Special Diodes

Semiconductor Devices and Circuits

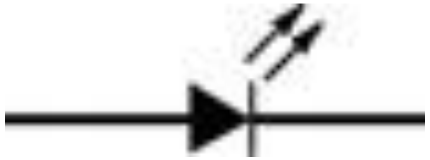
(ECE 181302)

10th December 2021

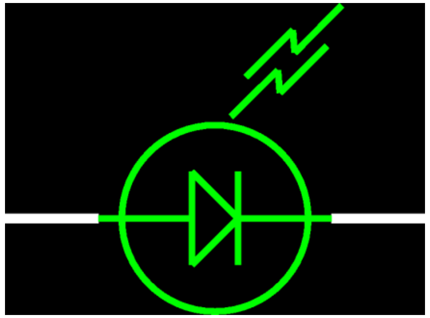
Special Purpose Diodes

- Besides rectification, a semiconductor diode has many other useful applications.
- Semiconductor diodes can be manufactured to regulate voltage or emit different colors of light.
- Examples of two special purpose diodes are
  - Light-emitting diode
  - Zener diode

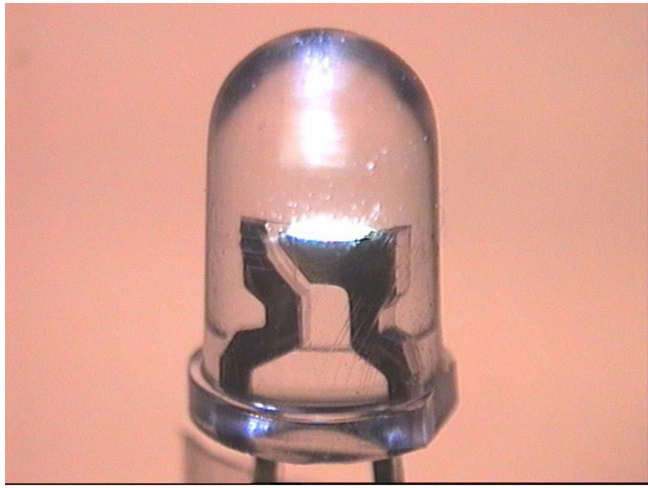
Light Emitting Diode (LED)



- LED emits a certain color of light when forward-biased.
- Material is more exotic than silicon used in ordinary diodes/ transistors:
  - gallium arsenide (GaAs), gallium phosphide (GaP), or gallium arsenide phosphide (GaAsP)
  - typically 2-volt drop instead of 0.6 V drop



- Different semiconductor materials and different impurities result in different colours of light.
- When electron flows through LED, it loses energy by emitting a photon of light rather than by vibration of the crystal lattice (heat).
- LED efficiency is 30% (compare to incandescent bulb at 10%).

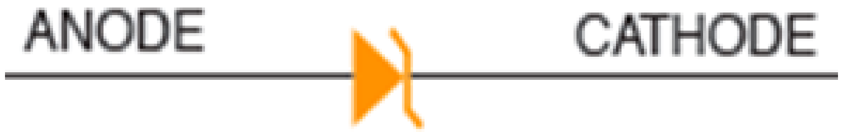


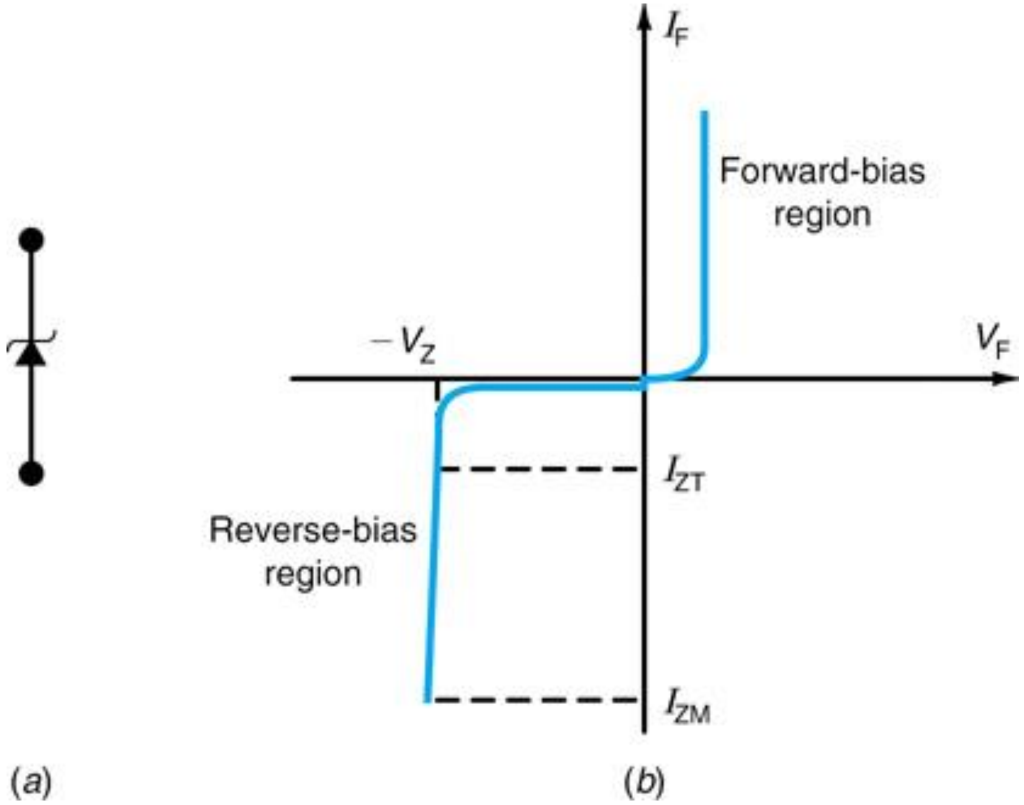
Zener Diode

- Zener diode is a special type of diode that is designed to work in reverse condition.
- Acts as a normal diode in the forward bias region.
- Designed to operate at voltages greater than the breakdown voltage (peak inverse voltage).
- It is heavily doped to have a thin depletion region, as a result breakdown voltage occurs at a lower voltage:
  - Operates at voltages that exceed breakdown voltage
  - Manufactured with a specific breakdown voltage (E_Z)
  - Packaged like PN junction diodes
- The breakdown voltage is determined by the resistivity of the diode.
- Zener diodes are used to stabilize or regulate voltage.

Zener Diode Characteristics

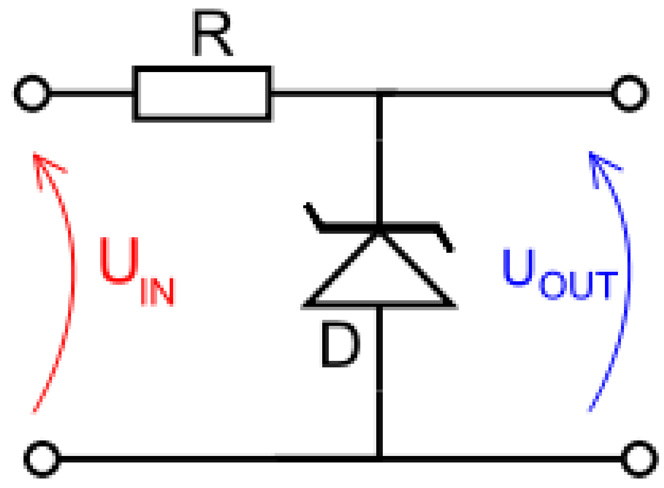
- Schematic symbol:

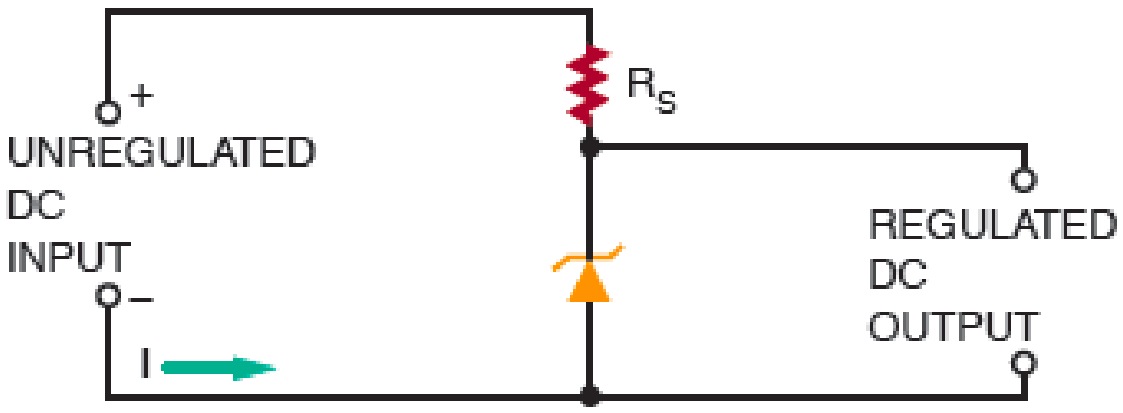




Voltage Regulation

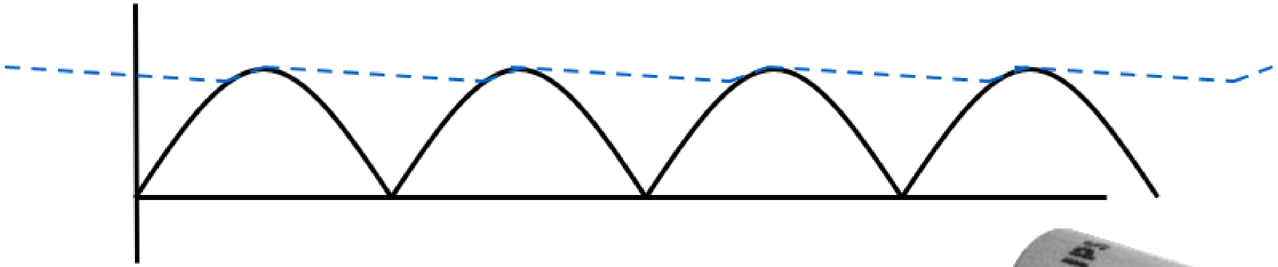
- **Voltage regulation** is the most common application of a zener diode.
- Provides a constant output voltage despite changes in the input voltage or output current

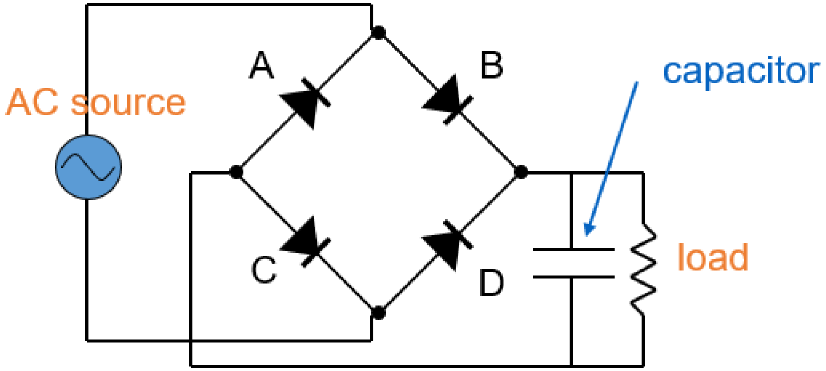


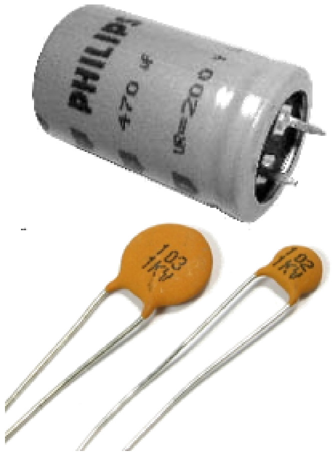


Recall: Rectifier Output is a Bumpy Ride

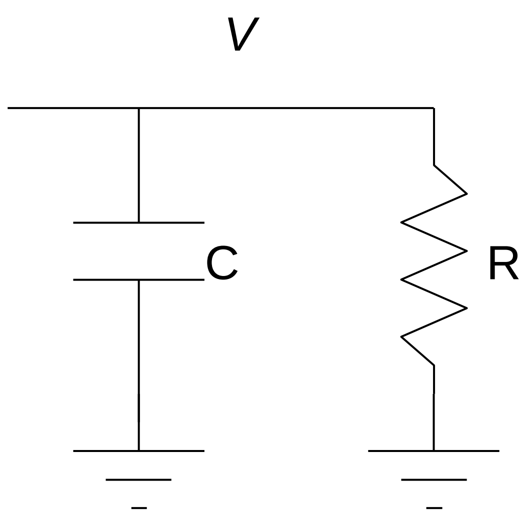
- Rectifier uses a capacitor to smooth out pulses
  - capacitors have capacity for storing charge
  - acts like a reservoir to supply current during low spots
  - voltage regulator smoothers out remaining ripple



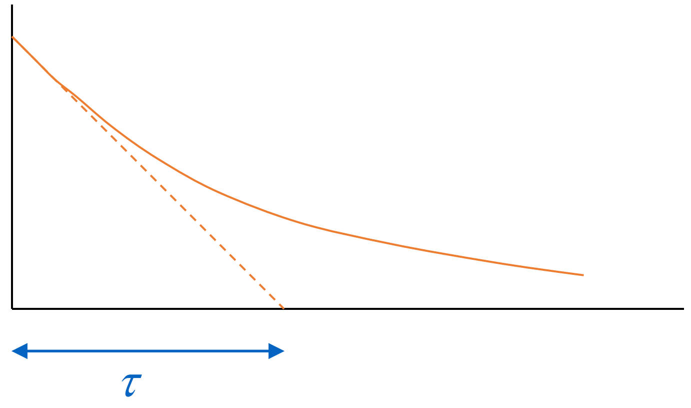




How smooth is smooth?

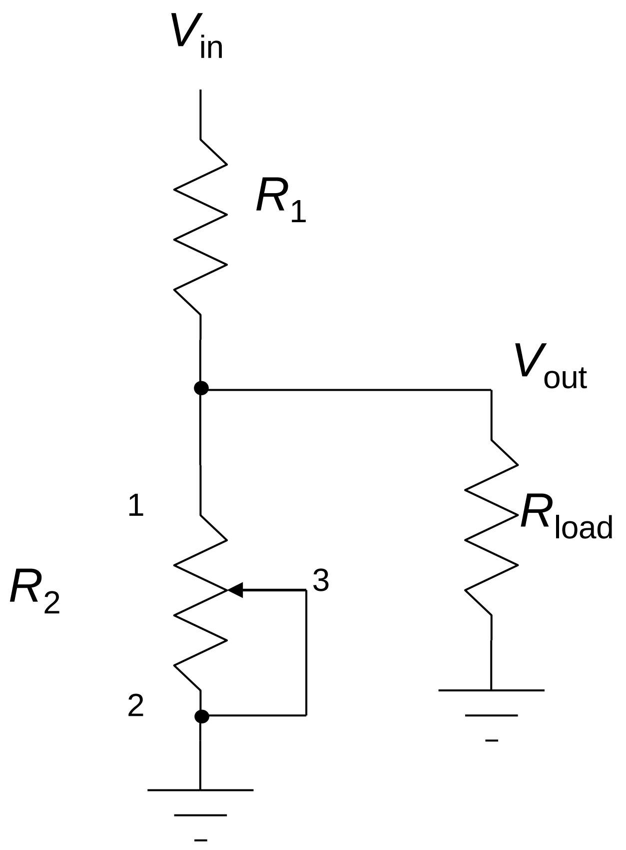


- An RC circuit has a time constant $\tau = RC$
  - because $dV/dt = I/C$, and $I = V/R \rightarrow dV/dt = V/RC$
  - so V is $V_0\exp(\pm t/\tau)$
- Any exponential function starts out with slope = Amplitude/τ
- So if you want < 10% ripple over 120 Hz (8.3 ms) timescale…
  - must have $\tau = RC > 83$ ms
  - if $R = 100\ \Omega$, $C > 830\ \mu\text{F}$



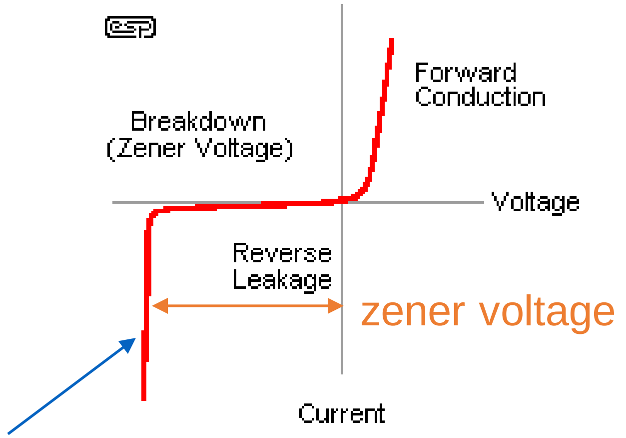
Regulating the Voltage

- The unregulated, ripply voltage may not be at the value you want:
  - depends on transformer, etc.
  - suppose you want 15.0 V
- You *could* use a voltage divider to set the voltage.
- But it would droop (bend or hang downwards limply) under load
  - output impedance $\rightarrow R_1 \,||\, R_2$
  - need to have very small R_1, R_2 to make it “stiff”
  - the divider will draw a lot of current
  - perhaps straining the source
  - power expended in divider >> power in load
- Not a “real” solution
- Important note: a “big load” means a small resistor value: 1 Ω demands more current than 1 MΩ

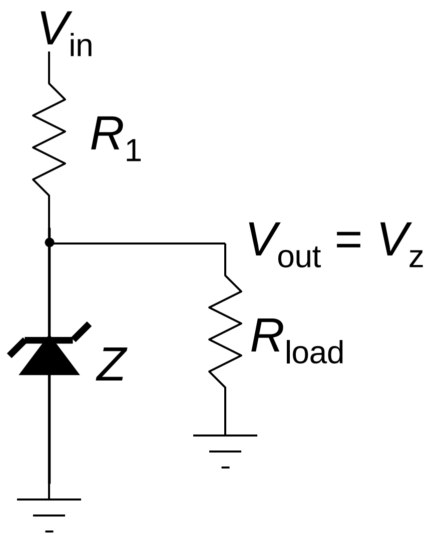


The Zener Regulator

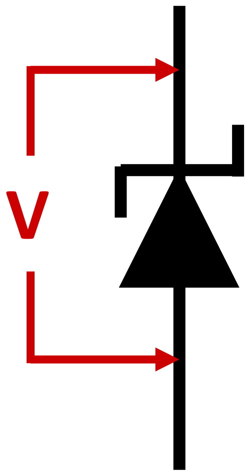
- Zener diodes break down at some reverse voltage
  - can be at specific breakdown voltages
  - as long as *some* current goes through zener, it'll work
- Conditions for working:
  - let's maintain some minimal current, I_z through zener (say a few mA)
  - then $(V_{in} - V_{out})/R_1 = I_z + V_{out}/R_{load}$ sets the requirement on R_1 because presumably all else is known
  - if load current increases too much, zener shuts off (node drops below breakdown) and you just have a voltage divider with the load

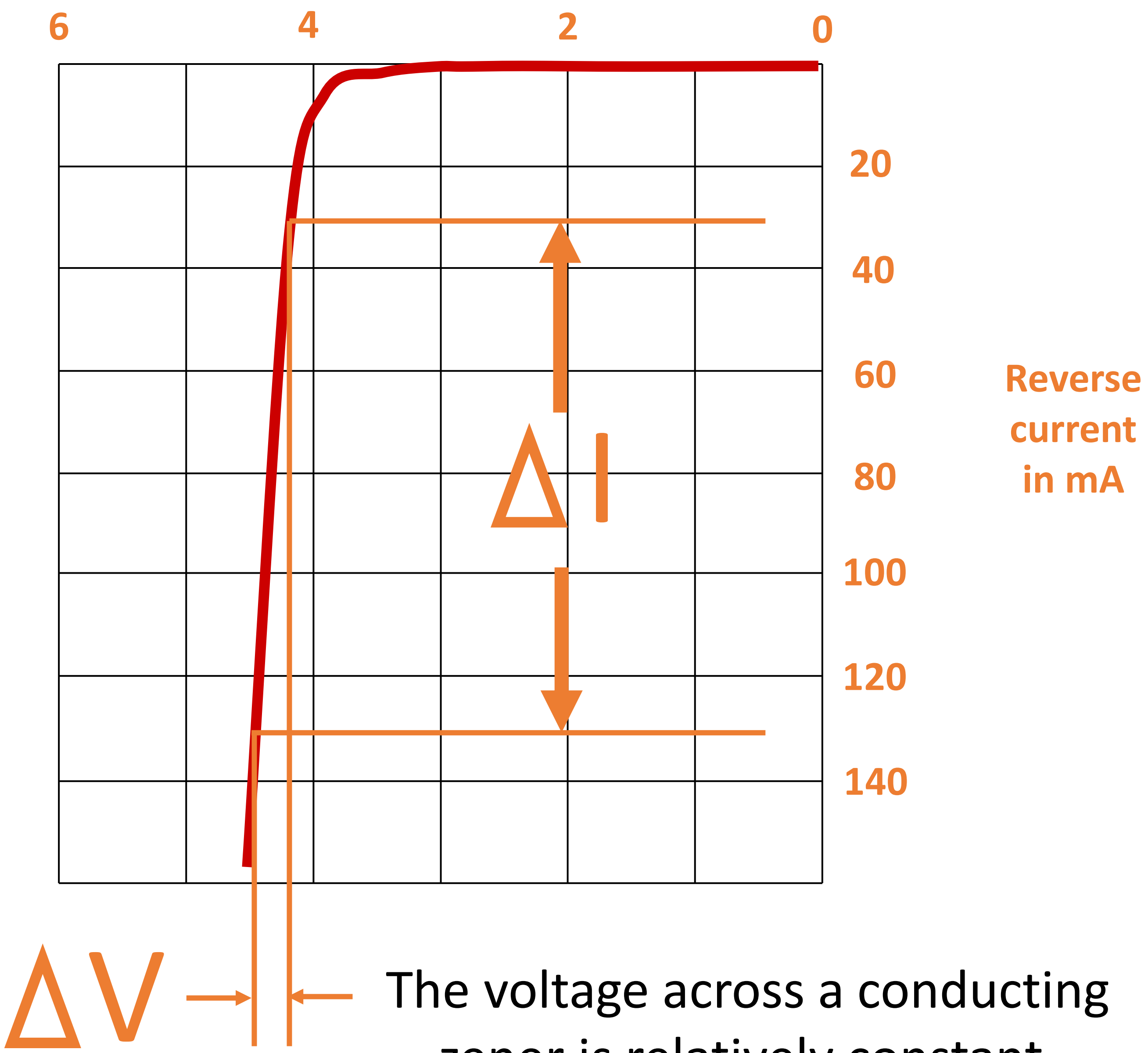


high slope is what makes the zener a decent voltage regulator



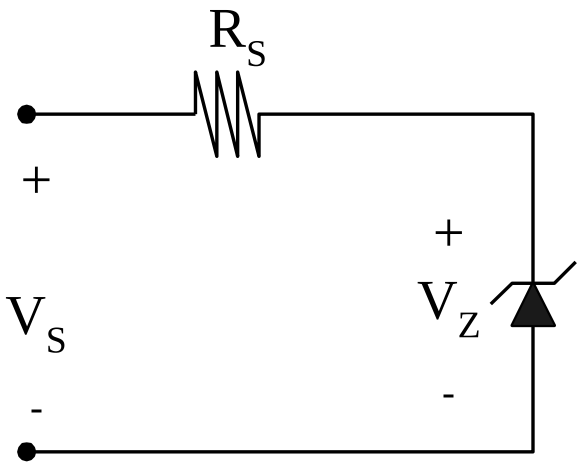
Reverse Bias in Volts



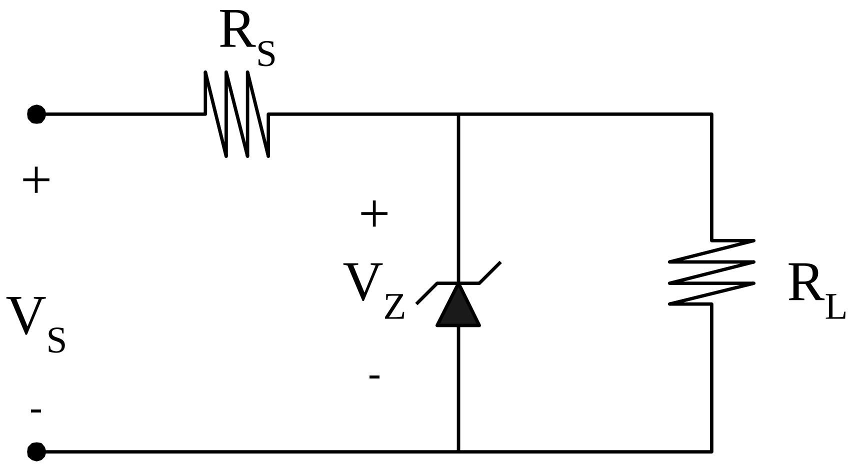


The voltage across a conducting zener is relatively constant.

Zener as Regulator



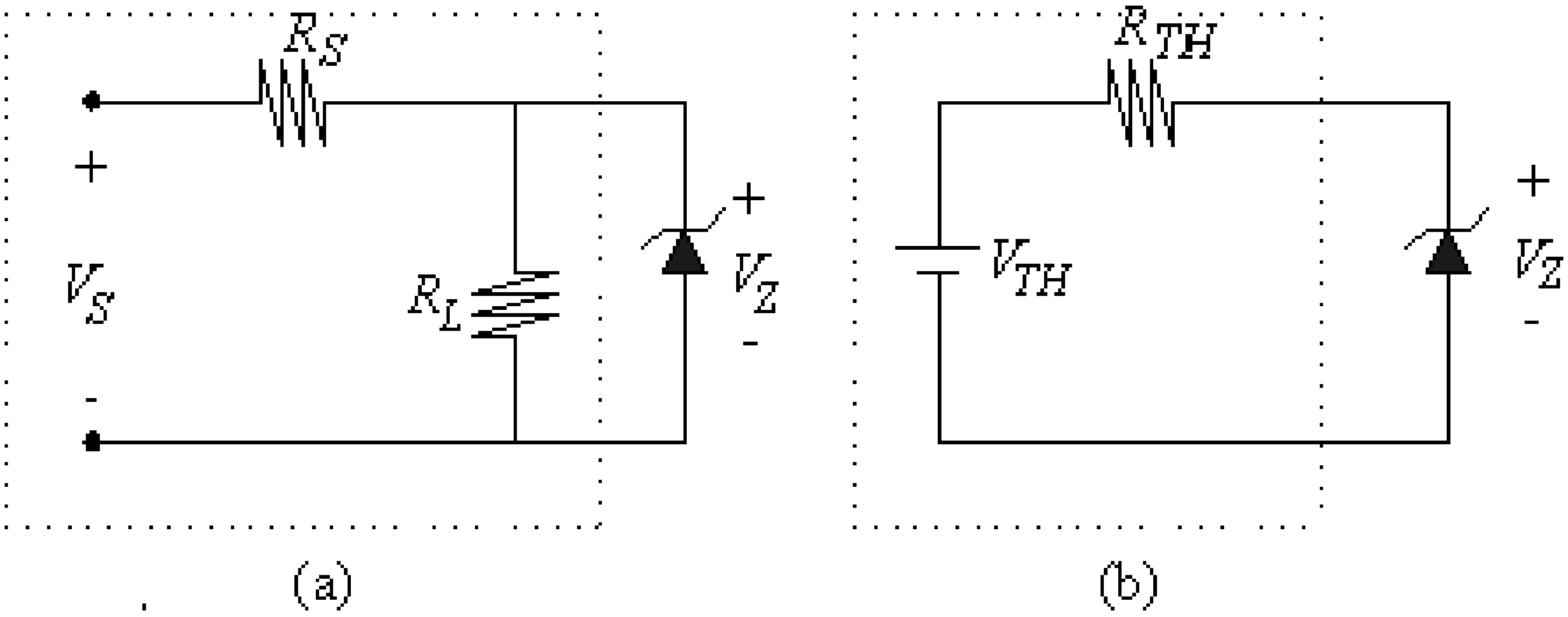
A simple regulator circuit



A regulator circuit with load resistance

- R_S is to limit the zener current, I_Z so that it is less than the maximum current, I_{ZM} (to avoid the zener diode from broken).
- How to determine whether the zener acts as a regulator or not??
  - Use Thevenin Theorem

Thevenin Equivalent Circuit

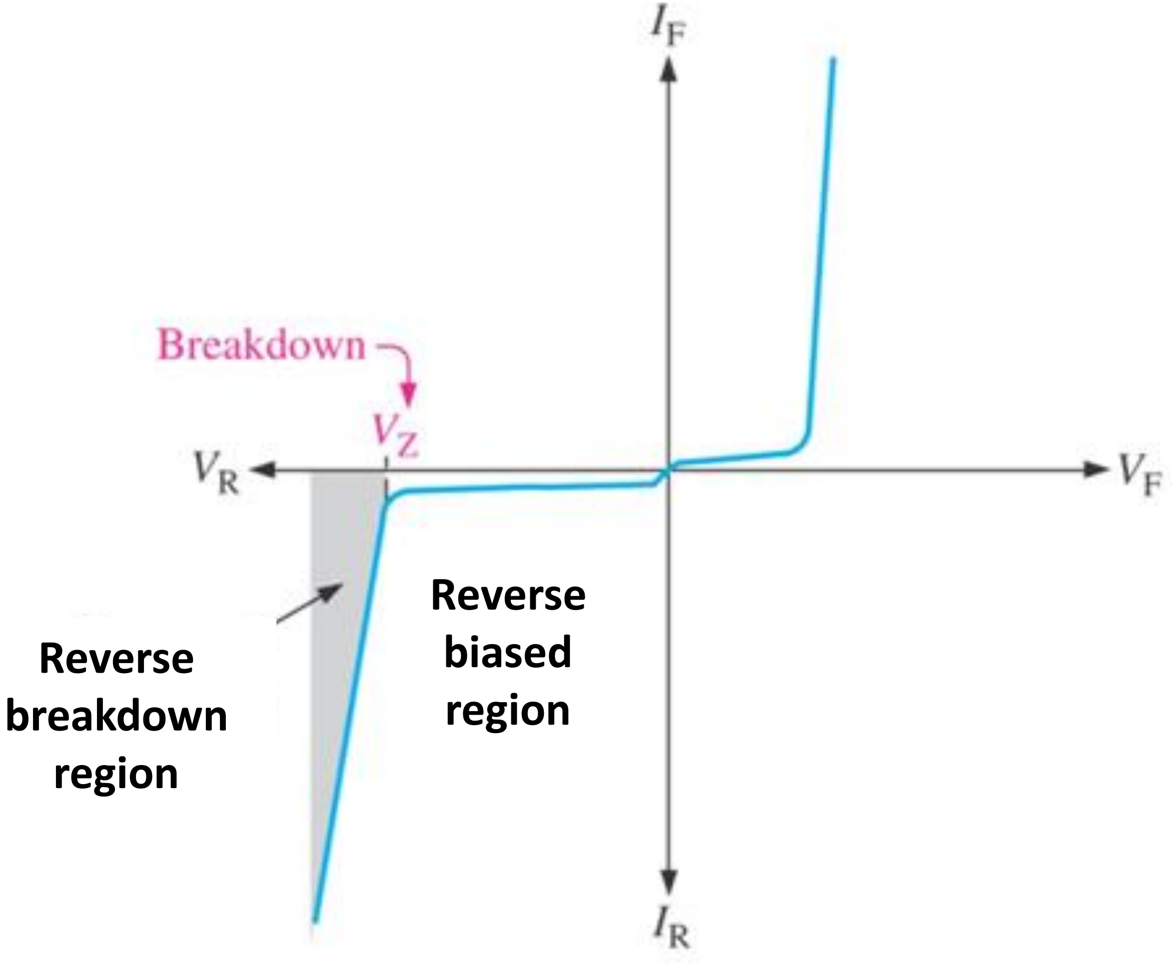


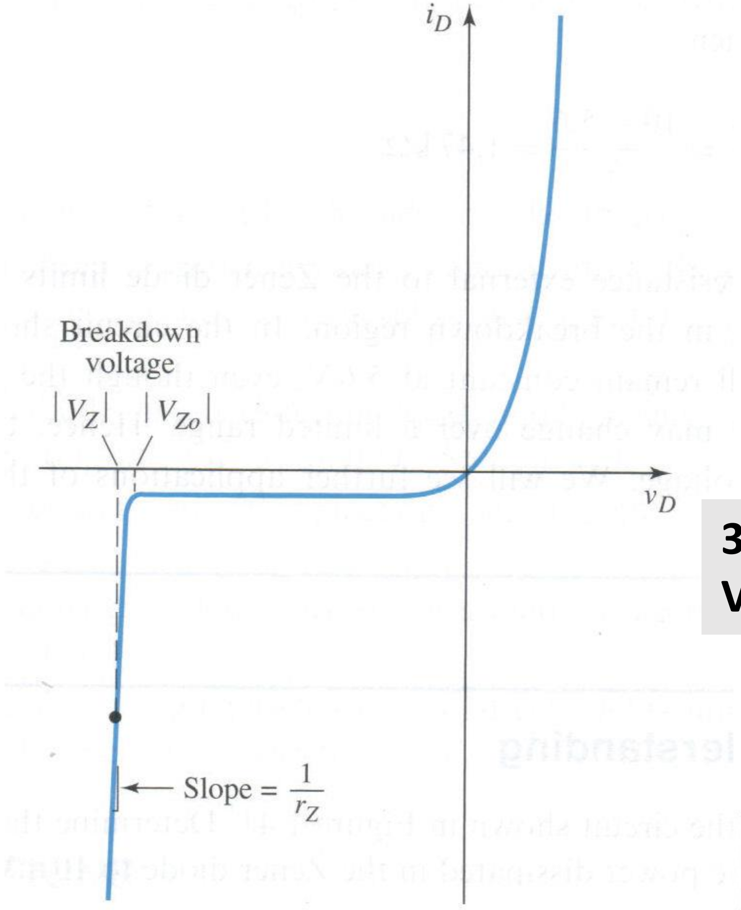
- If $V_{TH}<V_Z$, regulation does not occur.

Zener I-V Charateristic

- In the zener **I-V charateristic curve**, if the voltage across the zener diode zener is between **0-V_Z**, the zener diode is operating in the **reverse bias region**, thus it **DOES NOT** functioned as a regulator.

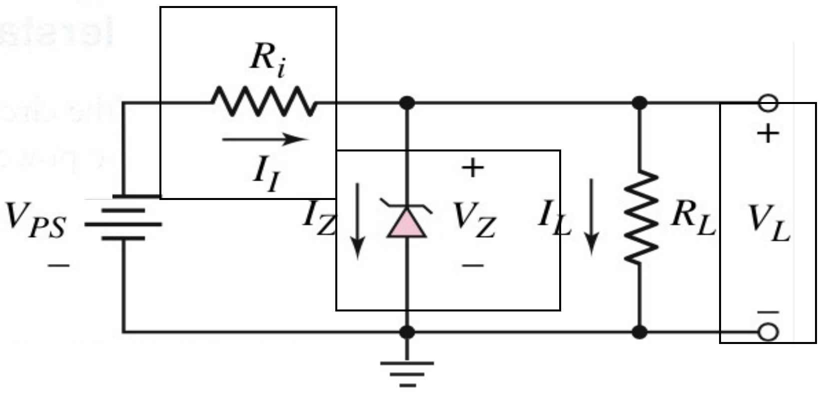
- ***V_{TH}*** must **at least** the **same value as V_Z** *($V_{TH} \geq V_Z$)* so that the diode **CAN** function as a voltage regulator because it is operating in **reverse breakdown region.**





- The breakdown voltage of a Zener diode is nearly constant over a wide range of reverse-bias currents.
- This make the Zener diode useful in a **voltage regulator**, or a constant-voltage reference circuit.

3. The remainder of V_{PS} drops across R_i



2. The load resistor sees a constant voltage regardless of the current

1. The zener diode holds the voltage constant regardless of the current

Zener Analysis

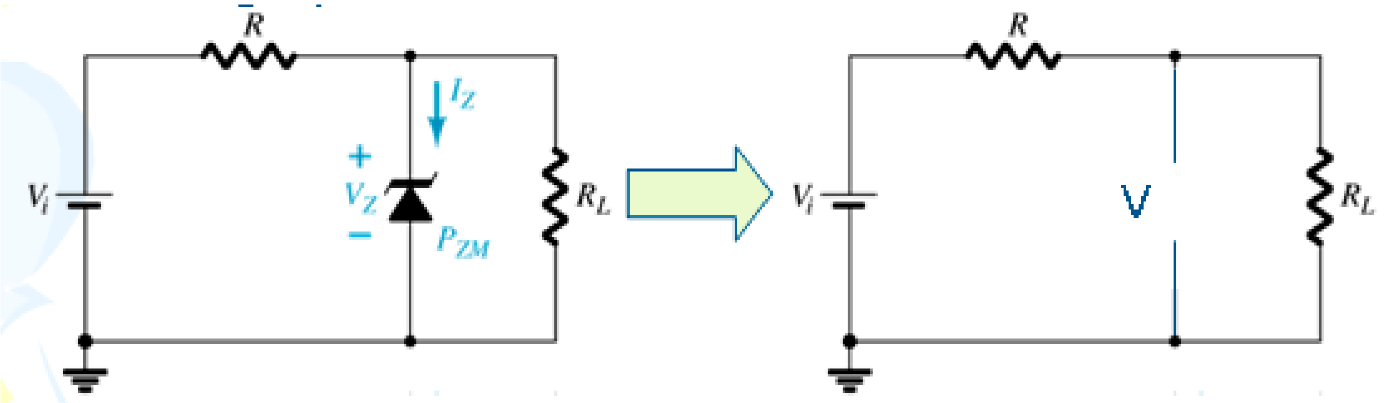
- Three types of Zener analysis
  - Fixed V_S and R_L
  - Fixed V_S and variable R_L
  - Variable V_S and fixed R_L

Fixed V_S and R_L

The applied dc voltage is fixed, as the load resistor.

The analysis :

1. Determine the state of the Zener diode by removing it from the network and calculating the voltage across the resulting open circuit.

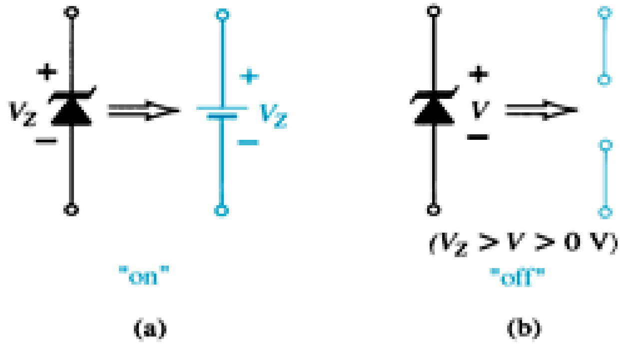


Calculate the V using voltage divider rule:

$$V = V_L = \frac{R_L V_i}{R_L + R}$$

if V ≥ Vz , the Zener diode is on

if V < Vz, the Zener diode is off



2. Substitute the appropriate equivalent circuit and solve for the desired unknowns.

- For the on state diode, the voltages across parallel elements must be the same.

$$V_L=V_Z$$

The Zener diode current is determined by KCL:

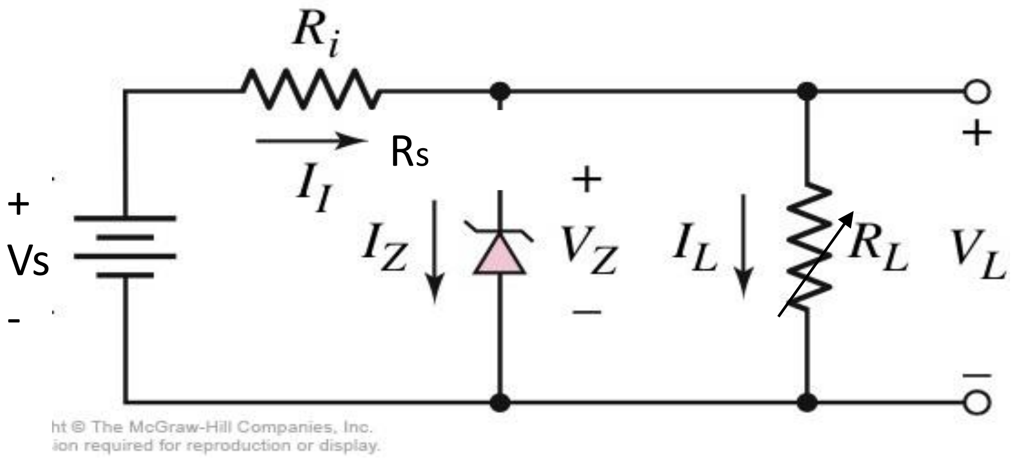
$$I_Z = I_R - I_L$$

The power dissipated by the Zener diode is determined by:

$$P_Z = V_Z I_Z$$

- For the off state diode, the equivalent circuit is open-circuit.

Fixed V_S and Variable R_L



Step 1- get the R_{Lmin} so that zener is on.

$$V_L = \frac{R_L Vs}{R_S + R_L} \longrightarrow R_{L\min} = \frac{R_S V_Z}{V_S - V_Z}$$

- if $R_L \geq R_{Lmin}$, zener diode 'on', so that $V_L = V_Z$

Step 2: Calculate the I_Z using KCL: 2 condition

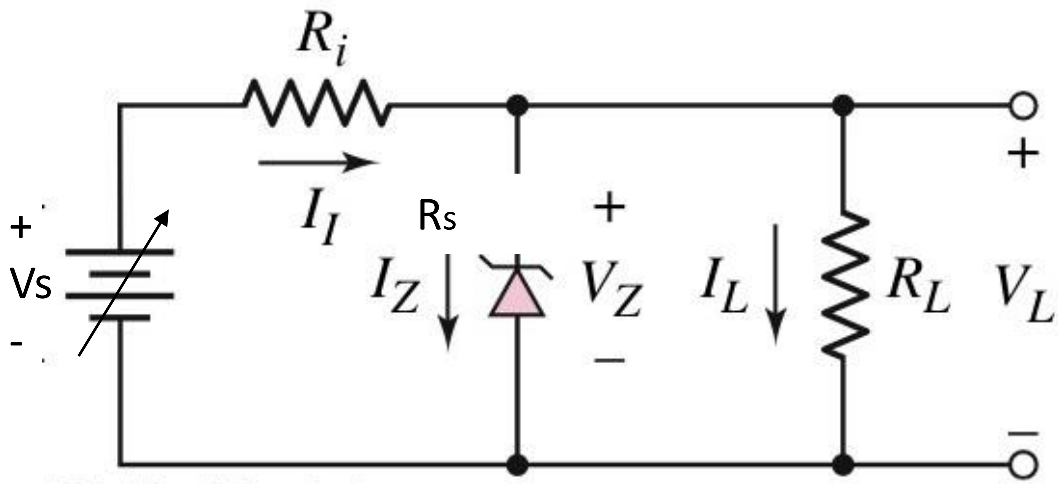
1. If R_{Lmin} , then I_{Lmax} and I_{Zmin} because of constant I_1
2. If R_{Lmax}, then I_{Lmin} and I_{Zmax}

$$I_{Z\min\ or\max} = I_{1\text{constant}} - I_{L\max\ or\min}$$

; Izmax taken from data sheet
Izmin = 0, if not given

Where $I_1 = \dfrac{V_S - V_Z}{R_S}$ and $I_{L\max} = \dfrac{V_Z}{R_{L\min}}$ or $R_{L\max} = \dfrac{V_Z}{I_{L\min}}$

Variable V_S and fixed R_L



Step 1- get the V_{Smin} so that zener is on.

$$V_L = \frac{R_L Vs}{R_S + R_L} \longrightarrow V_{S\min} = \frac{(R_L + R_S)V_Z}{R_L}$$

if $V_S \geq V_{Smin}$, zener diode will 'on', so that $V_L=V_Z$

Step 2: Calculate the I_Z using KCL: 2 condition

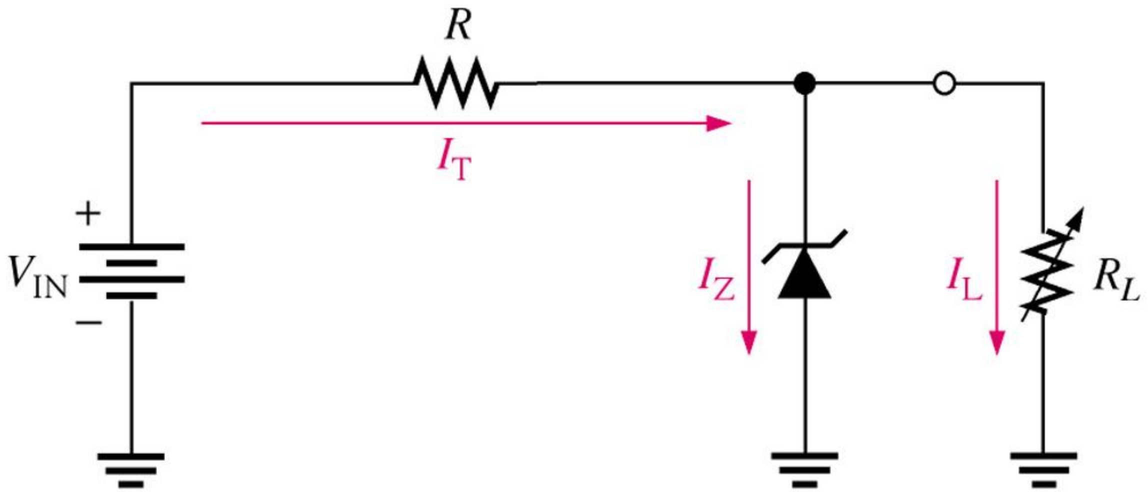
1. if V_{Smin} , then I_{1min} and I_{Zmin} because of constant I_L
2. if V_{Smax}, thenI_{1max} and I_{Zmax}

$$I_{Z\min\ or\max} = I_{1\min\ or\max} - I_{L\text{constant}}$$; Izmax= Pzmax/Vz

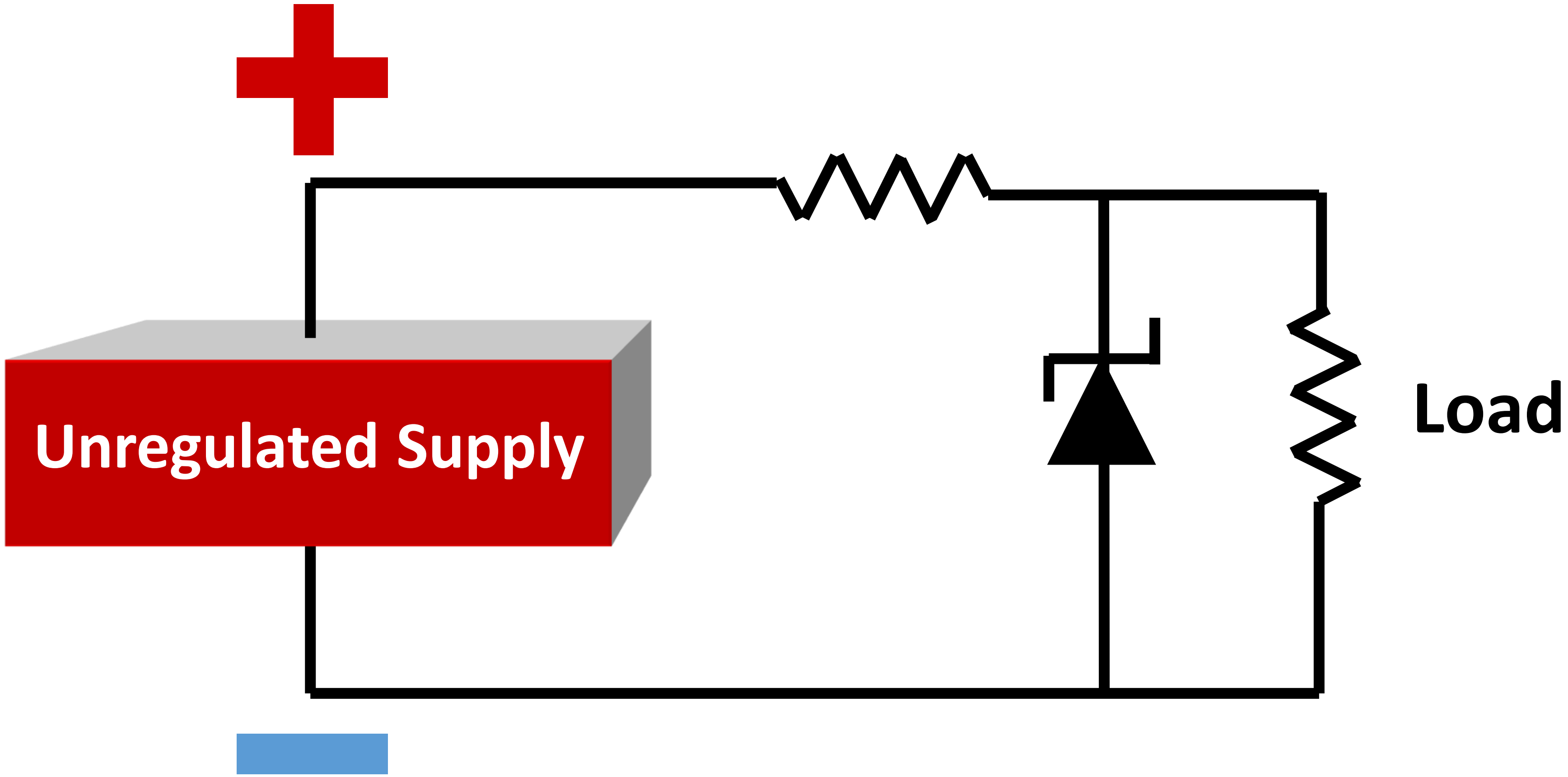
where $I_L = \frac{V_L}{R_L}$ and $I_{1\min} = \frac{V_{S\min} - V_Z}{R_S}$ or $V_{S\max} = I_{1\max} R_S + V_Z$

Zener Regulation Circuit

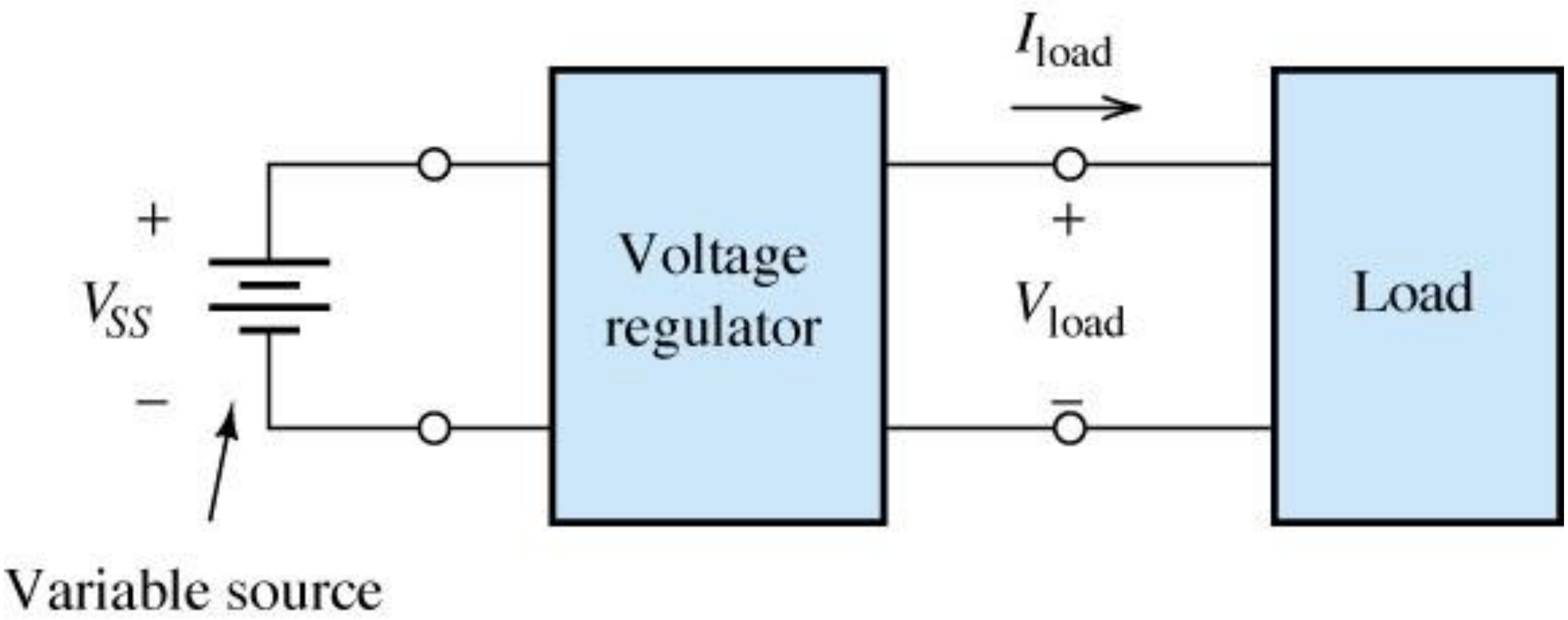
- The zener diode will "adjust" its impedance based on varying input voltages and loads (R_L) to be able to maintain its designated zener voltage.
- Zener current will increase or decrease directly with voltage input changes.
- The zener current will increase or decrease inversely with varying loads.
- Again, the zener diode has a finite range of operation.



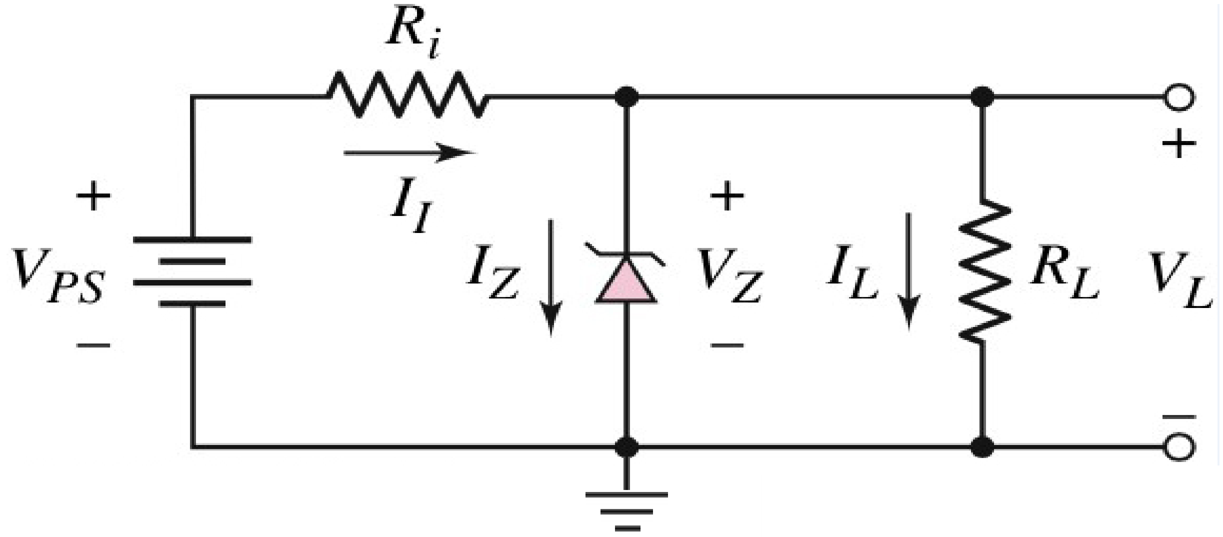
Zener Diode as Voltage Regulator



The load is in parallel with the zener and will see a relatively constant voltage as long as the zener is conducting.

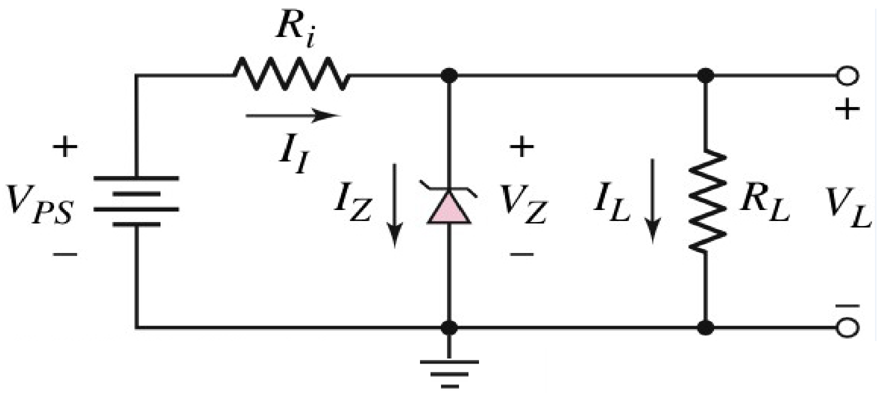

I_{load}
+
V_{SS}
−
Voltage regulator
+
V_{load}
−
Load
Variable source

Example 1



A Zener diode is connected in a voltage regulator circuit. It is given that V_{PS} = 20V, the Zener voltage, V_Z = 10V, R_i = 222 Ω and $P_{Z(\text{max})}$ = 400 mW.

a. Determine the values of I_L, I_Z and I_I if R_L = 380 Ω.
b. Determine the value of R_L that will establish $P_{Z(\text{max})}$ = 400 mW in the diode.



For proper function the circuit must satisfied the following conditions.

1. The power dissipation in the Zener diode is less than the rated value
2. When the power supply is a minimum, V_{PS}(min), there must be minimum current in the zener diode I_Z(min), hence the load current is a maximum, I_L(max),
3. When the power supply is a maximum, V_{PS}(max), the current in the diode is a maximum, I_Z(max), hence the load current is a minimum, I_L(min)

$$R_i = \frac{V_{PS}(\text{min}) - V_Z}{I_Z(\text{min}) + I_L(\text{max})}$$ **AND** $$R_i = \frac{V_{PS}(\text{max}) - V_Z}{I_Z(\text{max}) + I_L(\text{min})}$$ Or, we can write

$$[V_{PS}(\text{min}) - V_Z] \,.\, [I_Z(\text{max}) + I_L(\text{min})] = [V_{PS}(\text{max}) - V_Z] .\, [I_Z(\text{min}) + I_L(\text{max})]$$

For general thumb of rule for design this circuit is, so from the last Equation

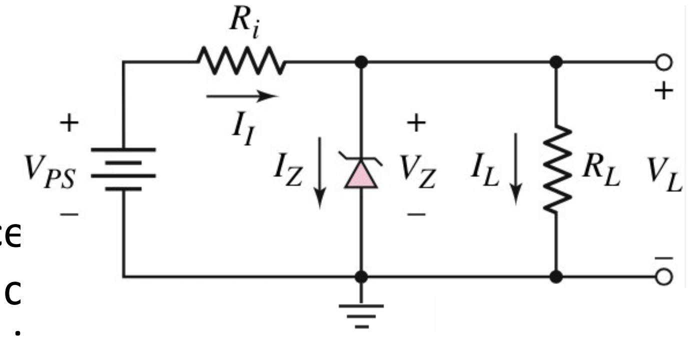
$$I_Z(\max) = \frac{I_L(\max).[V_{PS}(\max) - V_Z] - I_L(\min).[V_{PS}(\min) - V_Z]}{V_{PS}(\min) - 0.9V_Z - 0.1V_{PS}(\max)}$$

Maximum power dispassion in the Zener diode is

$$P_Z(\max) = I_Z(\max) \times V_Z$$

EXAMPLE

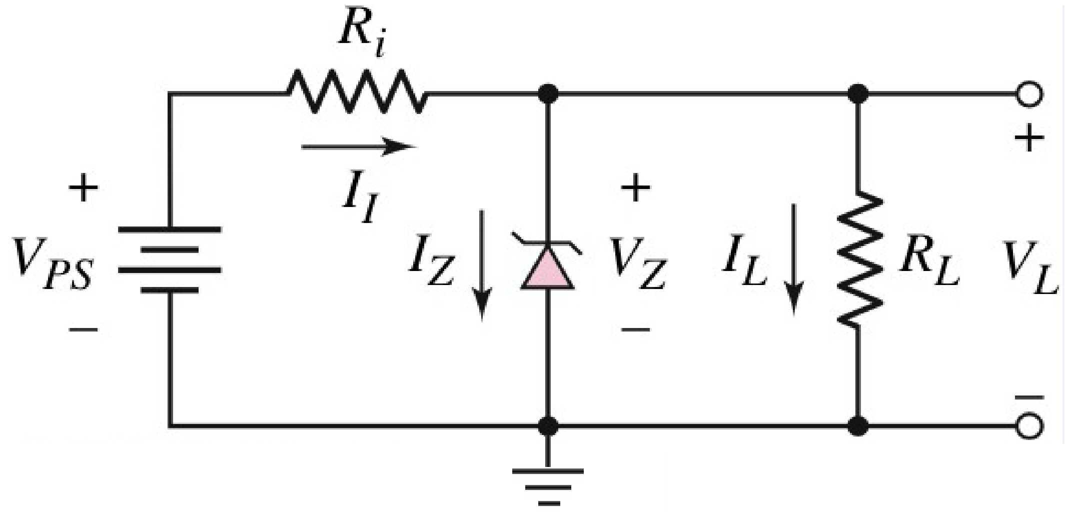
Consider voltage regulator is used to power the ce phone at 2.5 V from the lithium ion battery, whic voltage may vary between 3 and 3.6 V. The current in the phone will vary 0 (off) to 100 mA(when talking). Calculate the value of R_i and the Zener diode power dissipation



simple Zener diode voltage regulator circuit

Example 2

Consider voltage regulator is used to power the cell phone at 2.5 V from the lithium ion battery, which voltage may vary between 3 and 3.6 V. The current in the phone will vary 0 (off) to 100 mA(when talking). Calculate the value of R_i and the Zener diode power dissipation



Solution:

The stabilized voltage V_L = 2.5 V, so the Zener diode voltage must be V_Z = 2.5 V. The maximum Zener diode current is

$$I_Z(\max) = \frac{I_L(\max).[V_{PS}(\max) - V_Z] - I_L(\min).[V_{PS}(\min) - V_Z]}{V_{PS}(\min) - 0.9V_Z - 0.1V_{PS}(\max)}$$

Or, $$I_Z(\max) = \frac{100 \times [3.6 - 2.5] - 0 \times [3 - 2.5]}{3 - 0.9 \times 2.5 - 0.1 \times 3.6} = 282.05 \text{ mA}$$

The maximum power dispassion in the Zener diode is $P_Z(\max) = I_Z(\max) \times V_Z = 282.05 \times 2.5 = 705.13 \text{ mW}$

The value of the current limiting resistance is

$$R_i = \frac{V_{PS}(\max) - V_Z}{I_Z(\max) + I_L(\min)} = \frac{3.6 - 2.5}{282.05 + 0} \approx 3.9\ \Omega$$

References:

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