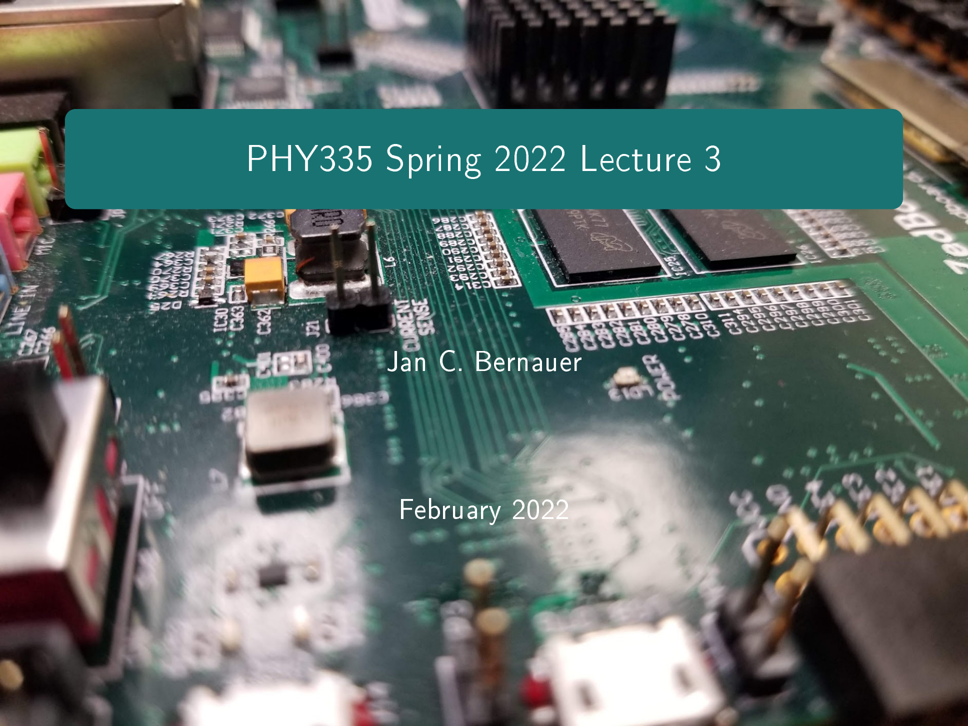


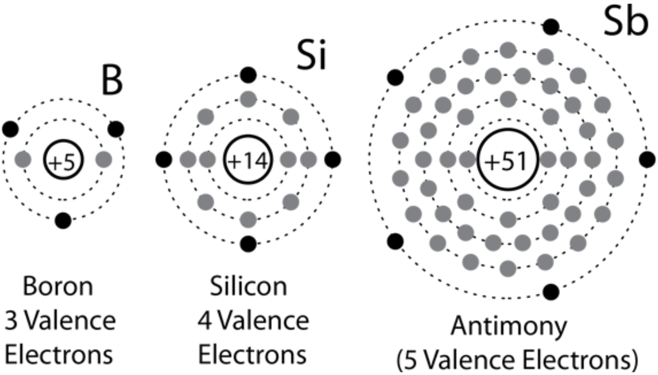
PHY335 Spring 2022 Lecture 3

Jan C. Bernauer

February 2022

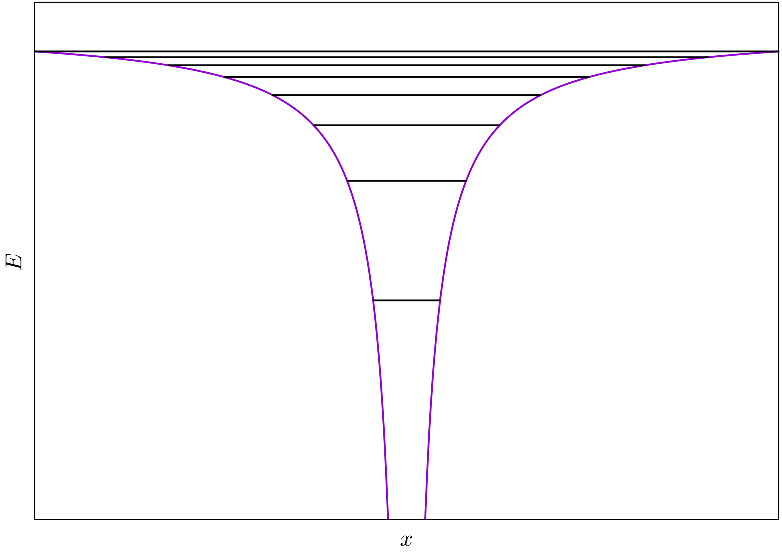
Valence electrons

The electrons in the outermost shell of an atom are called valence electrons.

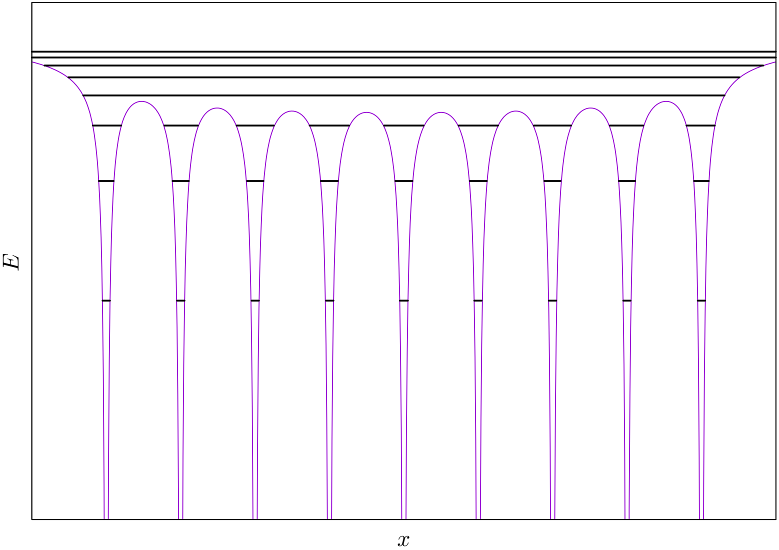


They determine the chemical but also the electrical properties of the material.

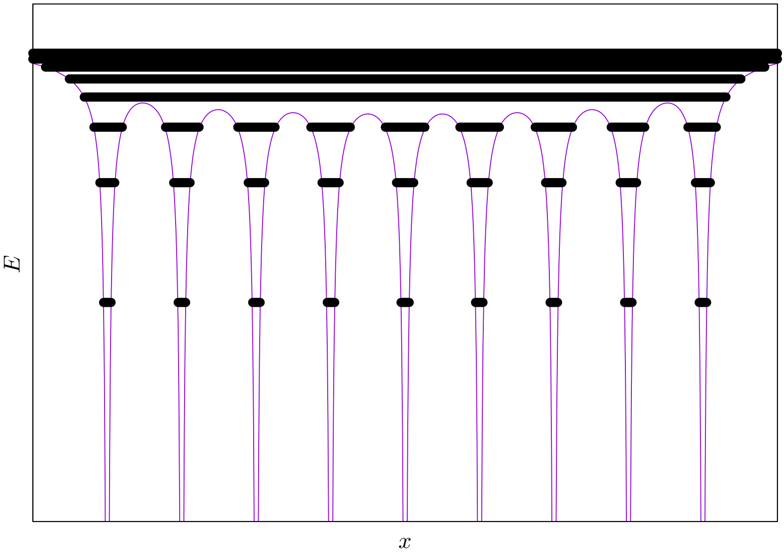
Energy levels



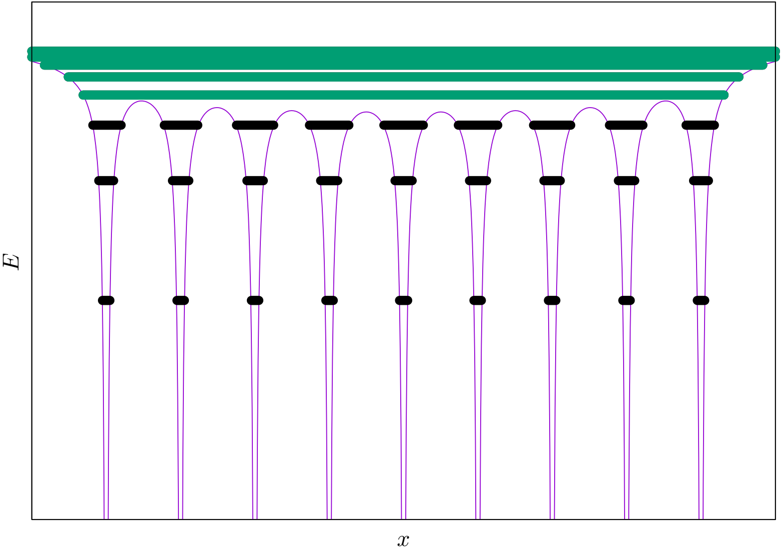
Energy levels



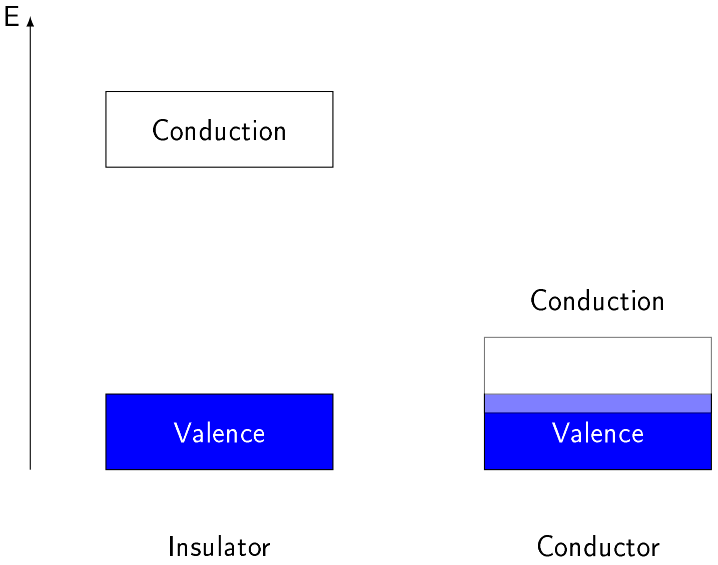
Energy levels



Energy levels

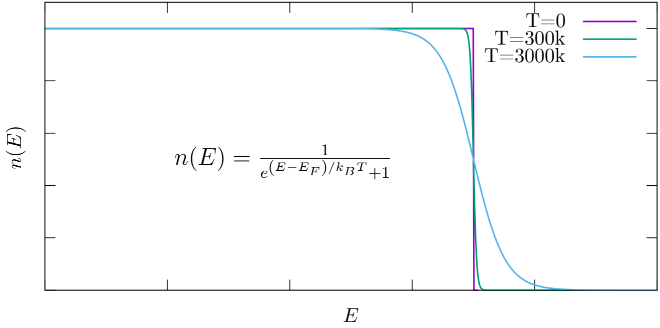


Insulator and conductors

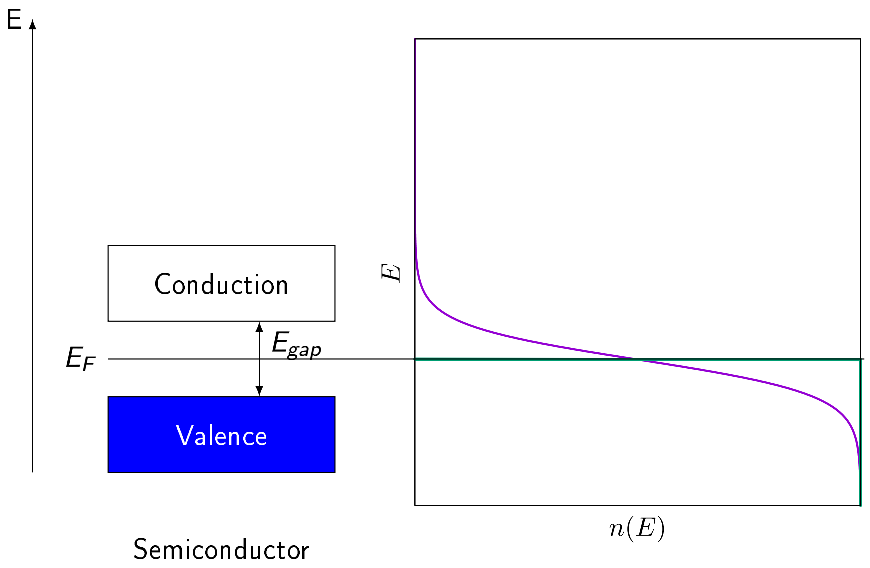


Fermi Level

At absolute zero, T=0K, electrons have a maximum energy called the Fermi level, E_F. At higher temperatures, higher levels can be occupied, according to the Fermi function.



Semiconductor



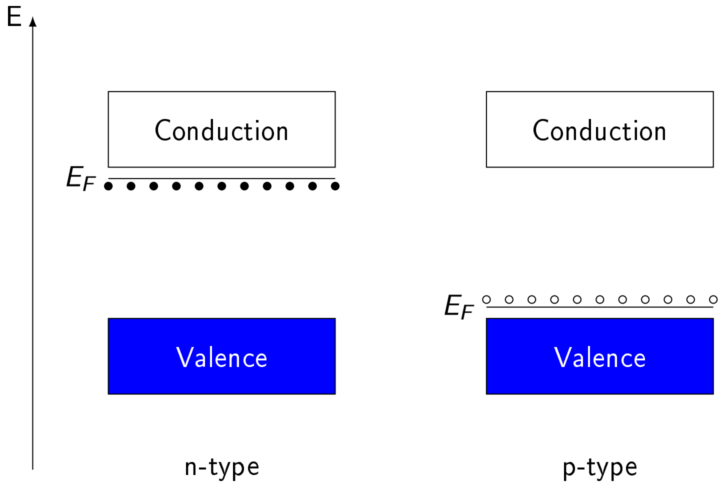
Doping

- Gap for semiconductors ~eV, $k_B T \sim 26meV$ at room temperature, so very few electron/hole pairs

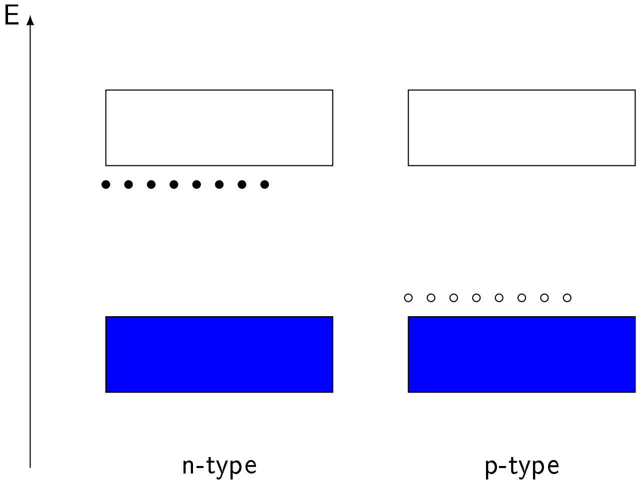
Doping

- Gap for semiconductors ~eV, $k_B T \sim 26 meV$ at room temperature, so very few electron/hole pairs
- We can add electrons / holes by doping the semiconductor (with elements of the 3th/5th group)
- n-doped: Additional electrons from donor atoms with E_F close to the conduction band. Electrons majority carrier, holes minority.
- p-doped: Additional holes from acceptor atoms with E_F close to the valence band. Holes majority carrier, electrons minority.

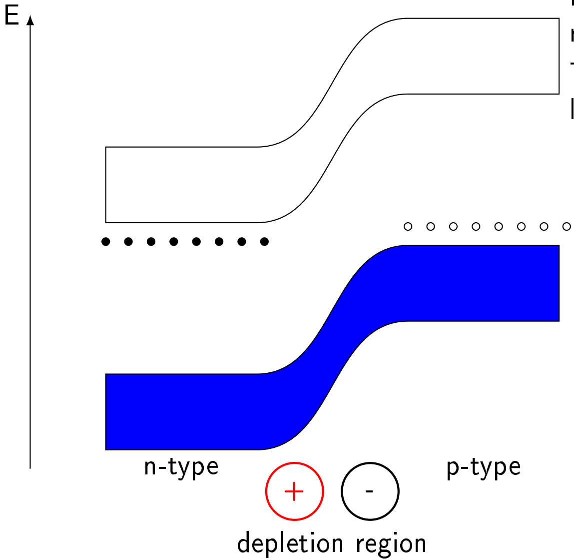
Doped semiconductor



pn Junction



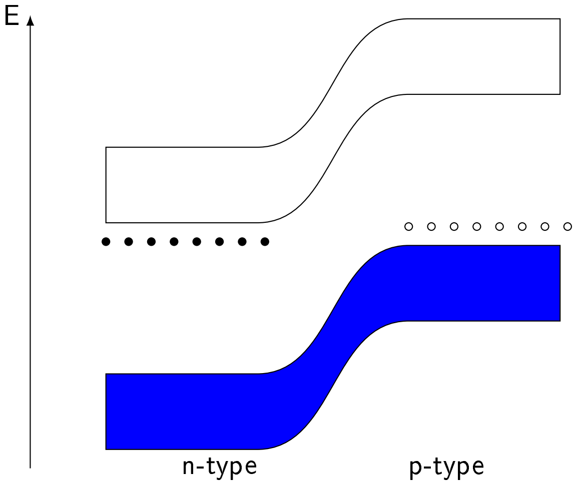
pn Junction



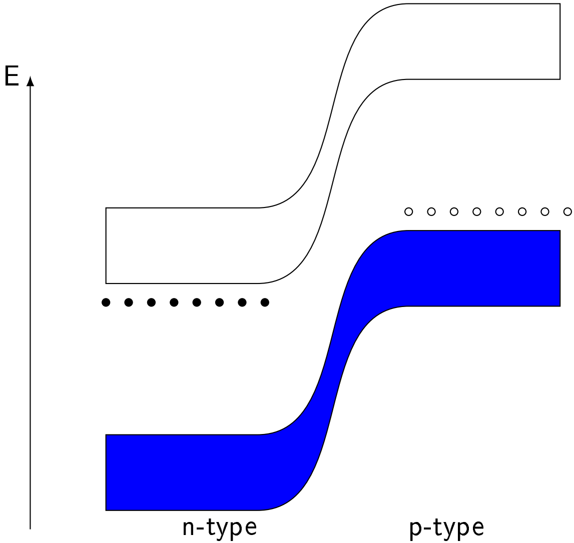
Electrons drift n⟶p recombine, form ions

This produces an E-field, levels shift.

Reverse bias



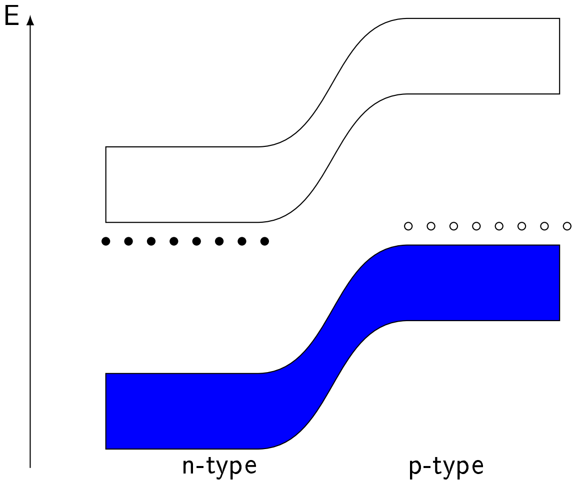
Reverse bias



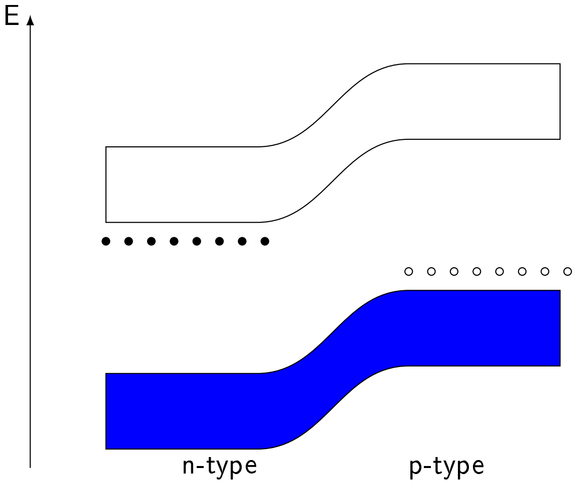
If an external voltage is applied,
+ to n, - to p

the bands shift more,
no current can flow

Forward bias



Forward bias



If an external voltage is applied,
+ to p, - to n

the bands shift back, current can flow

Some formulas

- Forward current I_F: Thermally excited electrons/holes can pass the barrier
- Reverse current I_R : Minority carriers are swept through the depletion region

(Both are defined from p to n!)

No bias voltage:

$$I = I_{F,0} + I_{R,0} = 0$$

Some formulas

- Forward current I_F: Thermally excited electrons/holes can pass the barrier
- Reverse current I_R : Minority carriers are swept through the depletion region

(Both are defined from p to n!)

No bias voltage:

$$I = I_{F,0} + I_{R,0} = 0$$

Reverse Bias: Harder to have enough energy for I_F, I_R unaffected

$$I = I_F + I_R \approx I_{F,0} e^{-\frac{eV}{k_B T}} + I_R = I_R$$

Forward Bias: Easier to have enough energy:

$$I \approx I_{F,0} e^{\frac{eV}{k_B T}} + I_{R,0}$$

Ideal diode equation

Define saturation/scale current

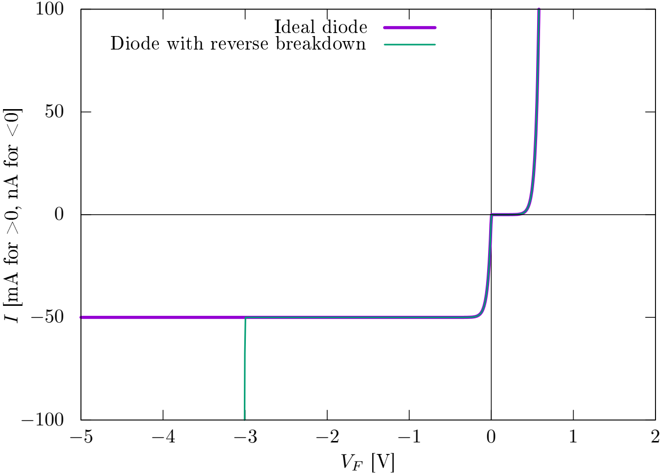
$$I_S = I_{F,0} = -I_{R,0}$$

Ideal Diode equation (Schokley):

$$I = I_S \left(e^{\frac{eV}{k_B T}} - 1 \right)$$

where voltage V is positive when "plus" is connected to p

Diode I-V



Ideal diode
Diode with reverse breakdown
100
50
0
−50
−100
−5
−4
−3
−2
−1
0
1
2
I [mA for >0, nA for <0]
V_F [V]

Reverse breakdown

- Zener breakdown: Enough field to rip electrons out of valence bounds.
- Avalanche: electrons gain enough energy during drift that they knock out more electrons.

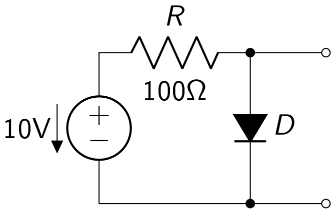
This is used in Zener diodes (<8V mostly Zener, >8V mostly Avalanche)

Useful approximations we will use

- For an applied voltage between reverse breakdown and V_F (the "knee", diode forward voltage drop), there is no current.
- For voltages outside the band, the current is so that the voltage is reduced to the border values.
- Typical V_F is 0.6-0.7V for standard pn-diodes

Some diode applications

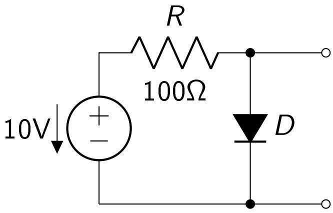
Diodes as voltage references



Current I_D so that $V_D = 0.6V$:

Some diode applications

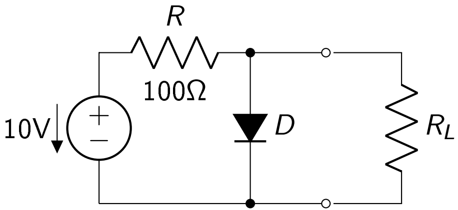
Diodes as voltage references



Current I_D so that $V_D = 0.6V$:
$V_R = 10V - 0.6V = 9.4V$, $I_R = I_D = \frac{9.4V}{100\Omega} = 94mA$
With load: $V_L = 0.6V$ as long as $R_L > \frac{0.6V}{94mA} = 6.4\Omega$

Some diode applications

Diodes as voltage references



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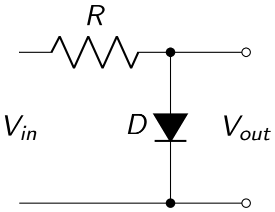
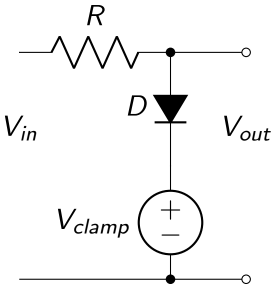
Voltage clamping



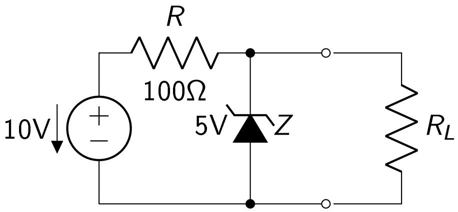
$$V_{out} = \min(0.6V, V_{in})$$

Voltage clamping



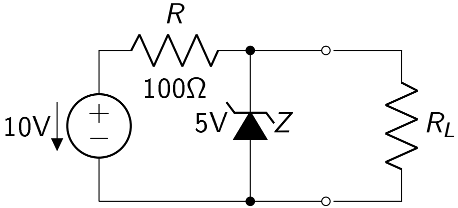
$$V_{out} = \min(V_{clamp} + 0.6V, V_{in})$$

Zener diode in reverse



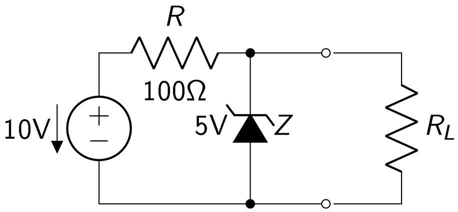
Current I_D so that $V_D = 5V$:

Zener diode in reverse



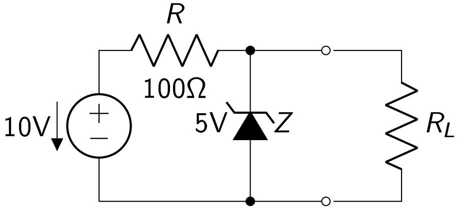
Current I_D so that $V_D = 5V$:
$V_R = 10V - 5V = 5V$, $I_R = I_D = \frac{5V}{100\Omega} = 50mA$
With load: $V_L = 5V$ as long as $R_L > \frac{5V}{50mA} = 100\Omega$

Zener diode in reverse



Current I_D so that $V_D = 5V$:
$V_R = 10V - 5V = 5V$, $I_R = I_D = \frac{5V}{100\Omega} = 50mA$
With load: $V_L = 5V$ as long as $R_L > \frac{5V}{50mA} = 100\Omega$
Compare to a resistive divider: $R_2 = 100\Omega$, $R_L$of 100Ω would change V_L by ∼2V!

Zener diode in reverse



Current I_D so that $V_D = 5V$:

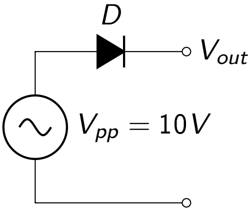
$V_R = 10V - 5V = 5V$, $I_R = I_D = \frac{5V}{100\Omega} = 50mA$

With load: $V_L = 5V$ as long as $R_L > \frac{5V}{50mA} = 100\Omega$

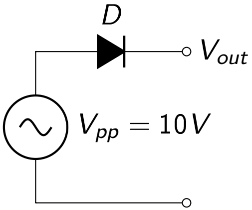
Compare to a resistive divider: $R_2 = 100\Omega$, $R_L$of 100Ω would change V_L by $\sim$2V!

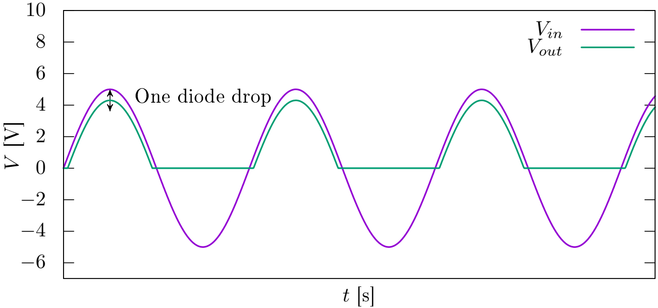
Zener can be very useful for voltage clamps!

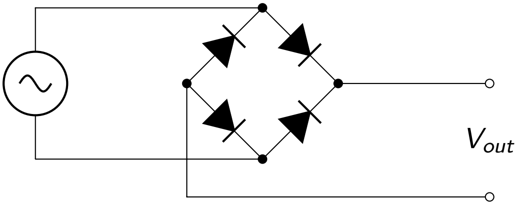
Half-wave rectifier

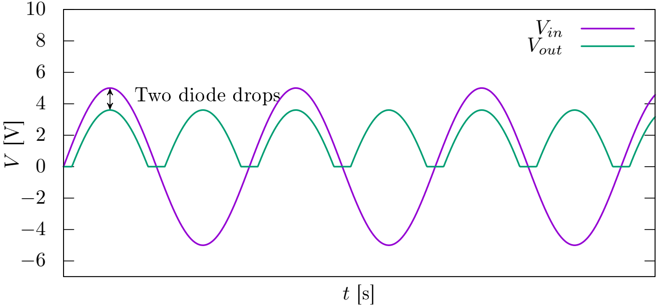


Half-wave rectifier

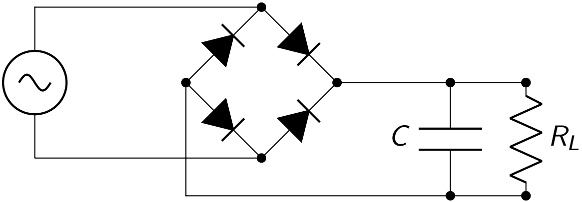




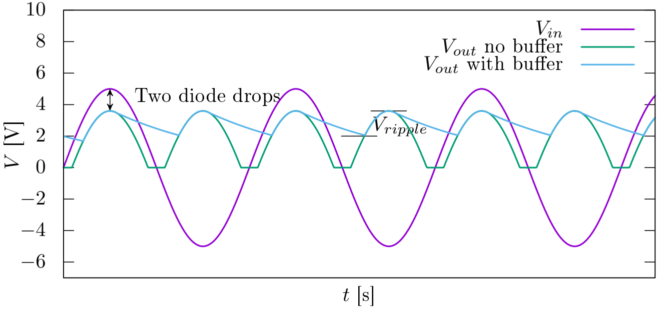

V_{out}


10
8
6
4
2
0
−2
−4
−6
V [V]
t [s]
V_{in}
V_{out}
Two diode drops

Buffer capacitor



If $RC \gg T/2$, V_{out} between V_{max} and $V_{max} - V_{ripple}$

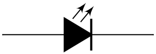


Ripple

If V_{ripple} is small compared to V_{max}, I ~constant,

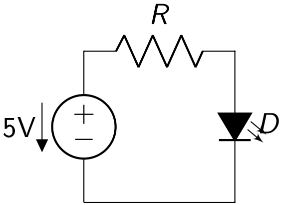
$$V_{ripple} \approx \frac{I}{C}\Delta T \approx \frac{I}{C}\frac{T}{2} = \frac{V_{max}}{RC}\frac{T}{2}$$

Light emitting diodes



- The forward current has electrons fall into holes at the np interface layer. The energy of the electrons is released in the form of photons.
- The frequency of that light depends on the energy: $E = \hbar f$. This roughly aligns LED color with V_f: red (610-760nm): 1.6-2V, to violet (400-450nm) 2.8-4V
- White LED: either RGB, or blue/violet with white phosphor (like CFL)

LED II



- They burn out quickly if the current is too high (the junction gets too hot). That's why you need to limit the current. Mostly: Resistor
- Example: 5V, red LED. Resistor needs to drop 3.4V at 15mA, so 226Ω in series