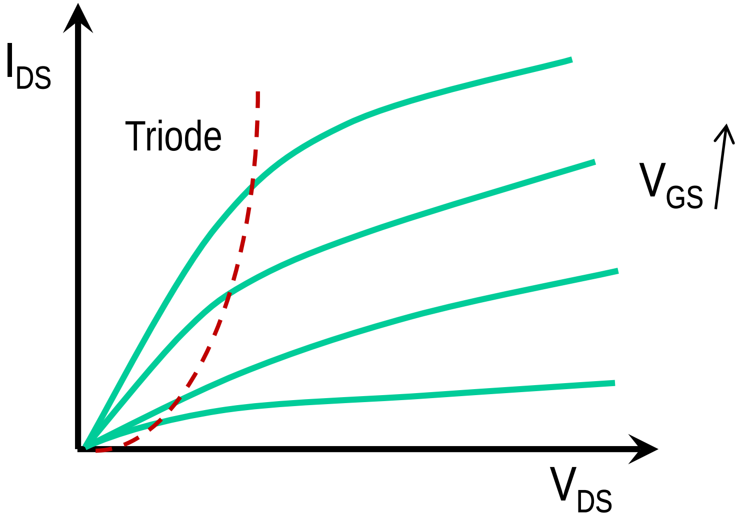
- For small V_{DS} the controlled resistance is almost linear

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

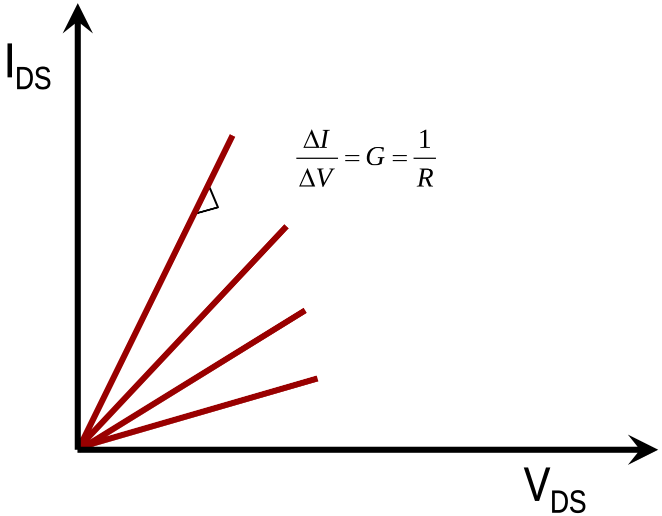
$$I_D = \frac{K}{2}\left[2(V_{GS} - V_{TH})V_{DS} - V_{DS}^{\,2}\right]$$

$$K = \mu_n C_{ox}\frac{W}{L'}$$



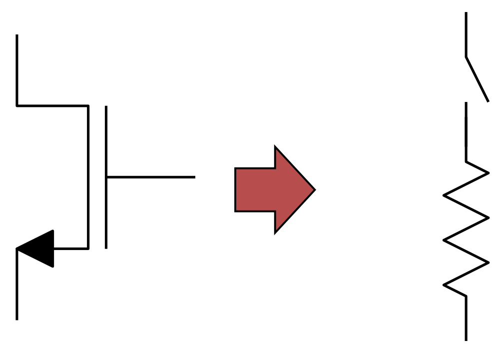


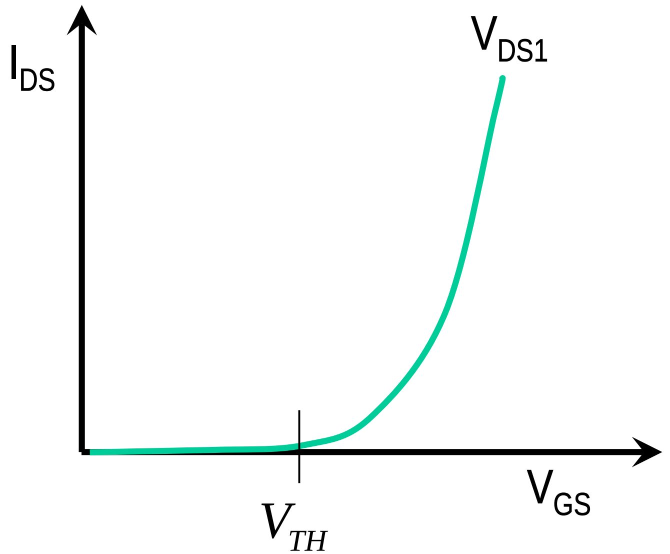
$$G \approx fct(V_{GS})$$



MOSFET Switches

- For digital applications we often model the transistor as a switch
- But it only behaves like a switched resistance if the drain-to-source voltage is very small





$$I_D \cong 0 \quad \text{cutoff for } V_{GS} < V_{TH}$$

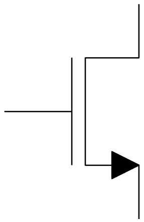
MOSFET Saturation

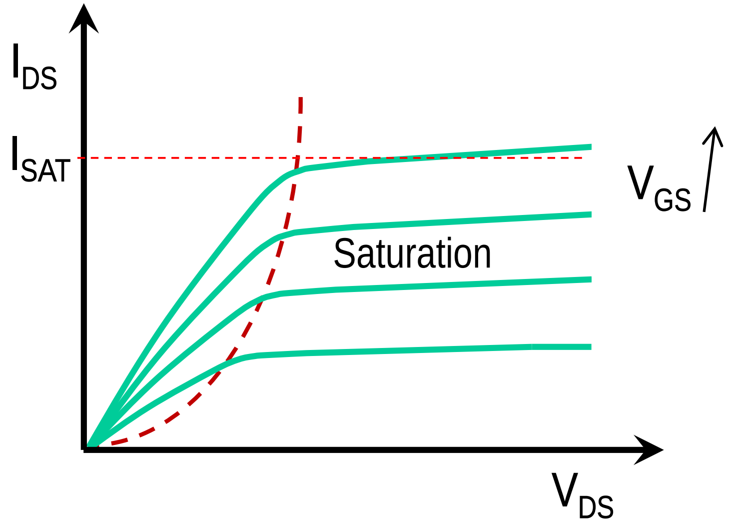
- The current *saturates* at a maximum value for each value of gate voltage
- MOSFET now behaves like a voltage-controlled current source

Saturation region:

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

$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L'}(V_{GS} - V_{TH})^2$$



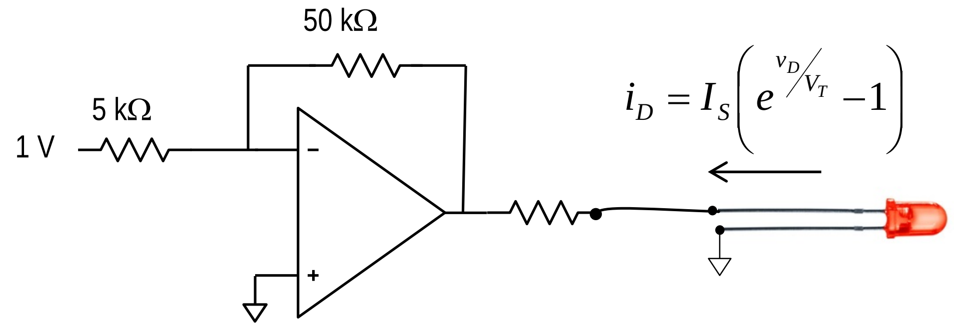


Take Aways from this Video

- Know the difference between a linear and a nonlinear circuit element
  - Be able to provide examples of nonlinear elements
- Understand the basics of diodes and LEDs
  - Diode equation
  - Does it deliver or dissipate power?
- Appreciate the fundamental operation of a MOSFET
  - Eventually you'll more fully understand the equations and how to use them
- Recognize a resistance switch model

Example Problem

- What is the current through the diode assuming a 0.7 V drop?
- Is 0.7 V across the diode a good approximation?



$$i_D = I_S\left(e^{v_D/V_T} - 1\right)$$

Example Problem

- What is the current through the diode assuming a 0.7 V drop?
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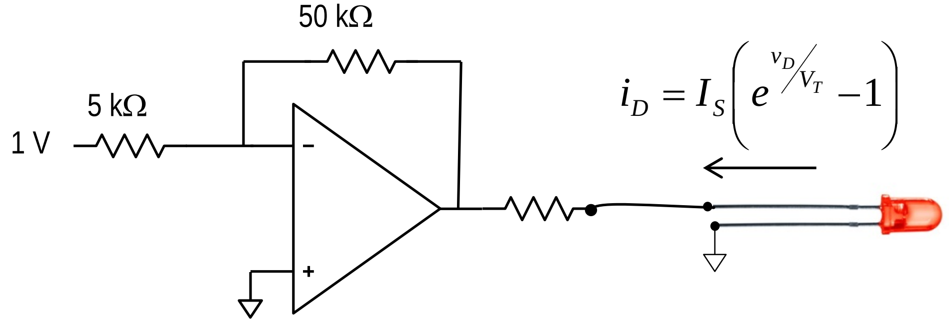

$$i_D = I_S\left(e^{v_D/V_T} - 1\right)$$