Introductory Material

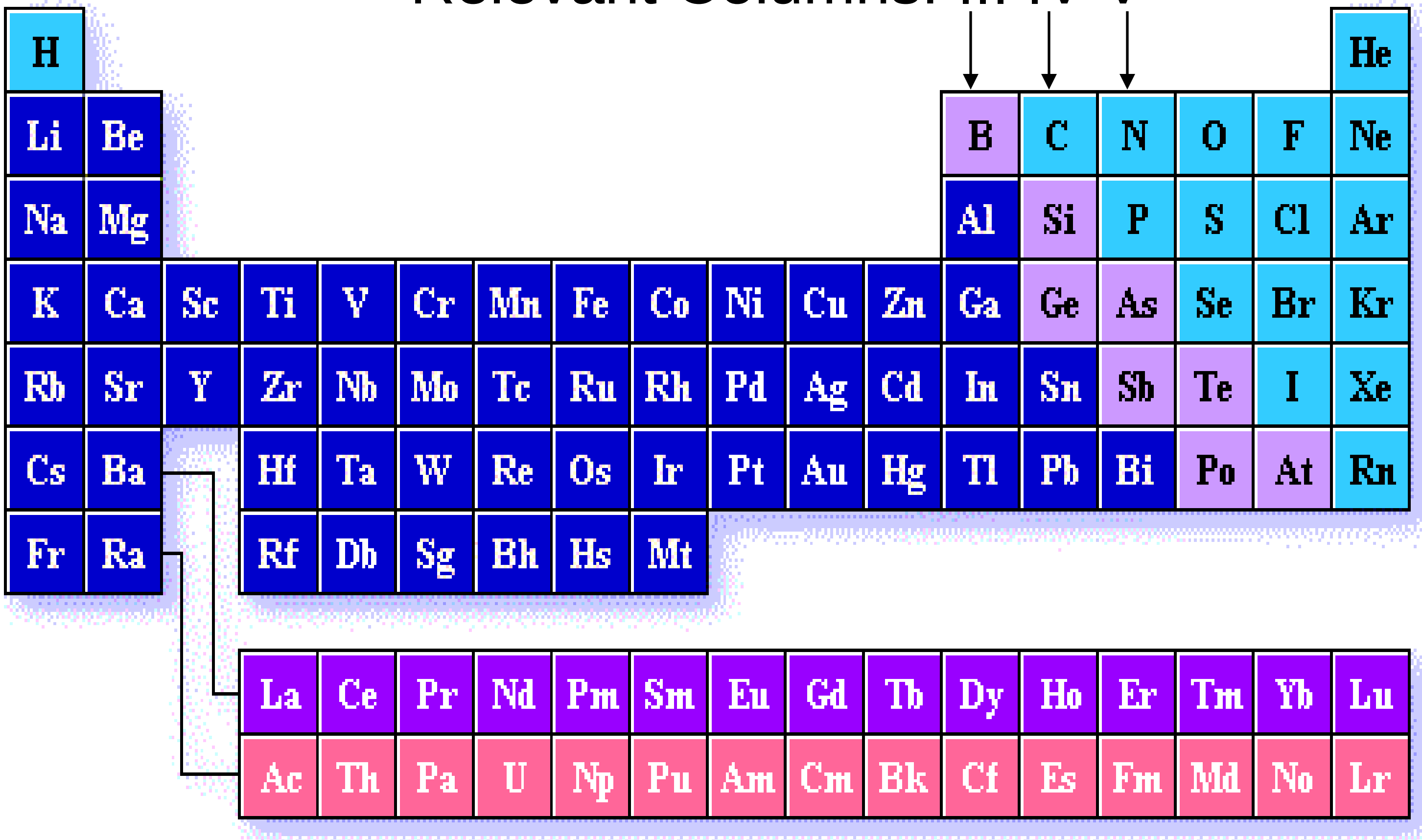
- Goal: to give you a quick, intuitive concept of how semiconductors, diodes, BJTs and MOSFETs work
  - as a review of electronics and an overview of this course
- This discussion will be *qualitative*
  - no equations for now, these will be added later
- Note that the concepts are often *over-simplified!*

Semiconductors and Physical Operation of Diodes

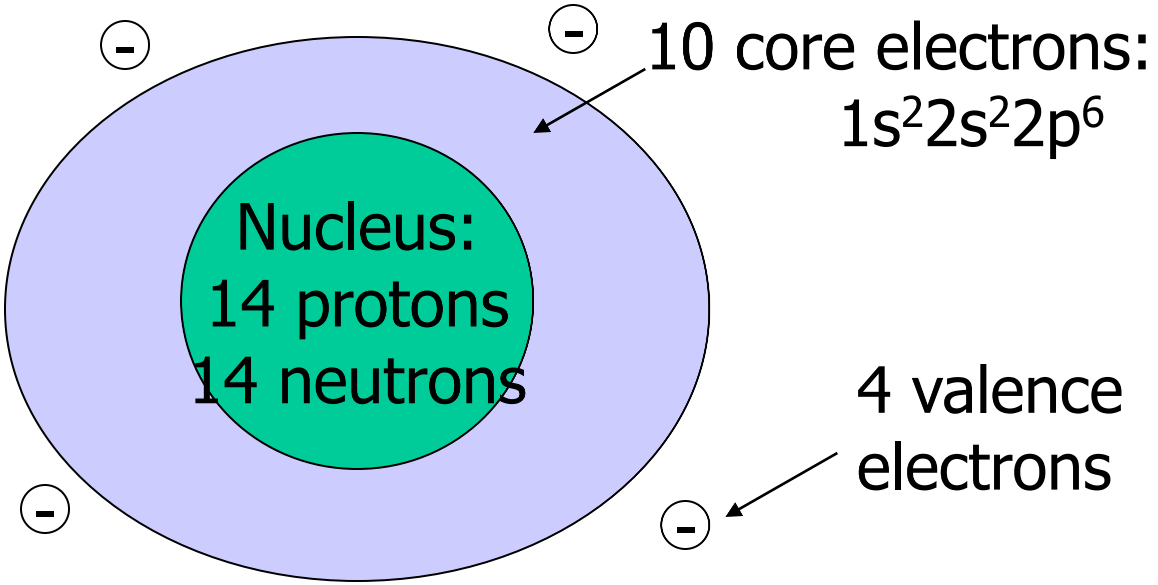
- Semiconductors
- Doping
  - n-type material
  - p-type material
- pn-Junctions
  - forward, reverse, breakdown
  - solar cells, LEDs, capacitance

Periodic Table of Elements

Relevant Columns: III IV V



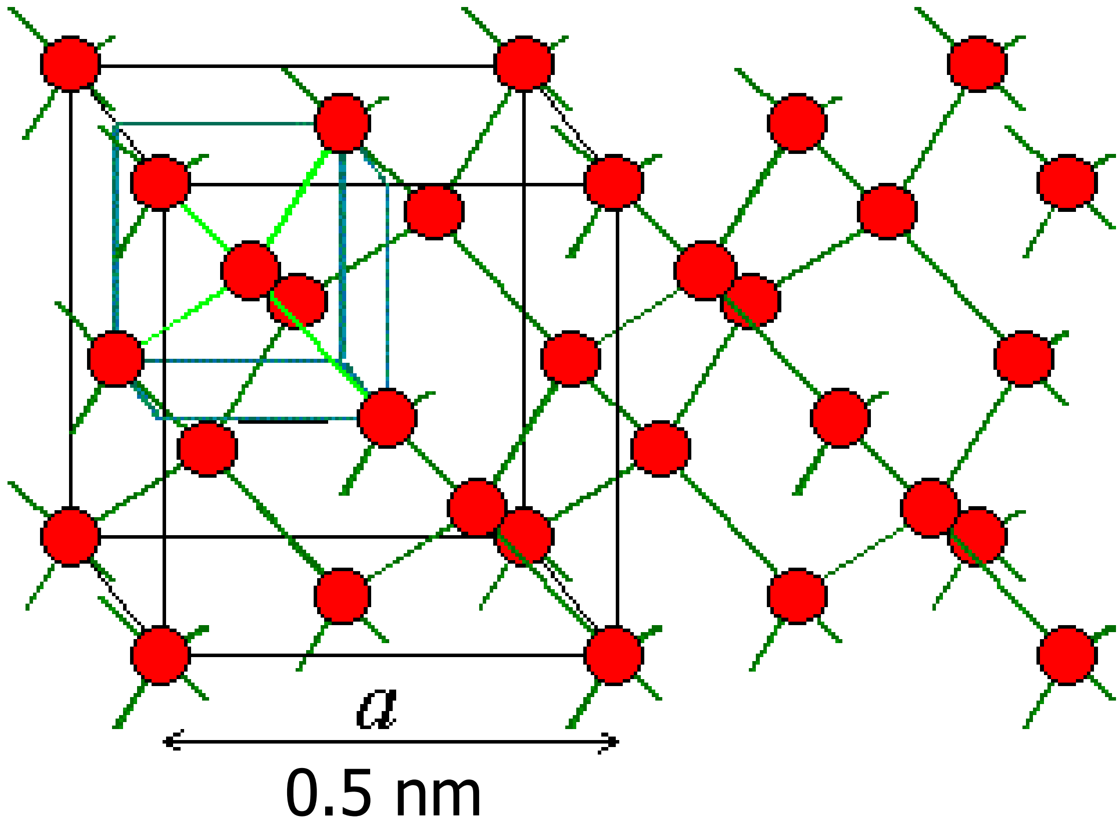
The Silicon Atom



The 4 valence electrons are responsible for forming covalent bonds

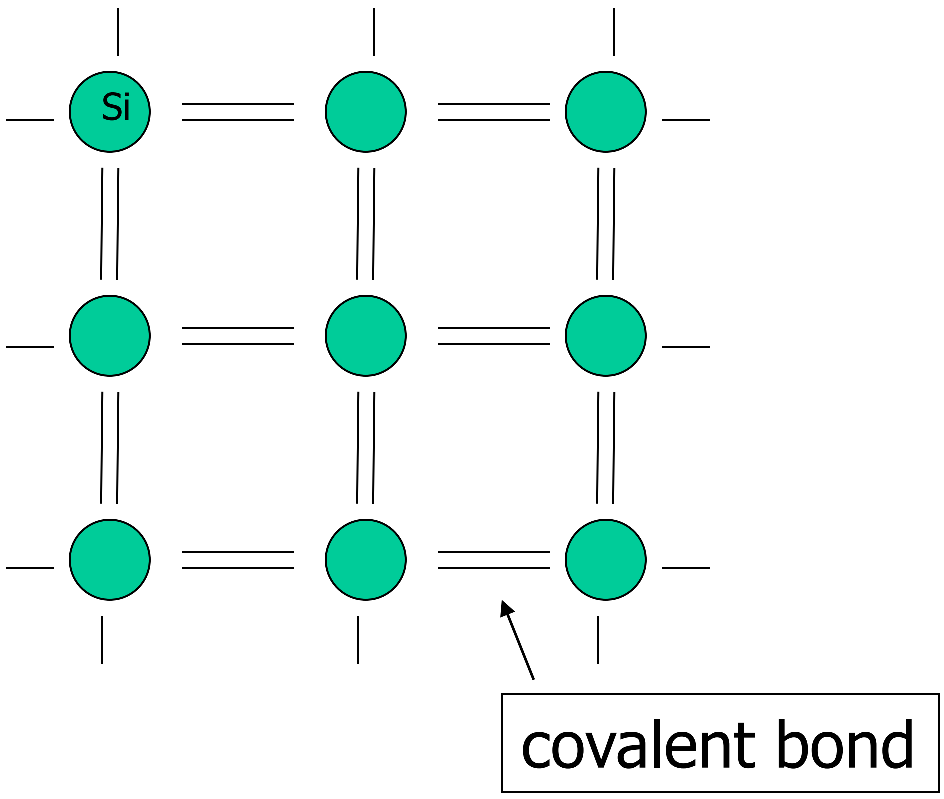
Silicon Crystal

Each Si atom has four nearest neighbors — one for each valence electron



Two-dimensional Picture of Si

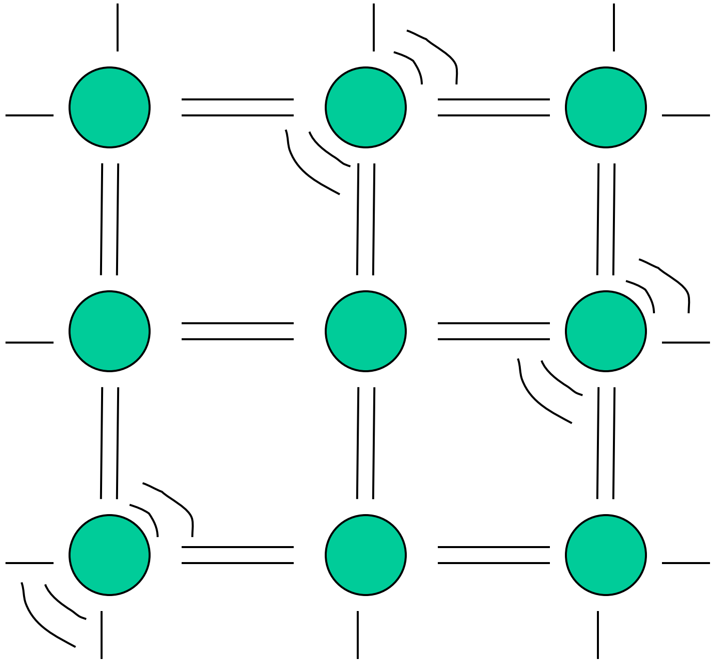
note: each line (—) represents a valence electron



At T=0 Kelvin, all of the valence electrons are participating in covalent bonds

There are no "free" electrons, therefore no current can flow in the silicon → INSULATOR

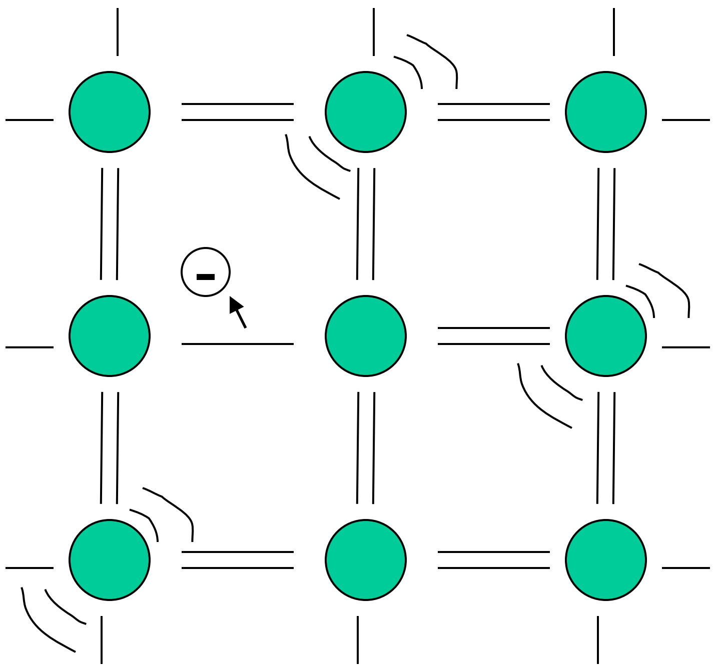
Silicon at Room Temperature



For T>0 K, the silicon atoms vibrate in the lattice. This is what we humans sense as "heat."

Occasionally, the vibrations cause a covalent bond to break and a valence electron is free to move about the silicon.

Silicon at Room Temperature



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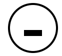
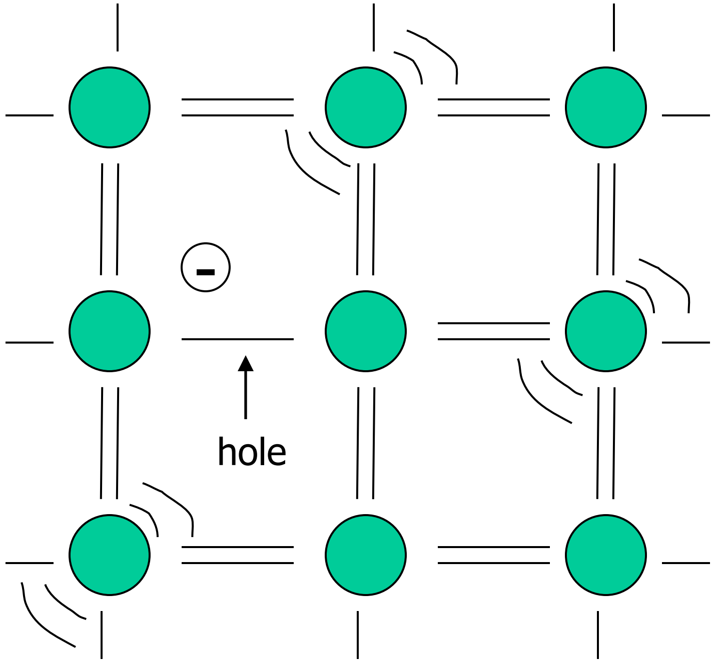


= free electron

Silicon at Room Temperature



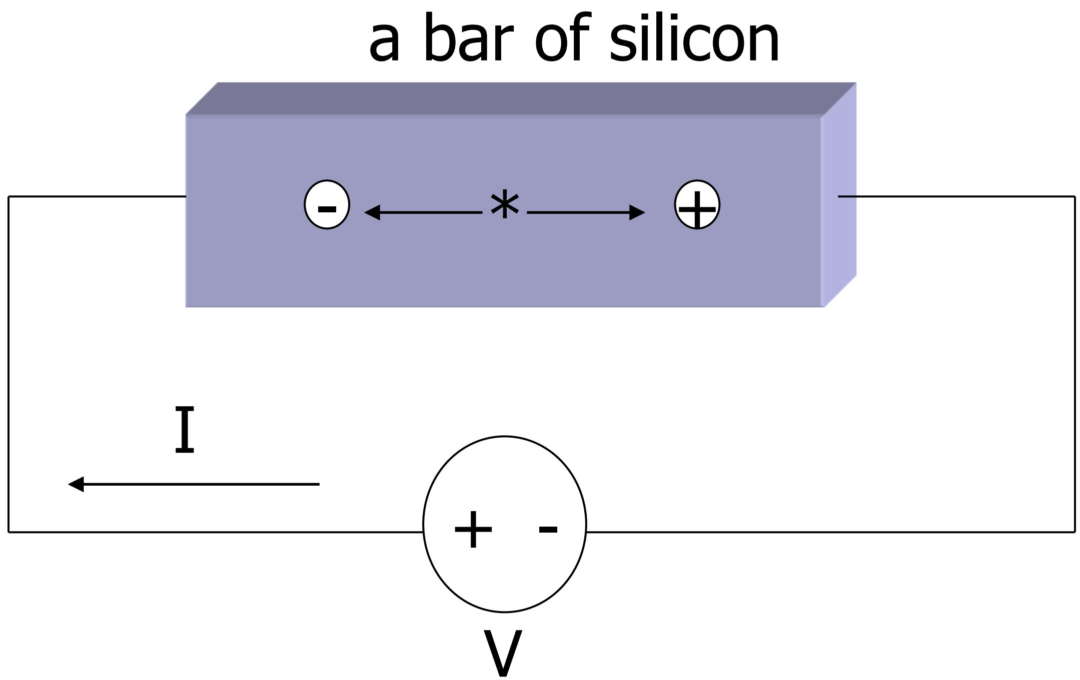
The broken covalent bond site is now *missing* an electron.

This is called a "hole"

The hole is a missing negative charge and has a charge of **+1**.

⊕= a hole

Current Flow in Silicon



Bond breaking due to:
-heat (phonons)
-light (photons)

Conductance is proportional to the number of electrons and holes:
Si resistance depends on temp. and light

Some important facts

- The number of electrons = the number of holes
  - that is, n = p in pure silicon
  - this is called *intrinsic material*
- High temp →more electrons/holes→lower resistance
- Very few electrons/holes at room temperature
  - $n=1.5x10^{10}$ per cm^3, but $n_{Si} = 5x10^{22}$ per cm^3
  - $n/n_{Si} = 3x10^{-13}$ (less than 1 in a trillion Si bonds are broken
  - This is a SEMICONDUCTOR

Important Facts (cont.)

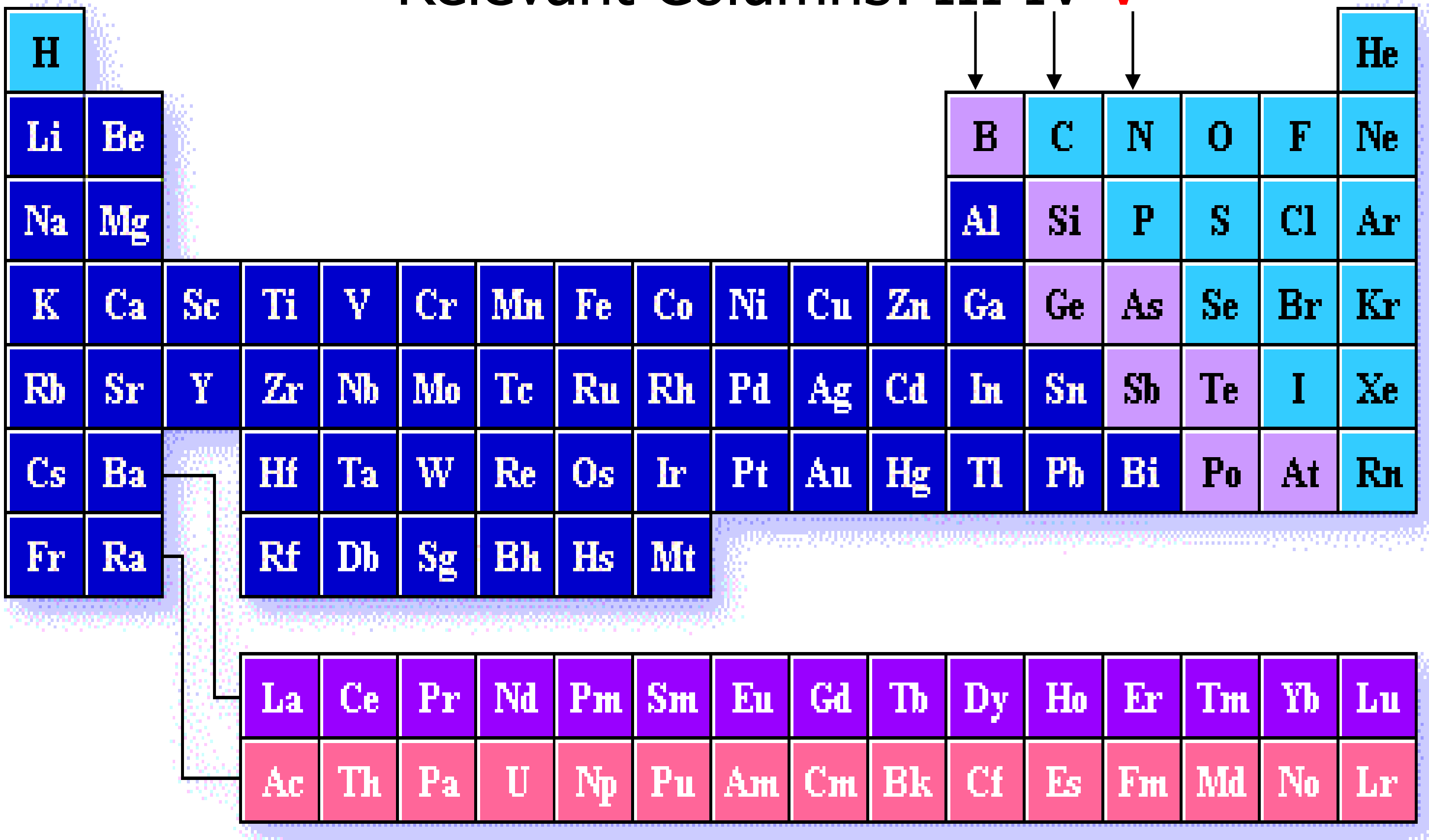
- Band Gap: energy required to break a covalent bond and free an electron
  - E_g = 0.66 eV (germanium)
  - E_g = 1.12 eV (silicon)
  - E_g = 3.36 eV (gallium nitride)
- Metals have $E_g = 0$
  - very large number of free electrons → high conductance
- Insulators have $E_g > 5$ eV
  - almost NO free electrons → zero conductance

Doping

- Intentionally adding impurities to a semiconductor to create more free electrons OR more holes (*extrinsic material)*
- n-type material
  - more electrons than holes (n>p)
- p-type material
  - more holes than electrons (p>n)
- HOW???

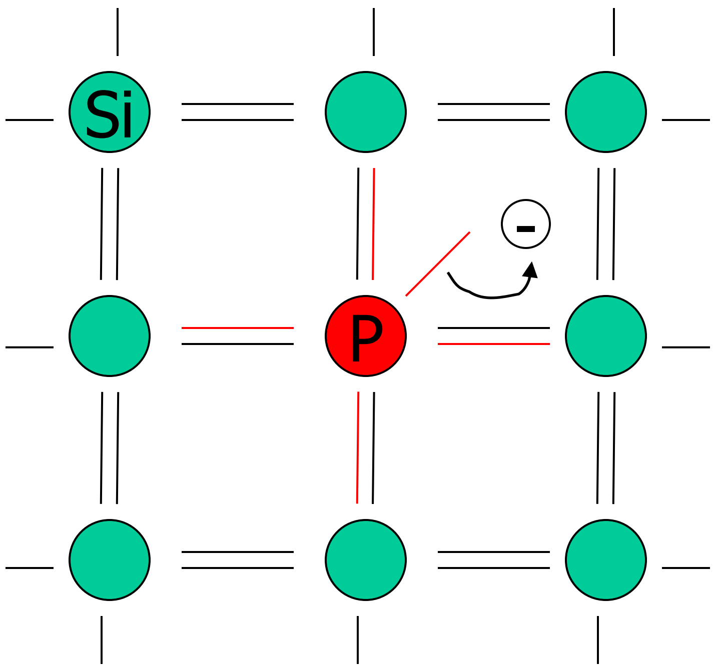
Periodic Table of Elements

Relevant Columns: III IV V



n-type silicon

add atoms from *column V* of the periodic table



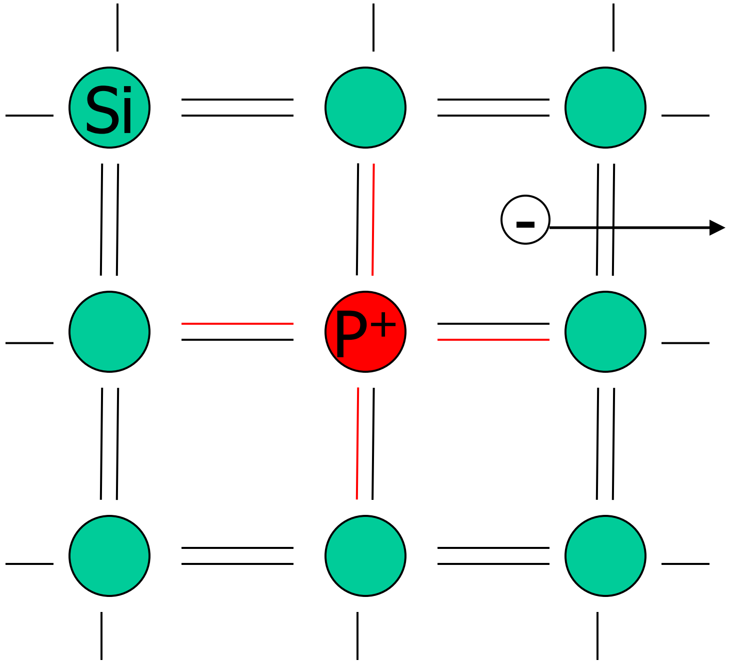
Column V elements have 5 valence electrons

Four of the electrons form covalent bonds with Si, but the 5th electron is unpaired.

Because the 5th electron is weakly bound, it almost always breaks away from the P atom

This is now a free electron.

VERY IMPORTANT POINT



The phosphorus atom has *donated* an electron to the semiconductor (Column V atoms are called *donors*)

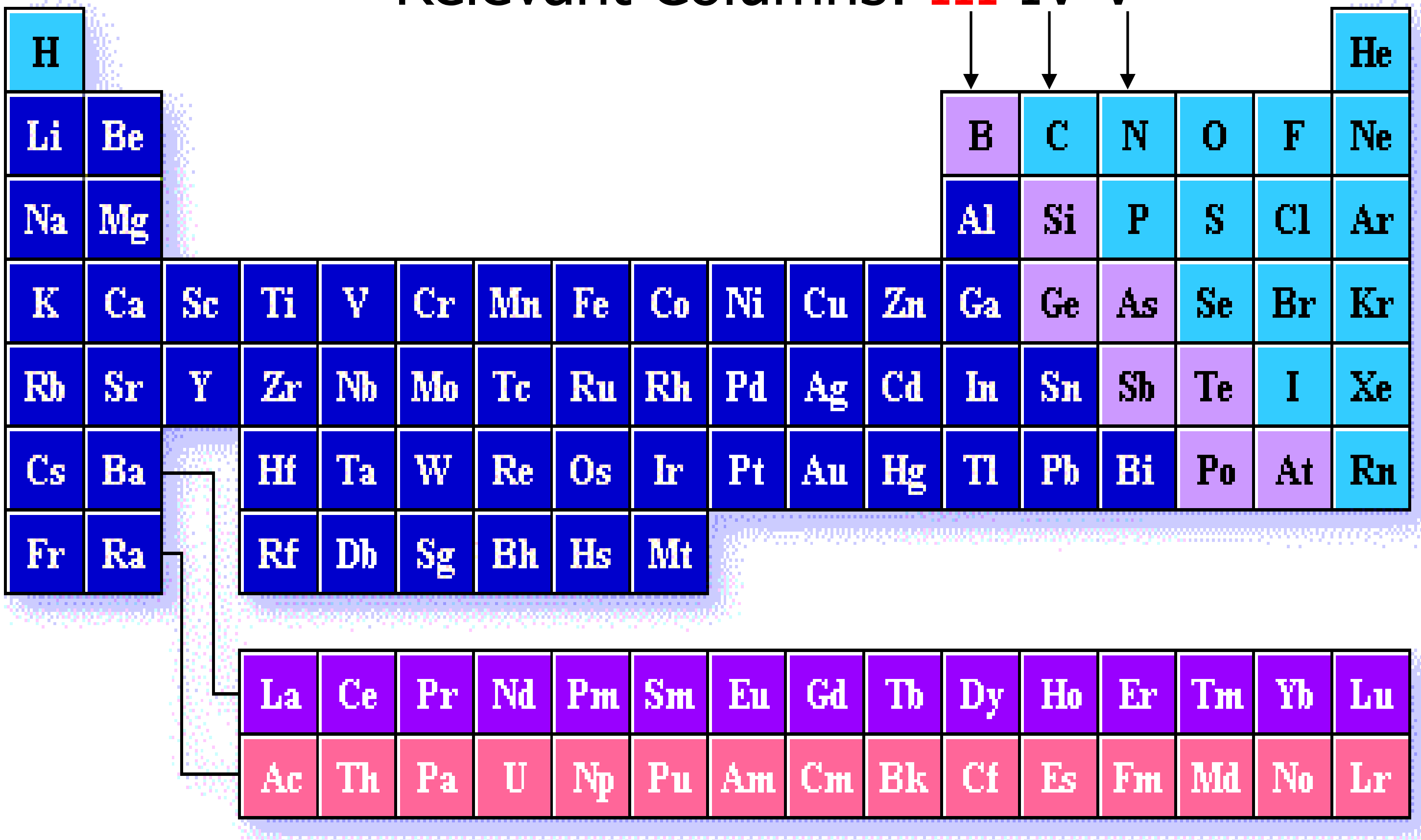
The phosphorus is *missing* one of its electrons, so it has a positive charge (+1)

The phosphorus ion is bound to the silicon, so this +1 charge can't move!

The number of electrons is equal to the number of phos. atoms: $n = N_d$

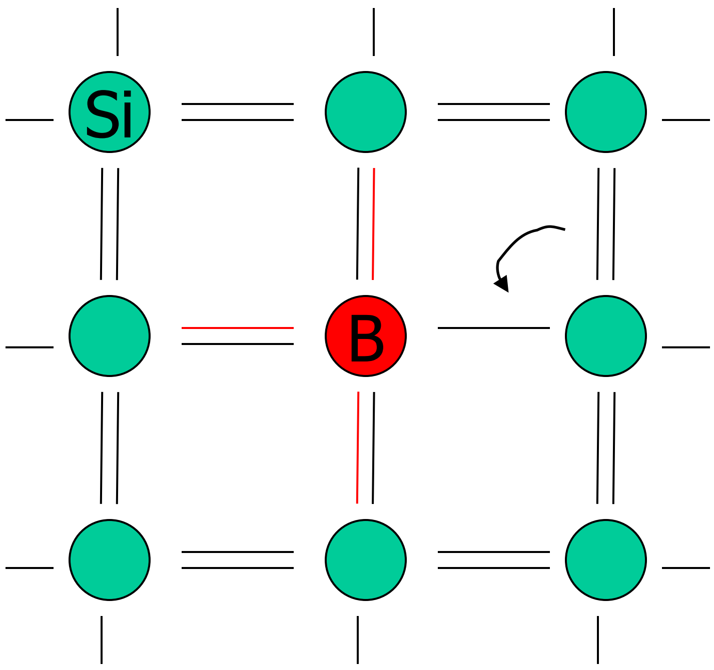
Periodic Table of Elements

Relevant Columns: III IV V



p-type silicon

add atoms from *column III* of the periodic table

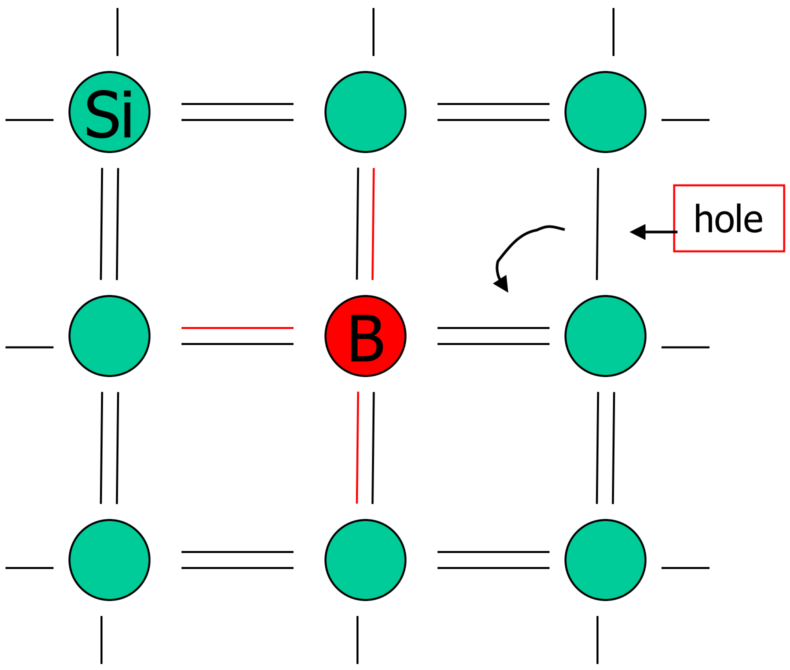


Column III elements have 3 valence electrons that form covalent bonds with Si, but the 4th electron is needed.

This 4th electron is taken from the nearby Si=Si bond

p-type silicon

add atoms from *column III* of the periodic table

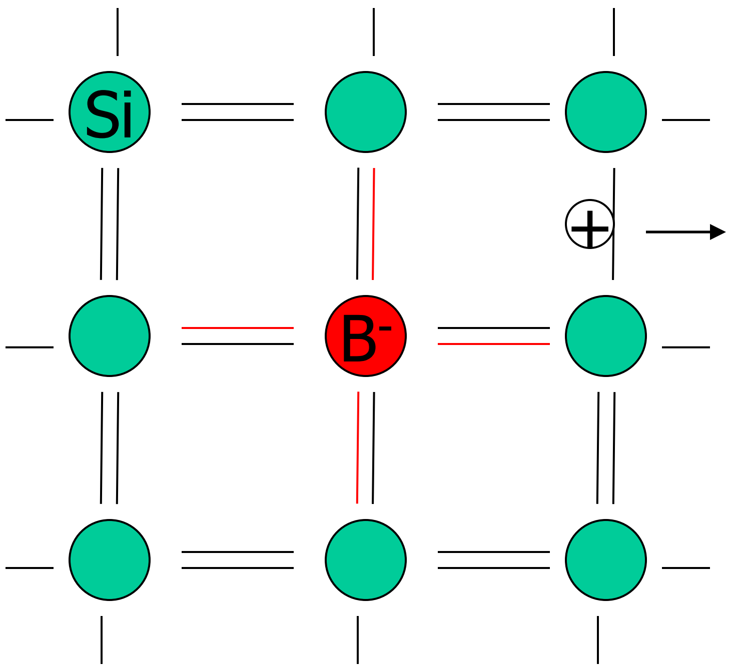


Column III elements have 3 valence electrons that form covalent bonds with Si, but the 4th electron is needed.

This 4th electron is taken from the nearby Si=Si bond

This "stolen" electron creates a free hole.

VERY IMPORTANT POINT



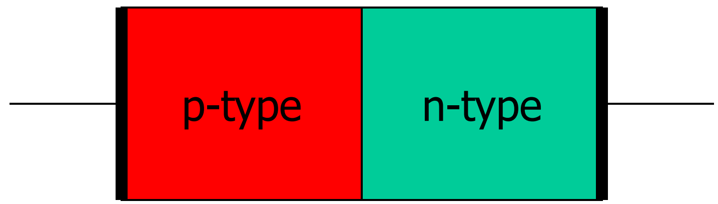
The boron atom has *accepted* an electron from the semiconductor (Column III atoms are called *acceptors*)

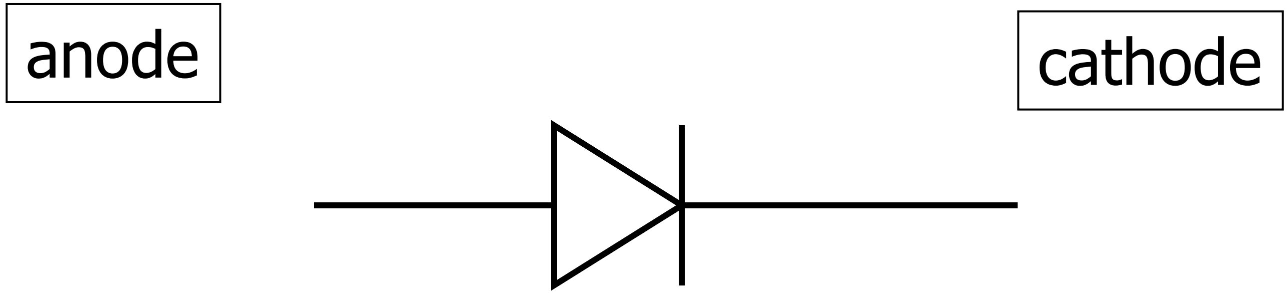
The boron has one extra electron, so it has a negative charge (-1)

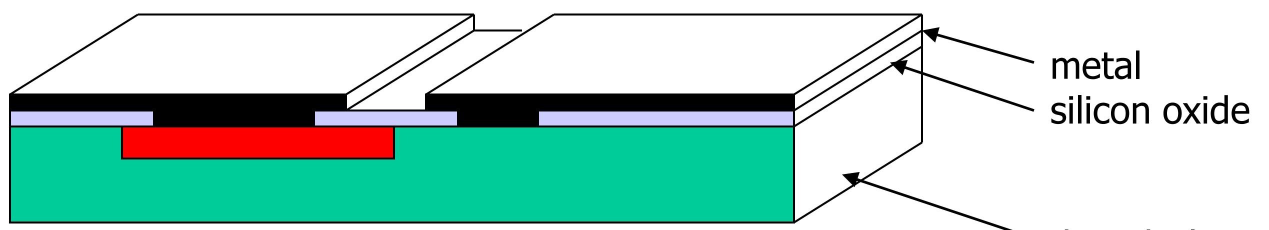
The boron ion is bound to the silicon, so this -1 charge can't move!

The number of holes is equal to the number of boron atoms: $p = N_a$

The pn Junction

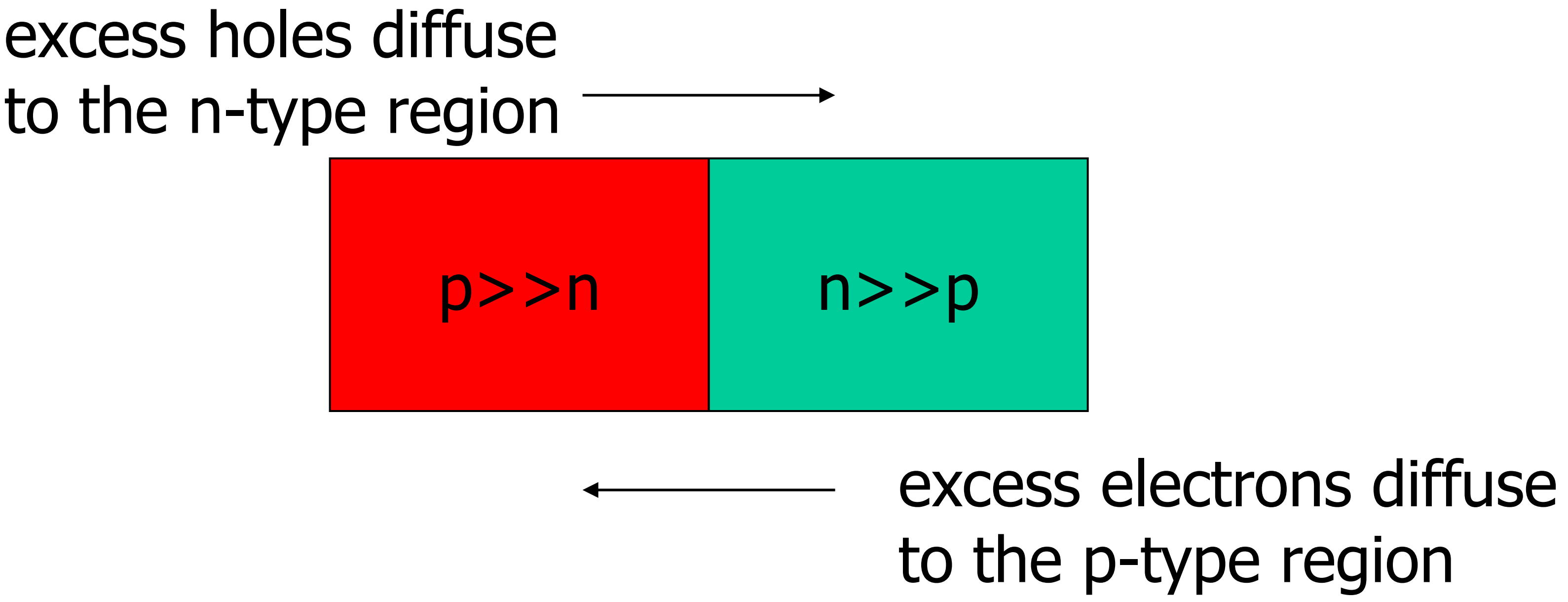




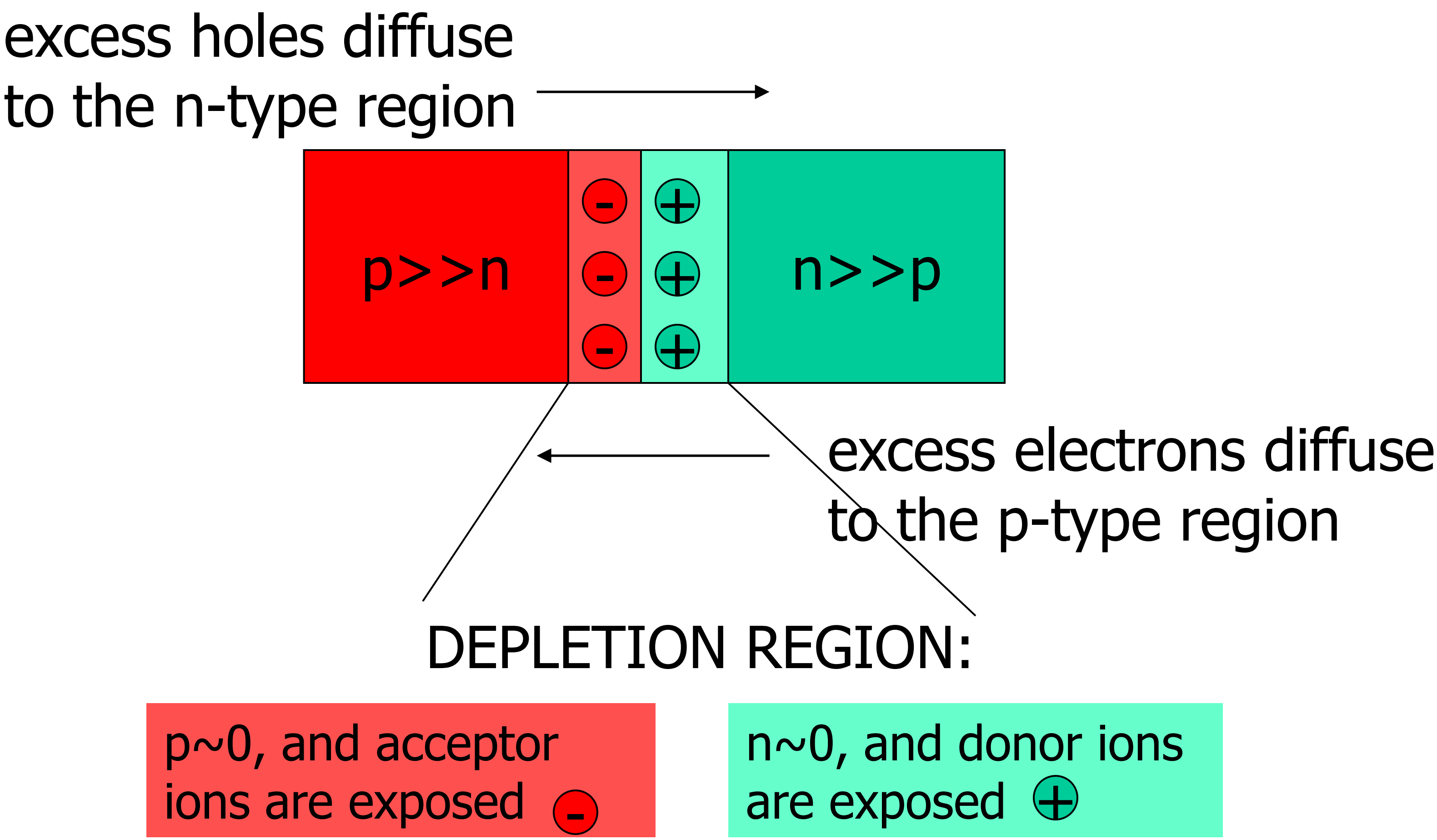


integrated circuit diode

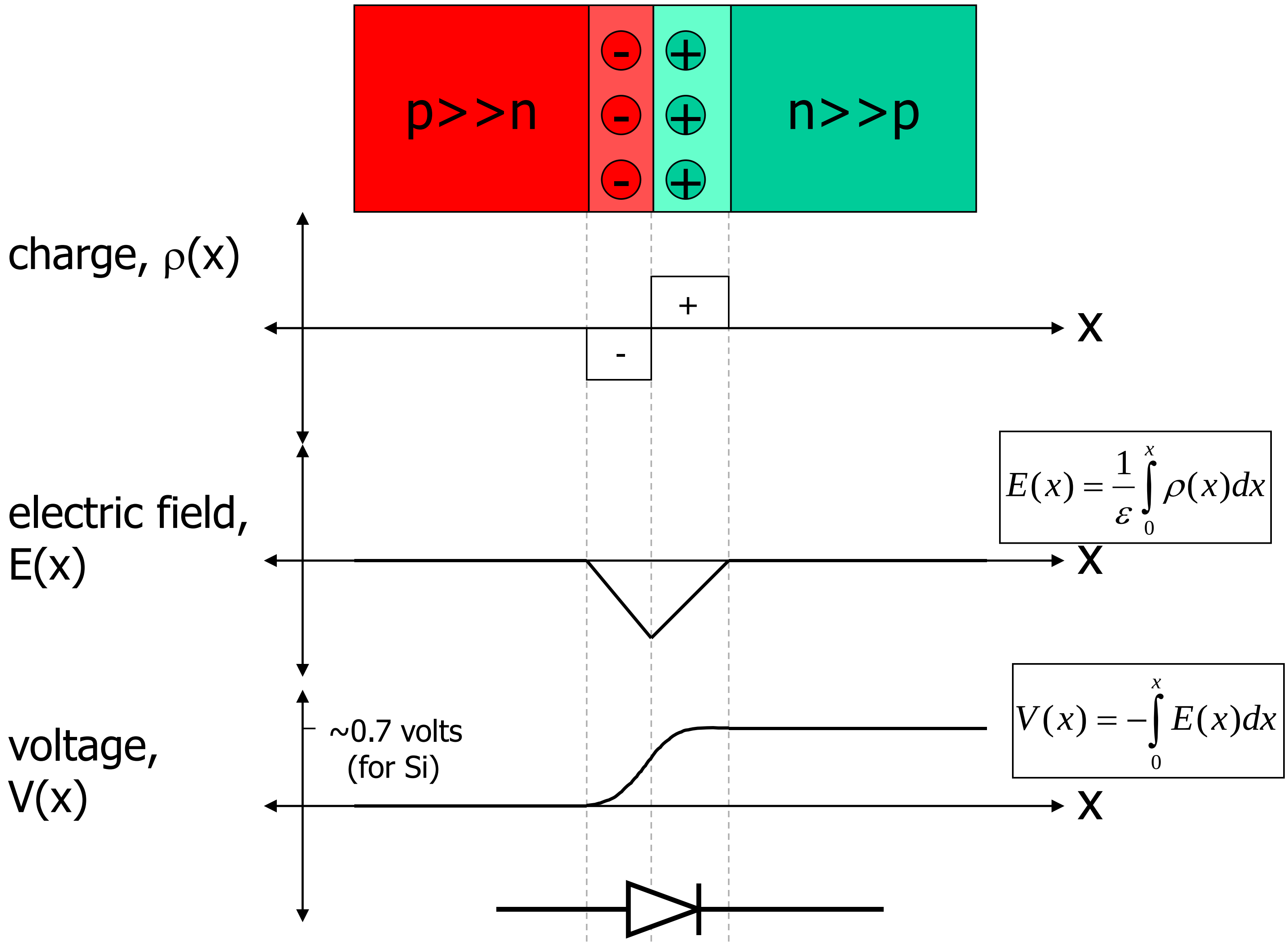
Dopant distribution inside a pn junction



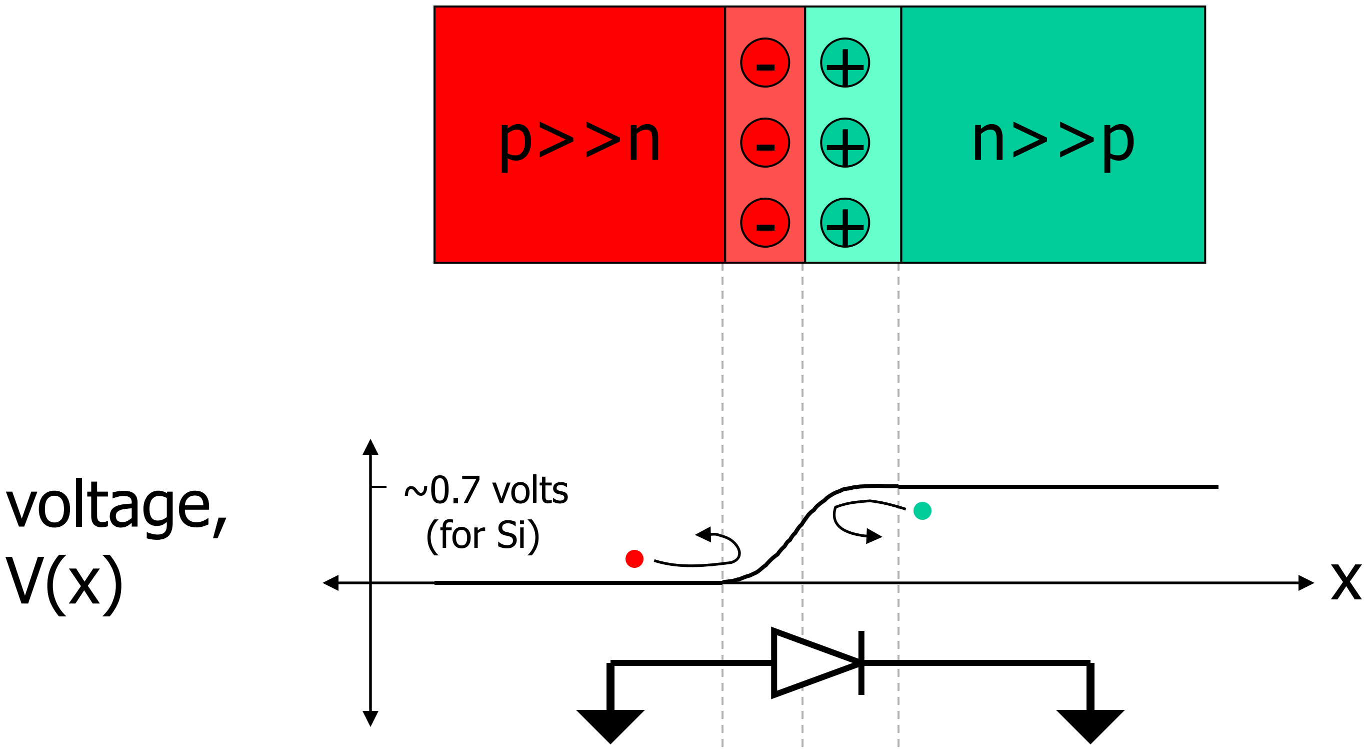
Dopant distribution inside a pn junction



Voltage in a pn junction



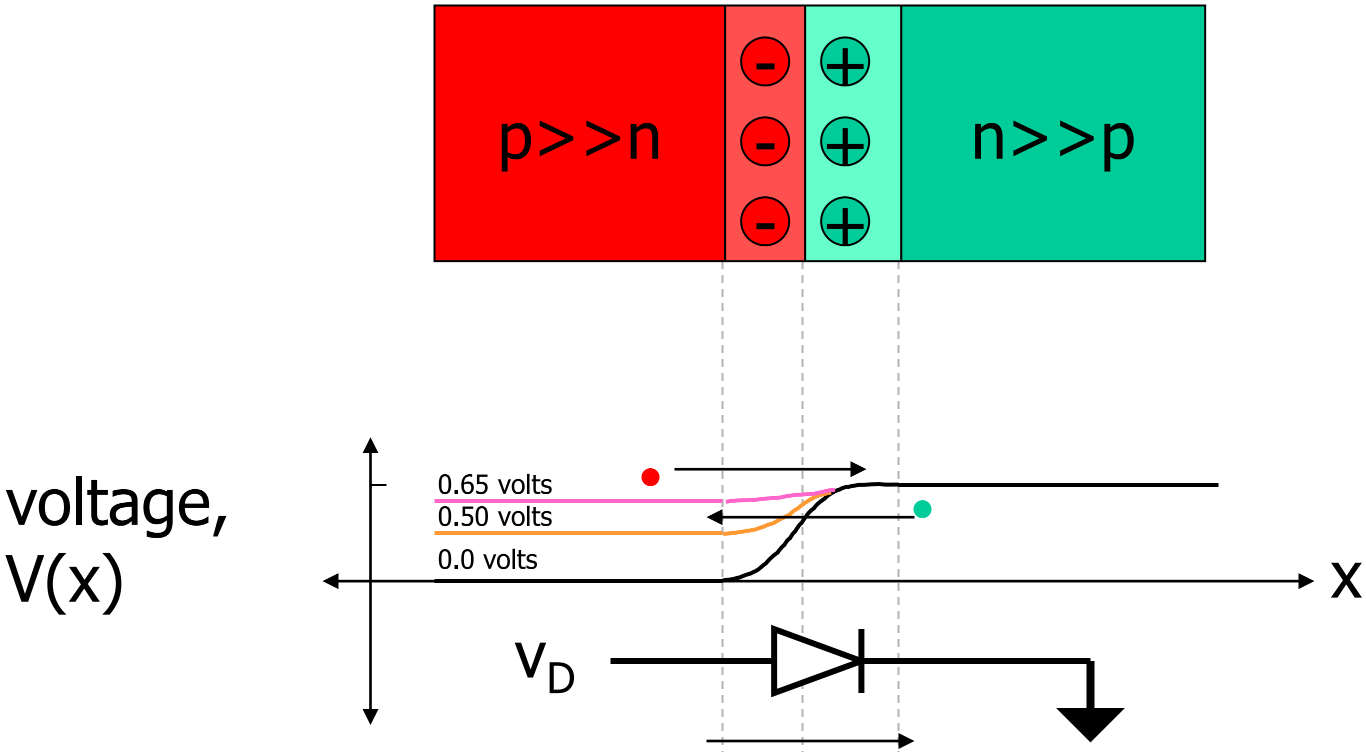
Zero Bias



At zero bias (v_D=0), very few electrons or holes can overcome this *built-in voltage barrier* of ~ 0.7 volts (and exactly balanced by diffusion)

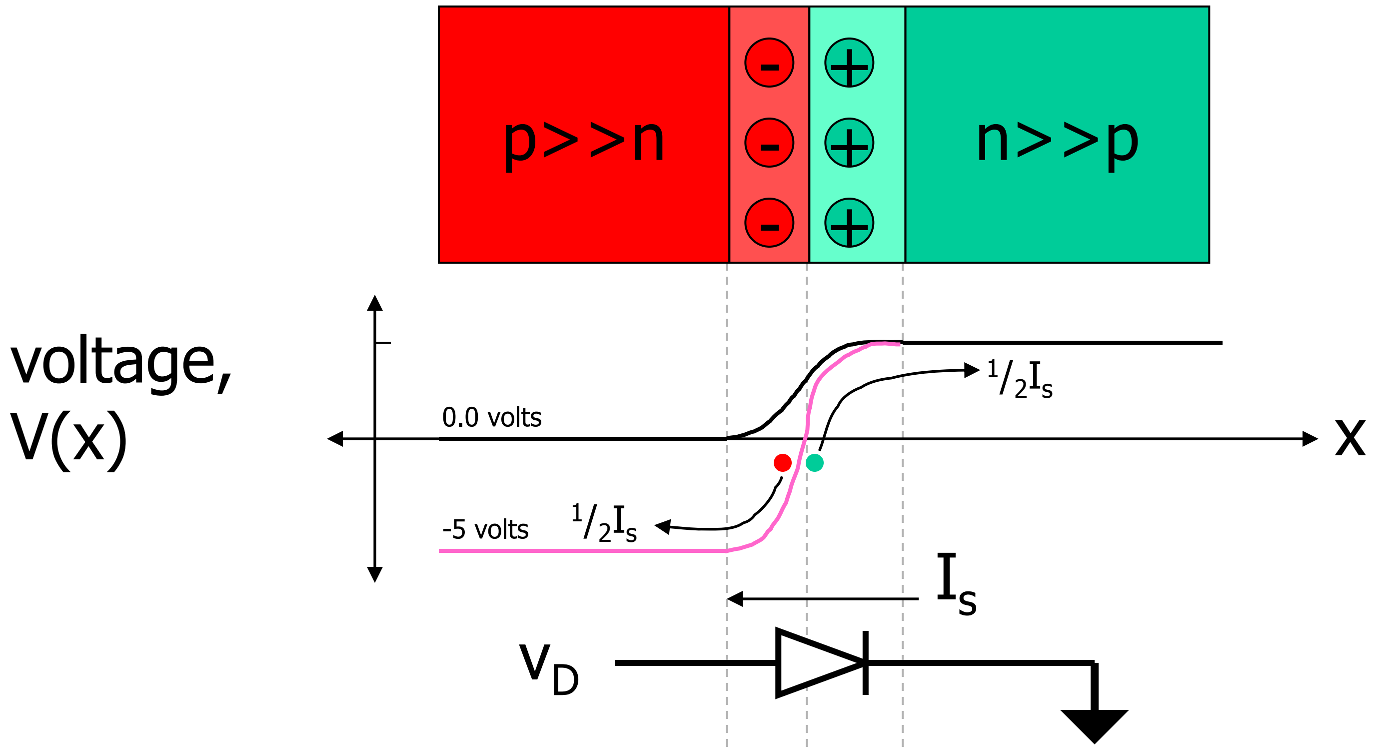
→ $i_D = 0$

Forward Bias



As the bias (v_D), increases toward 0.7V, more electrons and holes can overcome the *built-in voltage barrier* .→ $i_D > 0$

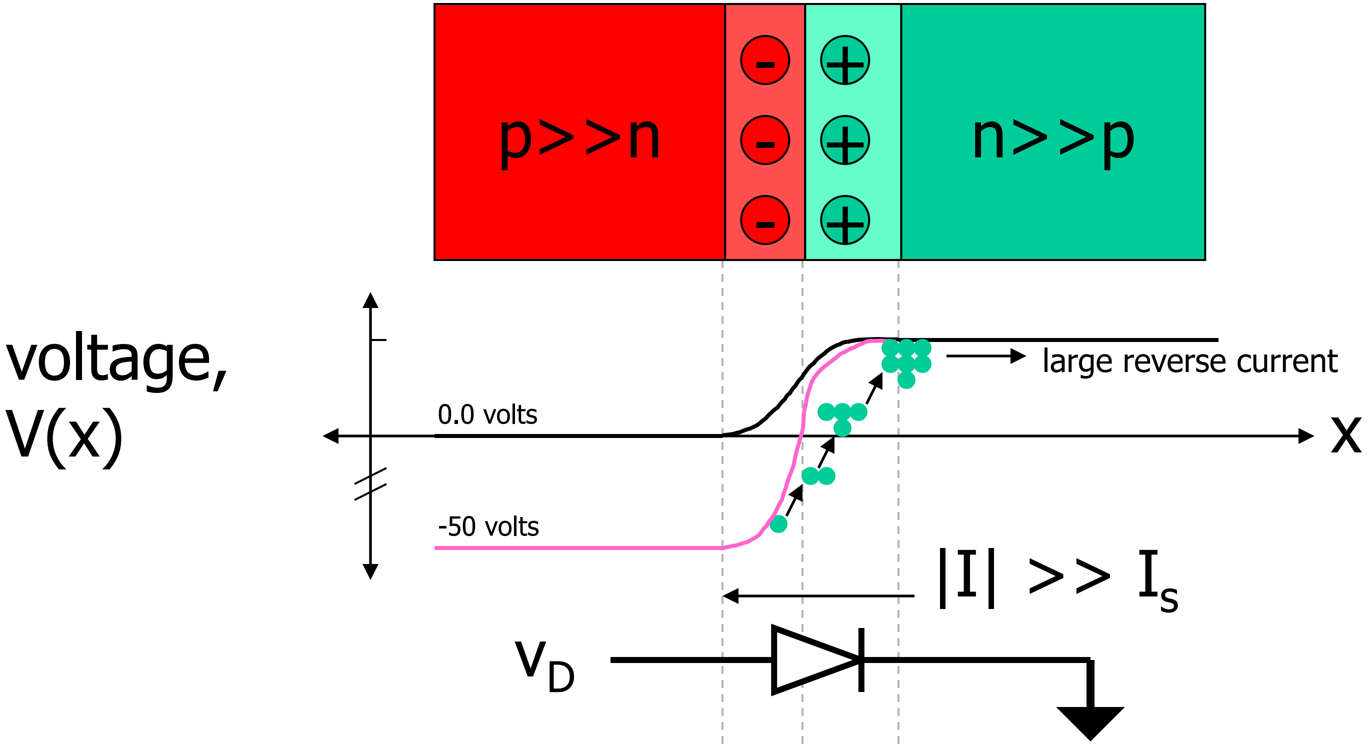
Reverse Bias



As the bias (v_D) becomes negative, the barrier becomes larger. Only electrons and holes due to broken bonds contribute to the diode current.

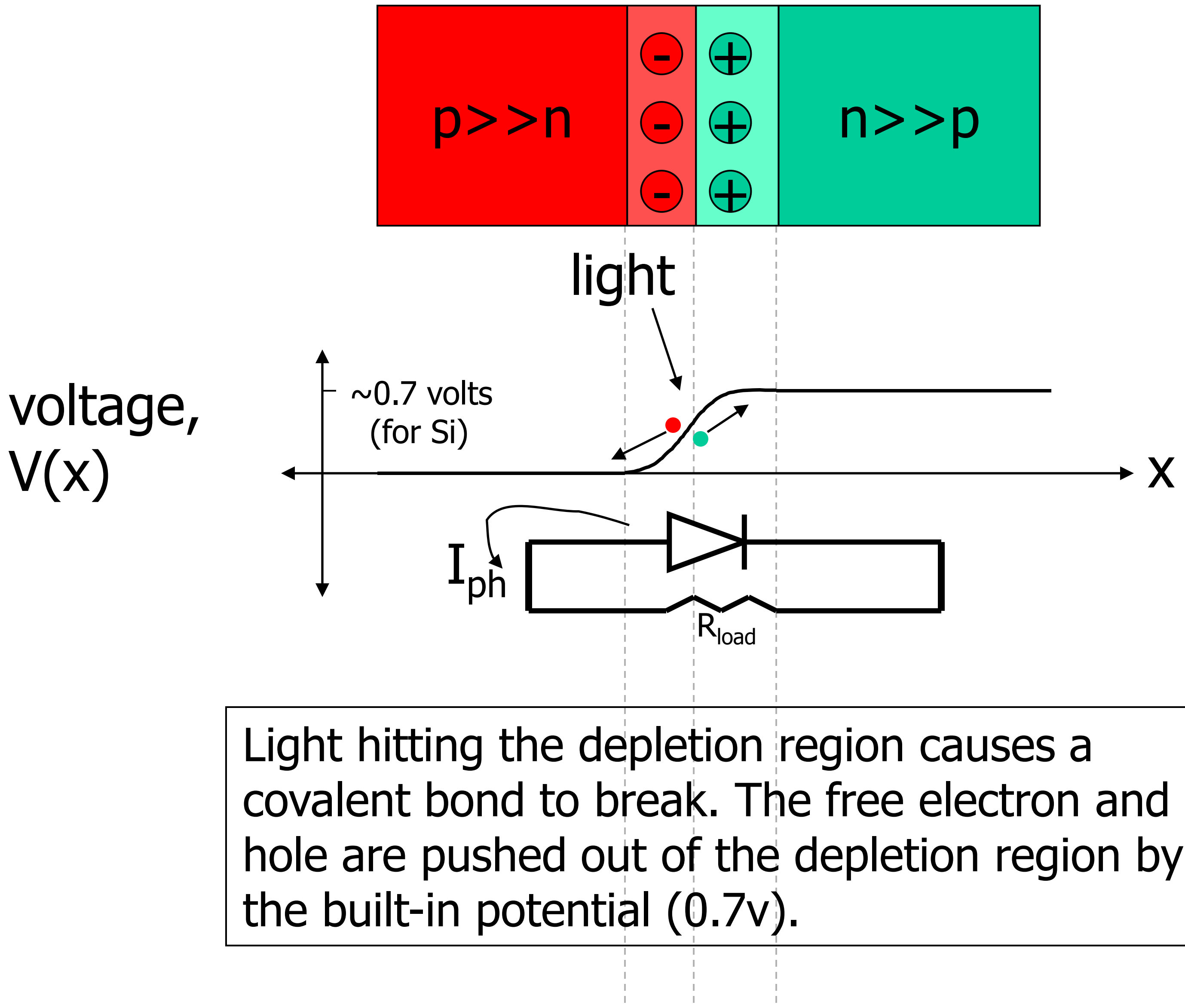
→ $i_D = -I_s$

Breakdown



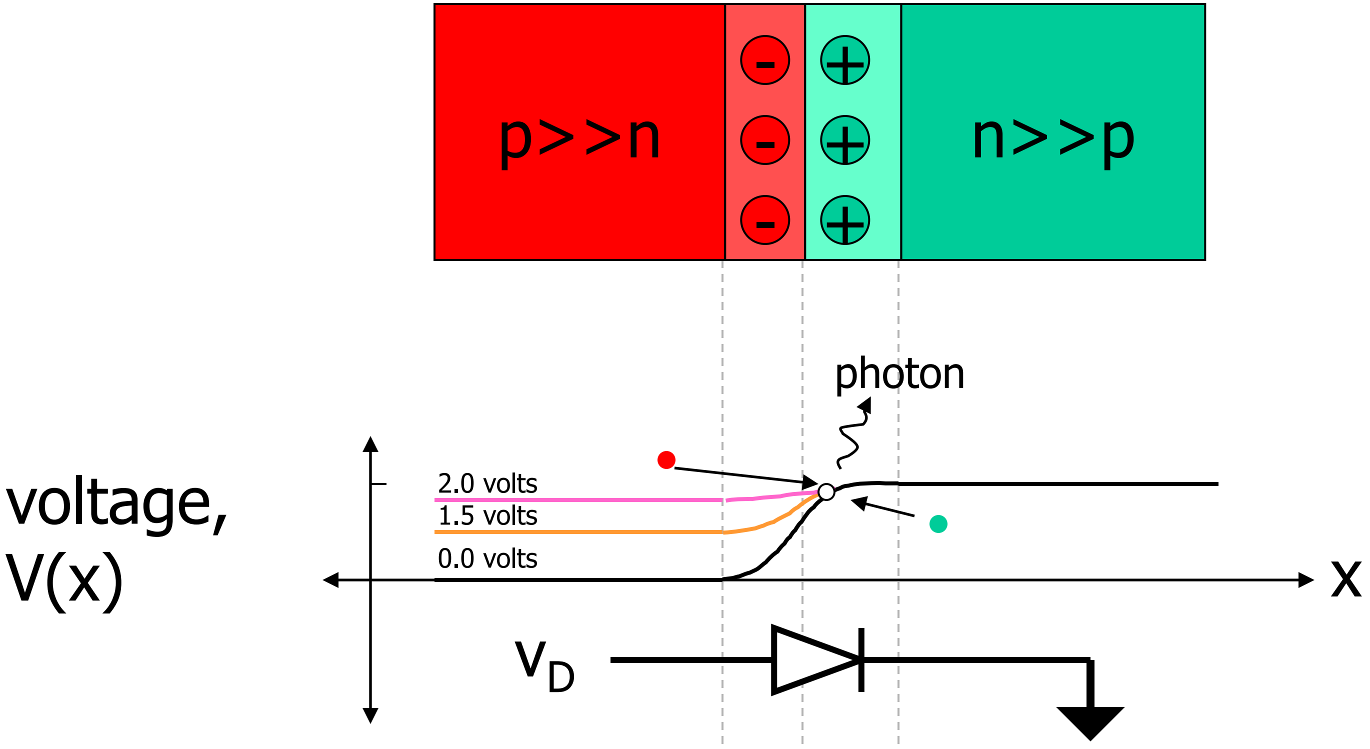
As the bias (v_D) becomes very negative, the barrier becomes larger. Free electrons and holes due to broken bonds are accelerated to high energy ($>E_g$) and break other covalent bonds – generating more electrons and holes (avalanche).

Solar Cell (Photovoltaic)



Light hitting the depletion region causes a covalent bond to break. The free electron and hole are pushed out of the depletion region by the built-in potential (0.7v).

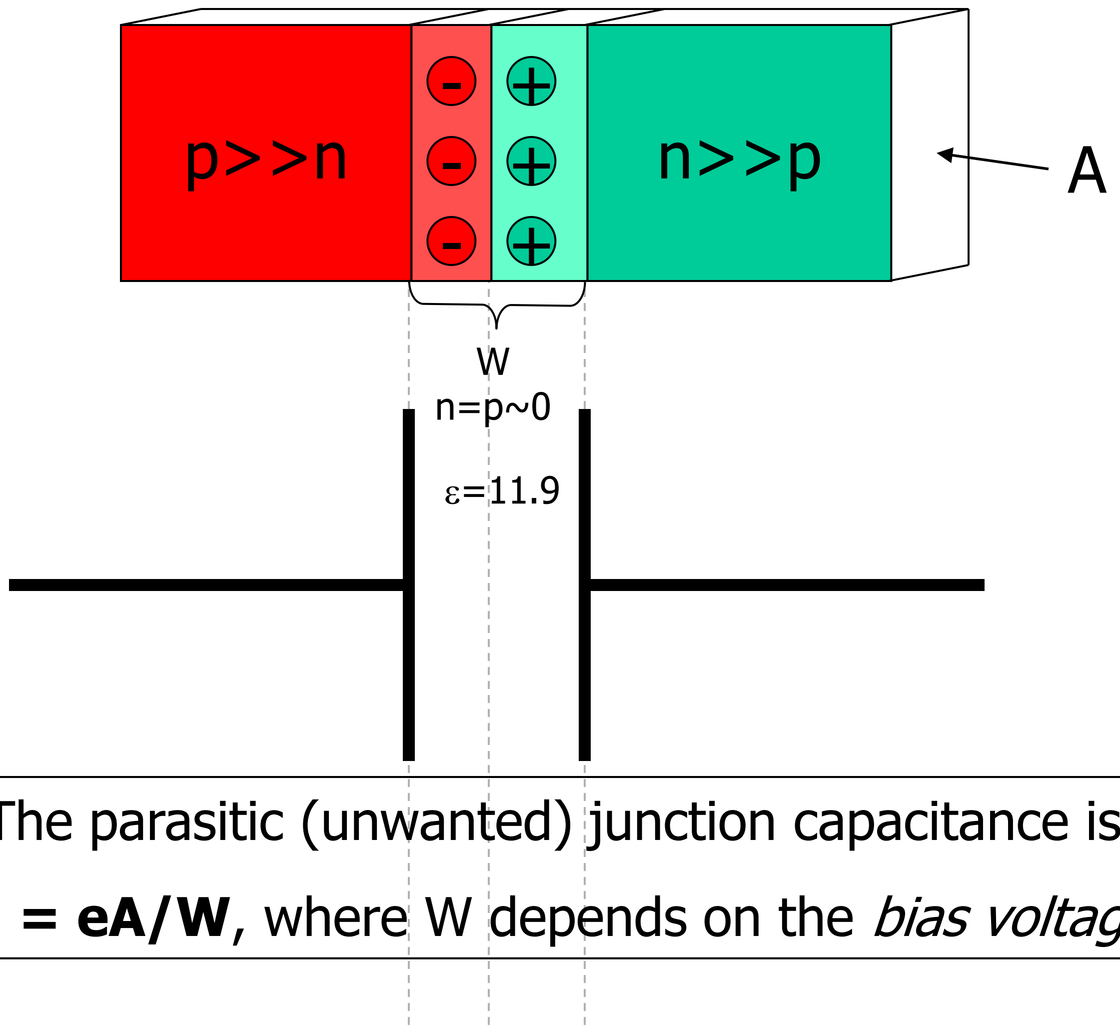
Light Emitting Diode (LED)



In forward bias, an electron and hole collide and self-annihilate in the depletion region. A photon with the gap energy is emitted. Only occurs in some materials (not silicon).

Junction Capacitance

semiconductor-"insulator"-semiconductor



The parasitic (unwanted) junction capacitance is

$\mathbf{C_j = eA/W}$, where W depends on the *bias voltage*

Junction Capacitance (C_j)

- The junction capacitance must be charged and discharged every time the diode is turned on and off
- Transistors are made of pn junctions. The capacitance due to these junctions limits the *high frequency* performance of transistors
  - *remember*, $Z_c = 1/j\omega C$ becomes a short circuit at high frequencies ($Z_c \rightarrow 0$)
  - this means that a pn junction looks like a short at high *f*
- *This is a fundamental principle that limits the performance of all electronic devices*