SECTION 1: DIODES

ECE 322 – Electronics I

Course Overview

Course Overview

- Your previous electrical engineering courses focused on circuits containing:
  - Sources
    - Voltage and current
    - Independent and dependent
  - Passive devices
    - Resistors, capacitors, inductors
  - Opamps
    - Integrated circuits (ICs)
    - Semiconductor devices
    - Comprised of transistors
- In this course, our focus will be on ***semiconductor devices:***
  - Diodes
  - Transistors

Course Overview

- We will learn to ***analyze and design circuits using semiconductor devices*** – diodes and transistors
- Our primary focus will be ***discrete, analog circuits***
- ***Discrete*** circuits:
  - Built using individual discrete components (transistors, diodes, Rs, Ls, Cs)
  - Not integrated circuits (ICs), though we will be laying the foundation for IC design
- ***Analog*** circuits:
  - Voltages/currents can vary ***continuously***
  - As opposed to digital circuits, where quantities can only assume discrete values

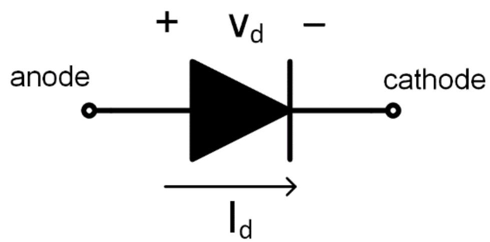
Course Overview

- ***Section 1: Diodes***
  - Introduction to semiconductors
  - Rectifier circuits
- **Section 2: *Bipolar Junction Transistors***
  - Device characteristics and models
- **Section 3: *BJT Amplifiers***
  - Various amplifier circuits using BJTs
- **Section 4: *MOSFETs***
  - Device characteristics and models
- **Section 5: *MOSFET Amplifiers***
  - Various amplifier circuits using MOSFETs
- **Section 6: *Integrated Circuit Building Blocks***
  - Intro to basic components of integrated circuits

Diode Fundamentals

Diodes

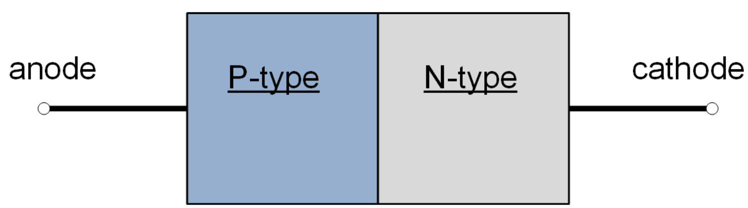
- Two terminal electrical components that ***allow current to flow in one direction only***

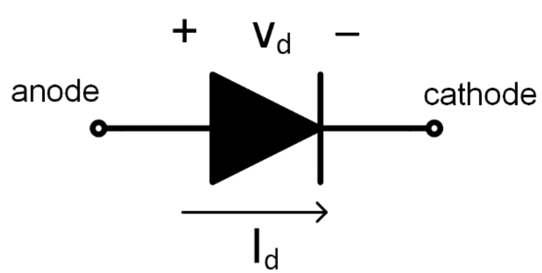


  - Current can flow from ***anode to cathode***, but not from cathode to anode
  - Analogous to ***check valves***
    - Fluid can flow in one direction only:

Diodes – PN Junctions

- Diodes are ***semiconductor*** devices
  - Formed from the junction of two dissimilar semiconductor materials
    - ***P-type*** and ***N-type*** semiconductors
  - ***P-N junctions***:

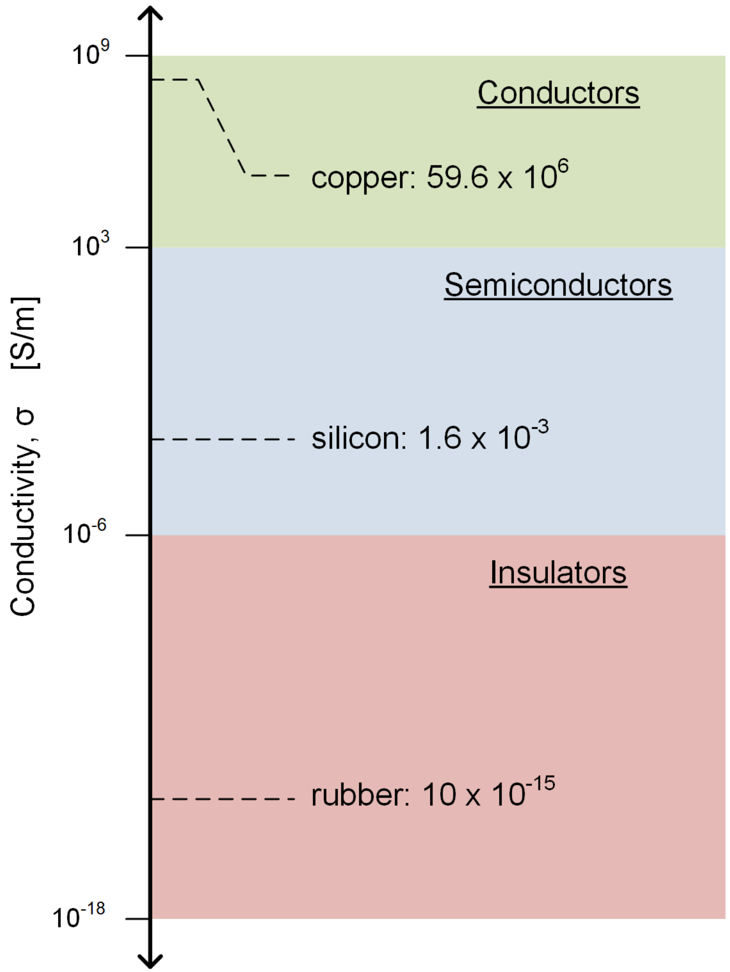




Semiconductor Fundamentals

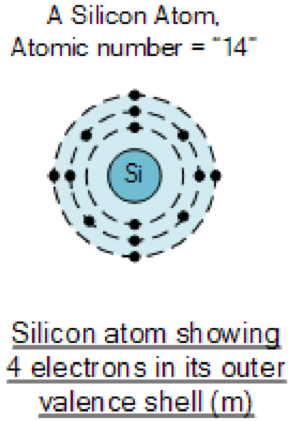
Semiconductors

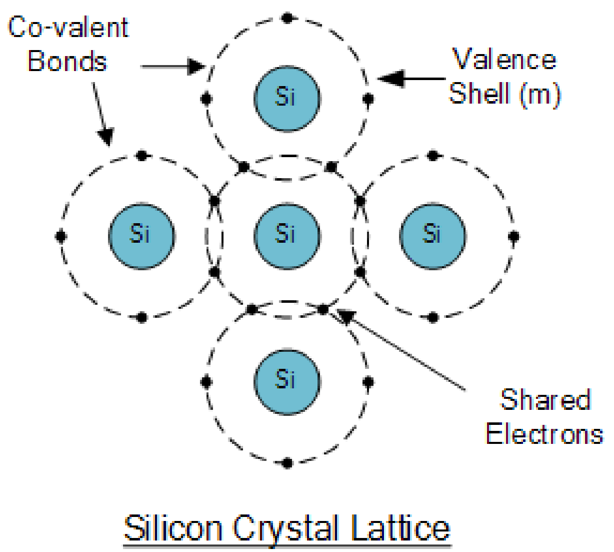
- Semiconductors have ***conductivities*** between those of conductors and insulators
- Conductivity can be modified by adding impurities
  - ***Doping***



Semiconductors

- Semiconductors have ***four valence electrons***
  - Valence bands are half full
  - Atoms bond together in a crystalline lattice structure
  - Each atom shares covalent bonds with four adjacent atoms
  - Few free charge carriers – poor conductivity





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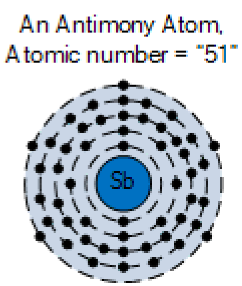
Semiconductors – Doping

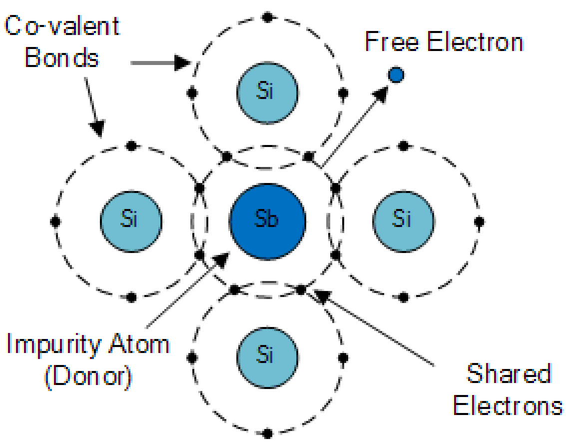
- ***Intrinsic*** semiconductors are poor conductors
- Conductivity can be altered by adding ***impurities*** through a process called ***doping***
- ***Doping***: addition of a small amount of another element to the intrinsic semiconductor
  - Low concentration: 10 ppb – 100 ppm
  - Free charge carriers are increased
  - Conductivity is increased
- Type of dopant determines type of semiconductor
  - N-type or P-type

Semiconductors – N-Type

- ***N-type*** material created by doping with ***pentavalent*** dopant atoms
  - Five valence electrons
  - E.g., phosphorous (P) or antimony (Sb)
  - Bonding with four Si atoms creates a ***free electron***
  - Dopants are called ***donors*** – they donate free electrons



Antimony atom showing 5 electrons in its outer valence shell (o)



N-Type Semiconductor

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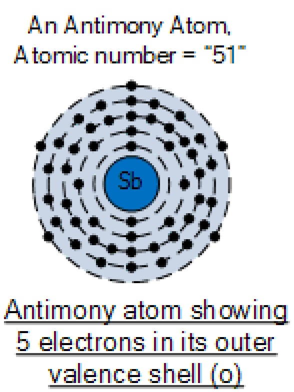
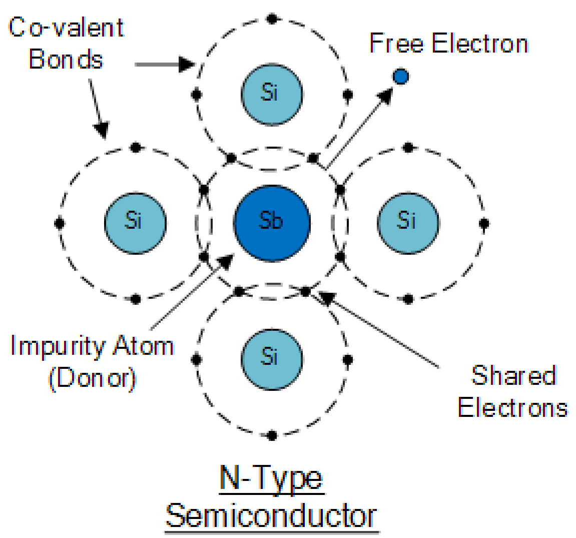
Semiconductors – N-Type

- Donor atoms lose an electron
  - These free electrons are ***majority carriers***
- There will be some holes as well
  - Thermally-generated
  - Much lower concentration – ***minority carriers***





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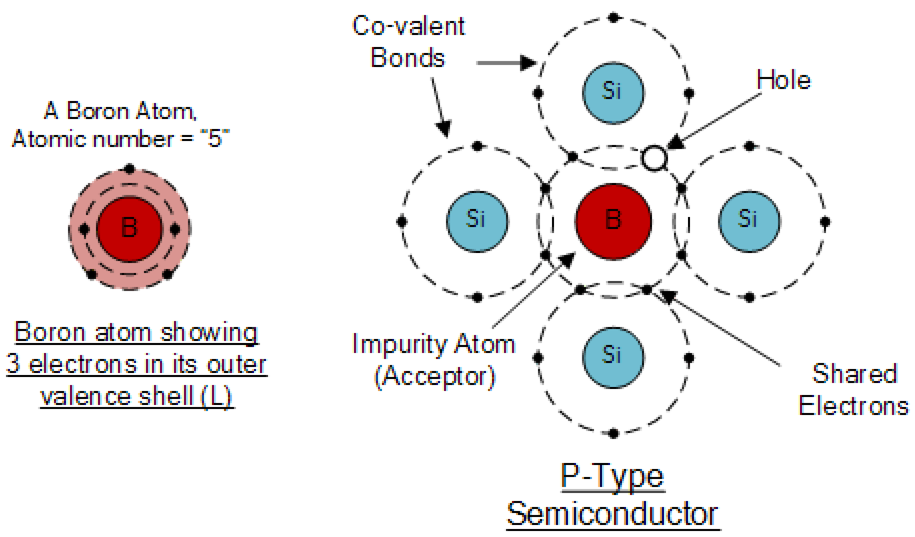
Semiconductors – P-Type

- ***P-type*** material created by doping with ***trivalent*** dopant atoms
  - Three valence electrons
  - E.g., Boron (B)
  - Bonding with four Si atoms creates a ***hole***
  - Dopants are called ***acceptors*** – they accept an electron from a Si atom



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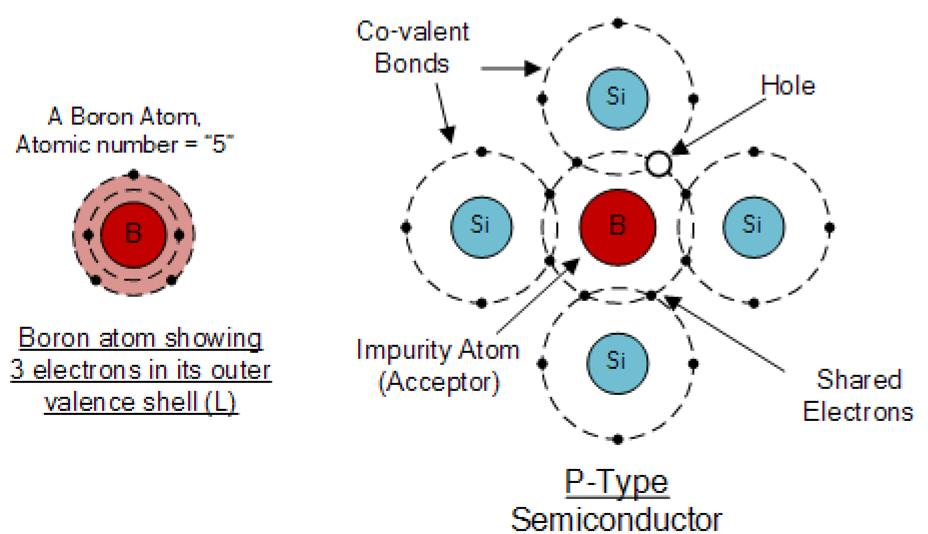
Semiconductors – P-Type

- Acceptor atoms introduce a hole
  - These holes are ***majority carriers***
- There will be some free electrons as well
  - Thermally-generated
  - Much lower concentration – ***minority carriers***



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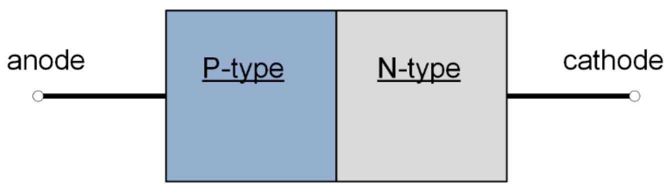
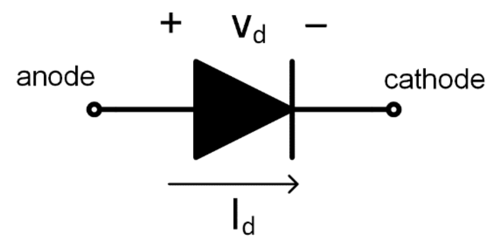
P-N Junctions

- P-N junctions – diodes – are formed by joining P-type and N-type semiconductors

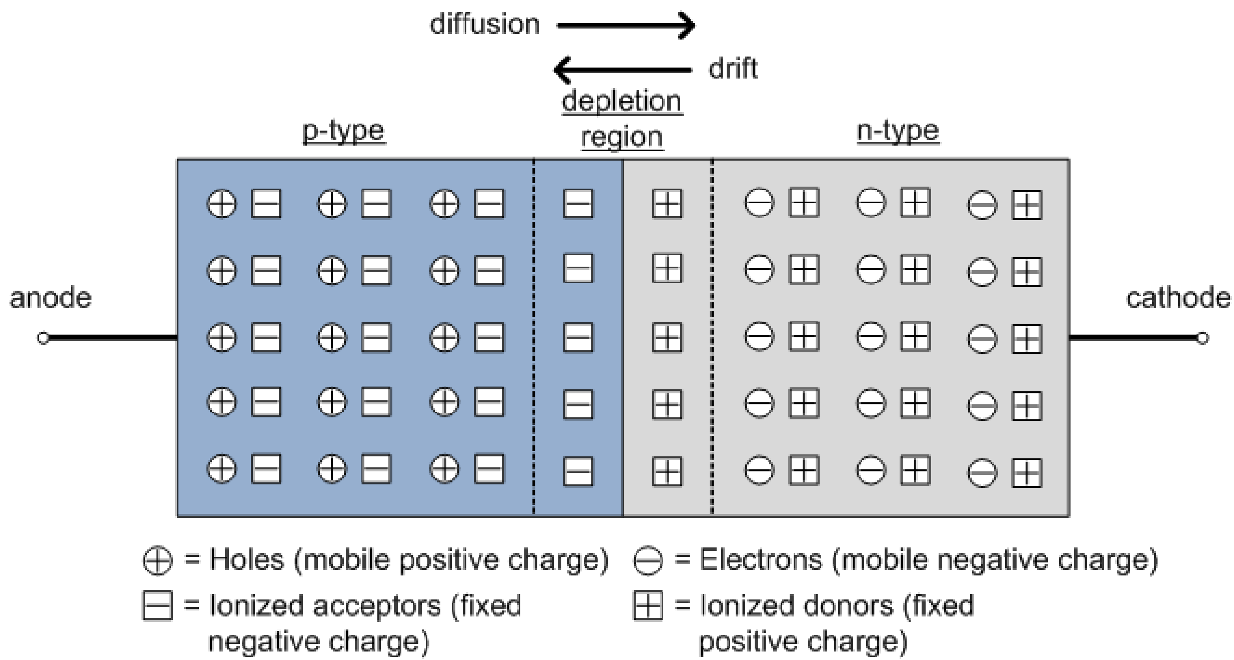




- P-type on one side of the junction
  - Majority carriers: ***holes*** – mobile positive charge
- N-type on the other
  - Majority carriers: ***electrons*** – mobile negative charge
- At the junction:
  - Holes want to ***diffuse*** across into the N-type material
  - Electrons want to ***diffuse*** across into the P-type material

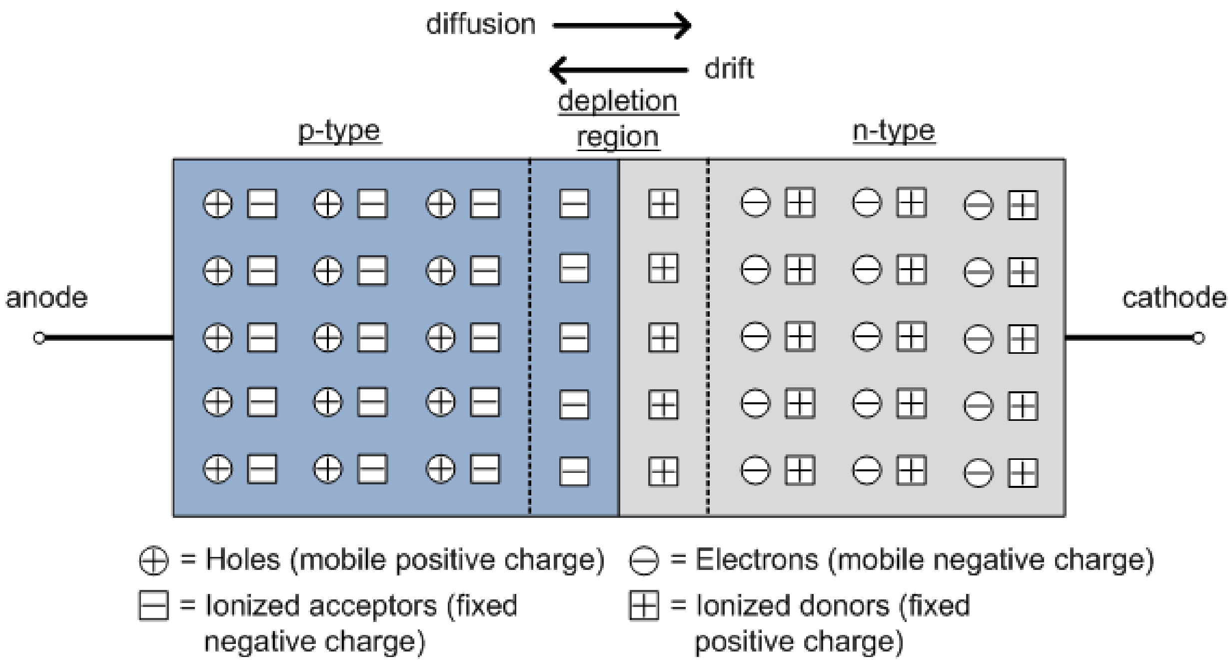
P-N Junctions

- Mobile holes want to diffuse from p-type to n-type
- Mobile electrons want to diffuse from n-type to p-type
- ***Space-charge layer*** or ***depletion region*** is created
- Diffusion drives negative charge one way, positive charge the other



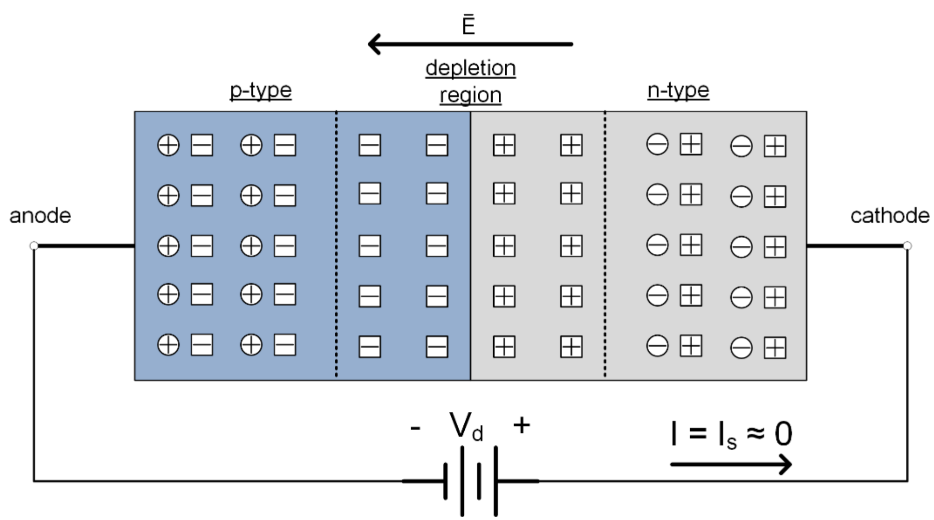
P-N Junctions

- Diffusion causes a ***charge gradient*** across the junction
  - ***Electric field*** established
- E-field drives mobile charge back in the opposite direction
  - ***Drift*** opposes and limits diffusion



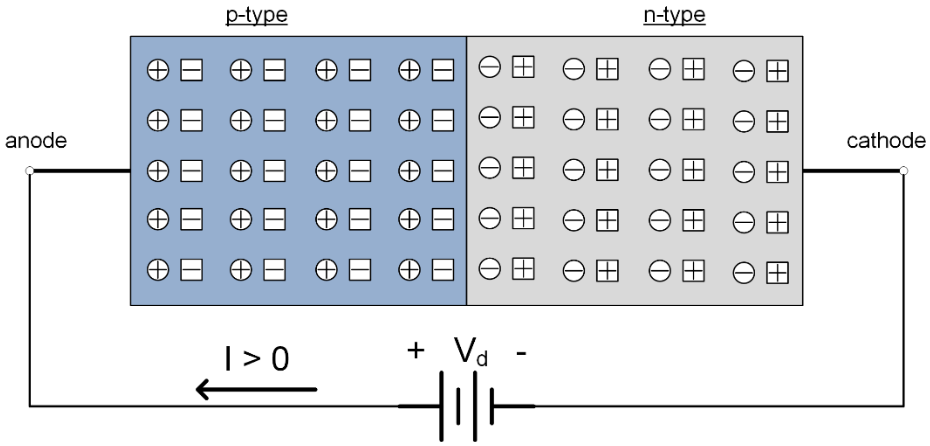
P-N Junction – Reverse Bias

- Reverse-bias voltage applied – $V_d < 0$ V
  - Applied voltage adds to depletion region E-field
  - Additional diffusion to balance larger E-field
  - Depletion region expands
  - Negligible reverse current flow due to ***drift*** of thermally-generated ***minority carriers***



P-N Junction – Forward Bias

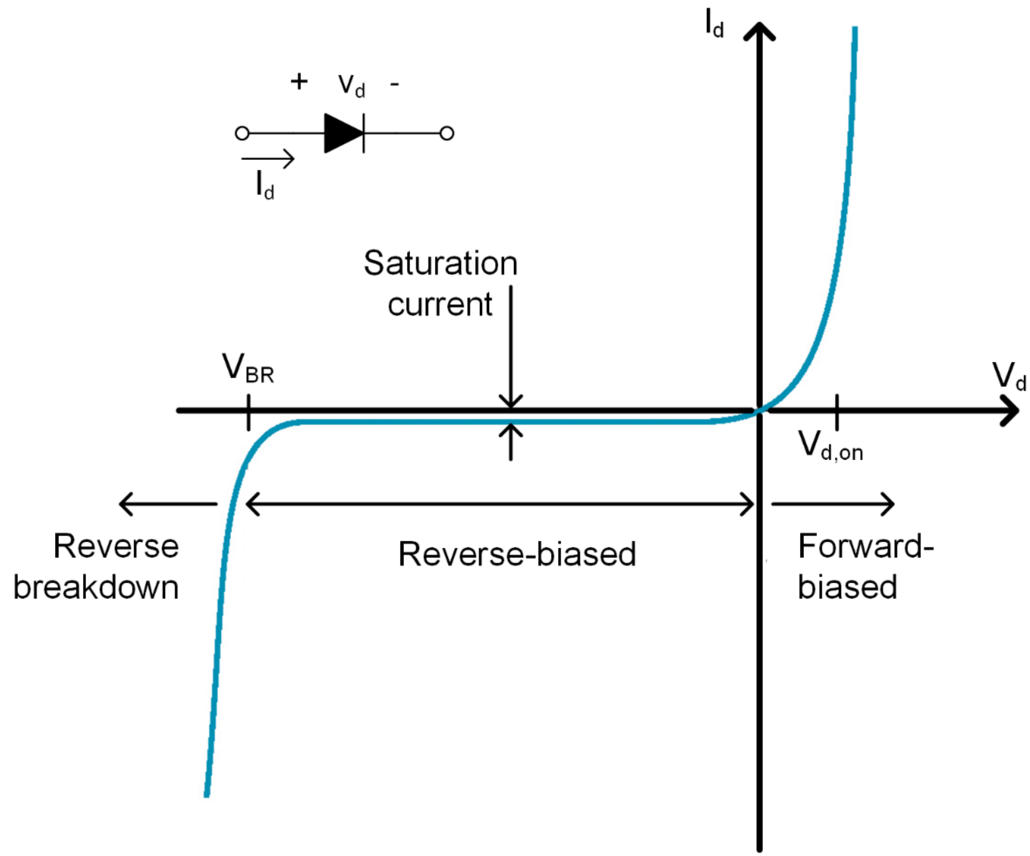
- Forward-bias voltage applied – $V_d > 0$ V
  - Applied voltage reduces depletion region E-field
  - Depletion region shrinks
- Significant forward current flows
  - ***Majority carriers diffuse*** across the junction
  - Carried to diode terminals by applied E-field



Diode I-V Characteristics

Diode I-V Characteristics

- Three operating regions:
  - Forward biased
    - $V_d > 0$ V
    - Current flows from anode to cathode
  - Reverse biased
    - $V_d < 0$ V
    - Negligible, nearly-constant saturation current, I_s, flow from cathode to anode
  - Reverse breakdown
    - $V_d < V_{BR}$
    - Large reverse current flows



Shockley Equation

- In the forward- and reverse-biased regions, diode behavior can be approximated by the ***Shockley Equation:***

$$I_d = I_s\left(e^{\frac{V_d}{V_{th}}} - 1\right)$$

  - V_{th} is the thermal voltage

$$V_{th} = \frac{kT}{q}$$

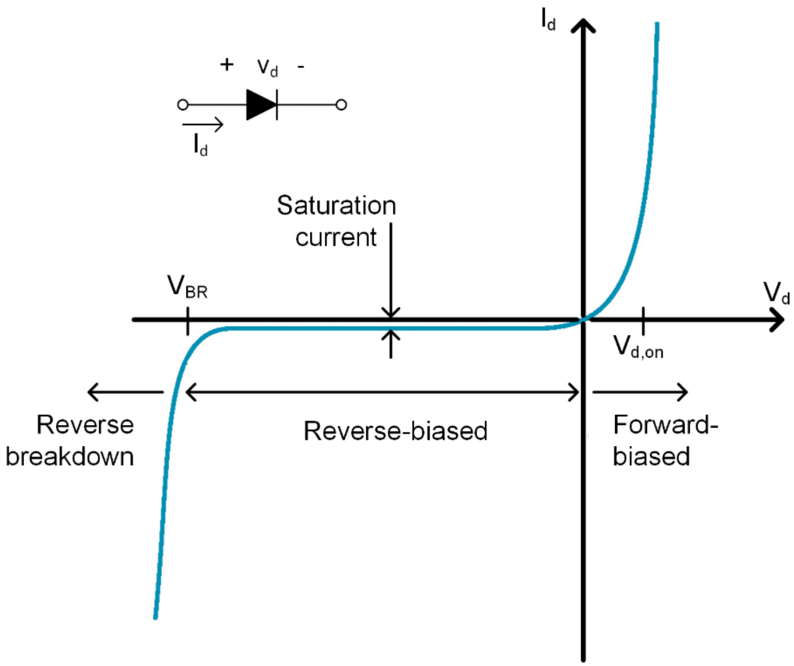
    - $k = 1.38 \times 10^{-23} J/K$ is ***Boltzmann's constant***
    - $q = 1.6 \times 10^{-19}\ C$ is the charge of an electron
    - At $T = 300\ K$, $V_{th} \approx 26\ mV$
  - I_s is the saturation current
    - Typically very small, e.g., $I_s \approx 35\ pA$

Shockley Equation

$$I_d = I_s\left(e^{\frac{V_d}{V_{th}}} - 1\right)$$

- In forward bias, the $-I_s$ term is negligible
  - Exponential current-voltage relationship

$$I_d \approx I_s e^{\frac{V_d}{V_{th}}}$$



- In reverse bias, the exponential term is negligible
  - Nearly-constant, and small, reverse current

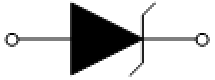
$$I_d \approx -I_s$$

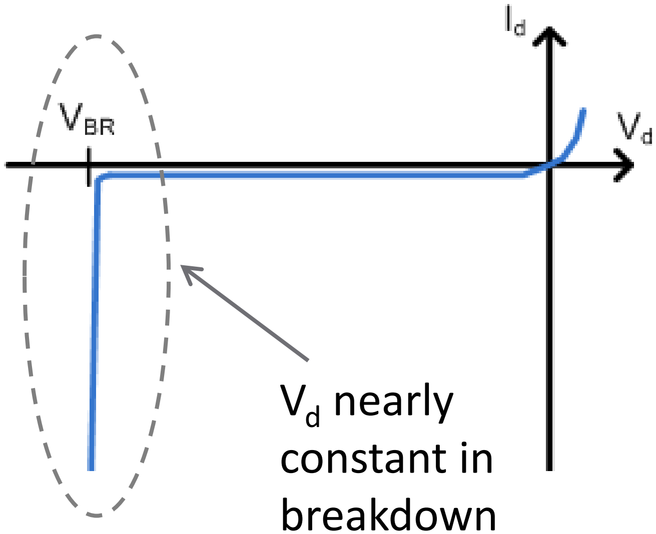
Reverse Breakdown

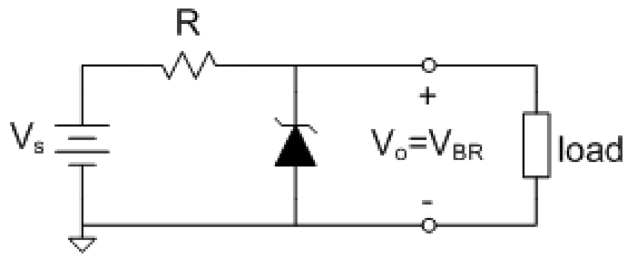
- Shockley equation does not describe reverse-breakdown behavior
- Typical Breakdown voltages are in the range of a few volts to hundreds of volts
- Typically, we want to avoid exceeding the breakdown voltage
- However, one class of diodes is designed to be used in breakdown: ***Zener diodes***

Zener Diodes

- ***Zener diodes*** designed to have a very steep I-V characteristic in the breakdown region
  - V_d is almost constant, independent of current
  - Useful in voltage regulation or voltage reference circuits
  - Schematic symbol:







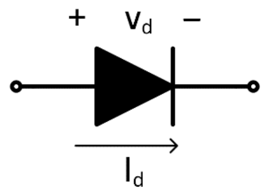
Diode Models

Diode Models

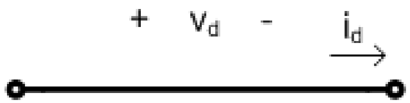
- Need a ***diode model*** to enable circuit analysis
- Shockley equation is one model
  - Simplified, but still complex for hand analysis
- Can trade off complexity and accuracy
  - Choose the simplest possible model that provides acceptable accuracy
- We'll look at three much simpler models
  - Appropriate for first-order type of analyses
    - Ideal diode model
    - Nearly-ideal diode model
    - Nearly-ideal model with resistance

Ideal Diode Model

- ***Ideal diode model***:
  - Short circuit for forward-bias current
  - Open circuit for reverse-bias voltage



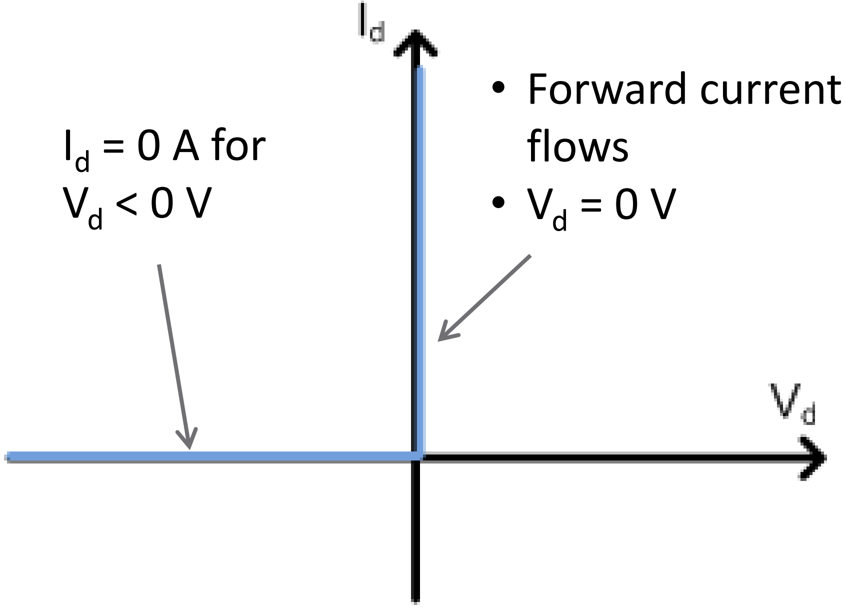
- ***Forward-bias equivalent circuit***:



  - $V_d = 0$ V
  - $I_d > 0$ A

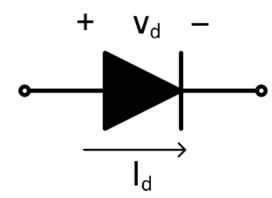
- ***Reverse-bias circuit***:

  - $V_d < 0$ V
  - $I_d = 0$ A



Nearly-Ideal Diode Model

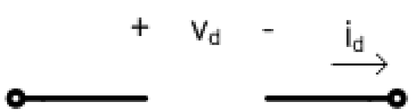
- ***Nearly-ideal diode model*:**
  - Accounts for diode forward voltage
  - Open circuit for $V_d < V_{d,on}$



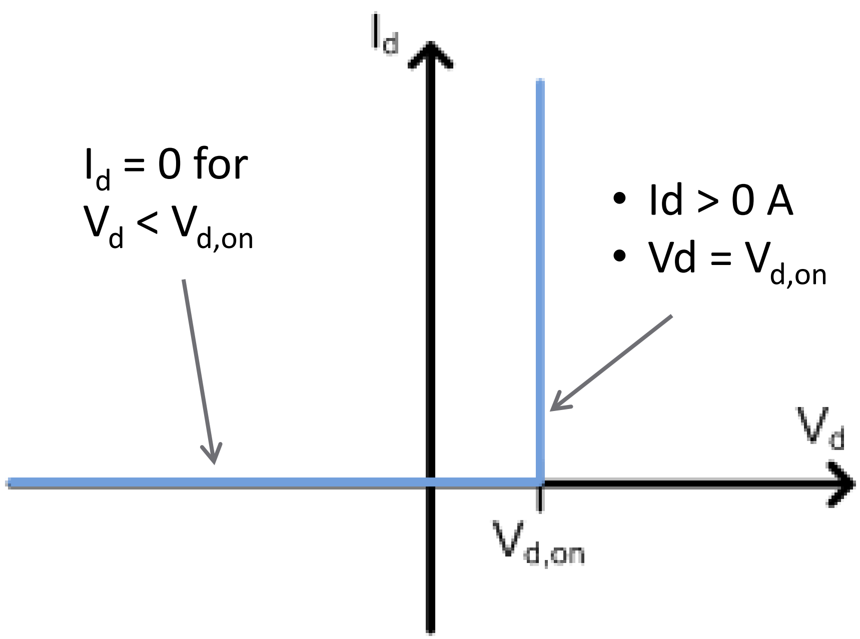
- ***Forward-bias equivalent circuit*:**

  - $V_d = V_{d,on} \approx 700$ mV
  - $I_d > 0$ A

- ***Reverse-bias circuit*:**

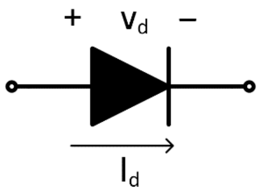


  - $V_d < V_{d,on} \approx 700$ mV
  - $I_d = 0$ A

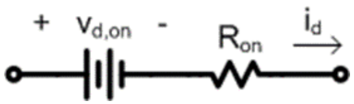


Nearly-Ideal Model with Resistance

- Add resistance to the nearly-ideal model
  - Account for real parasitic resistance, or
  - Provide a better fit to the diode's I-V curve

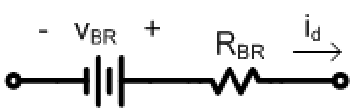


- ***Forward-bias circuit***:

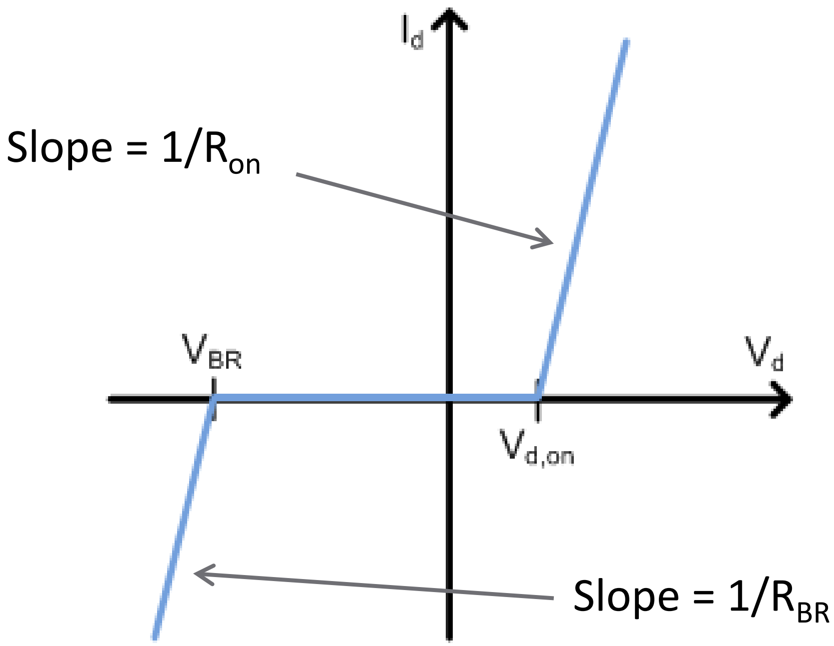


  - $V_d = V_{d,on} + I_d \cdot R_{on}$
- ***Reverse-bias circuit***:

- ***Reverse breakdown***:

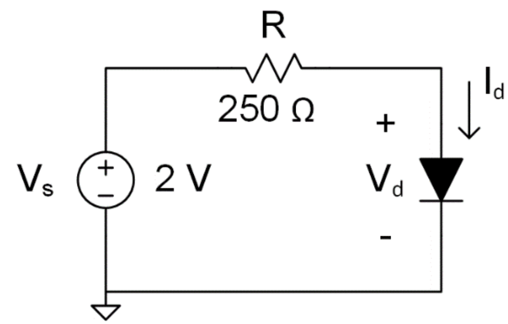


  - $V_d = -V_{BR} + I_d \cdot R_{BR}$



Load-Line Analysis

Diode Circuit Analysis



- Analyze the circuit to find the diode operating point: V_d and I_d
- Apply KVL around the circuit

$$V_s - I_d R - V_d = 0 \tag{1}$$

- One equation with two unknowns: V_d and I_d
  - Shockley equation give I_d in terms of V_d

$$I_d = I_s\left(e^{\frac{V_d}{V_{th}}} - 1\right) \approx I_s e^{\frac{V_d}{V_{th}}} \tag{2}$$

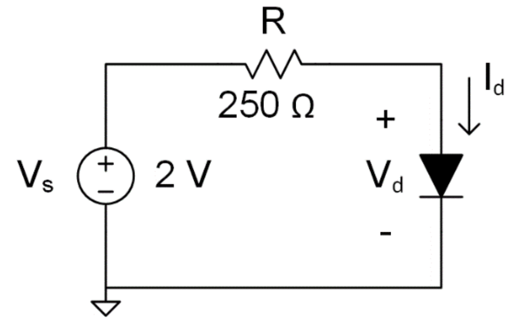
- Substituting (2) into (1) yields a ***transcendental equation***

$$I_s e^{\frac{V_d}{V_{th}}} \cdot R + V_d = V_s \tag{3}$$

  - Solve via iteration, or
  - Solve graphically – ***load-line analysis***

Diode Circuit Analysis

$$I_s e^{\frac{V_d}{V_{th}}} \cdot R + V_d = V_s \qquad (3)$$



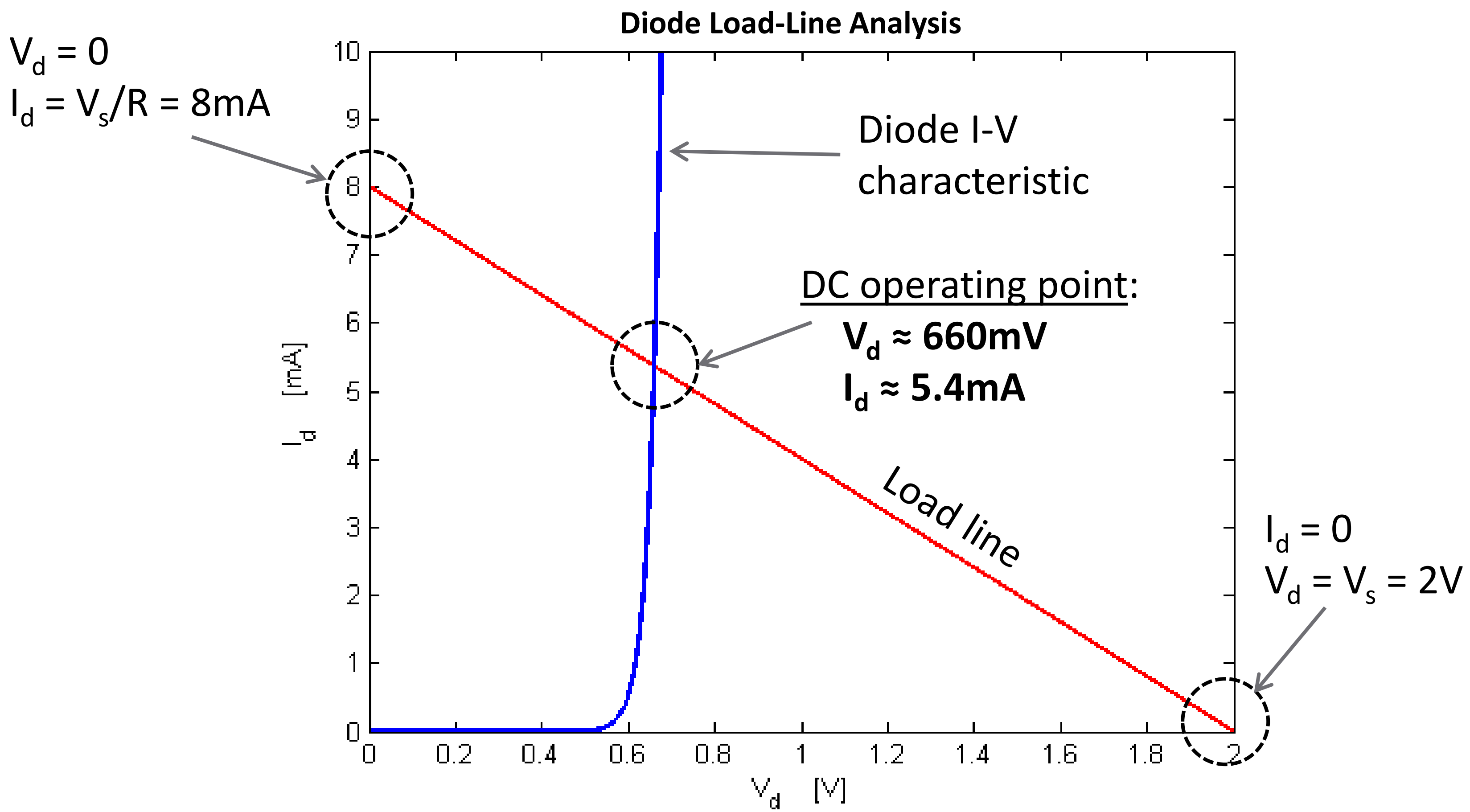
- Solving (3) amounts to solving the system of two equations given by (1) and (2)

$$I_d = -\frac{V_d}{R} + \frac{V_s}{R} \qquad (1)$$

$$I_d = I_s e^{\frac{V_d}{V_{th}}} \qquad (2)$$

  - Equation (1) is an equation for a line – the load line
  - Equation (2) is the exponential forward-biased diode characteristic
- Solution is the values of V_d and I_d that satisfy both equations
  - Point where the ***two curves intersect***
  - The ***DC operating point***
- Finding this solution graphically is ***load-line analysis***

Load-Line Analysis



Analysis with Simple Diode Models

Simplified Analysis – Ideal Model

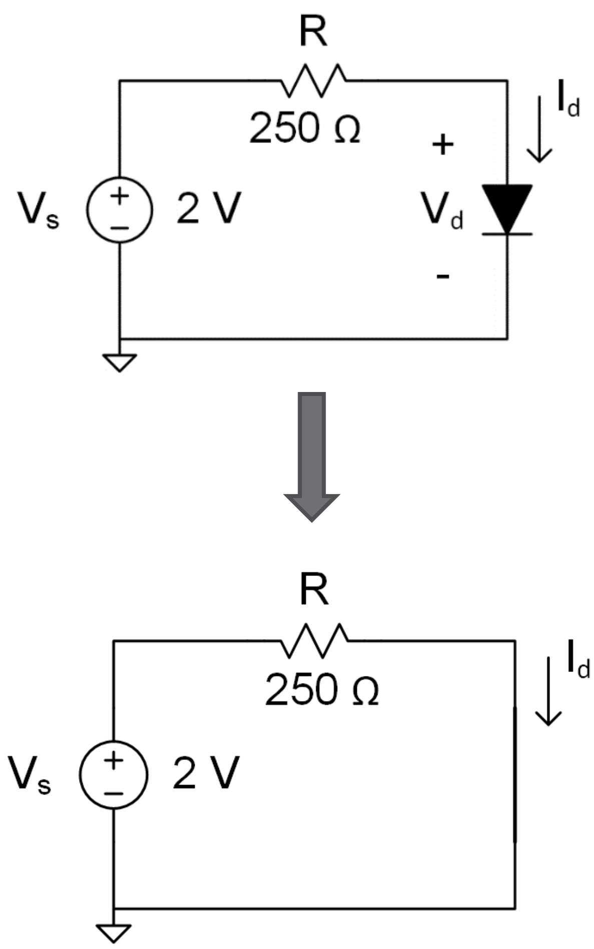
- Revisit the previous analysis using the ***ideal diode model***
- Diode is forward biased
  - Replace with a short circuit
- Diode modeled as a short, so

$$V_d = 0\ V$$

- Ohm's law gives current

$$I_d = \frac{V_s}{R} = \frac{2\ V}{250\ \Omega} = 8\ mA$$

- Current is in correct order of magnitude, but not very accurate
- Next, try the nearly-ideal model



Simplified Analysis – Nearly-Ideal Model

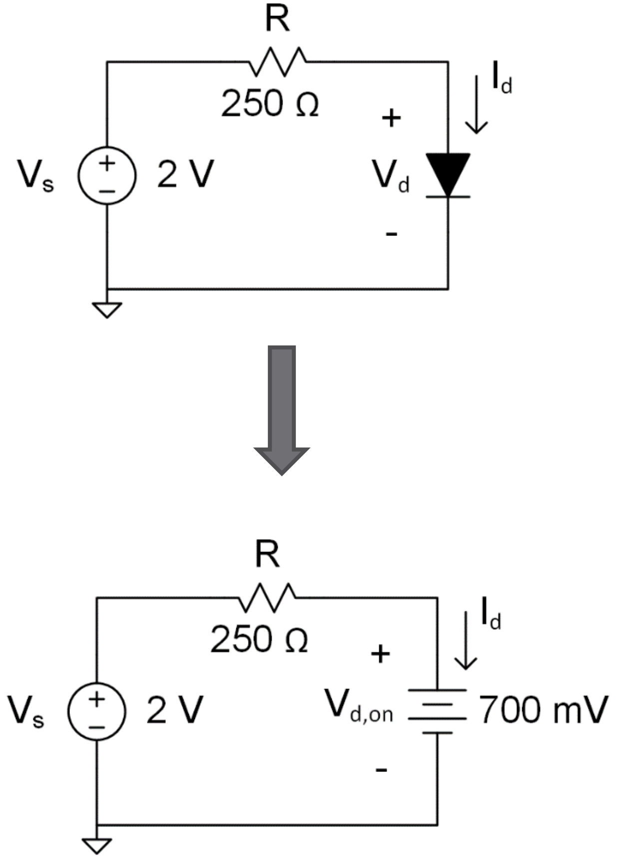
- Now, use the ***nearly-ideal model***
- Diode is forward biased
  - Replace with a voltage source
  - In practice, would have some idea of the appropriate value for $V_{d,on}$

$$V_d = V_{d,on} \approx 700\ mV$$

- Ohm's law gives current

$$I_d = \frac{V_s - V_{d,on}}{R} = \frac{2\ V - 0.7\ V}{250\ \Omega} = 5.2\ mA$$

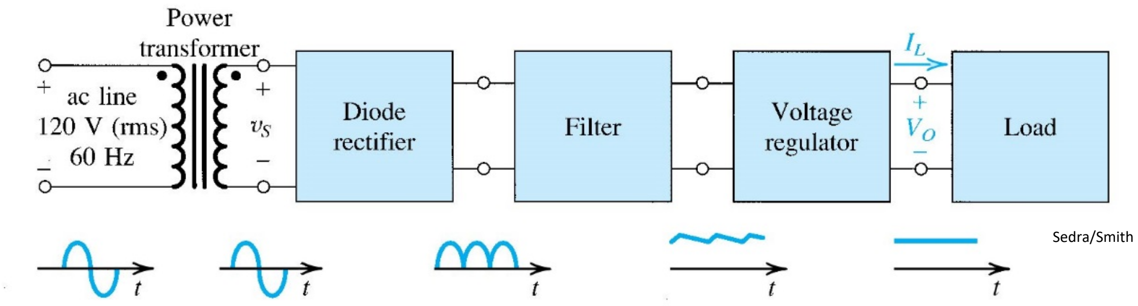
- Much more accurate result
- This is our go-to model for hand analysis



Rectifier Circuits

Rectifier Circuits

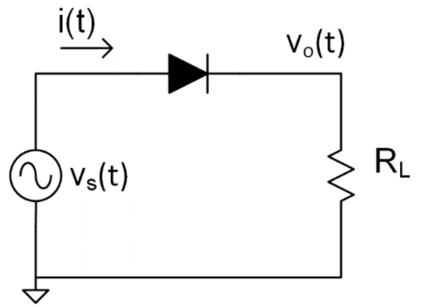
- ***Rectifier circuits*** are circuits that convert AC signals into DC signals
  - ***AC-to-DC power converters:***



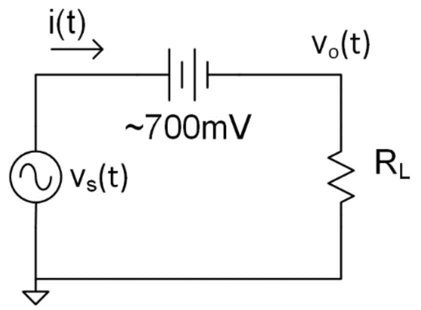
  - Also used as ***peak detectors***
    - AM receivers
    - Measurement instruments
- Rectifiers rely on the unidirectional nature of diodes
  - Eliminate negative voltages or make them positive

Half-Wave Rectifier

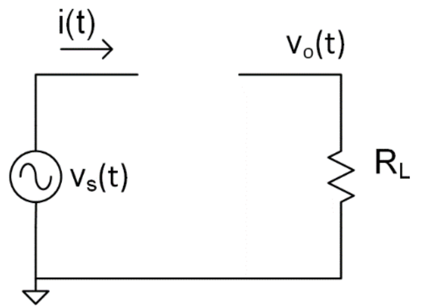
- Half-wave rectifier
  - Sinusoidal input, e.g., powerline voltage
  - Negative half-periods removed
  - Only positive voltages at rectifier output



- For $v_s(t) \geq V_{d,on} \approx 700\ mV$:
  - $i(t) > 0\ A$
  - $v_o(t) = v_s(t) - V_{d,on}$



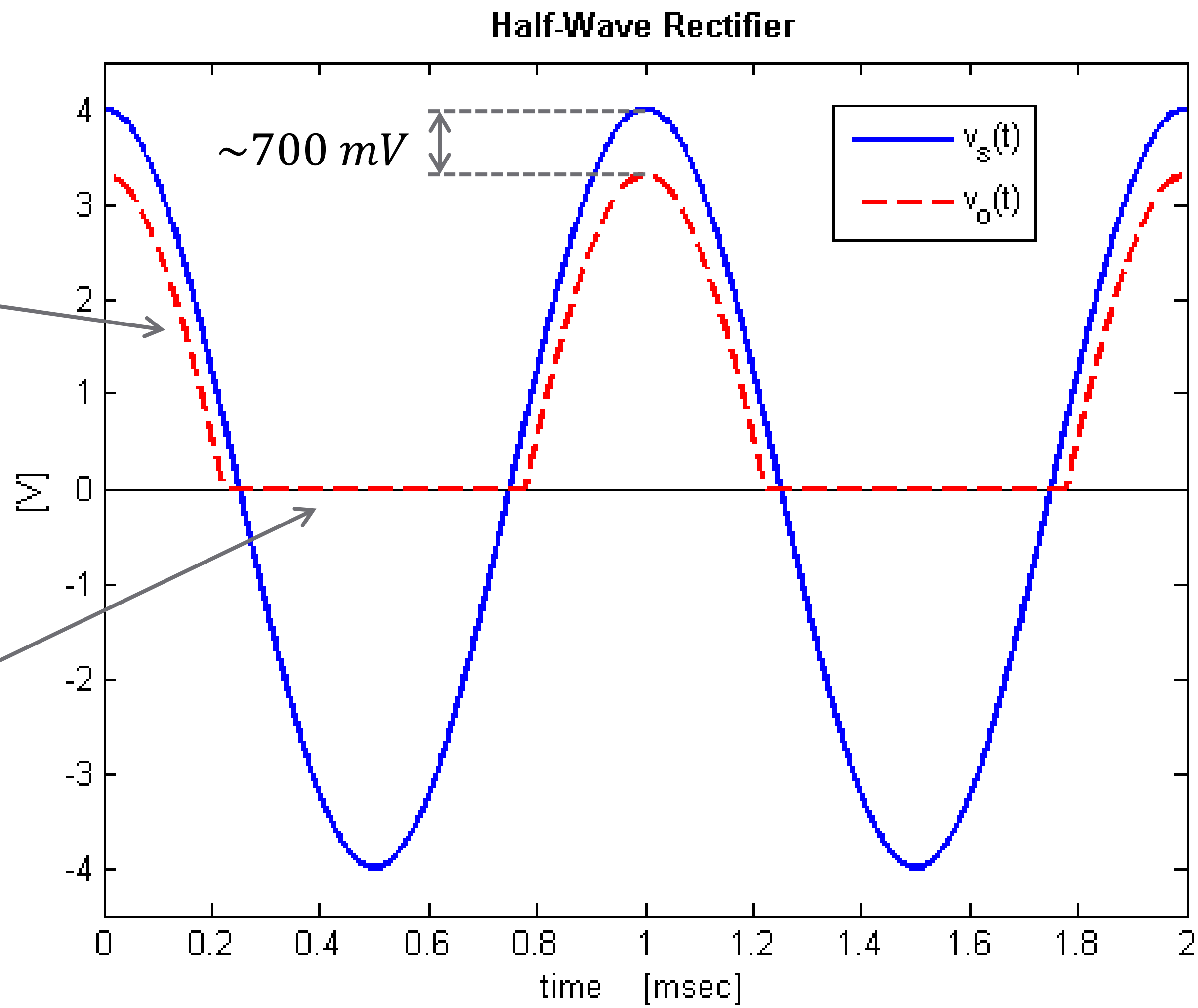
- For $v_s(t) \leq V_{d,on} \approx 700\ mV$:
  - $i(t) = 0\ A$
  - $v_o(t) = 0\ V$



Half-Wave Rectifier

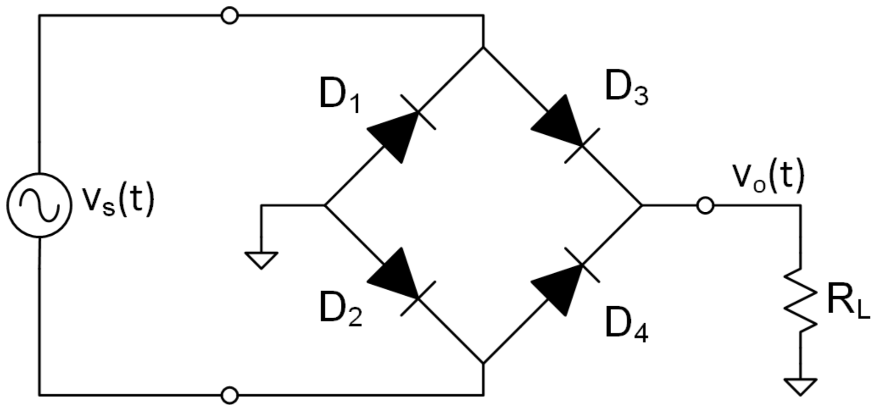
For $v_s(t) \geq 700\ mV$:
$v_{o(t)} = v_s(t) - 700\ mV$

For $v_s(t) \leq 700\ mV$:
$v_{o(t)} = 0\ V$

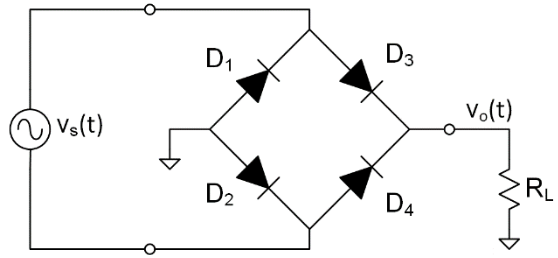


Full-Wave Rectifier

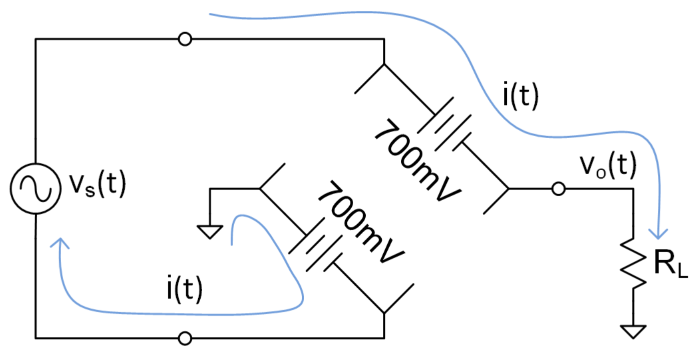
- Typical goal of a rectifier: extract power from an AC voltage, supply it to a load as a DC voltage
- Half-wave rectification is inefficient
  - Half of the signal – and its energy – is discarded
- ***Full-wave rectification*** improves efficiency
  - Negative voltages are not discarded – they are made positive
- A ***diode bridge*** configuration
- Source must be ***floating***
  - Neither side grounded
  - Typically the output of a transformer, so not a problem



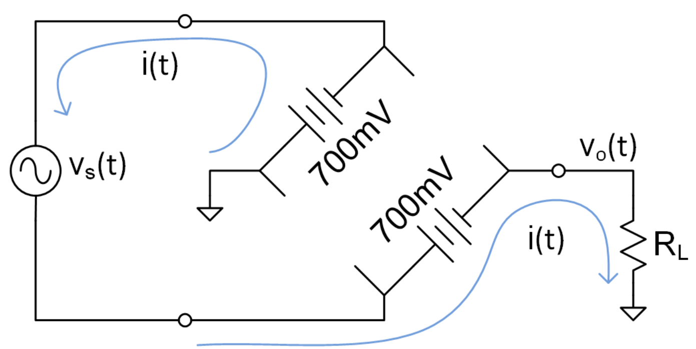
Full-Wave Rectifier



- For $v_s(t) \geq 2 \cdot V_{d,on}$:
  - D_2 and D_3 are forward-biased
  - D_1 and D_4 are reverse-biased
  - $v_o(t) = v_s(t) - 1.4\ V$



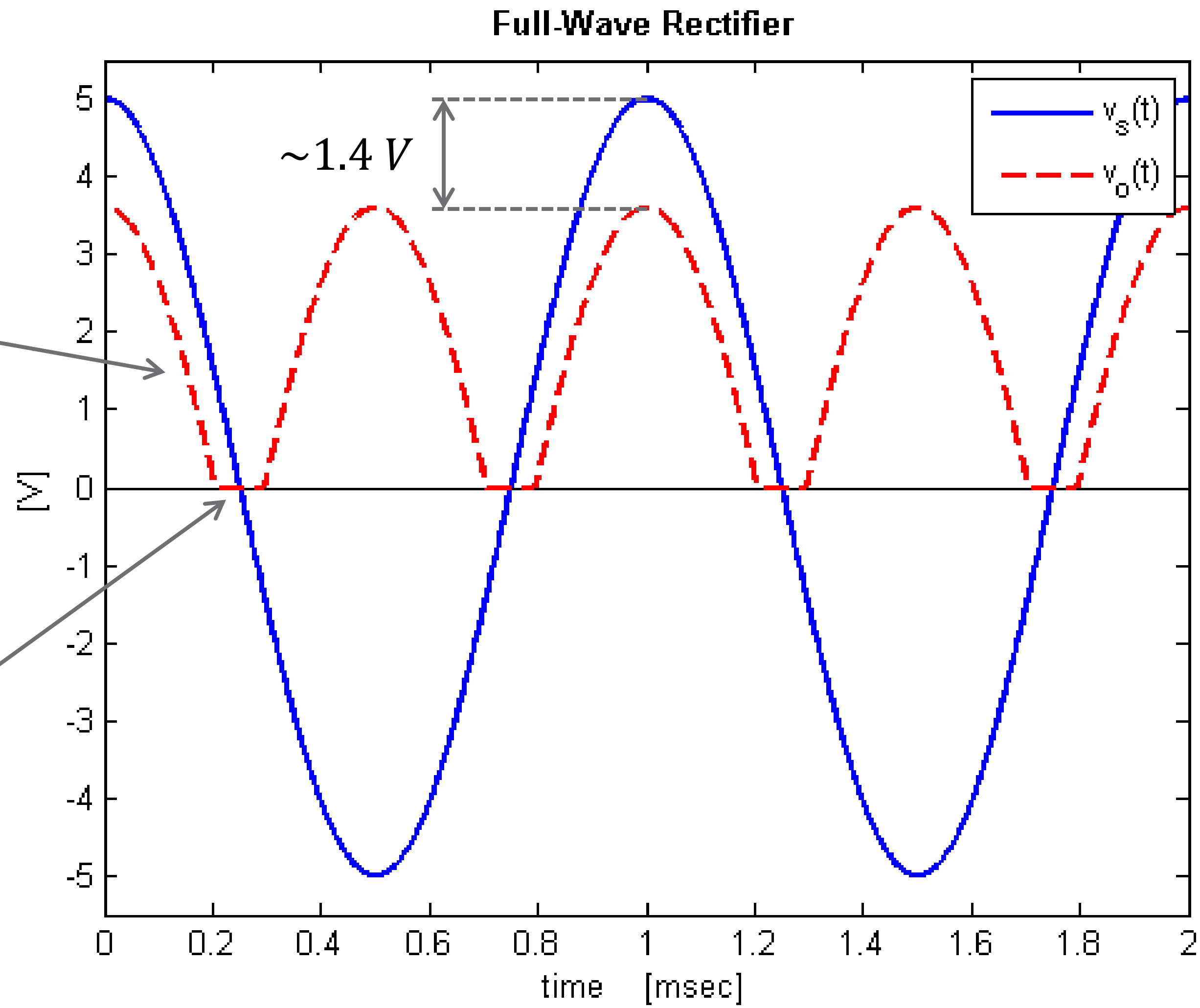
- For $v_s(t) \leq -2 \cdot V_{d,on}$:
  - D_1 and D_4 are forward-biased
  - D_2 and D_3 are reverse-biased
  - $v_o(t) = -v_s(t) - 1.4\ V$



Full-Wave Rectifier

For $|v_s(t)| \geq 1.4\ V$:
$v_{o(t)} = |v_s(t)| - 1.4\ V$

For $|v_s(t)| \leq 1.4\ V$:
$v_{o(t)} = 0\ V$

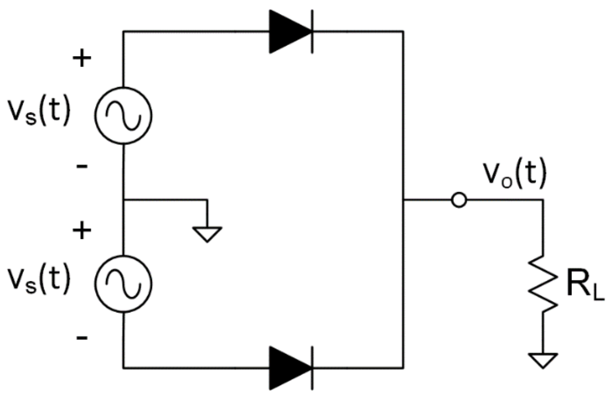


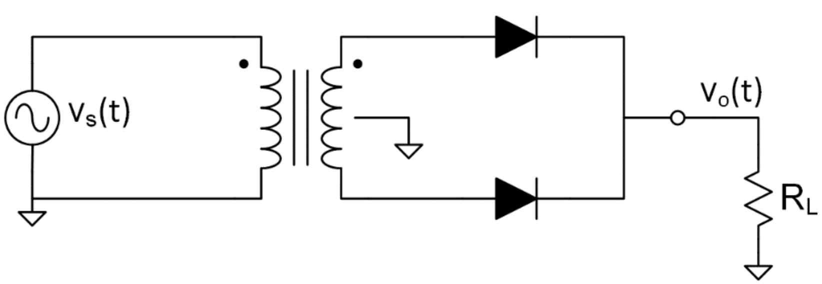
Full-Wave Rectifier – Differential Source

- If we have a ***differential source***, full-wave rectifier requires only two diodes
- Now, only a single diode drop between input and output

$$v_o(t) = |v_s(t)| - V_{d,on}$$

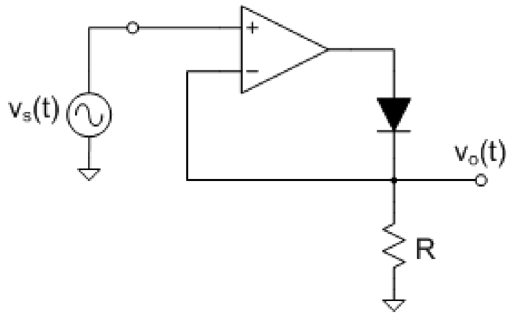
- Differential source may come from a transformer with a grounded center tap on the secondary winding



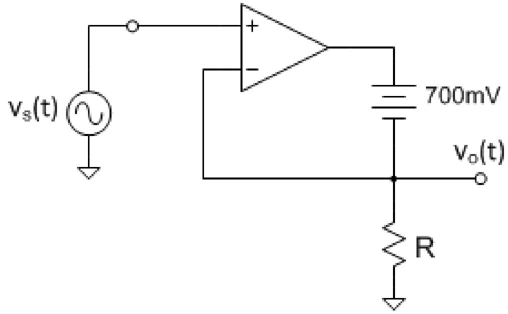


Precision Half-Wave Rectifier

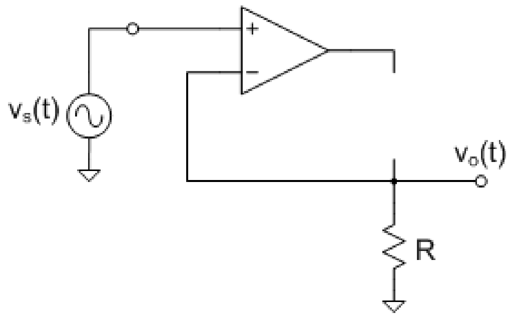
- A ***precision rectifier*** or ***super diode*** encloses a diode in an opamp feedback loop
  - Feedback forces the output equal to the input
  - Input-to-output diode drop is eliminated
  - Negative feedback only for positive inputs



- For $v_s(t) \geq 0\ V$:
  - Negative feedback path exists
  - Unity-gain buffer
  - $v_o(t) = v_s(t)$



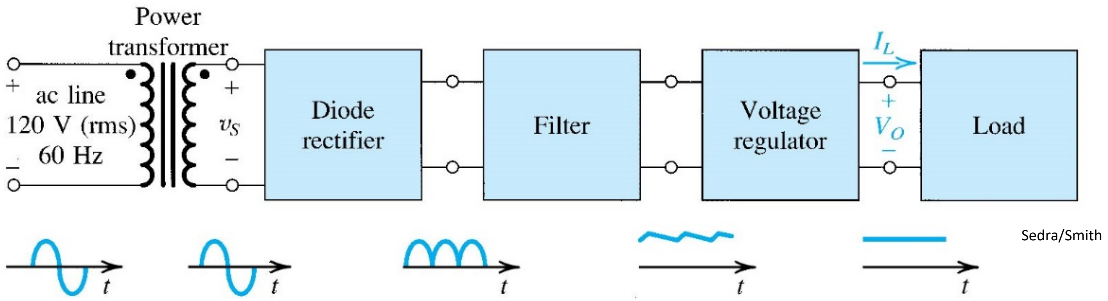
- For $v_s(t) \leq 0\ V$:
  - No feedback – output saturates
  - v_o(t) pulled to ground by resistor
  - $v_o(t) = 0\ V$



Smoothing Capacitors & Peak Detectors

Smoothing Capacitors

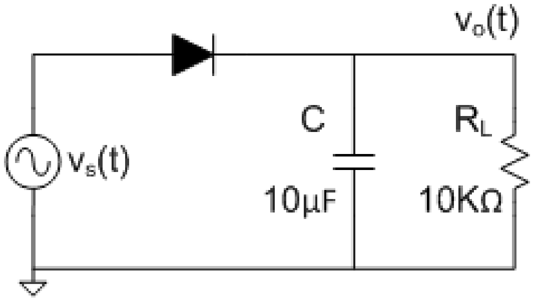
- If our goal is ***AC-to-DC conversion***, rectification is only the first step
  - Rectified output is positive, but far from DC

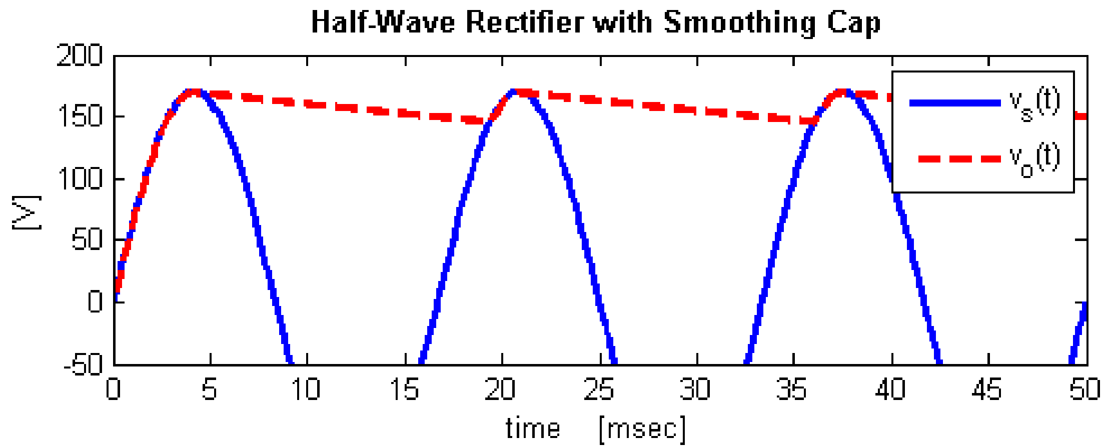


- A capacitor in parallel with the rectifier's load resistor will smooth out the output
  - A ***smoothing capacitor***
  - A ***low pass filter*** to average out the rectified signal
- The same circuit can be used for ***peak detection***
  - Demodulation of an AM radio signal, for example

Smoothing Capacitors

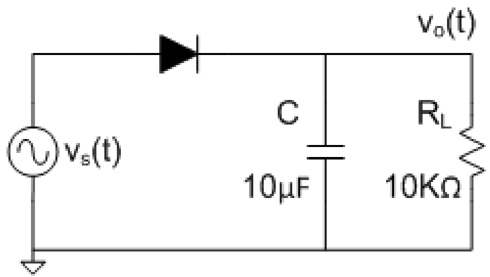
- Add a ***smoothing capacitor*** to half-wave rectifier
  - Input is 60 Hz powerline voltage

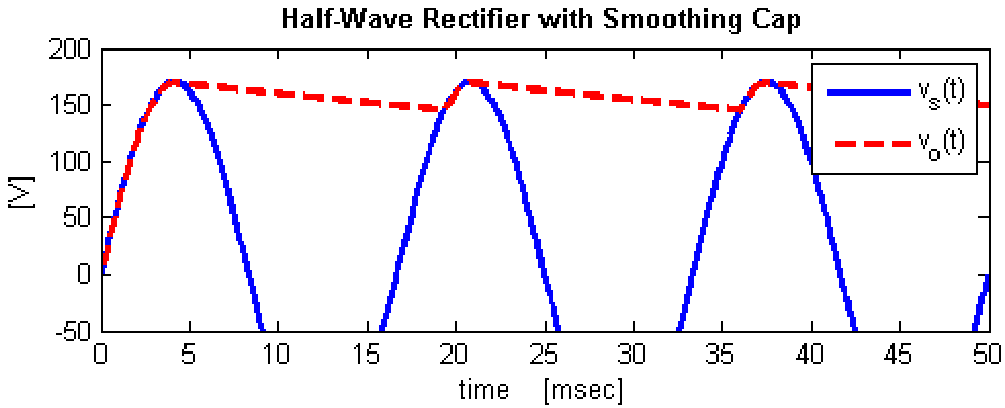




- When $v_o \leq v_s - V_{d,on}$:
  - Current flows through the diode
  - Capacitor charges
- When $v_s \leq v_o + V_{d,on}$:
  - Diode is off
  - Capacitor discharges at a rate determined by the RC time constant

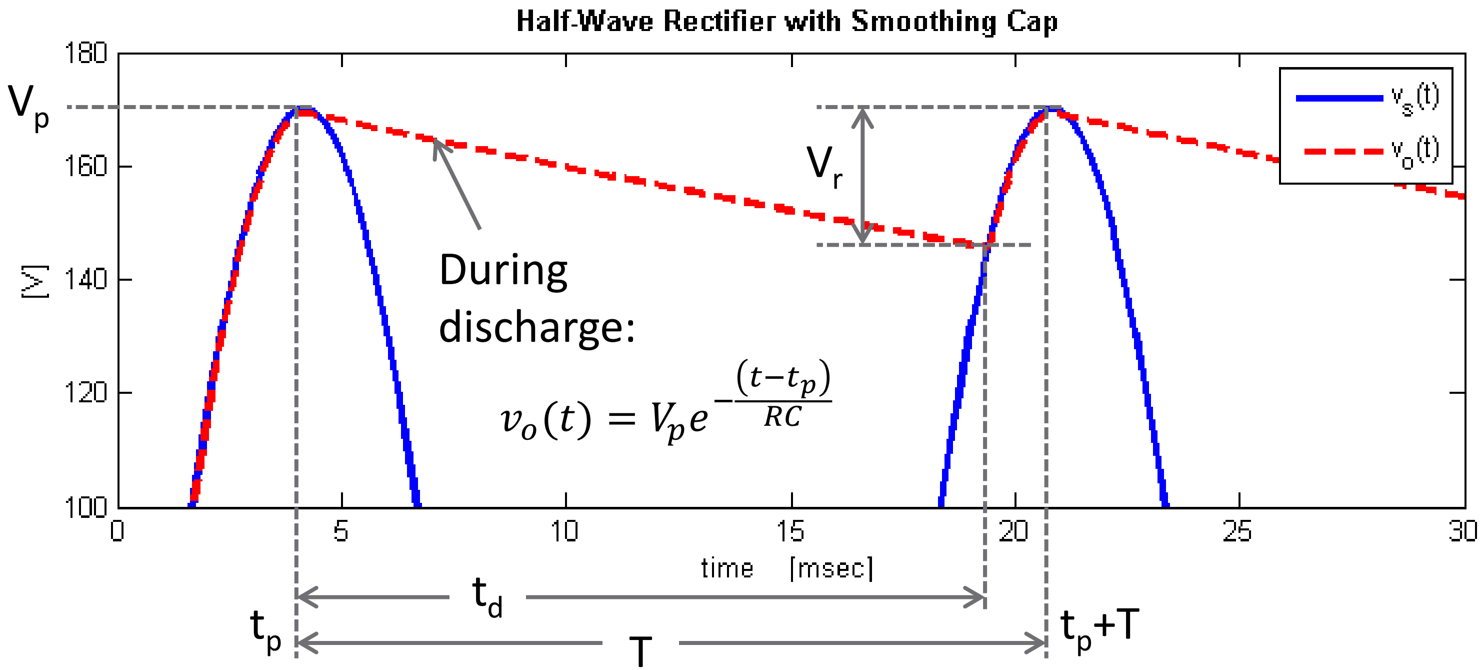
Smoothing Capacitors





- Capacitor helps filter or smooth the output
  - Nearly DC
  - Remaining AC component is referred to as ***ripple***
- Ripple magnitude determined by how far the capacitor can discharge before charging again
  - Determined by RC time constant
- To reduce ripple
  - Increase the RC time constant
  - Larger resistor and/or capacitor

Calculating Ripple – Half Wave Rectifier



- V_r: pk-pk ripple voltage
- V_p: peak input voltage
- t_p: time at input peak
- T: input period
- t_d: capacitor discharge time
- Diode modeled as ideal

Calculating Ripple – Half Wave Rectifier

- V_r is the difference between the output voltage at $t = t_p$ and at $t = t_p + t_d$

$$V_r = v_o(t_p) - v_o(t_p + t_d)$$

where

$$v_o(t_p) = V_p \quad \text{and} \quad v_o(t_p + t_d) = V_p e^{-\frac{t_d}{RC}}$$

so

$$V_r = V_p - V_p e^{-\frac{t_d}{RC}} = V_p\left(1 - e^{-\frac{t_d}{RC}}\right)$$

- Problem is, we do not know t_d
  - Could calculate it, but, instead, assume the following:

$$\tau = RC \gg T$$

- From which it follows that
  - $V_r \ll V_p$
  - $t_d \approx T$
  - Discharge current is approximately constant:

$$i(t) \approx \frac{V_p}{R} \quad \left(t_p \leq t \leq t_p + t_d\right)$$

Approximating Ripple – Half Wave Rectifier

- Recall that the change in voltage across a capacitor discharged at a constant current is

$$V = \frac{I \cdot t}{C}$$

- Using our approximations for current and discharge time gives an approximation for the ripple voltage:

$$V_r \approx \frac{V_p \cdot T}{RC} = \frac{V_p}{fRC}$$