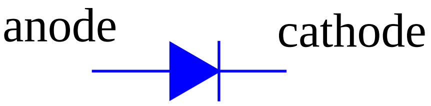
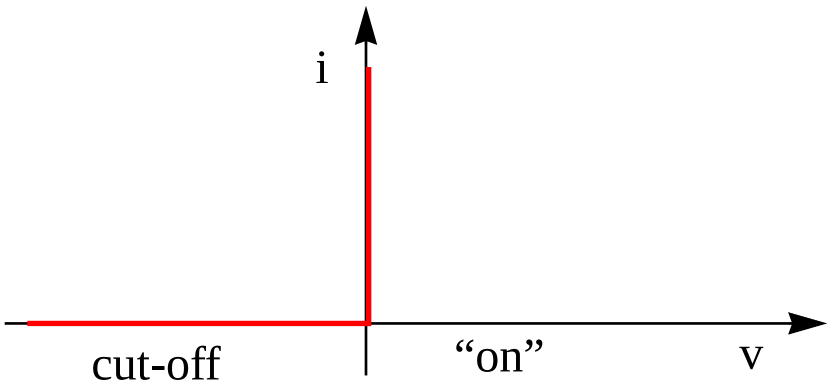
Diodes

- Simplest nonlinear circuit element
- Basic operation sets the foundation for Bipolar Junction Transistors (BJTs)
- Also present in Field Effect Transistors (FETs)
- Ideal diode characteristic

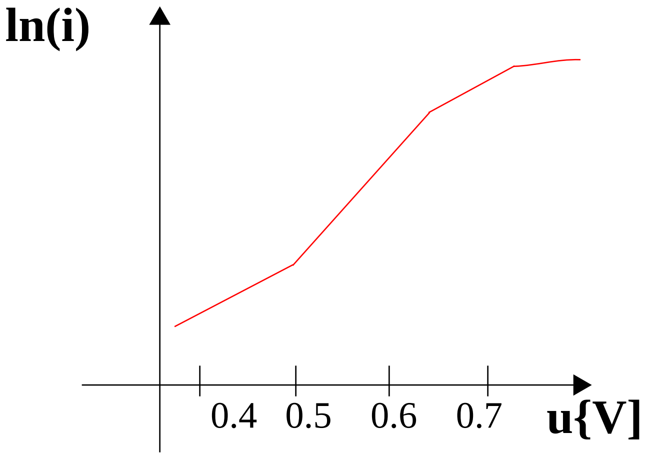


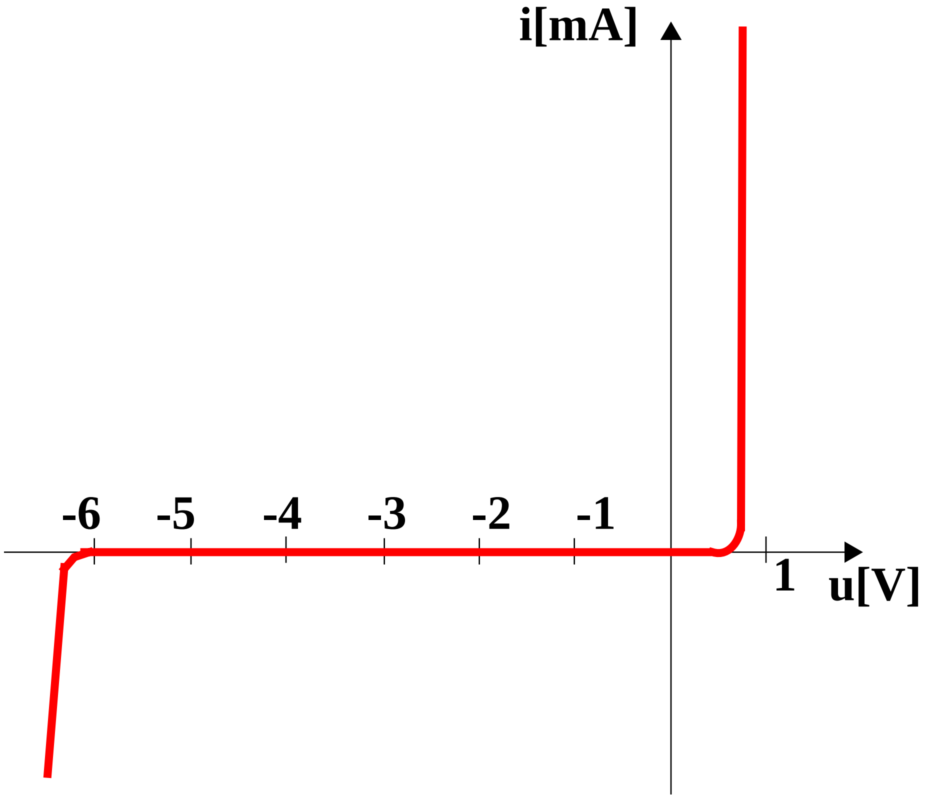


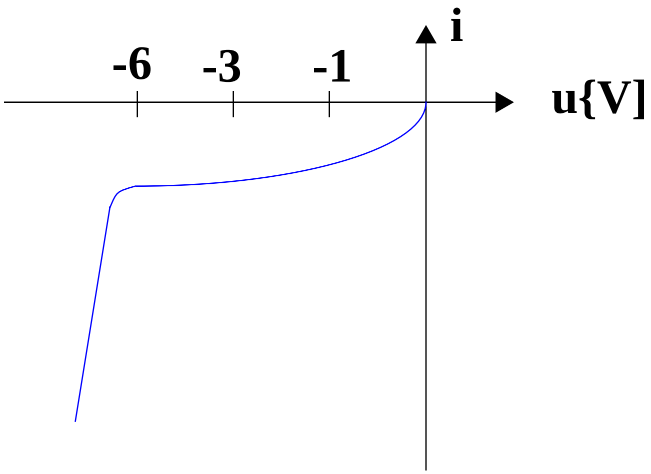
- Can be approximated by a piecewise-linear-like characteristic

Actual p-n Diode Characteristic

- An actual diode does not follow this ideal behavior
- The “turn-on” voltage is generally between 0.5 and 0.8 volts
- The diode breaks down for large reverse bias

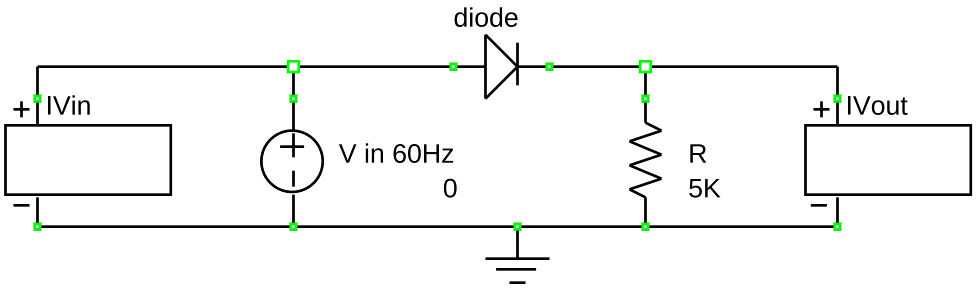


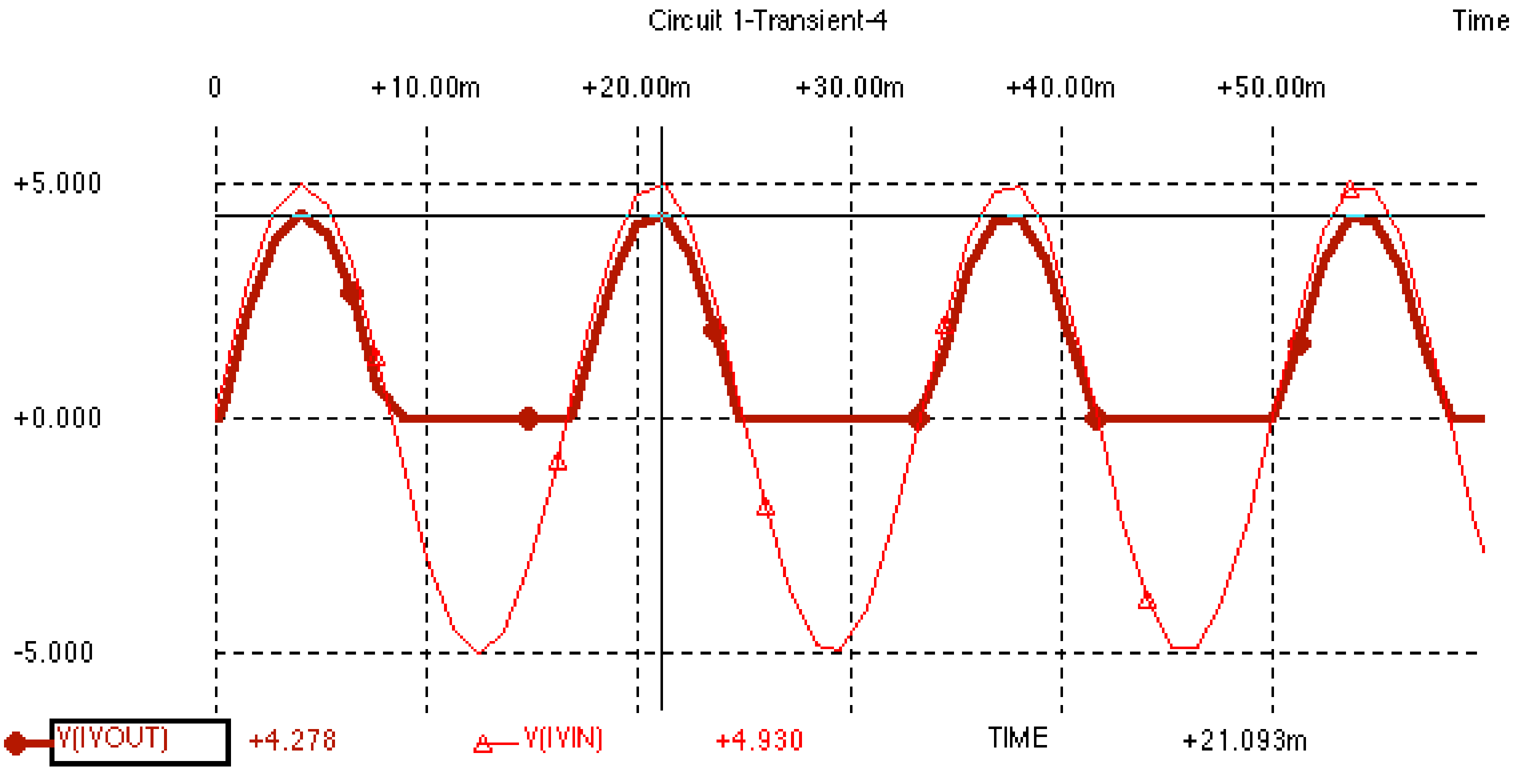




Diodes for Rectification

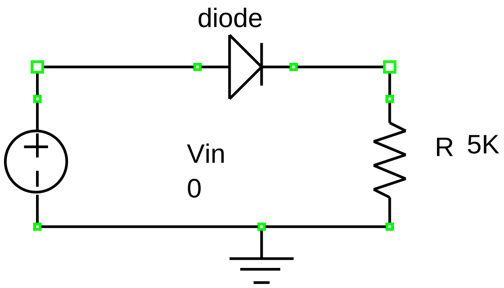
- Commonly used for power supplies and to convert ac signals to dc signals

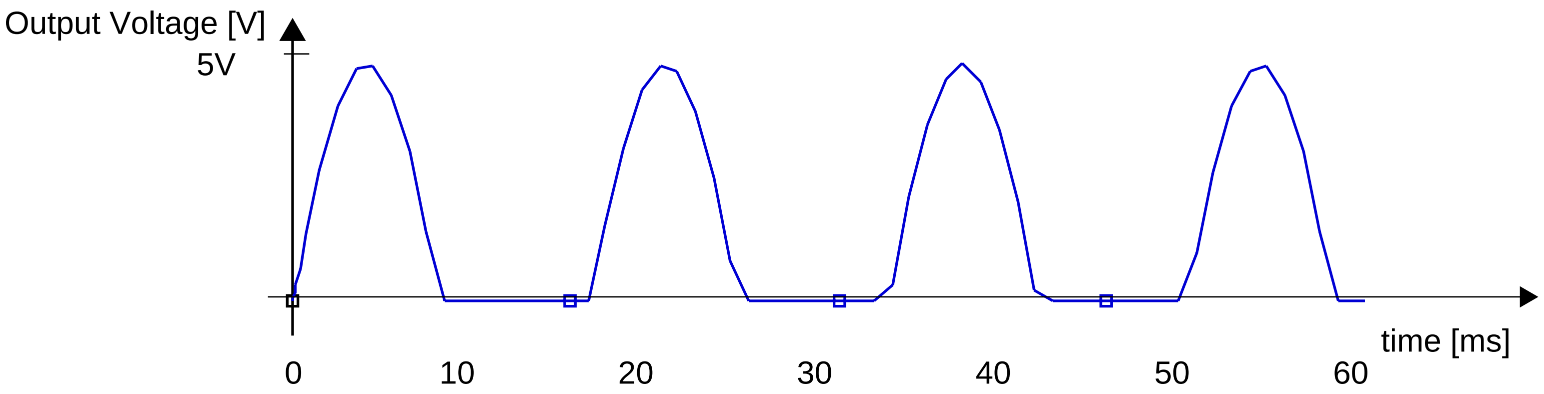




Diodes for Rectification

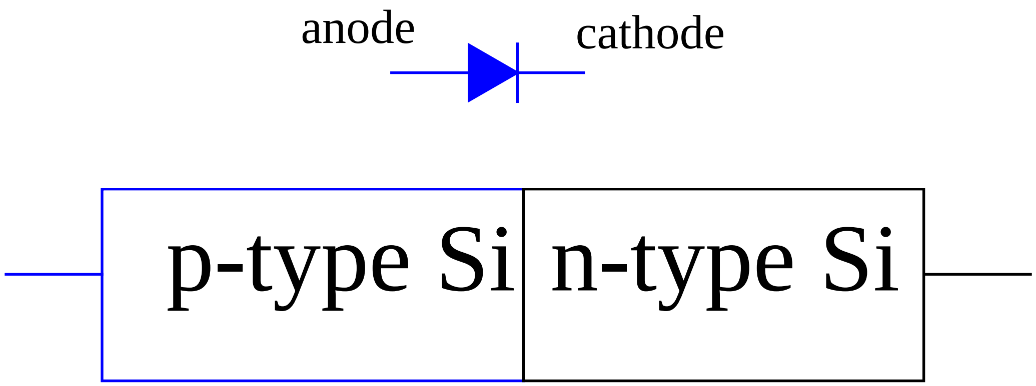
- This is a half-wave recitifier





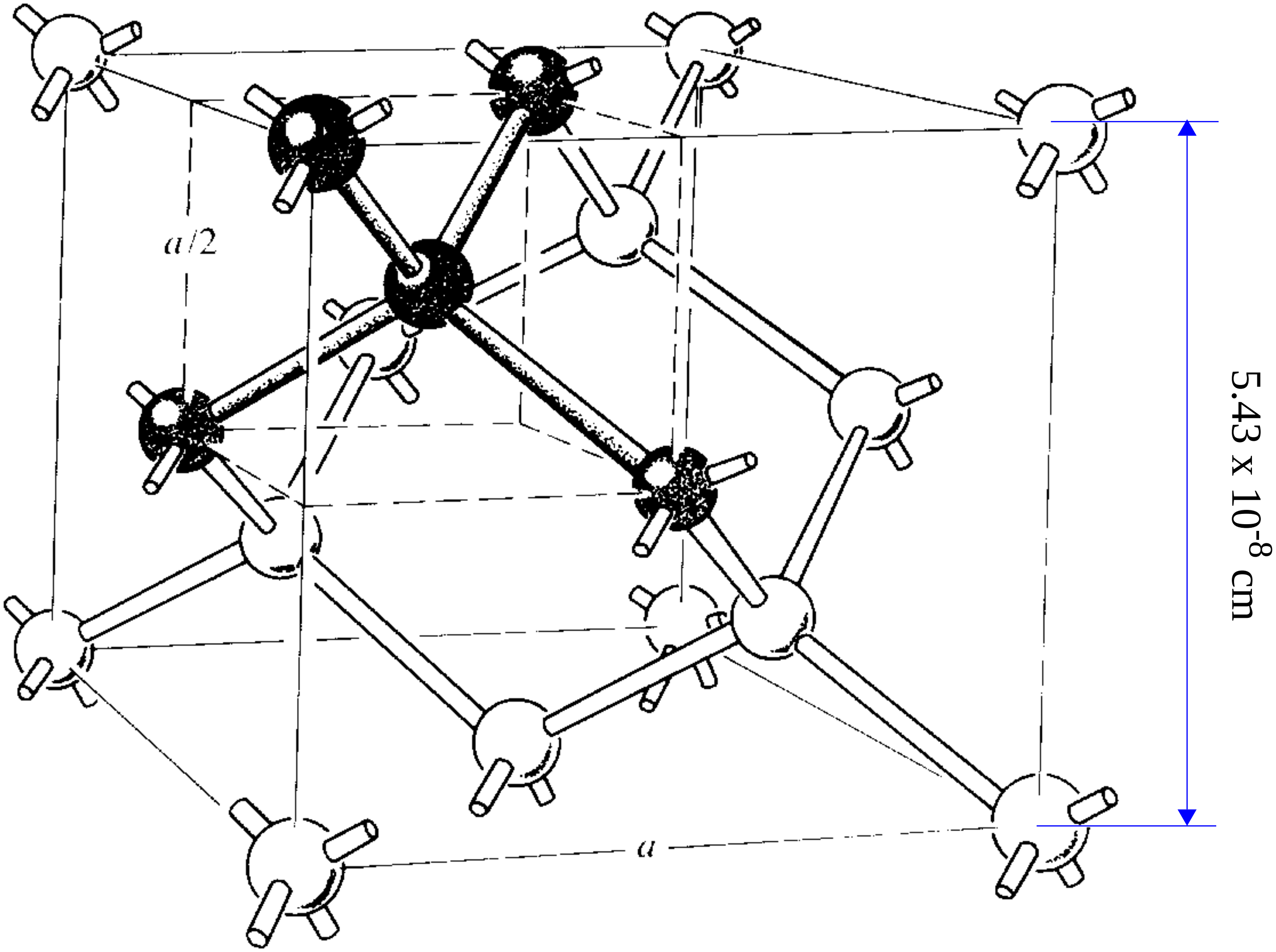
Silicon Diodes

- Different types of diodes, but we’re interested in semiconductor silicon diodes
- Si diodes are formed by the junction of n- and p-type silicon



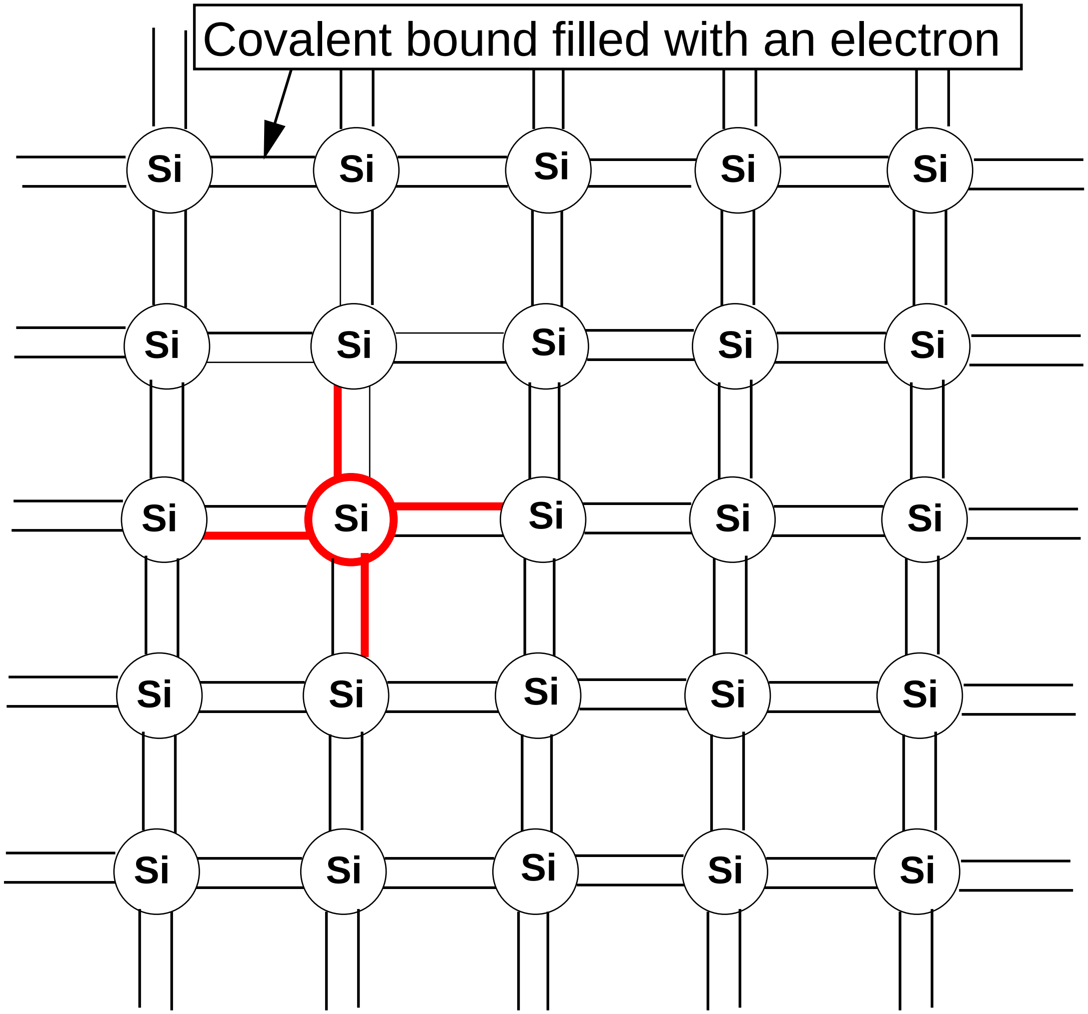
- What is a semiconductor?
  - “a material which can have electrons and holes as charge carriers”
  (naive definition, but useful for our purpose)
- What are holes?
- What is n-type and p-type silicon?

Electrons and Holes(1) - Mono crystal of Silicon



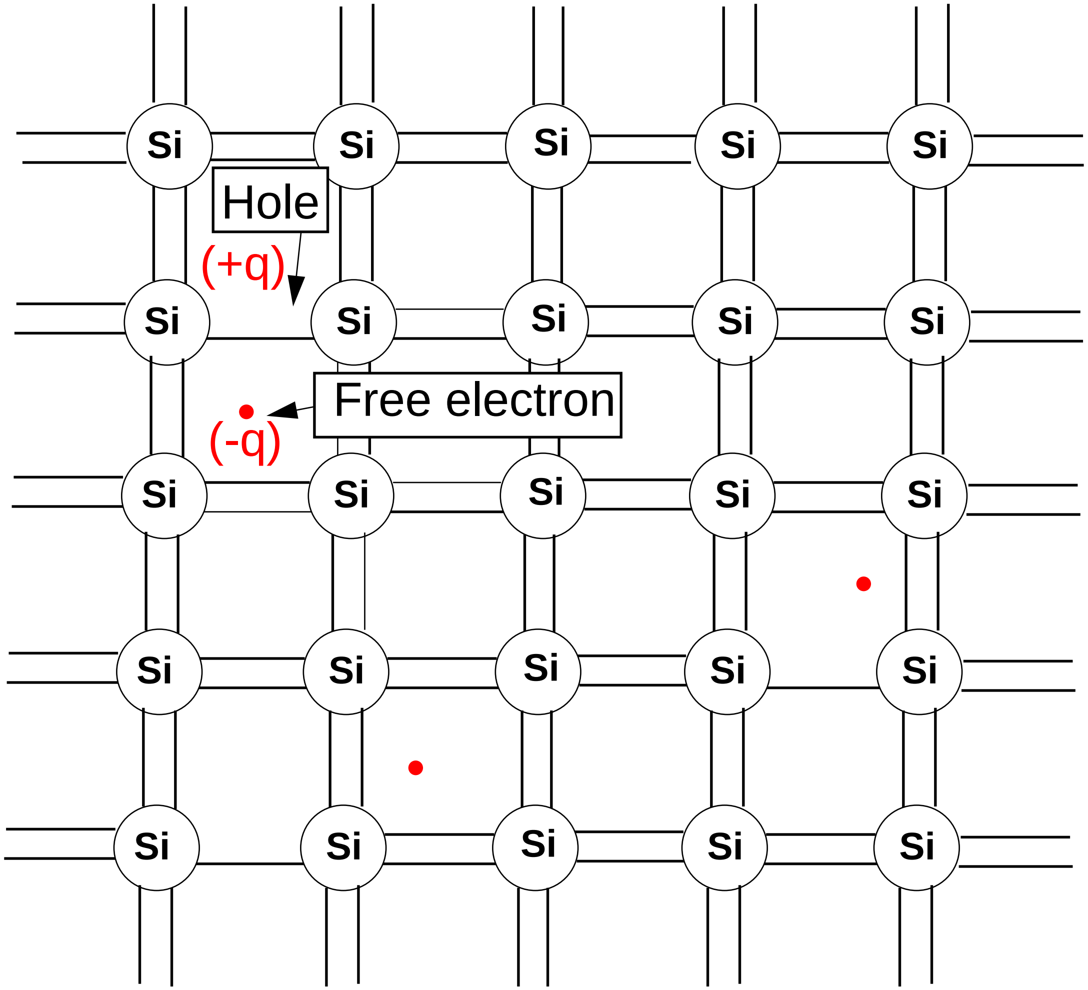
- In this regular lattice, each Si atom is bound with its four nearest neighbors.
- This ideal crystal lattice looks the same from each node.

Electrons and Holes(2) - Two-dimensional silicon lattice



There is about 5 x 10^{22} Si atoms in 1 cm^3

Electrons and Holes(3) - Generation and recombination



- Free electrons and holes:
  - appear (generation)
  - disappear(recombination)

- The number of electron-hole pairs increases with temperature. It depends upon the number of electrons which have energy high enough to break free from the bounds

In pure Si crystal at room temperature (300 K), there is about 1.4×10^{10} electron-hole pairs in 1 cm^3. This is so-called intrinsic concentration n_i.
In the absolute zero (0 K) there would be no such pairs at all.

Electrons and Holes(4) - Drift Current

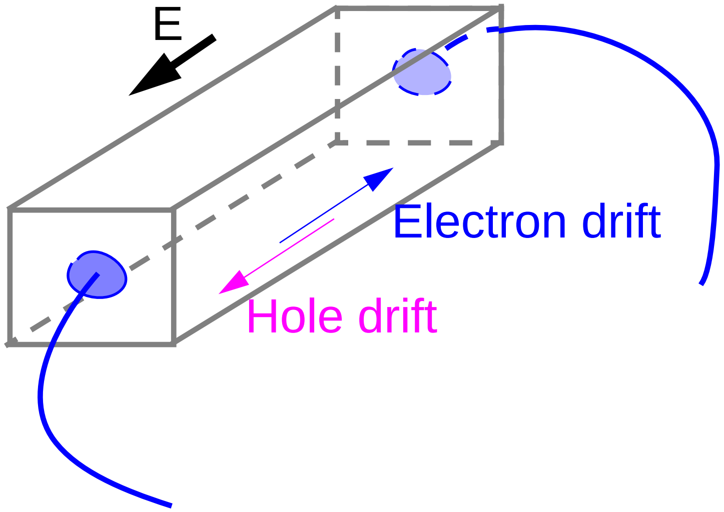
- A voltage applied to a silicon sample produces an electric field that causes the free electrons and holes to drift with an average velocity (different for electrons than for holes).
- Assuming we know the average velocity of the electrons in the electric field, we can easily calculate the current density J (current per unit area):
  J = (free charge concentration)*(drift velocity)

$v = \mu E$ - average drift velocity

Holes: $J_p \text{ (drift)} = q\mu_p pE$

Electrons: $J_n \text{ (drift)} = q\mu_n nE$

$J = J_n + J_p \qquad J = q(\mu_n n + \mu_p p)E$

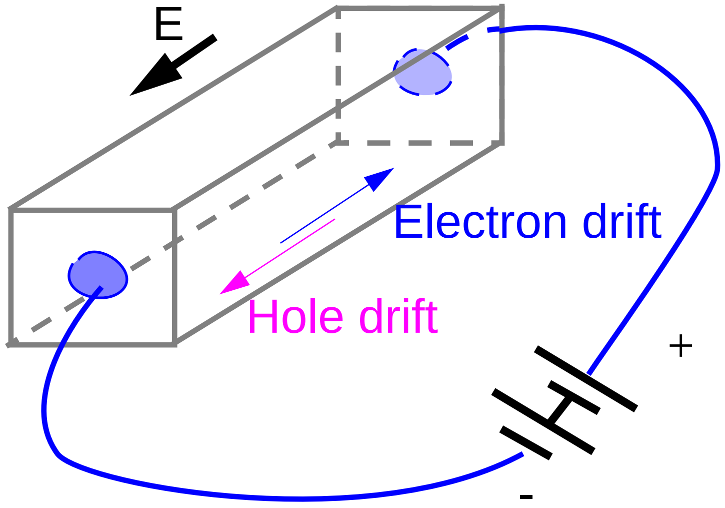


- p, n - concentration of holes and electrons [cm^{-3}]
- μ_p, μ_n - mobility of holes and electrons [cm^2/Vs]
- q - electronic charge (magnitude) = 1.6×10^{-19}[Q]

Electrons and Holes(5) - Drift Current

- What is the current through this sample then?

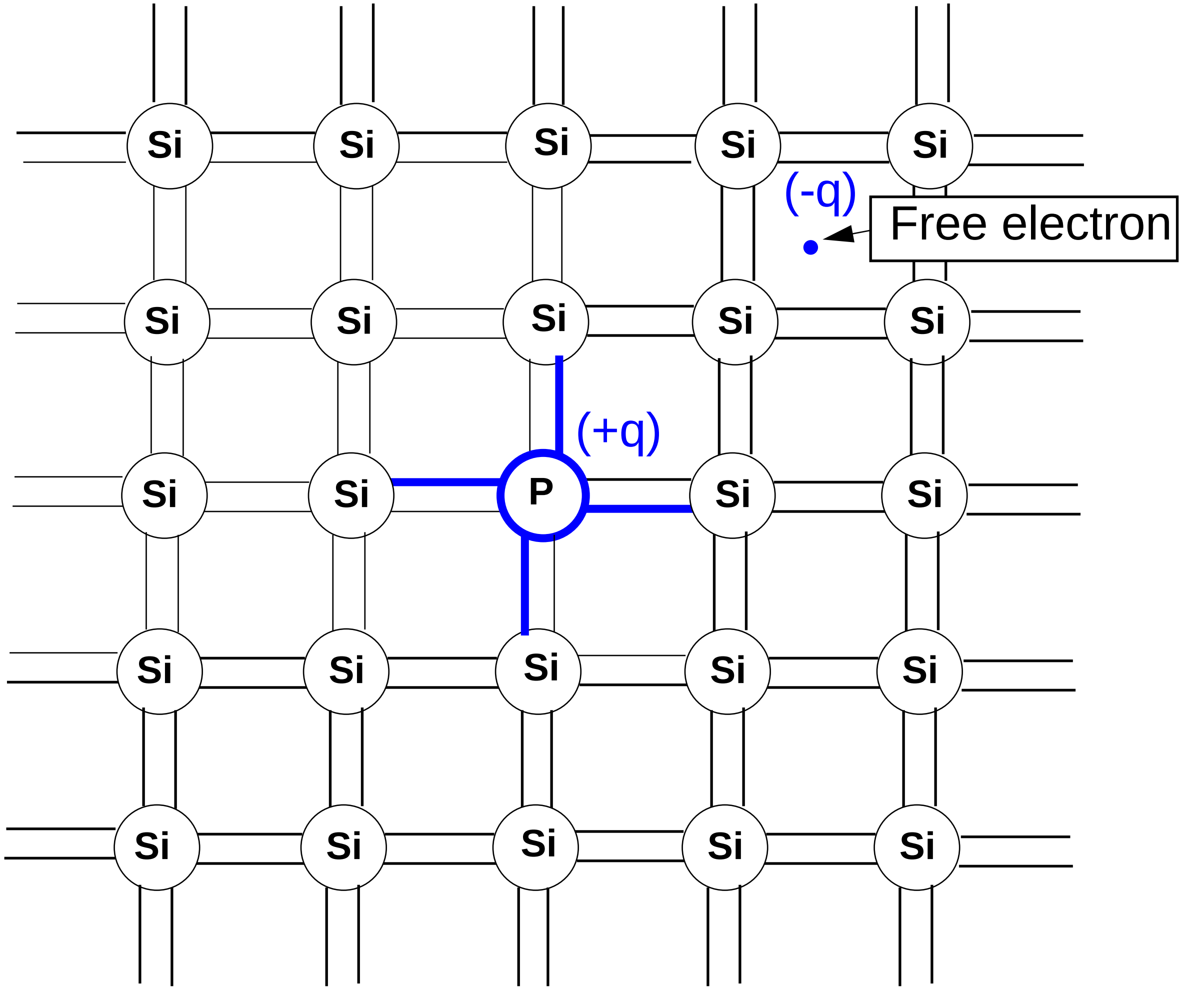
$$J = q(\mu_n n+\mu_p p)E$$

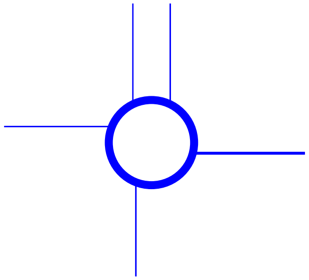


- What happens with the resistance when we increase carrier concentration?

Doped Silicon(1) - Donor

Donor has “one electron too much” - four of its electrons are bound. The excess electron is “donated” as a free electron. The donor is ionized.

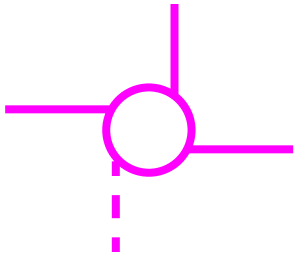


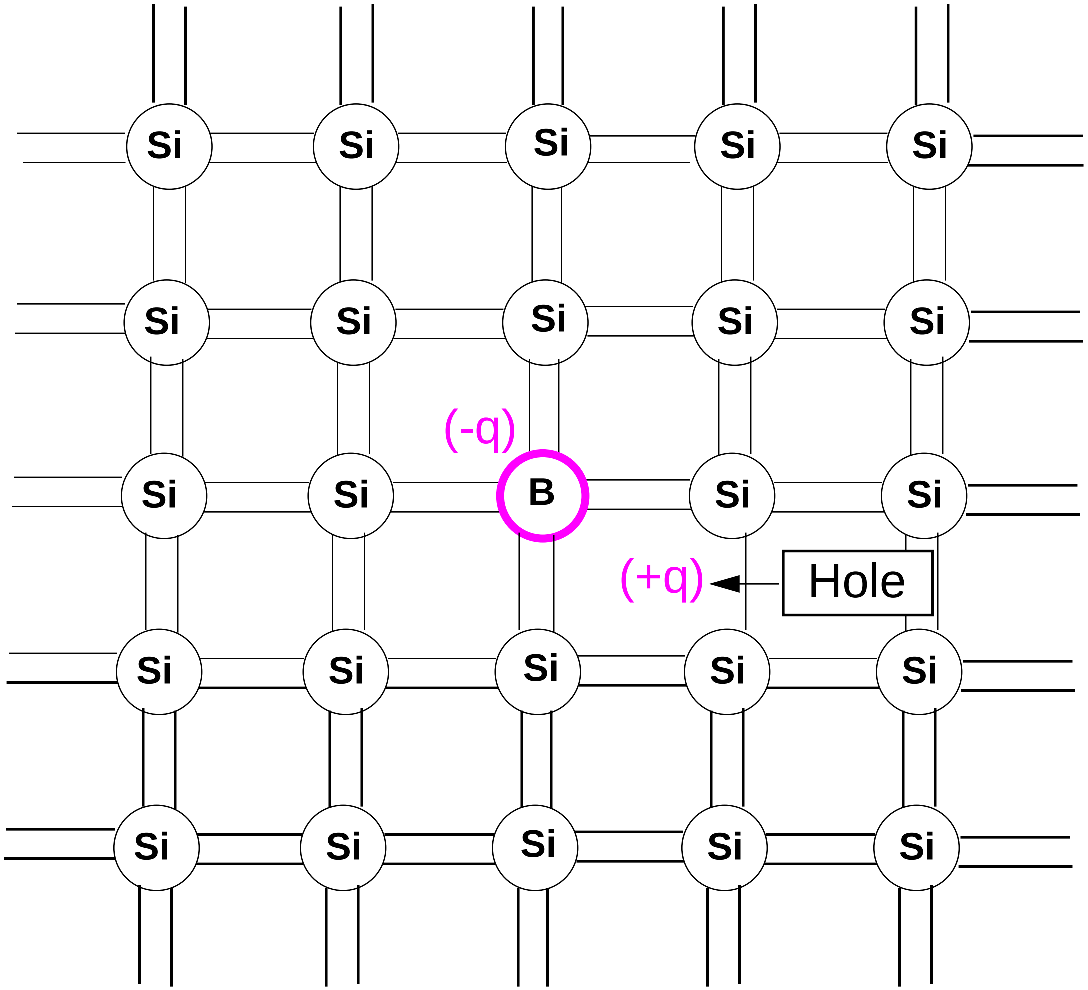


- There is an increase in free electrons which will tend to recombine with the holes. There are more electrons than holes in n type Si.
- Donor ions are immobile.
- Free electrons move.

Doped Silicon(2) - Acceptor

Donor has “one electron less than needed” - three of its electrons are bound. For the fourth bound, the donor catches a free electron. The donor is ionized.

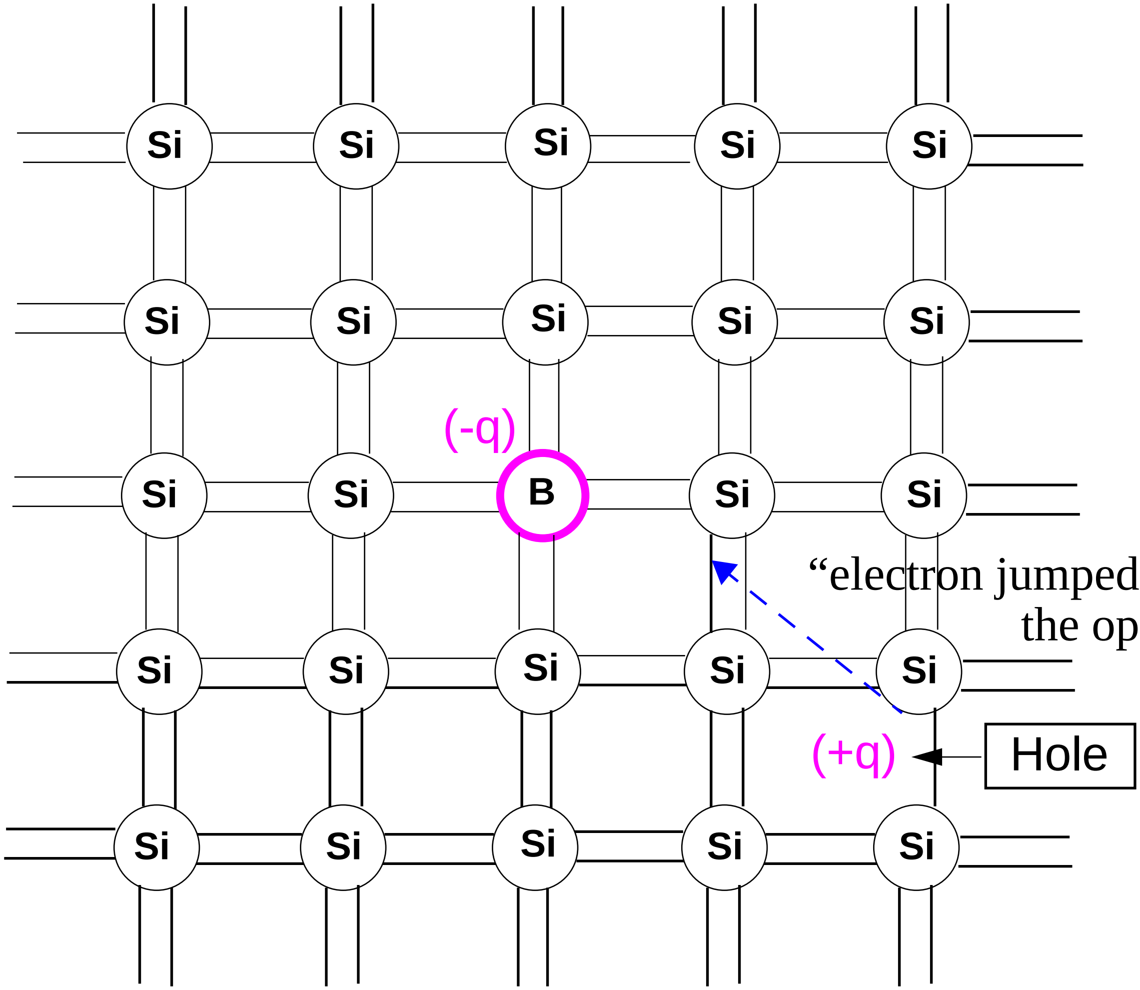




- There is an increase in hole concentration since free electrons tend to “get trapped” by acceptors and leave the holes behind. There are more holes than electrons in p type Si.
- Acceptor ions are immobile.
- Holes move.

Doped Silicon(3) - Holes Move

An electron may “jump” into the place where the hole is, but this will leave a hole somewhere else.

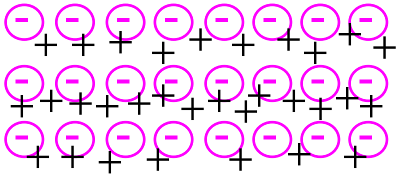


“electron jumped - hole moved in the opposite direction”

Doped Silicon (4) - p-type, n-type

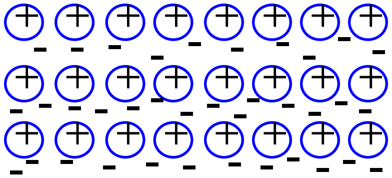
You can think of a doped silicon as of a material which:

- has a lot of “charged nodes” (impurities, dopants) built-in into the crystal lattice,
- is filled with gas of free charge carriers



p-type:

- vast majority of charge carriers are holes,
- negative built-in charge from acceptors.



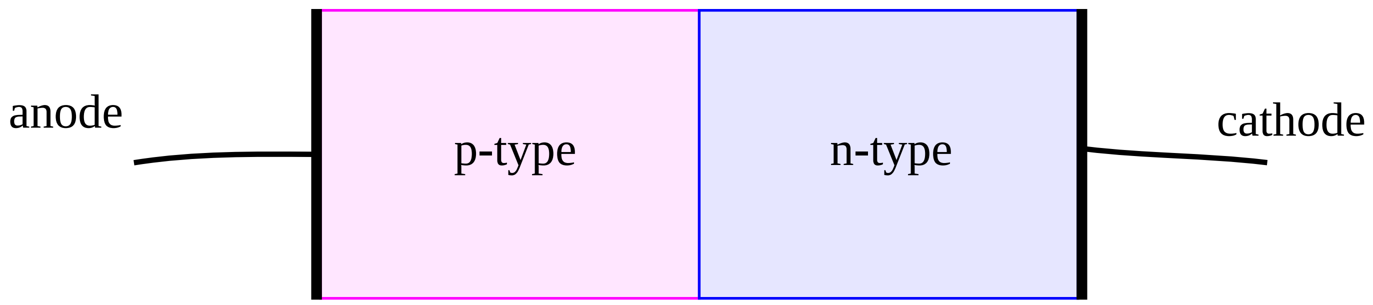
n-type:

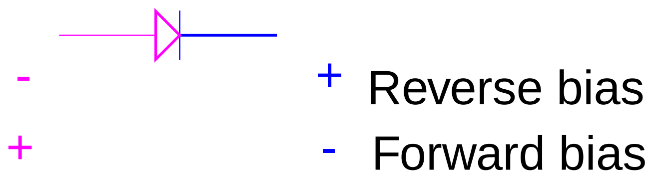
- vast majority of charge carriers are electrons,
- positive built-in charge from donors.

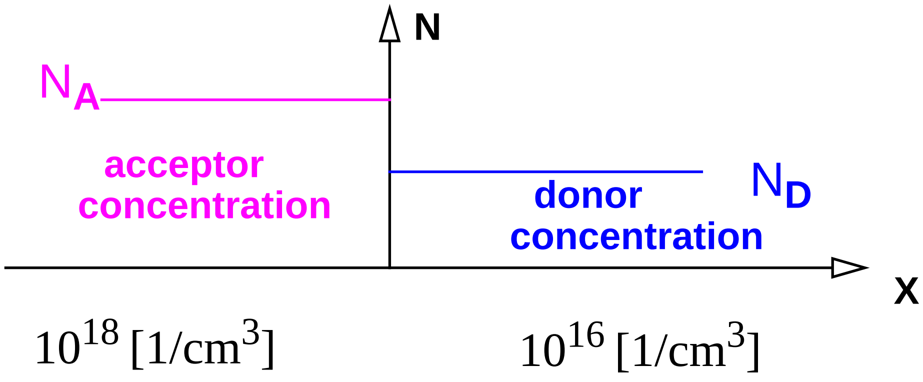
- Note that even with doping, the impure silicon is still charged neutral since:
  - every “donated” free electron leaves behind a positively charged donor atom,
  - every negatively charged acceptor atom caused creation of a hole.

p-n Junction Diode

Generally formed by introducing p-type impurities into n-type silicon, or vice versa

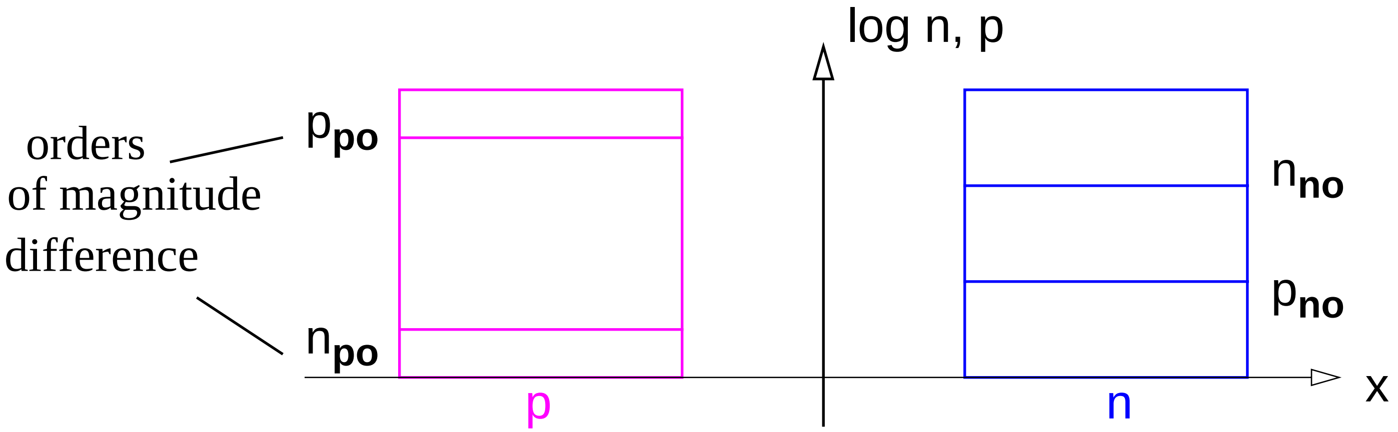






p-n Junction - Example carrier concentrations

In equilibrium: $p_{po}\ n_{po} = n_i^2 = n_{no}\, p_{no}$



p-type region:

$N_A^- - p_{po} + n_{po} = 0$

$p_{po} >> n_{po} => p_{po} = N_A^-$

$n_{po} =$

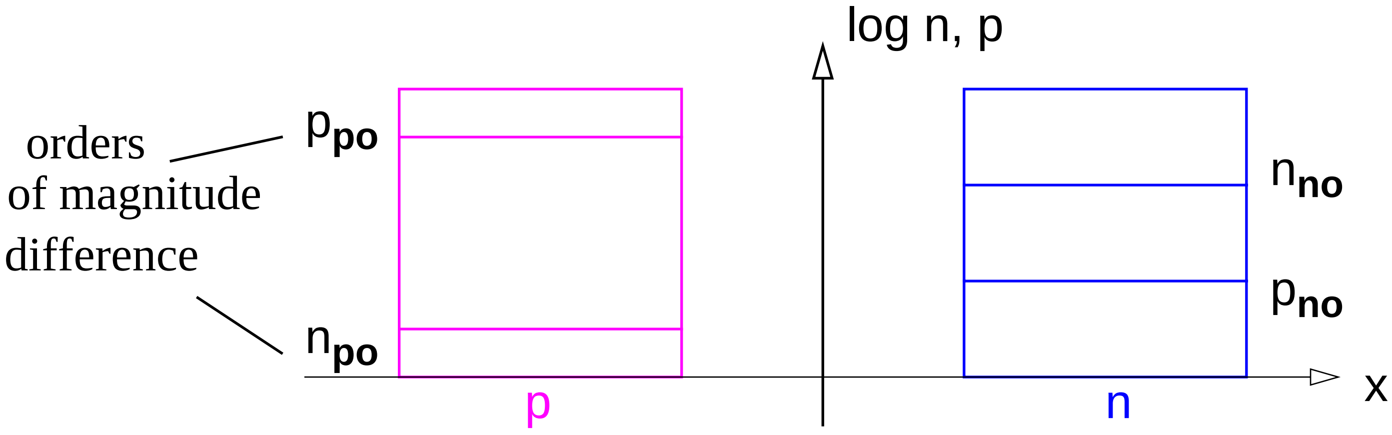
n-type region:

$N_D^+ - n_{no} + p_{no} = 0$

$n_{no} >> p_{no} => p_{po} = N_D^+$

$p_{no} =$

p-n Junction - Example carrier concentrations (2)



p region

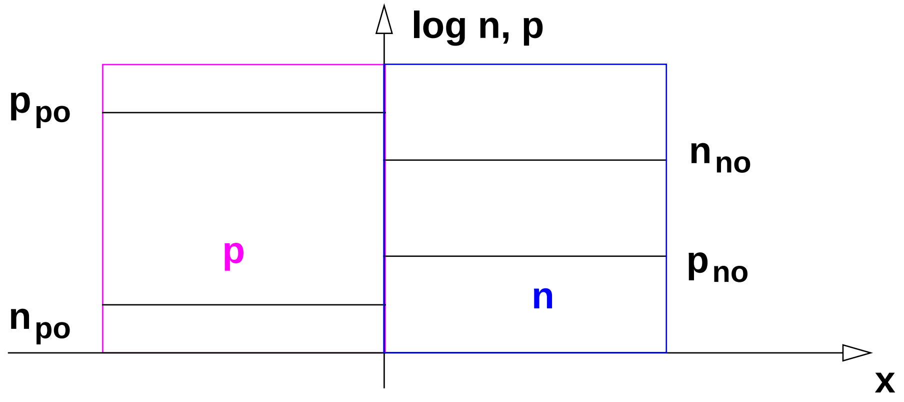
- **majority carriers:** $p_{po} \approx N_A$ $\quad 10^{18}$
- **minority carriers:** $n_{po} = \frac{n_i^2}{p_{po}} \approx \frac{n_i^2}{N_A}$ $\quad 200$

n region

- **majority carriers:** $n_{no} \approx N_D$ $\quad 10^{16}$
- **minority carriers:** $p_{no} \approx \frac{n_i^2}{N_D}$ $\quad 10^{4}$

For comparison: how many Si atoms are in 1 cm^3 ?

Let us join the p and n regions

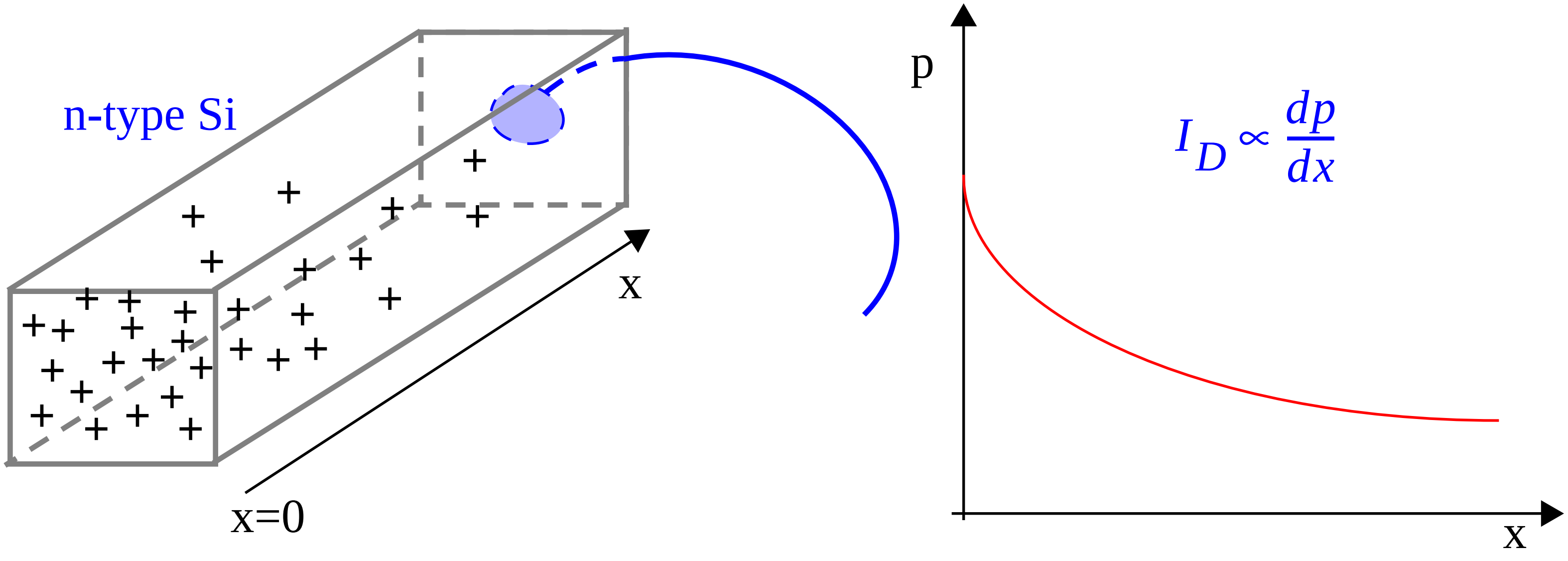


- At the interface enormous gradients of electron and hole concentrations.
- The holes will move towards n - region, electrons towards p - region. Acceptor and donor ions cannot move.
- Why will holes and electrons move to the opposite regions?

Diffusion Current

- Holes enter the n-side then diffuse toward equilibrium
- If the source of holes were constant, this would continue indefinitely, with holes continually recombining with electrons

$$J_p \text{ (diff)} = -qD_p \frac{dp}{dx}$$



$$I_D \propto \frac{dp}{dx}$$

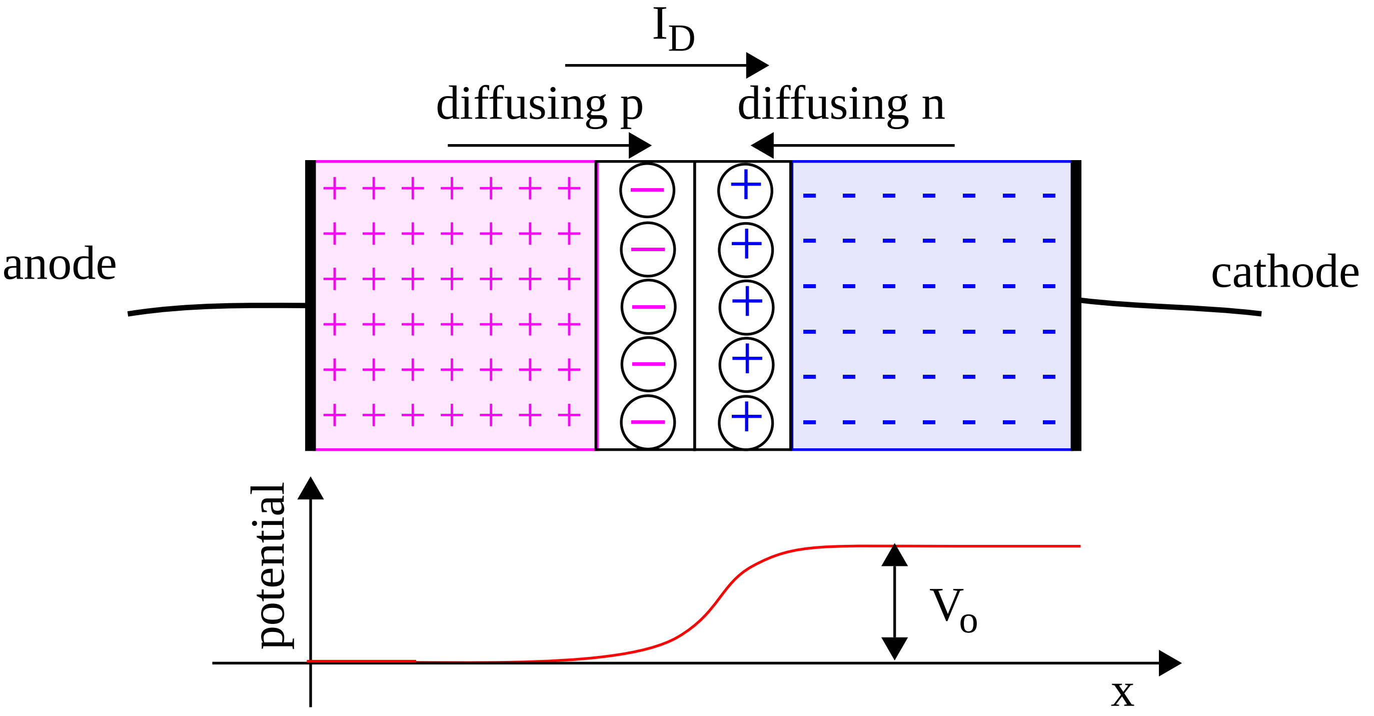
- There is a similar component of diffusion current due to electrons diffusing from the n-side toward the p-side

$$J_n \text{ (diff)} = \boldsymbol{qD_n} \frac{dn}{dx}$$

- Diffusion currents <u>do not</u> result from electrostatic interactions!

Diffusion Current and Depletion Region

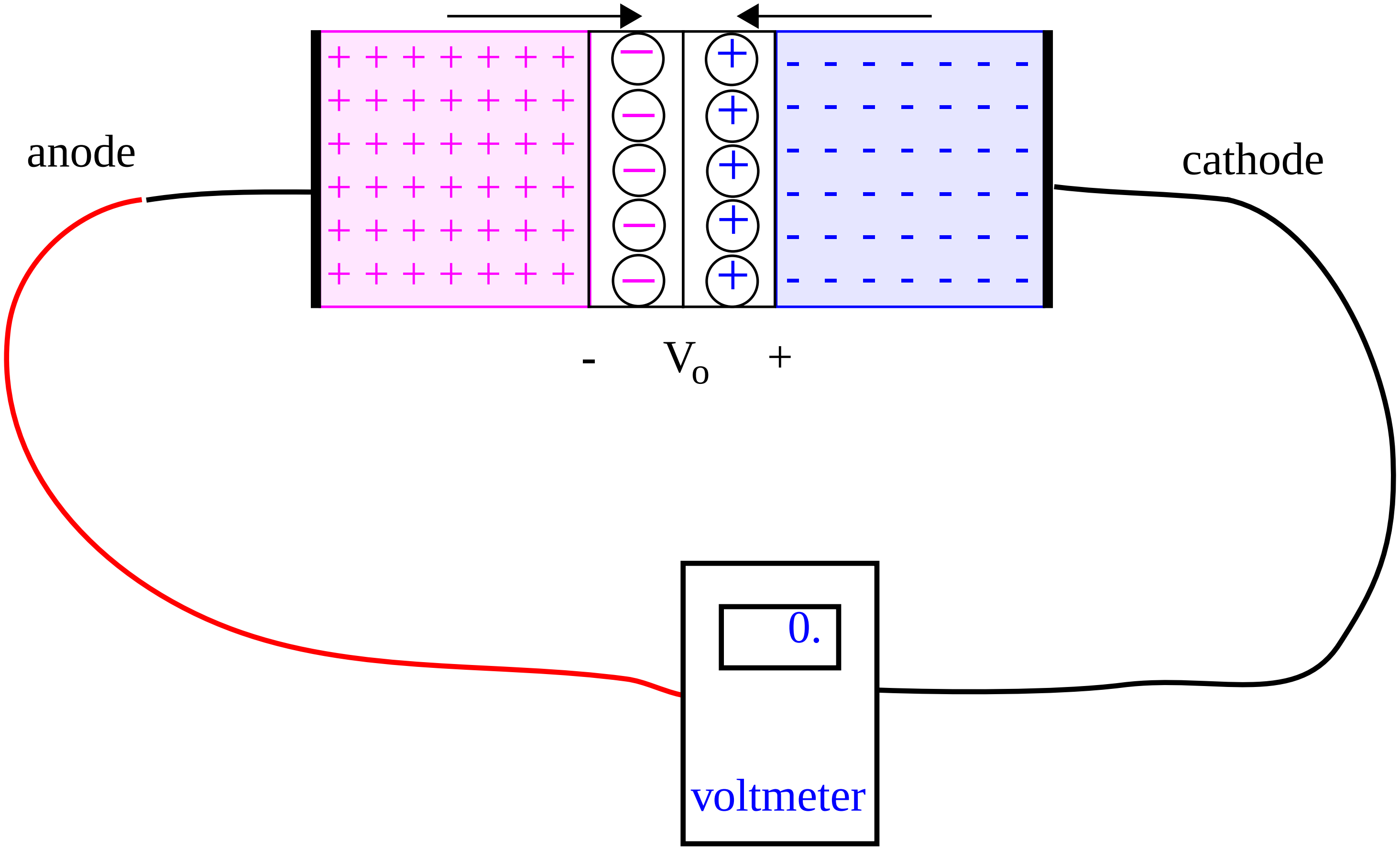
- Diffusing holes and electrons quickly recombine on the other side due to the high concentration of opposite free carriers there
- As they recombine they leave behind fixed charges due to uncovered bond charges on the donor and acceptor atoms
- This creates a depletion region



- The depletion region establishes an electric field
- Does this E-field oppose or aid the diffusion of holes and electrons?

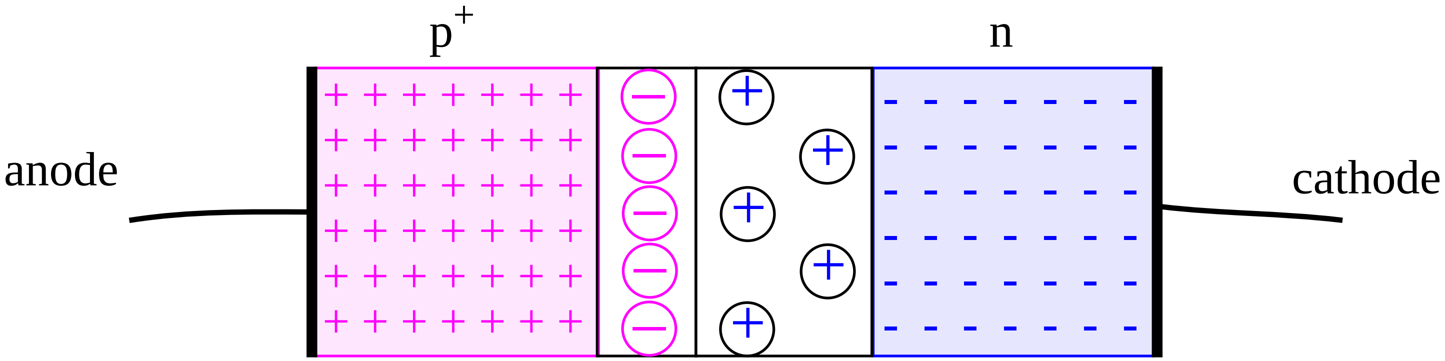
Barrier Voltage, V_o

- The barrier voltage cannot be measured with a voltmeter
  - cannot draw energy from a p-n junction
- Connecting it to a meter would register 0 volts, which would indicate that the V_o voltage is dropped across the metal-Si contact points

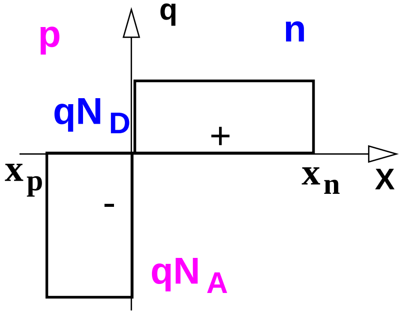


Depletion Region

- One of the concentrations, p or n, is generally much larger than the other (p^+ or n^+)



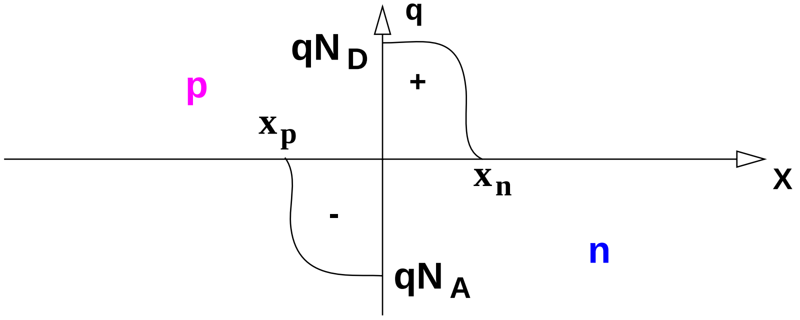
(Simplified plot for uniform doping)

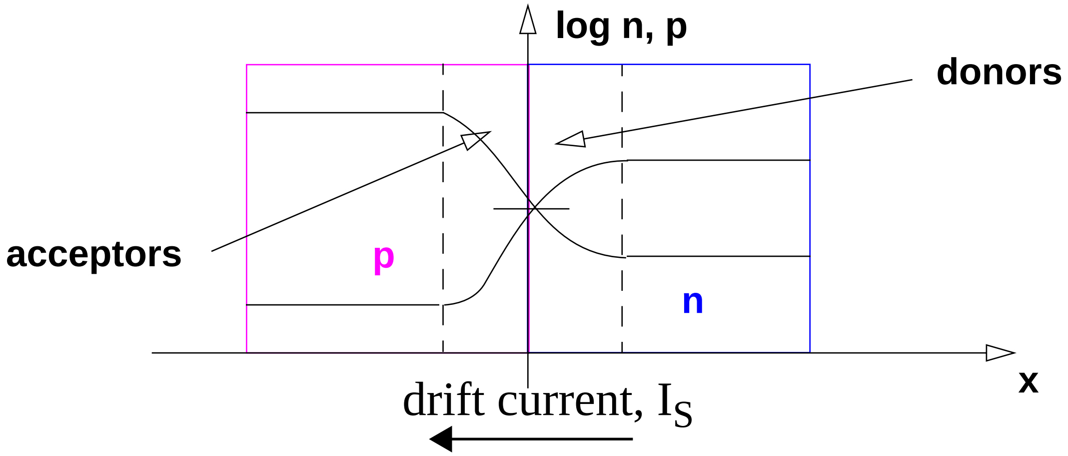


- The depletion region extends almost entirely into a lighter doped side of the junction.

Drift Current

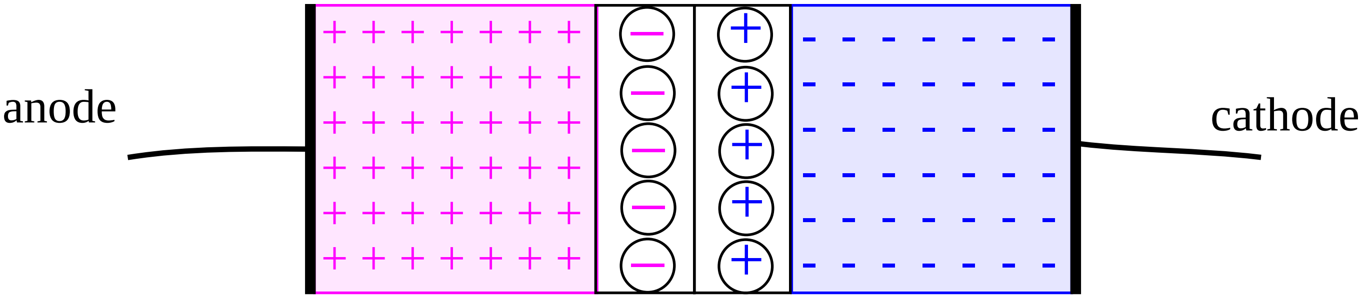
- The electric field in the depletion layer forces electrons to flow toward the n-region and holes to flow toward the p- region. Thus, diffusion and drift currents flow in opposite directions.
- The few minority carriers (holes on the n-side and electrons on the p-side) that wander to the depletion region are quickly swept to the other side due to the electric field.





Equilibrium

diffusing n
drifting n
diffusing p
drifting p



$$I_s = \underleftarrow{I_p \text{ (drift)} + I_n} \text{ (drift)}$$

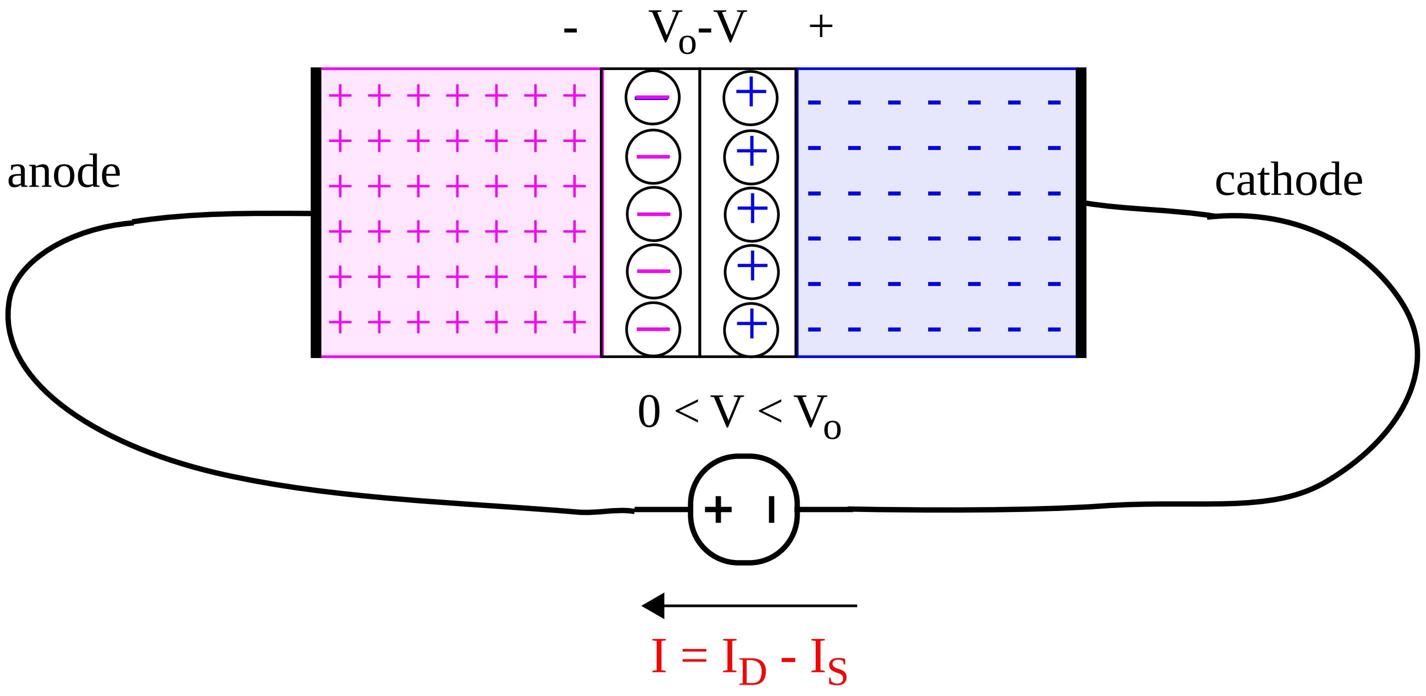
$$I_D = \underrightarrow{I_p \text{ (diff)} + I_n} \text{ (diff)}$$

At equilibrium, these currents cancel each other and there is no net current flow:

$$I_S + I_D = 0 = I_p \text{ (drift)} + I_n \text{ (drift)} + I_p \text{ (diff)} + I_n \text{ (diff)}$$

Positive Applied Voltage

- A positive external voltage will reduce the barrier and allow more carriers to diffuse. Current can be large, because the carriers flow from the regions where their concentrations are large.
- The depletion region width is also reduced



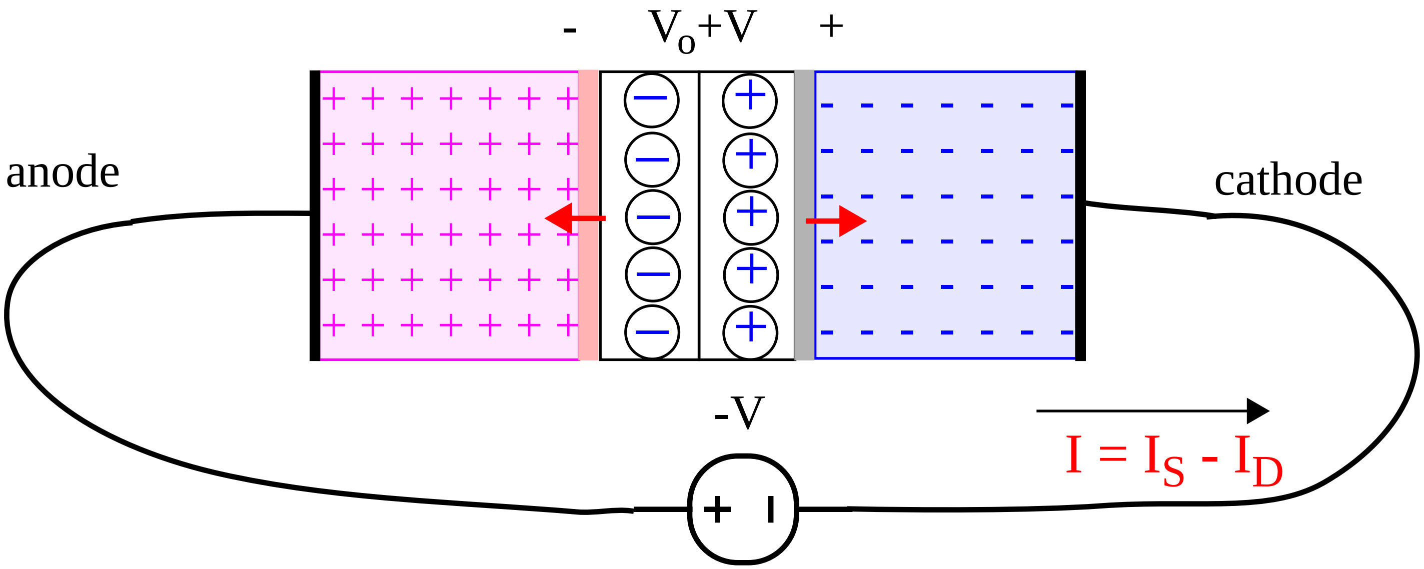
$0 < V < V_o$

$I = I_D - I_S$

- Now the diffusion current over the depletion region dominates the drift current

Negative Applied Voltage

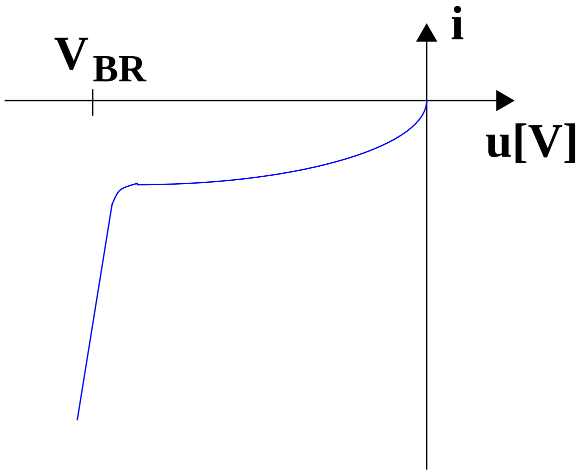
- A negative applied voltage will increase the width of the depletion region and increase the drift component of current, I_S. The diffusion current is decreased- Why?



- This current is small (e.g. 10^{-12}A), because the carriers flow from the regions in which their concentrations are low.
- I_s often negligible, depending on the circuit
- But there is a change in stored charge --- capacitance

Breakdown Voltage

- Zener breakdown: negative applied voltage is so large that E-field is huge enough to break atom bonds and create lots of electron/hole pairs
- Electric field then sweeps these carriers to appropriate sides of diode thereby creating a large current
- Voltage remains constant at about V_Z
- Diodes used for voltage regulation are designed for achieving a particular breakdown voltage



- Avalanche breakdown: E-field is so strong that electrons reach velocities that are fast enough that their collisions with atoms create new electron-hole pairs, which create more electron-hole pairs, and so on...

Symbols used in this lecture

N_D	- donor concentration	$[cm^{-3}]$
N_A	- acceptor concentration	$[cm^{-3}]$
J_p	- hole current density	$[A/cm^2]$
J_n	- electron current density	$[A/cm^2]$
q	- electron charge (magnitude)	$[1.6 \times 10^{-19} coulombs]$
μ_p	- hole mobility	$[cm^2/volt \bullet s]$
μ_n	- electron mobility	$[cm^2/volt \bullet s]$
p	- concentration of holes	$[cm^{-3}]$
n	- concentration of electrons	$[cm^{-3}]$
D_p	-diffusion coefficient for holes	$[cm^2/s]$
D_n	- diffusion coefficient for electrons	$[cm^2/s]$
$\frac{dp}{dx}$	- gradient of hole concentration	$[cm^{-4}/s]$
$\frac{dn}{dx}$	-gradient of electron concentration	$[cm^{-4}/s]$
p_{po}	- majority hole concentration	$[cm^{-3}]$

n_{no}	-majority electron concentration	$[cm^{-3}]$
p_{no}	-minority hole concentration	$[cm^{-3}]$
n_{po}	- minority electron concentration	$[cm^{-3}]$
n_i	- intrinsic concentration	$[1.4 \times 10^{10} cm^{-3}]$
A	- diode area	$[cm^2]$
x_n	- depletion region width in n-type semiconductor	$[cm]$
x_p	- depletion region width in p-type semiconductor	$[cm]$
V_o	- potential barrier	$[volt]$
V_T	- thermal voltage (26mV at room temperature)	$[volt]$
k	- Boltzmann’s constant	$[1.38 \times 10^{-23} J/K]$
V	- bias voltage	$[volt]$
T	- absolute temperature $[273 + T(^0C)]$	$[K]$