Outline of Section 3 - Diodes

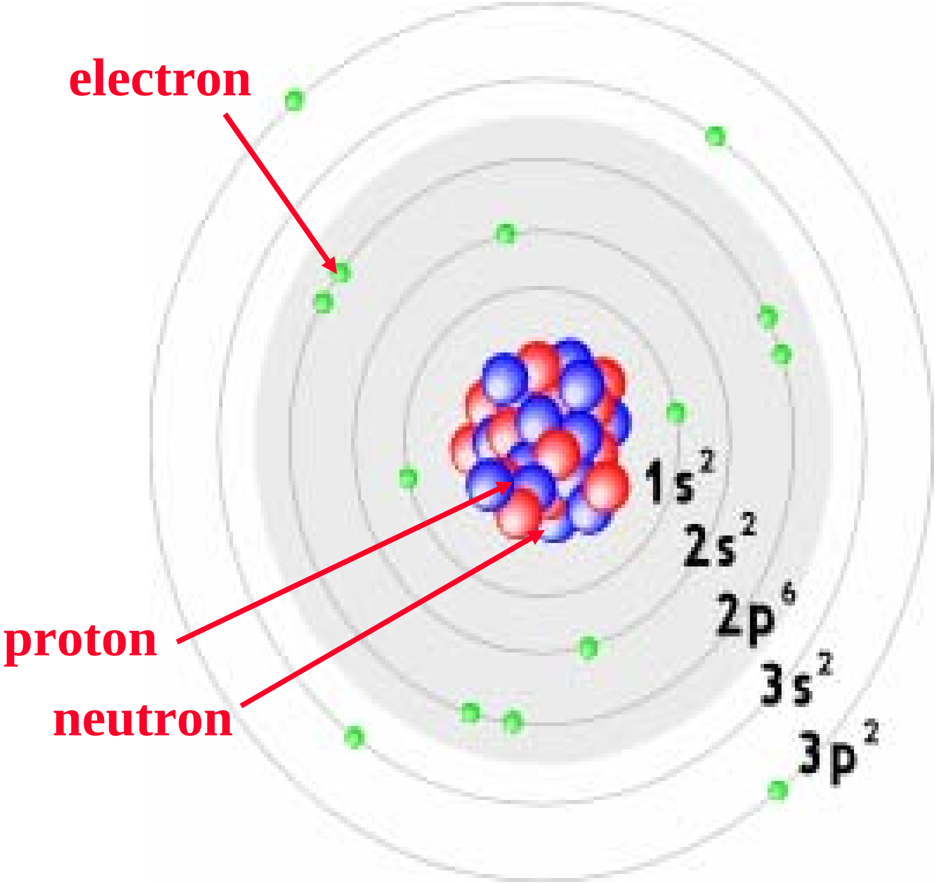
- Two terminal devices
- Diode models
- Exponential model
- Constant voltage drop model
- Reverse breakdown
- Applications
- Small-signal model
- *PN junctions*

Silicon

- Silicon
  - Atomic number 14
  - Atomic weight: 28.09au

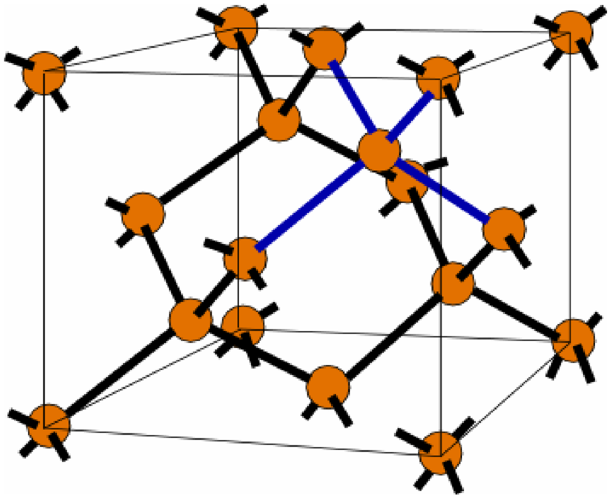
- The material is the most purified substance man has ever attempted to produce.

- It has 4 valence electrons and if properly grown in crystal-form it takes on a face-body cubic crystal pattern.

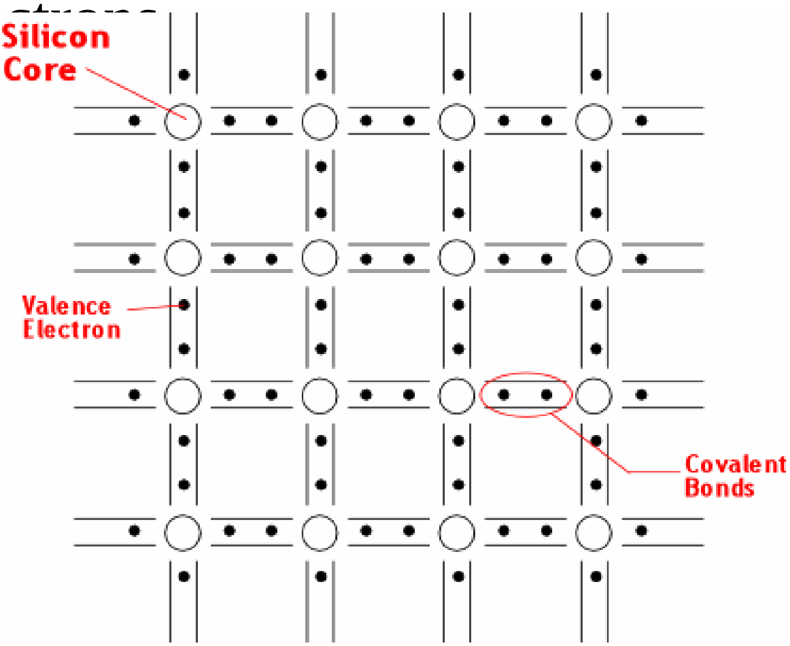


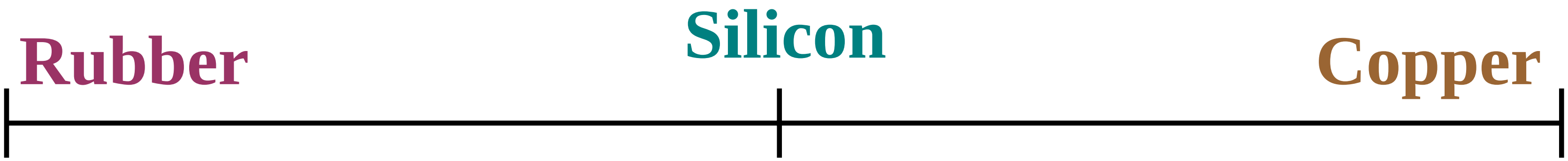
Silicon Semiconductor

- Intrinsic silicon has a regular crystal lattice of atoms
  - held together by covalent bonds
  - each atom has four valence electrons



5×10^{22} atoms/cm^3





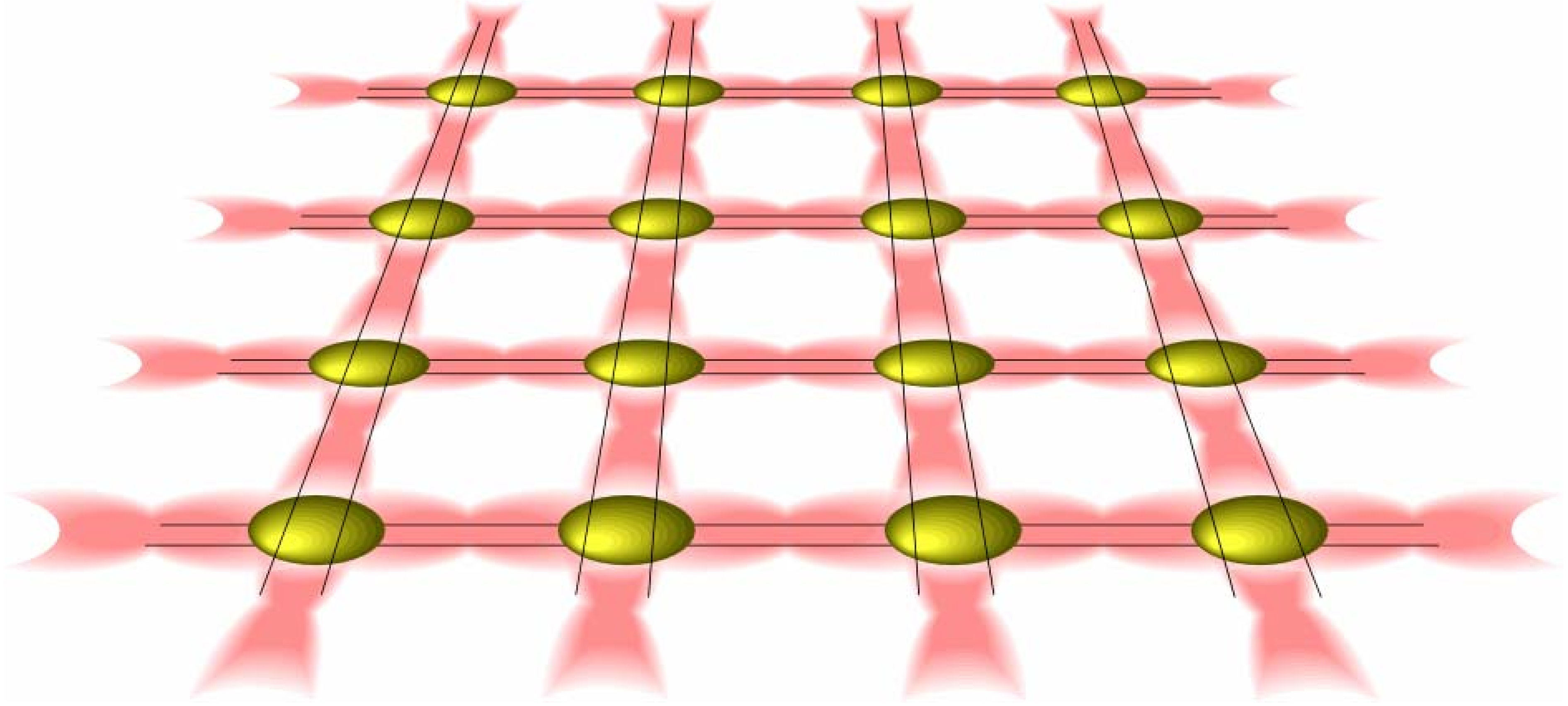
Rubber

Silicon

Copper

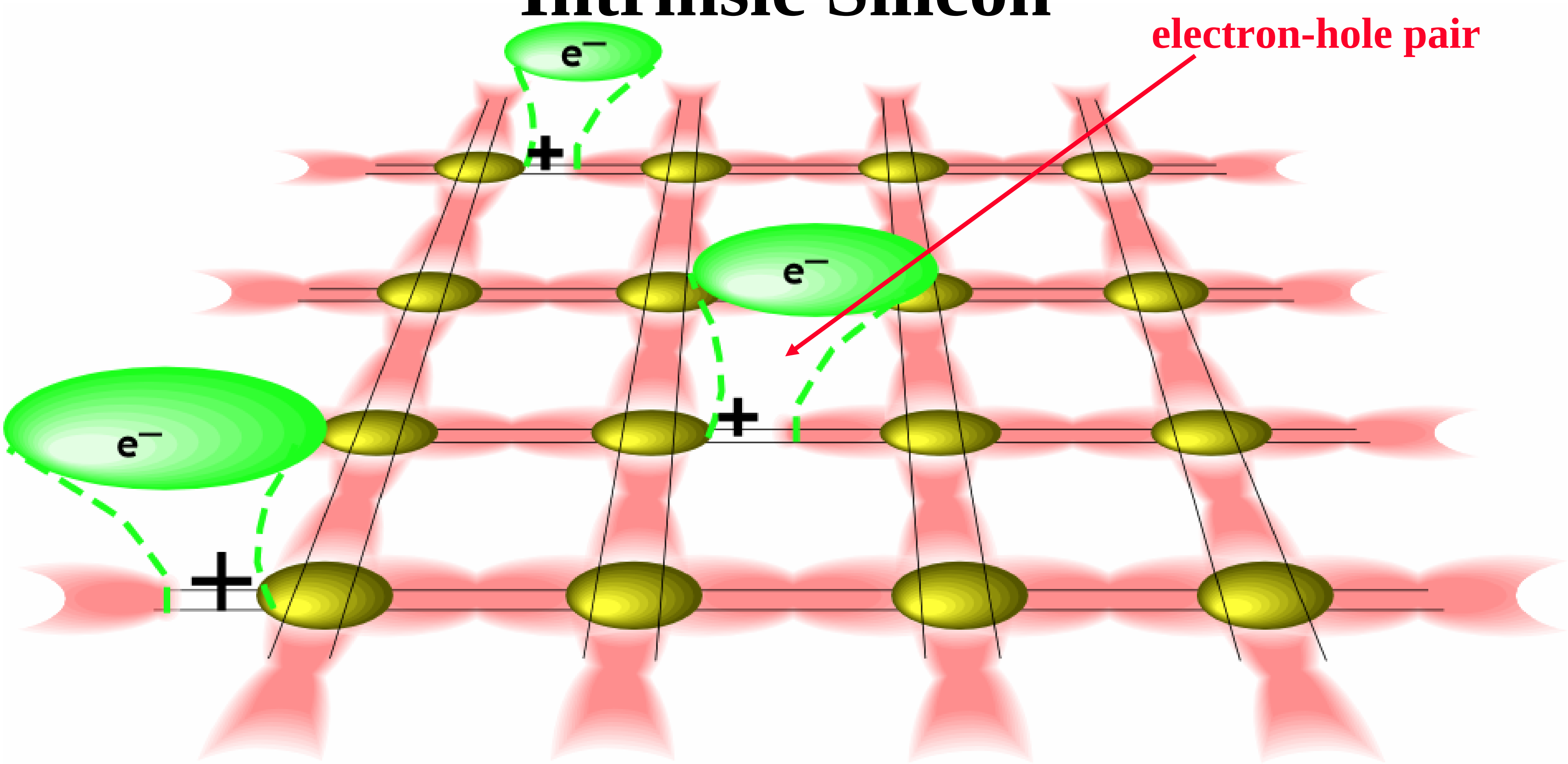
(semi-conductor)

Intrinsic Silicon



- At low temperatures, all covalent bonds are intact (T → 0K), there are no free electrons

Intrinsic Silicon

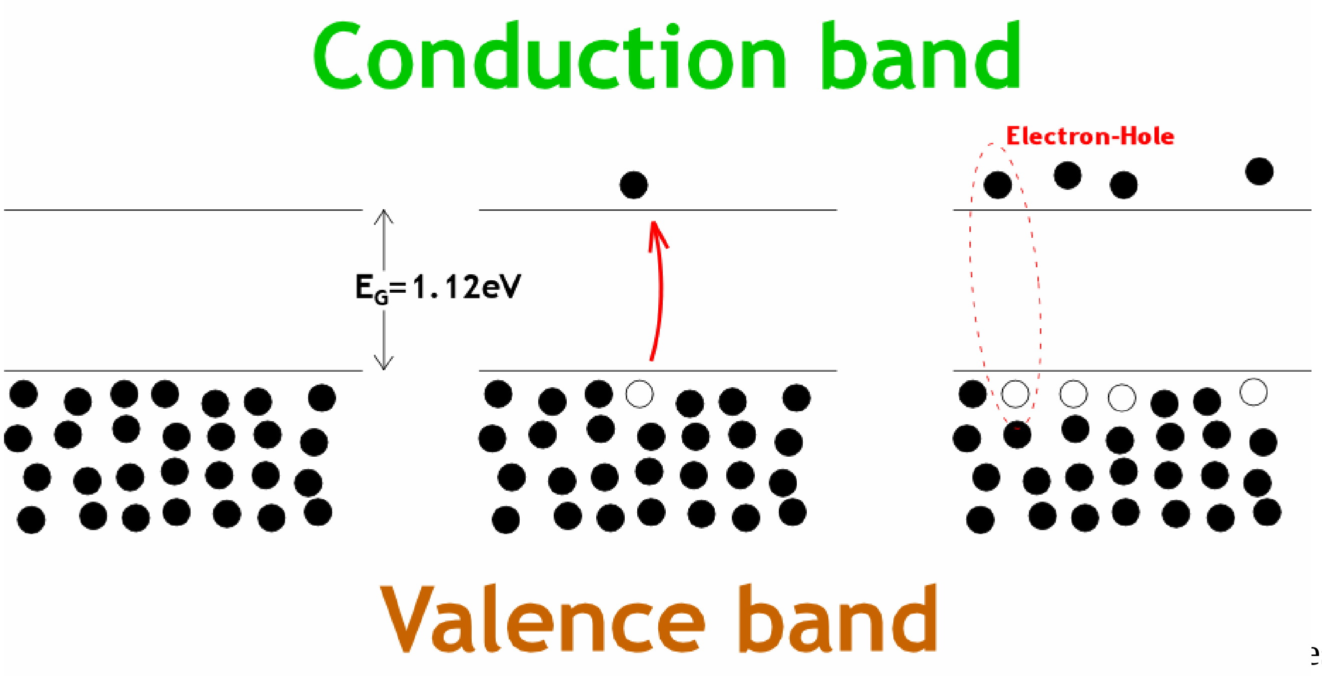


- As temperature rises, some electrons break free, leaving ***holes*** in lattice with positive charge.
- These are called ***Electron-hole pairs***. The electrons move in the ***conduction-band*** and holes move in the ***valence-band***

Intrinsic Silicon

- The number of holes ‘p’ and the number of electrons ‘n’ increases equally with temperature.
- At room-temperature (T>273K), n = p = 1.5×10^{10} carriers/cm^3.

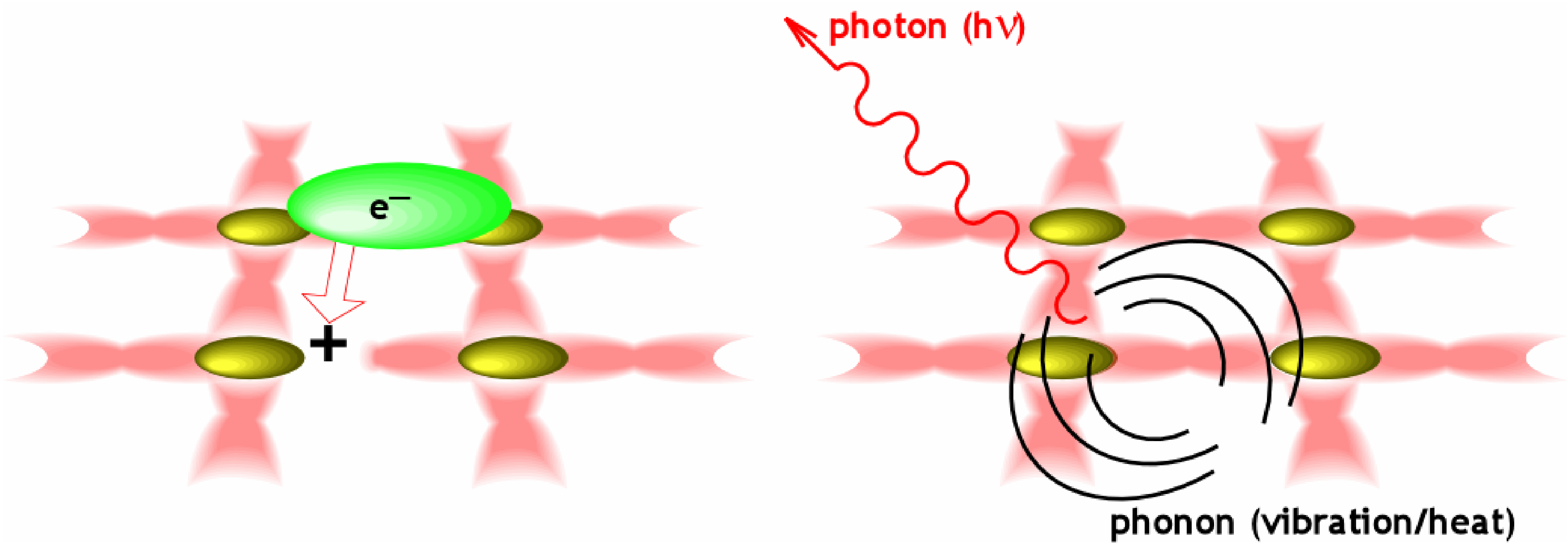
$$n_i = n = p \qquad n_i^2 = np$$



Electron-Hole Recombination

- Electrons in conduction band and holes in valence band may interact with each other.

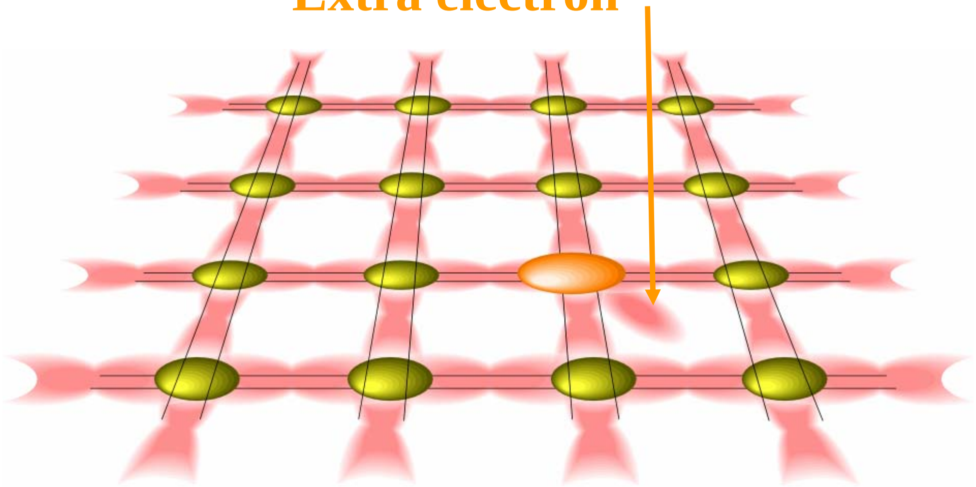
➡ A free electron and a free hole interact and annihilate each other.

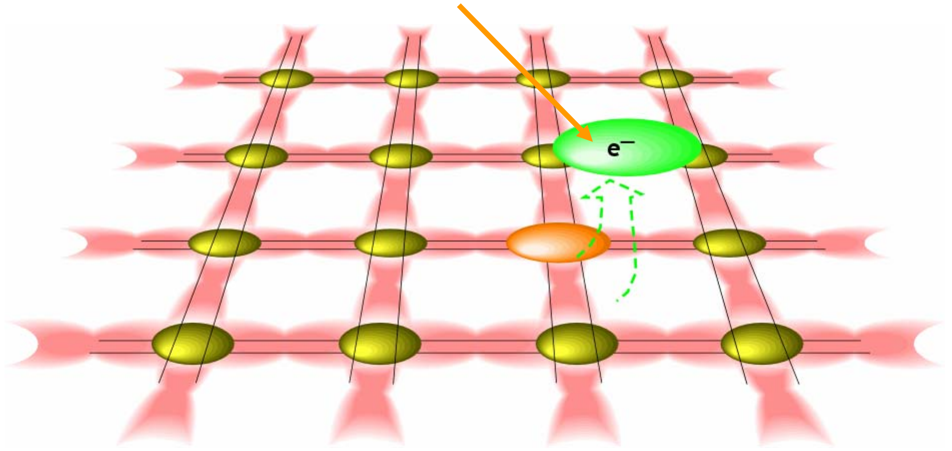


Before **After**

Semiconductor Doping

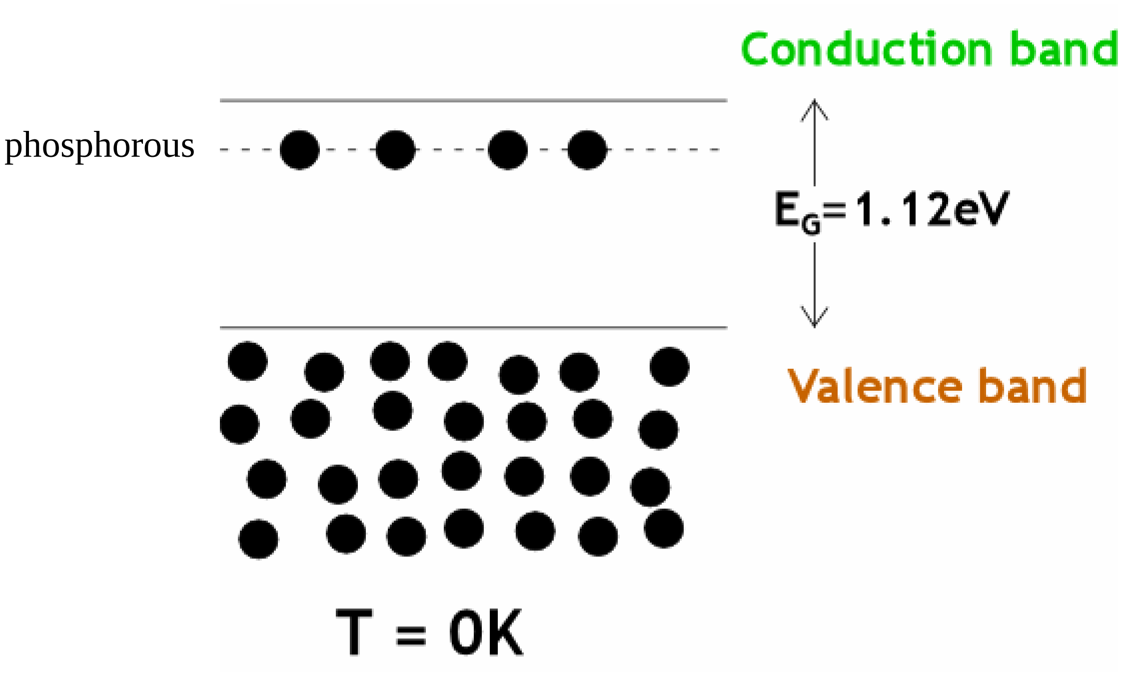
- Phosphorous-doping
  - This atom has 5 valence electrons.
- This creates a “N-type” semiconductor. It is also called a DONOR atom.
- At room temperature, there is an excess of FREE-electrons.
- If the doping is significant and T=273K, then: $\boldsymbol{n = N_D}$ ***and*** $\boldsymbol{p = n_i^2/N_D}$


Extra electron


Extra FREE electron

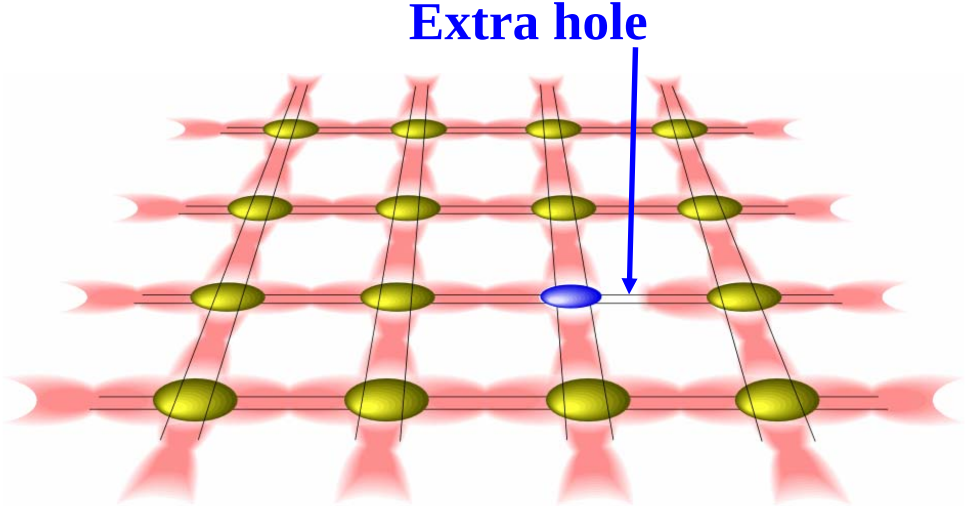
N-type Silicon

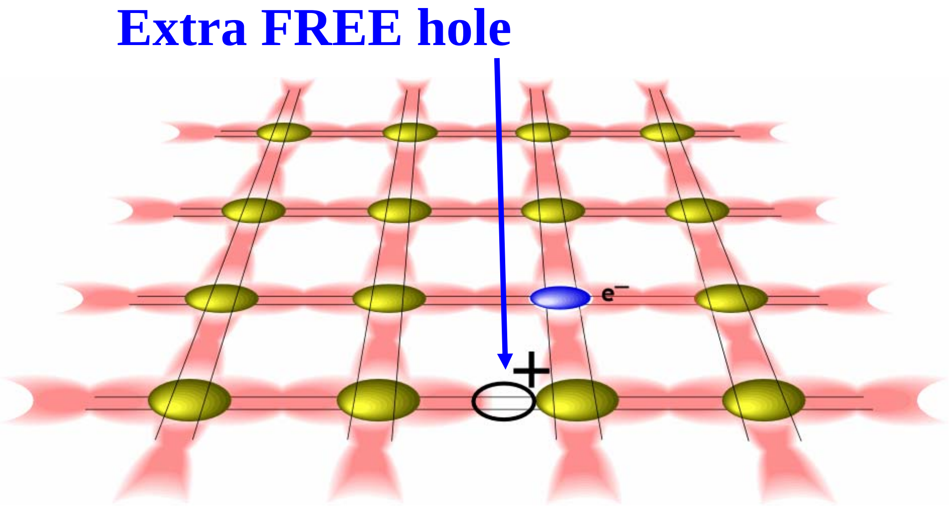
- In n-type silicon:
  - electrons are ***majority carriers*** and holes are ***minority carriers***



Semiconductor Doping

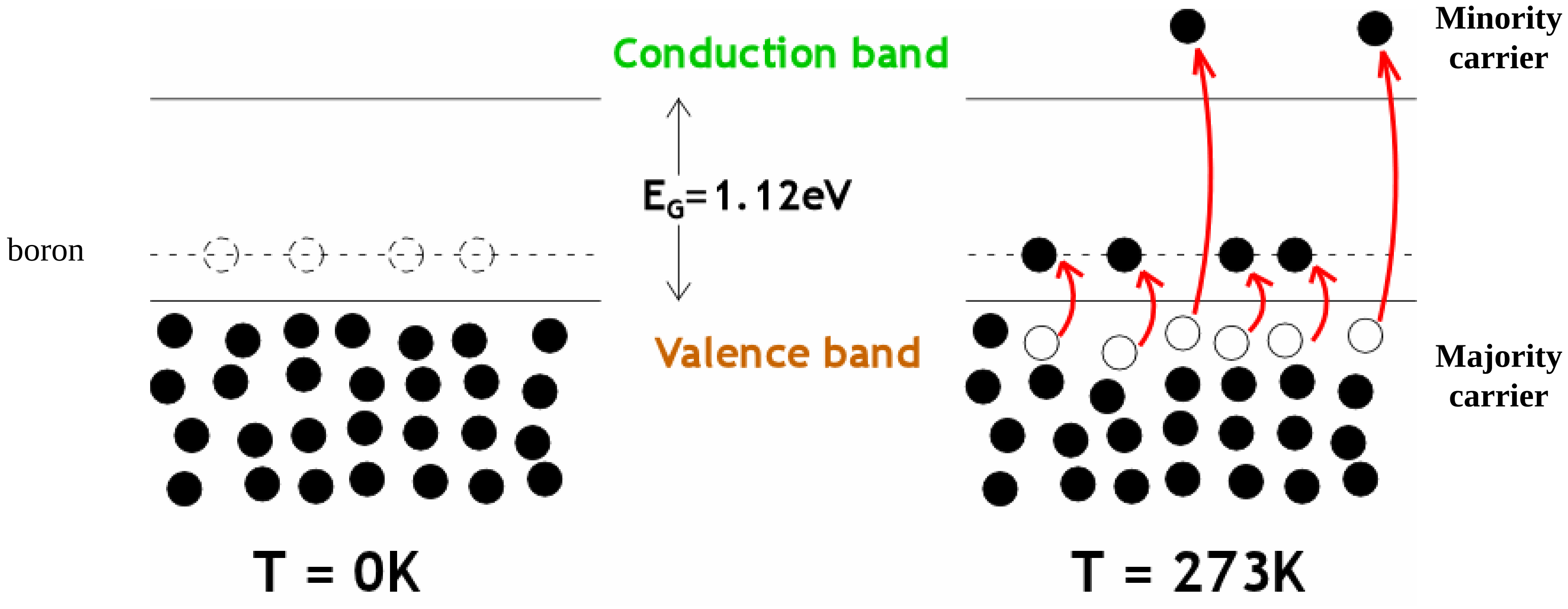
- Boron-doping
  - This atom has 3 valence electrons.
- This creates a "P-type" semiconductor. It is also called a ACCEPTOR.
- At room temperature, there is an excess of FREE-holes.
- If the doping is significant and T=273K, then: $p = N_A$ ***and*** $n = n_i^2/N_A$


Extra hole


Extra FREE hole

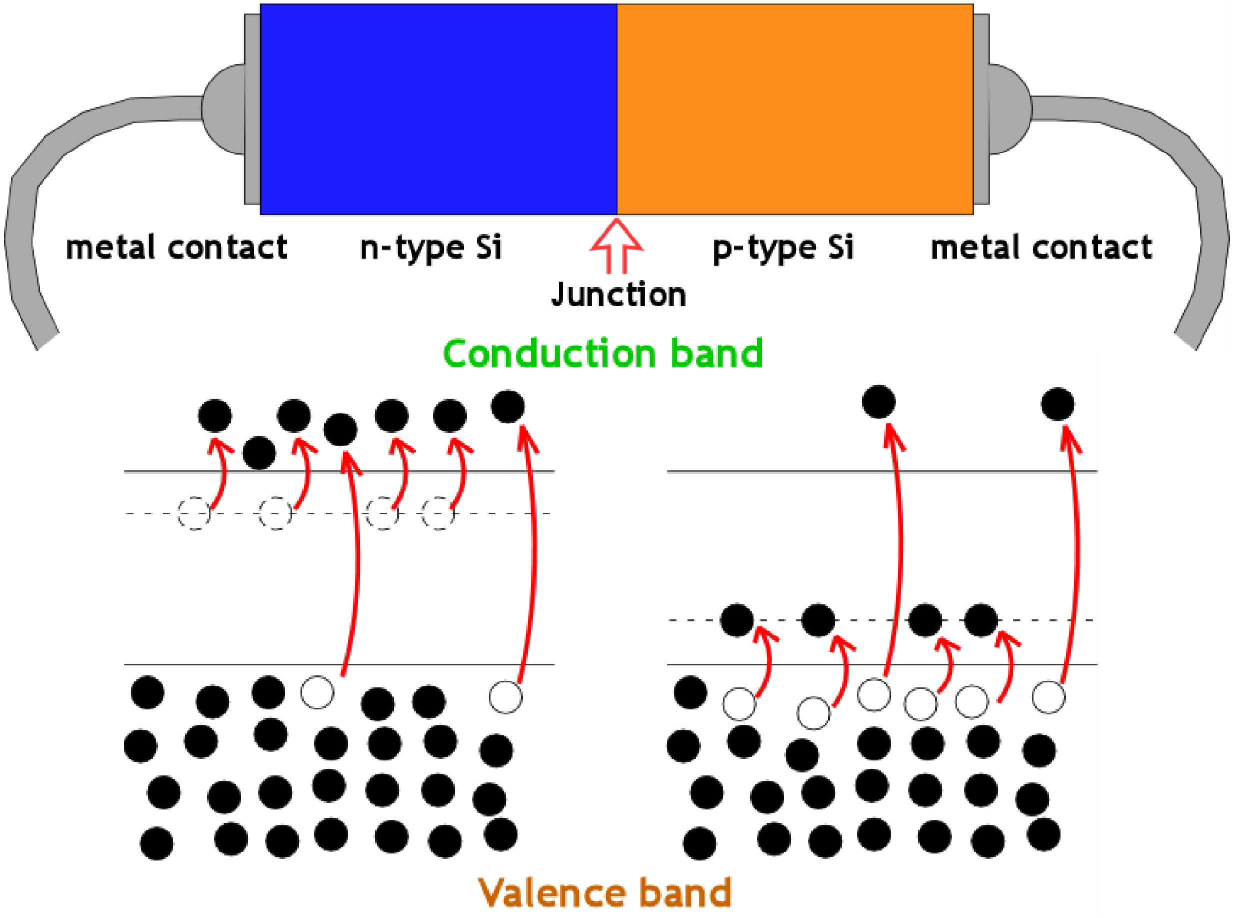
P-type Silicon

- In p-type silicon:
  - holes are ***majority carriers*** and electrons are ***minority carriers***



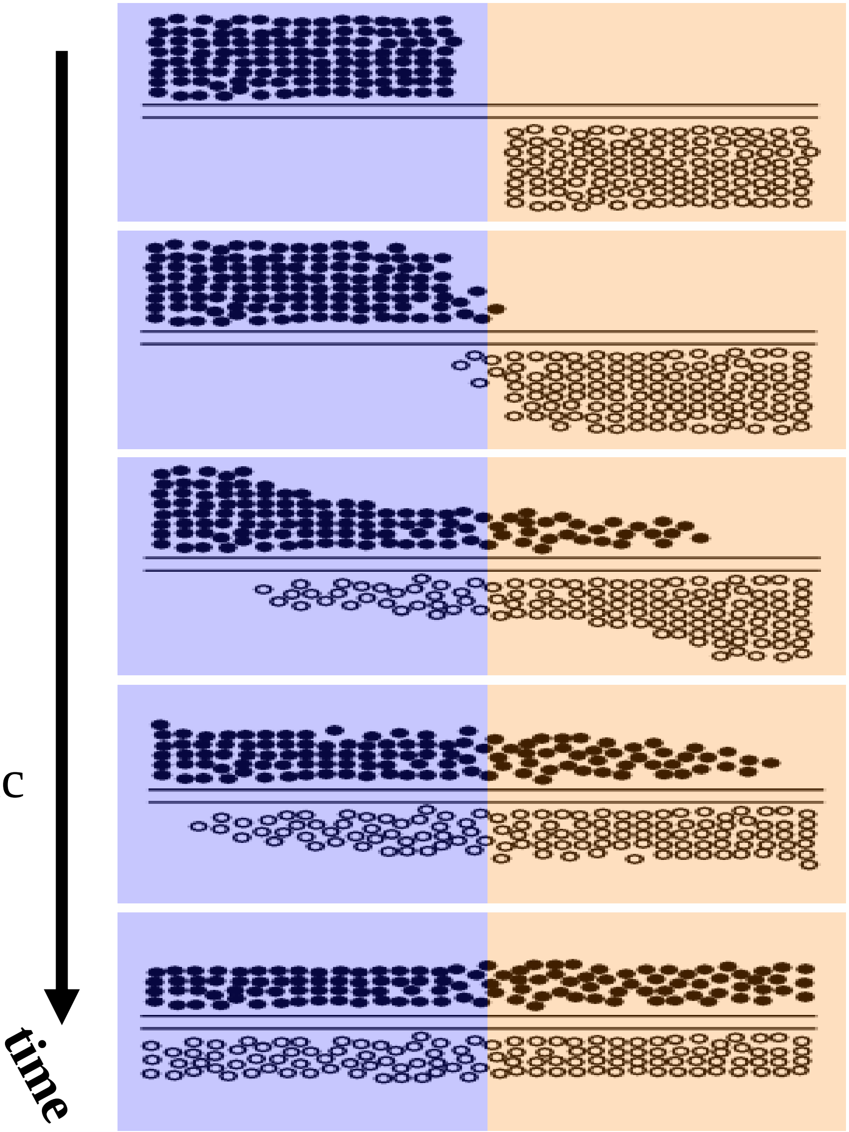
The PN Junction

- When a p-type material is brought into contact with an n-type material, the interface changes and creates a “built-in” voltage.



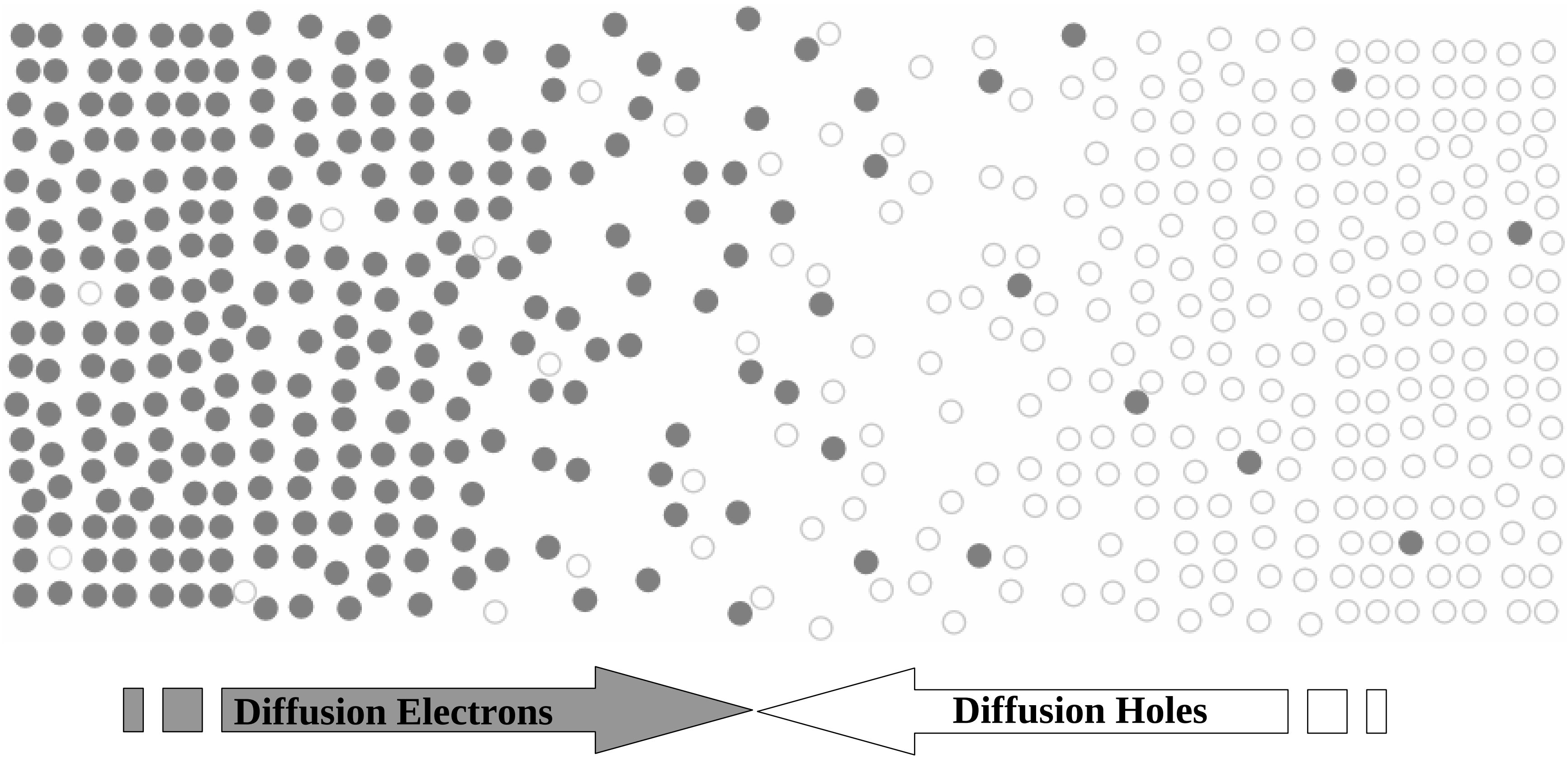
Diffusion of holes and electrons

- The FREE electrons from the n-type material diffuse to the right
- Diffusion is part of the thermodynamic law of MAXIMUM ENTROPY



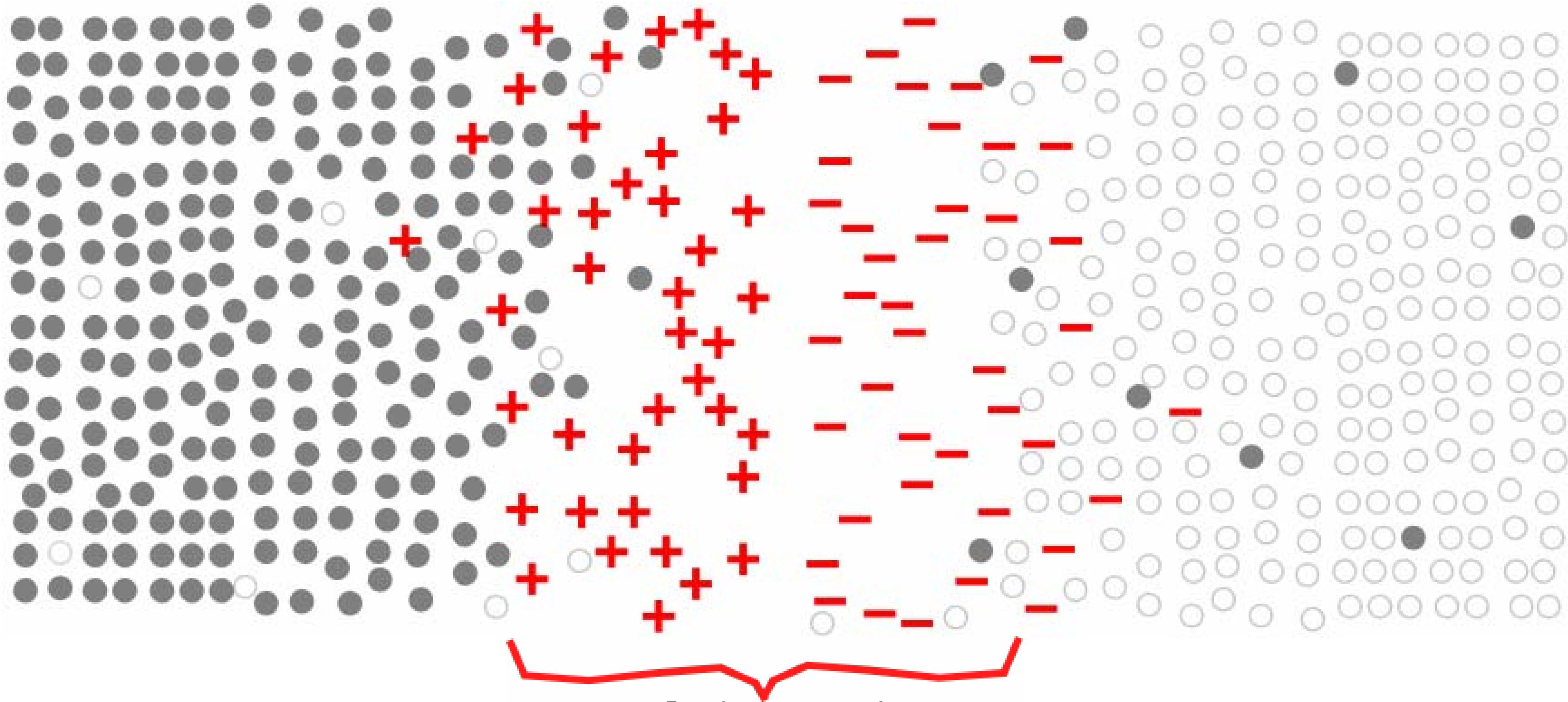
- The FREE holes from the p-type material diffuse to the left
- Just like the way perfume diffuses across a room over time

Diffusion and Drift



- As the carriers diffuse across the junction, they recombine with the majority carriers on the opposite side, this creates local charge sites and a depletion region.

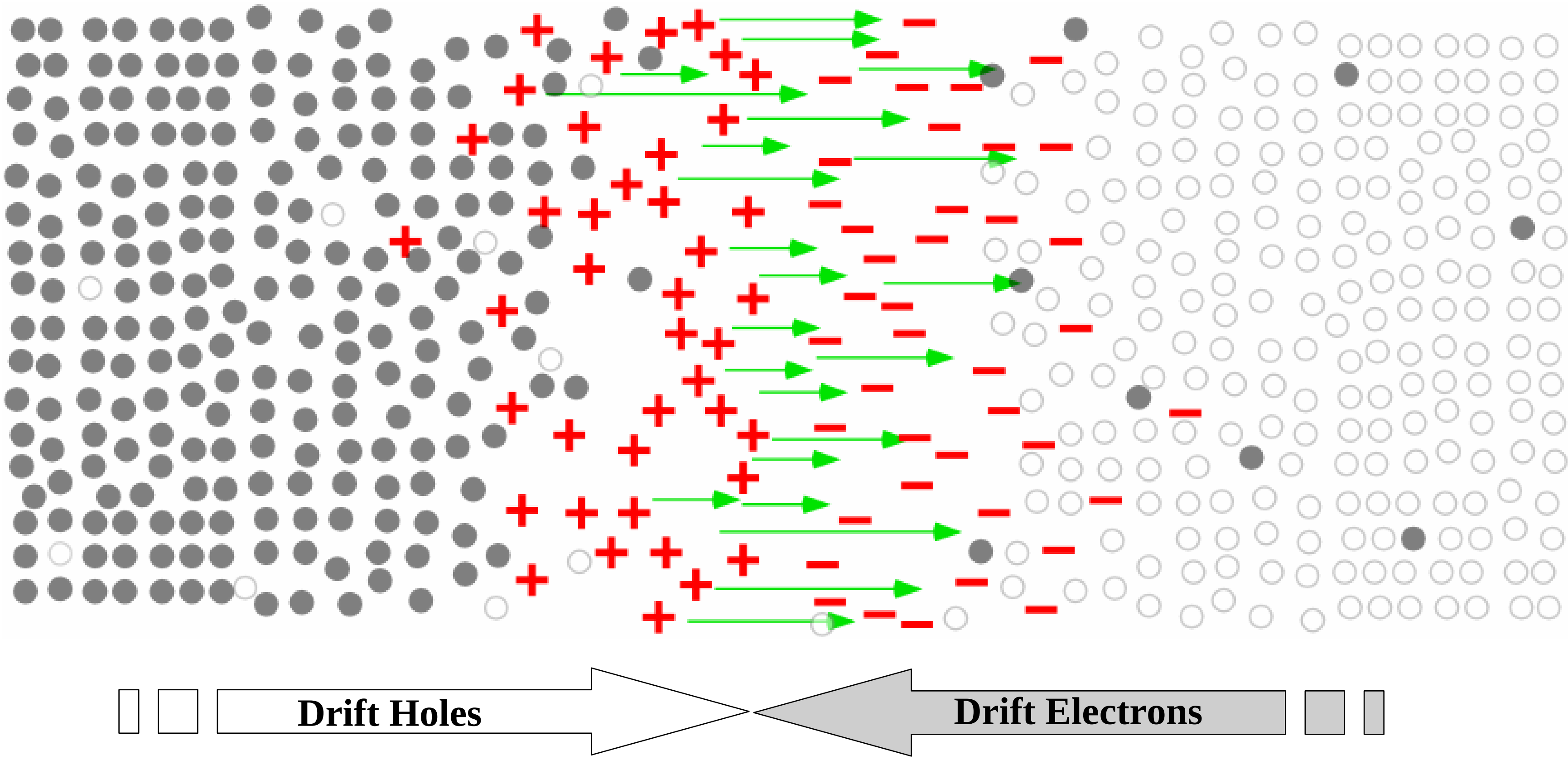
Diffusion and Drift



Depletion Region

- These local charge sites do not move and create an internal electric field. This field is the source of DRIFT for any free carriers that diffuse into the depletion region.

Diffusion and Drift



- When the rate of Diffusion equals the rate of Drift a steady-state condition is obtained and no more macroscopic changes occur.

The PN Junction Equations

Diffusion current $$I_{Diff} = qA\left(D_n \frac{dp}{dx} - D_p \frac{dn}{dx}\right)$$

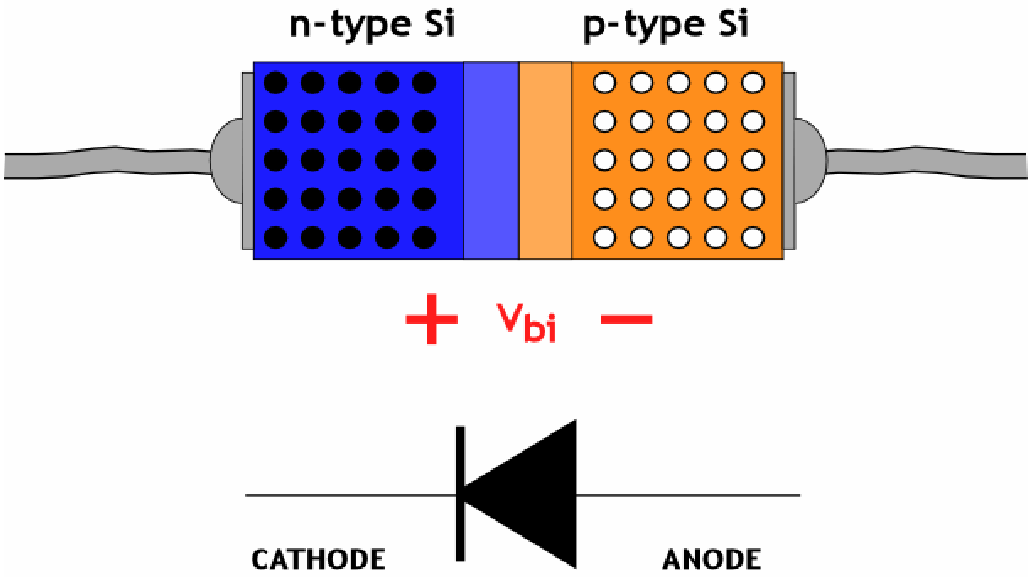
Drift current $$I_{Drift} = qA\left(p\mu_p + n\mu_n\right)E$$

When the external current I = 0 $I_{Diff} = I_{Drift}$

This produces a built-in voltage of:

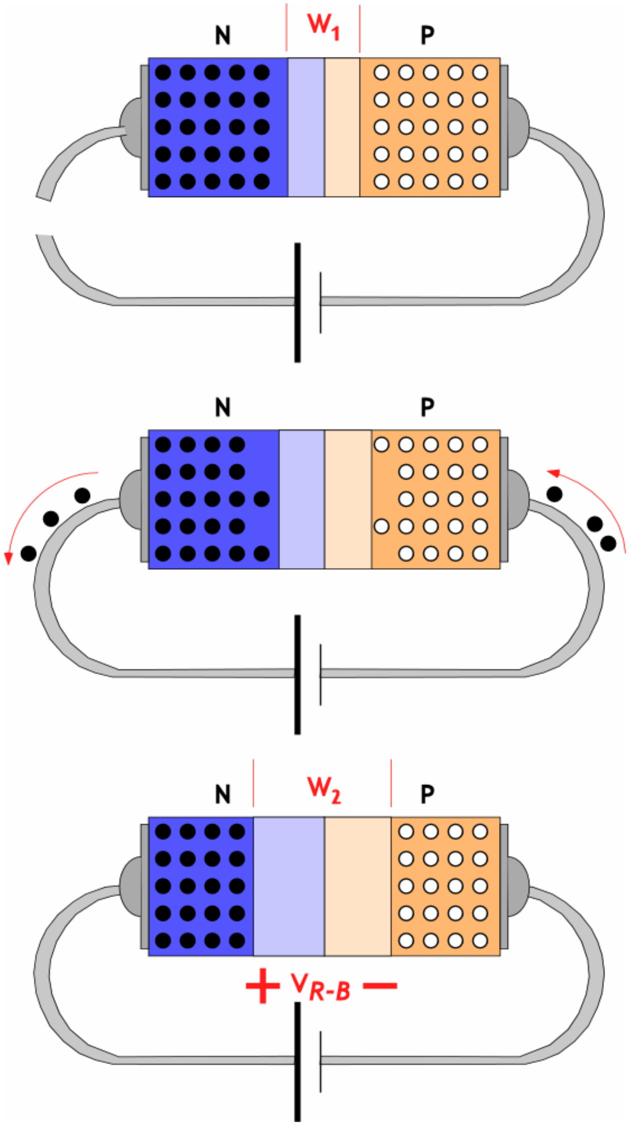
$$V_{bi} = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

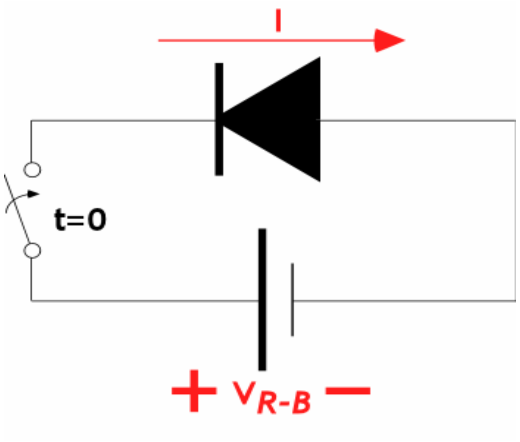
where $$V_T = \frac{kT}{q}$$



The PN Junction – Reverse Bias

- When a reverse-bias voltage is applied to junction, depletion-region widens to accommodate the higher reverse-bias.
- As the majority carriers are depleted from the junction, the diffusion current decreases, and the drift current increases until the junction voltage equals the applied reverse-bias. This stops the current.

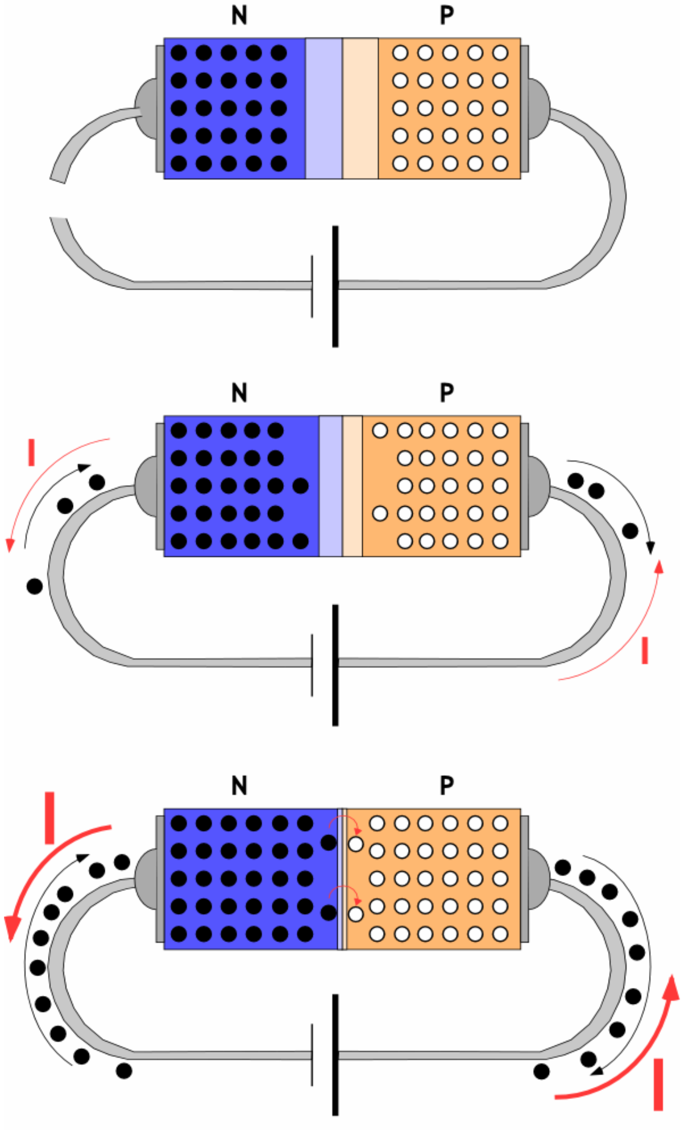


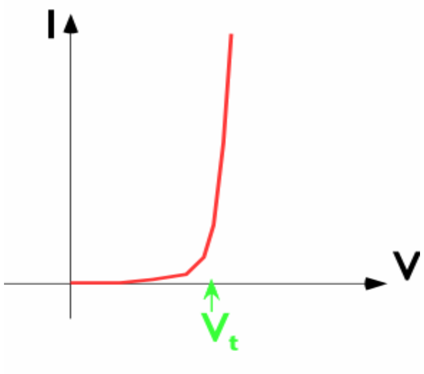


Note: explanation neglects saturation current I_S

The PN Junction – Forward Bias

- Forward-bias voltage injects majority carrier electrons into n-type, majority carrier holes into p-type material Dominant current is the diffusion current.
- Diffusion of carriers across the junction, and the subsequent recombination completes the circuit.
- The process “takes-off” after 0.7V and collapses the built-in voltage to almost zero.





$$I = I_S\left(e^{v/nV_T} - 1\right)$$

The PN Junction – Operational Summary

- Reverse bias operation dominated by:
  - drift current
  - minority carriers in majority type material (e.g. holes in n-type material)
  - magnitude of current flow limited by ability to reduce diffusion effects and onset of breakdown

- Forward bias operation dominated by:
  - diffusion current effects
  - majority carriers in majority type material (e.g. holes in p-type material)
  - magnitude of current flow limited by how many carriers one can shove into the device before it melts

PN Junction Devices Physics Summary

- Lattice structure of intrinsic silicon
- Electrons and holes in conduction and valence bands
- Recombination
- Doping: n-type and p-type silicon
- Charge carrier motion: diffusion and drift
- Open-circuit p-n junction: diffusion, drift, depletion region, built-in voltage
- Reverse-bias, reverse-breakdown and forward bias operation of pn junction