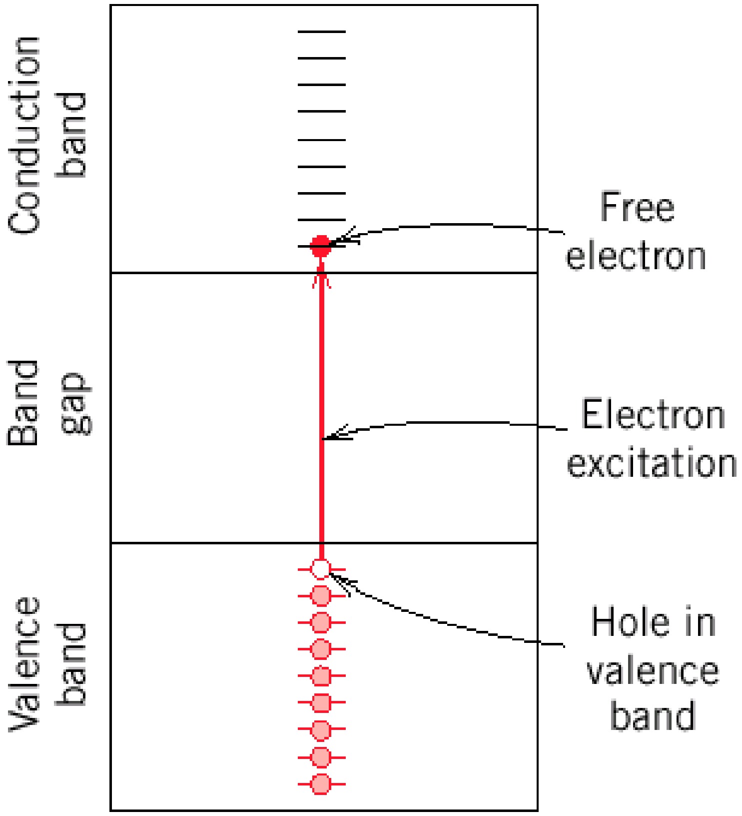
Semiconductivity



Intrinsic semiconductors - electrical conductivity is defined by the electronic structure of pure material.

Extrinsic semiconductors - electrical conductivity is defined by impurity atoms.

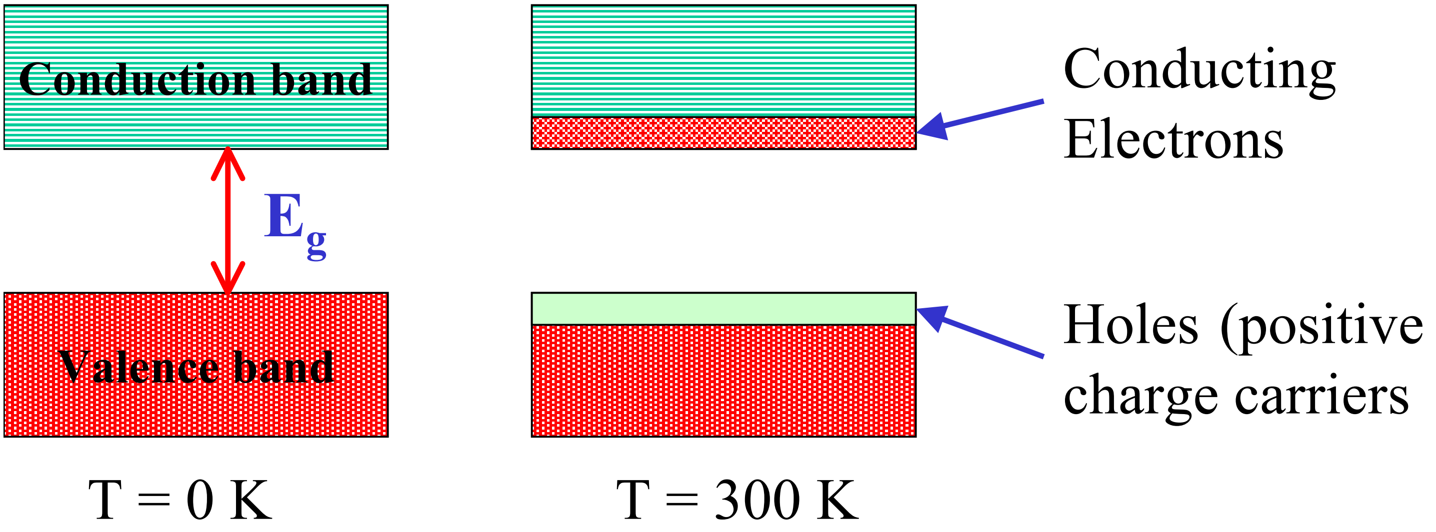
Intrinsic semiconductors (I)

Number of electrons in conduction band increases exponentially with temperature:

$$N_e \equiv n = C\, T^{3/2} \exp(-E_g/2kT)$$

C is a material constant

E_g is the bandgap width



An electron promoted into the conduction band leaves a **hole** (positive charge) in the valence band. In an electric field, electrons and holes move in opposite direction and participate in conduction.

In Si (E_g = 1.1 eV) one out of every 10^{13} atoms contributes an electron to the conduction band at room temperature.

Intrinsic semiconductors (II)

Since both electrons and holes conduct the conductivity of an intrinsic semiconductor is

$$\sigma = n|e|\mu_e + p|e|\mu_h$$

where p is the hole concentration and μ_h the hole mobility.

Electrons are more mobile than holes, $\mu_e > \mu_h$

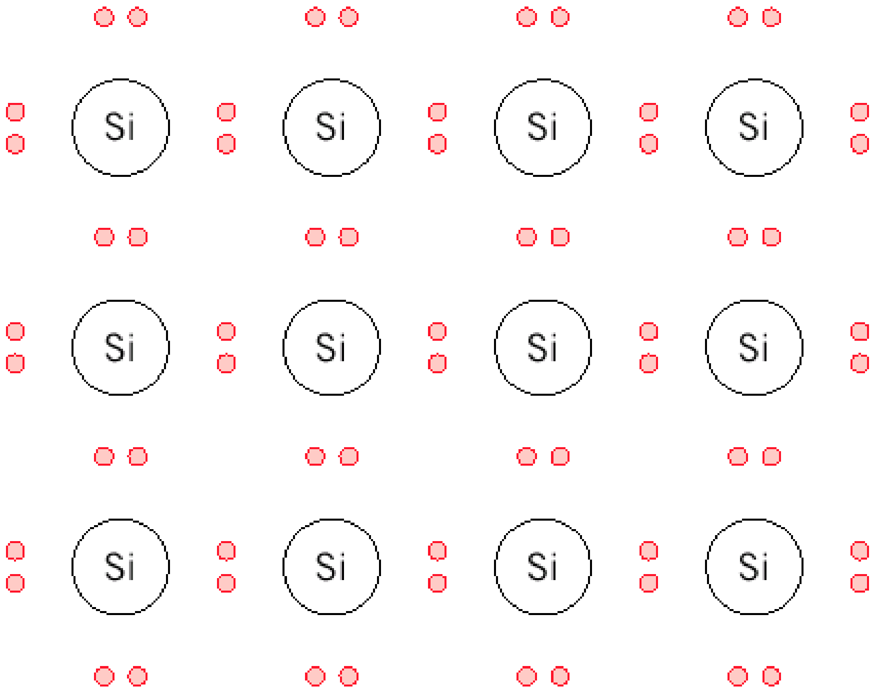
In an intrinsic semiconductor, a hole is produced by the promotion of each electron to the conduction band. Therefore, $n = p$ and

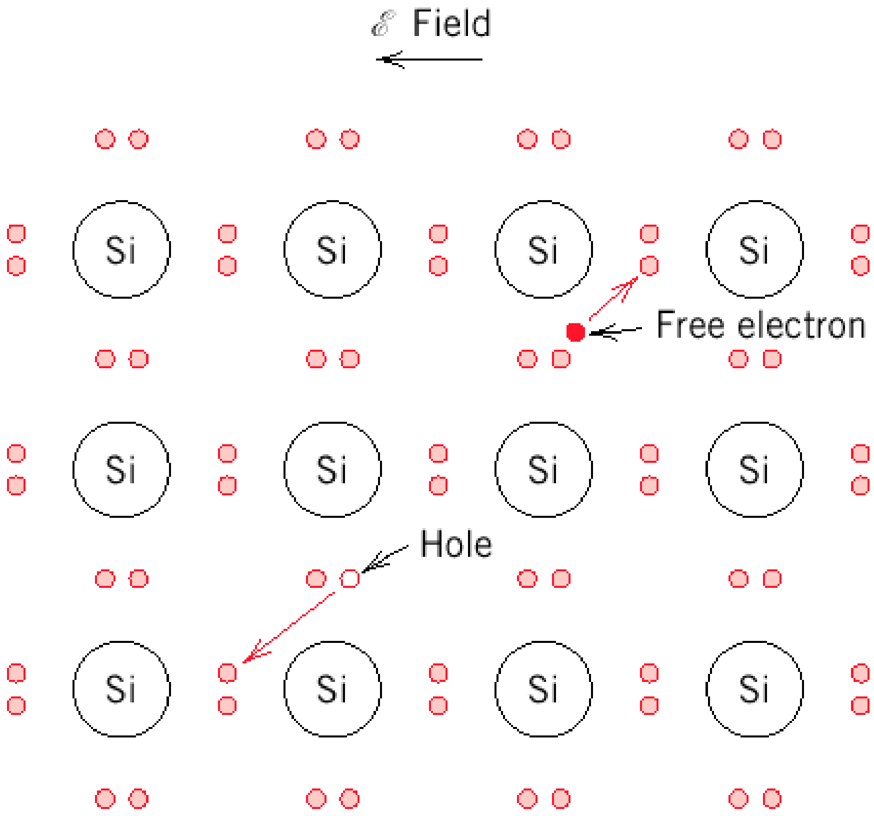
$$\sigma = n|e|(\mu_e + \mu_h) = p|e|(\mu_e + \mu_h)$$

(only for intrinsic semiconductors)

n (and p) increase exponentially with temperature, whereas μ_e and μ_h decrease (about linearly) with temperature. ⇒ **The conductivity of intrinsic semiconductors is increasing with temperature (different from metals!)**

Intrinsic semiconductors (III)





Extrinsic semiconductors

Extrinsic semiconductors - electrical conductivity is defined by impurity atoms.

Example: Si is considered to be extrinsic at room T if impurity concentration is one atom per 10^{12} (remember our estimation of the number of electrons promoted to the conduction band by thermal fluctuations at 300 K)

Unlike intrinsic semiconductors, an extrinsic semiconductor may have different concentrations of holes and electrons. It is called **p-type** if $p > n$ and **n-type** if $n > p$.

One can engineer conductivity of extrinsic semiconductors by controlled addition of impurity atoms – **doping** (addition of a very small concentration of impurity atoms). Two common methods of doping are diffusion and ion implantation.

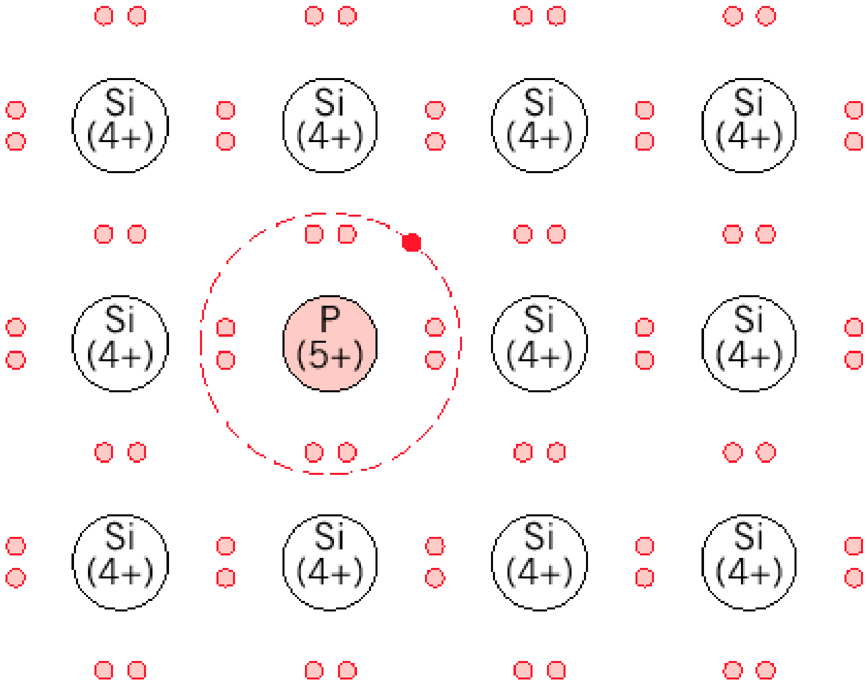
n-type extrinsic semiconductors (I)

Excess electron carriers are produced by substitutional impurities that have more valence electron per atom than the semiconductor matrix.

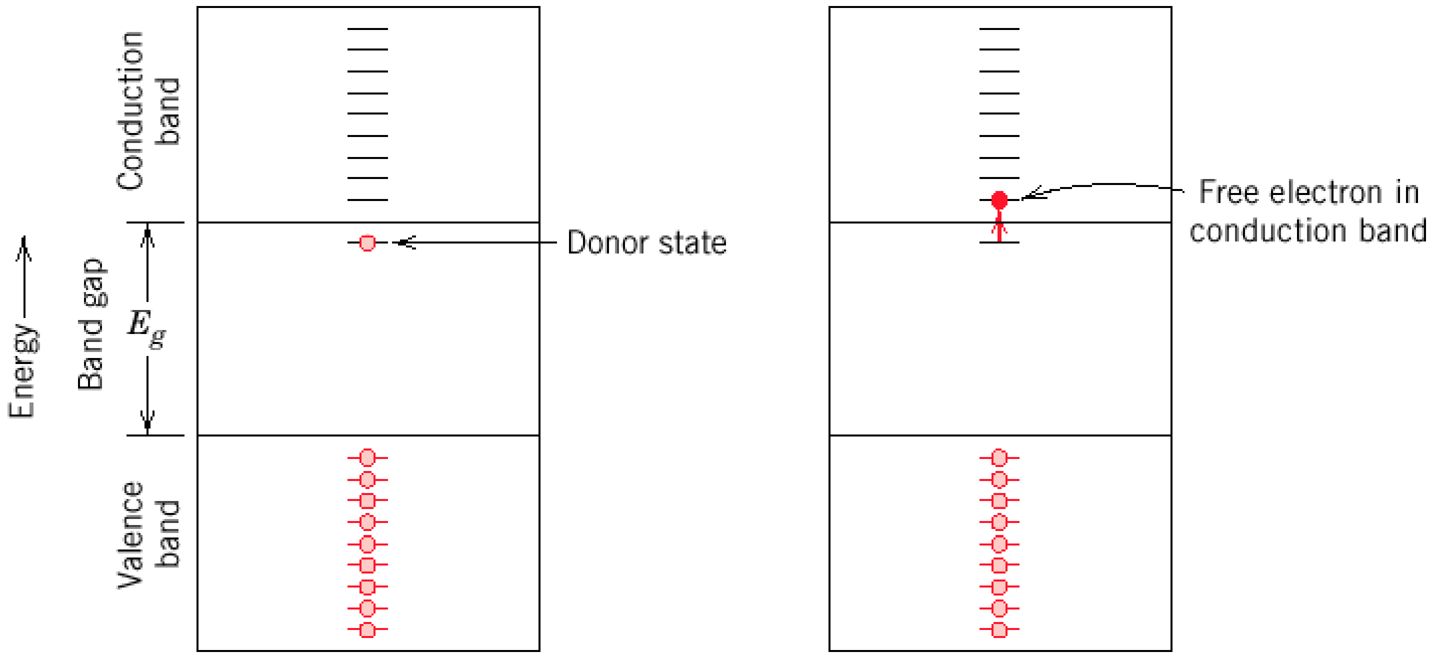
Example: phosphorus (or As, Sb..) with 5 valence electrons, is an electron donor in Si since only 4 electrons are used to bond to the Si lattice when it substitutes for a Si atom. Fifth outer electron of P atom is weakly bound in a **donor state** (~ 0.01 eV) and can be easily promoted to the conduction band.

Impurities which produce extra conduction electrons are called **donors**, $N_D = N_{Phosphorus} \sim n$

Elements in columns V and VI of the periodic table are donors for semiconductors in the IV column, Si and Ge.



n-type extrinsic semiconductors (II)



The hole created in donor state is far from the valence band and is immobile. Conduction occurs mainly by the donated electrons (thus n-type).

$$\sigma \sim n|e|\mu_e \sim N_D\,|e|\mu_e$$

(for extrinsic n-type semiconductors)

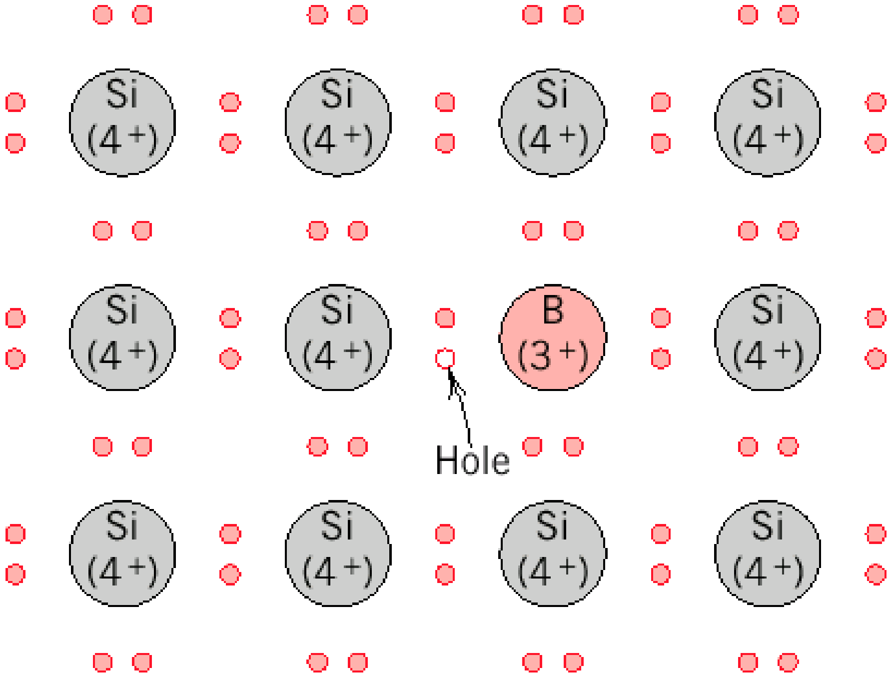
p-type extrinsic semiconductors (I)

Excess holes are produced by substitutional impurities that have fewer valence electrons per atom than the matrix.

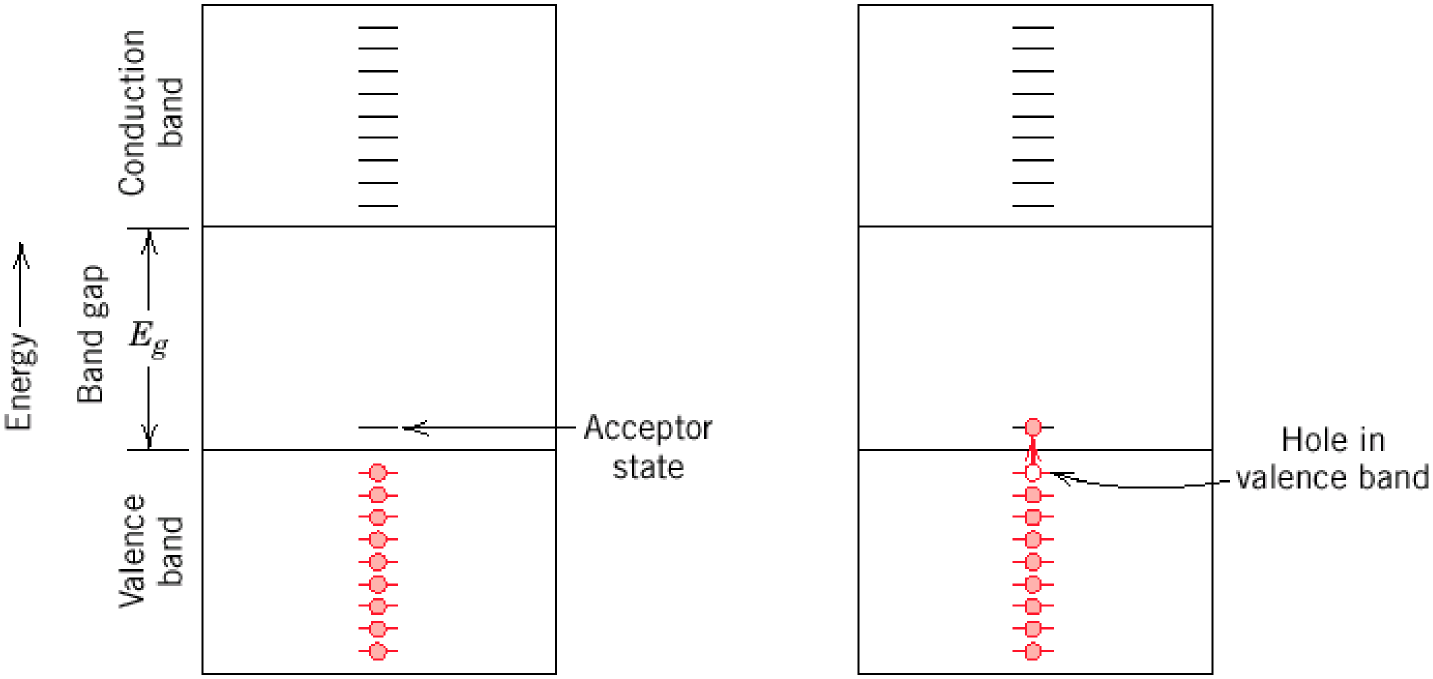
A bond with the neighbors is incomplete and can be viewed as a **hole** weakly bound to the impurity atom.

Elements in columns III of the periodic table (B, Al, Ga) are donors for semiconductors in the IV column, Si and Ge.

Impurities of this type are called **acceptors,** $N_A = N_{Boron} \sim p$



p-type extrinsic semiconductors (II)



The energy state that corresponds to the hole (**acceptor state**) is close to the top of the valence band. An electron may easily hop from the valence band to complete the bond leaving a hole behind. Conduction occurs mainly by the holes (thus p-type).

$$\sigma \sim p|e|\mu_p \sim N_A |e|\mu_p$$

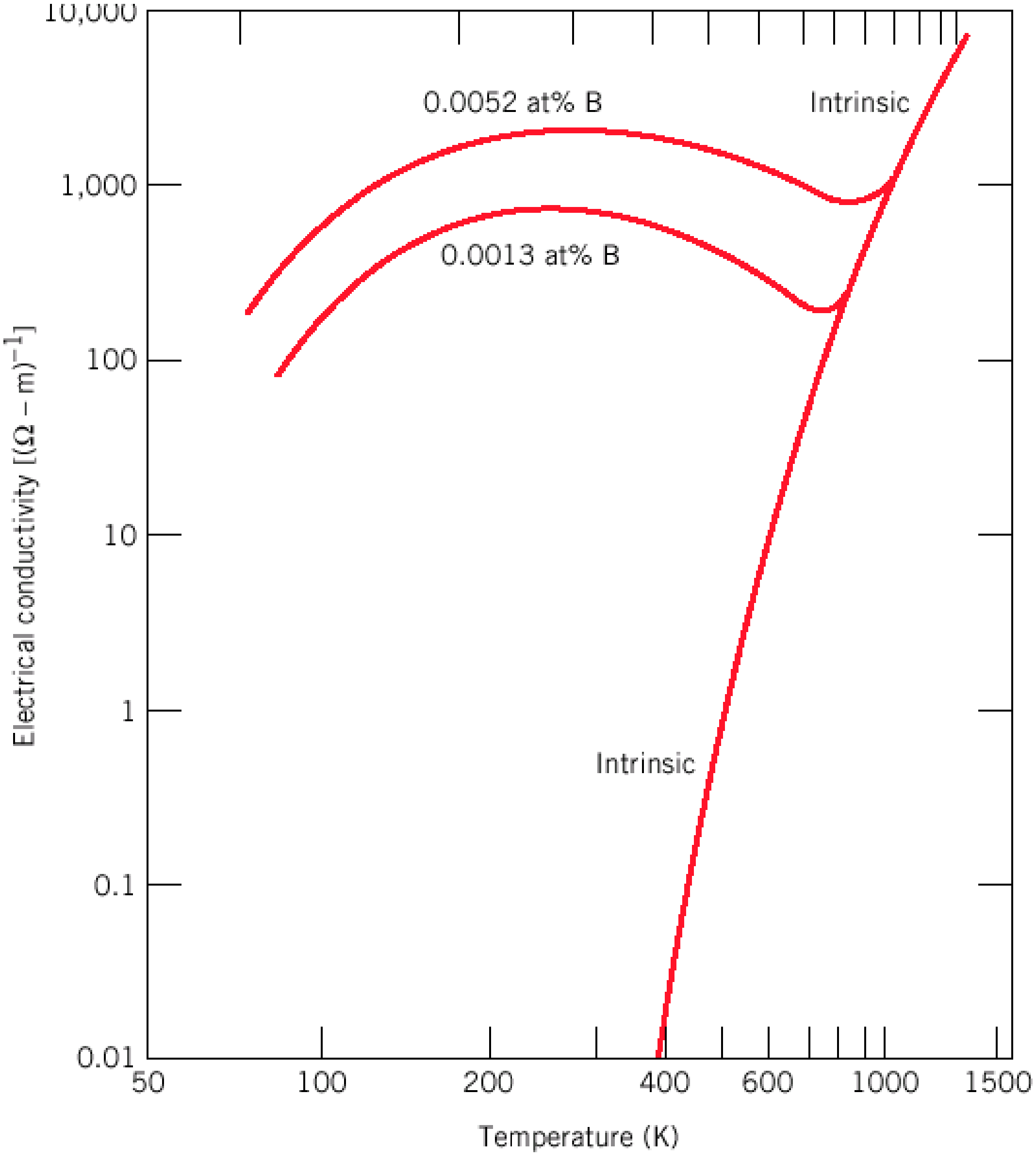
(for extrinsic p-type semiconductors)

Temperature variation of conductivity (I)

Basic equation for conductivity: $\sigma = n|e|\mu_e + p|e|\mu_h$

Temperature dependence of mobilities, μ_e and μ_h is weak as compared to the strong exponential dependence of carrier concentration in intrinsic semiconductors ($\exp(-E_g/2kT)$ is much stronger than $T^{3/2}$):

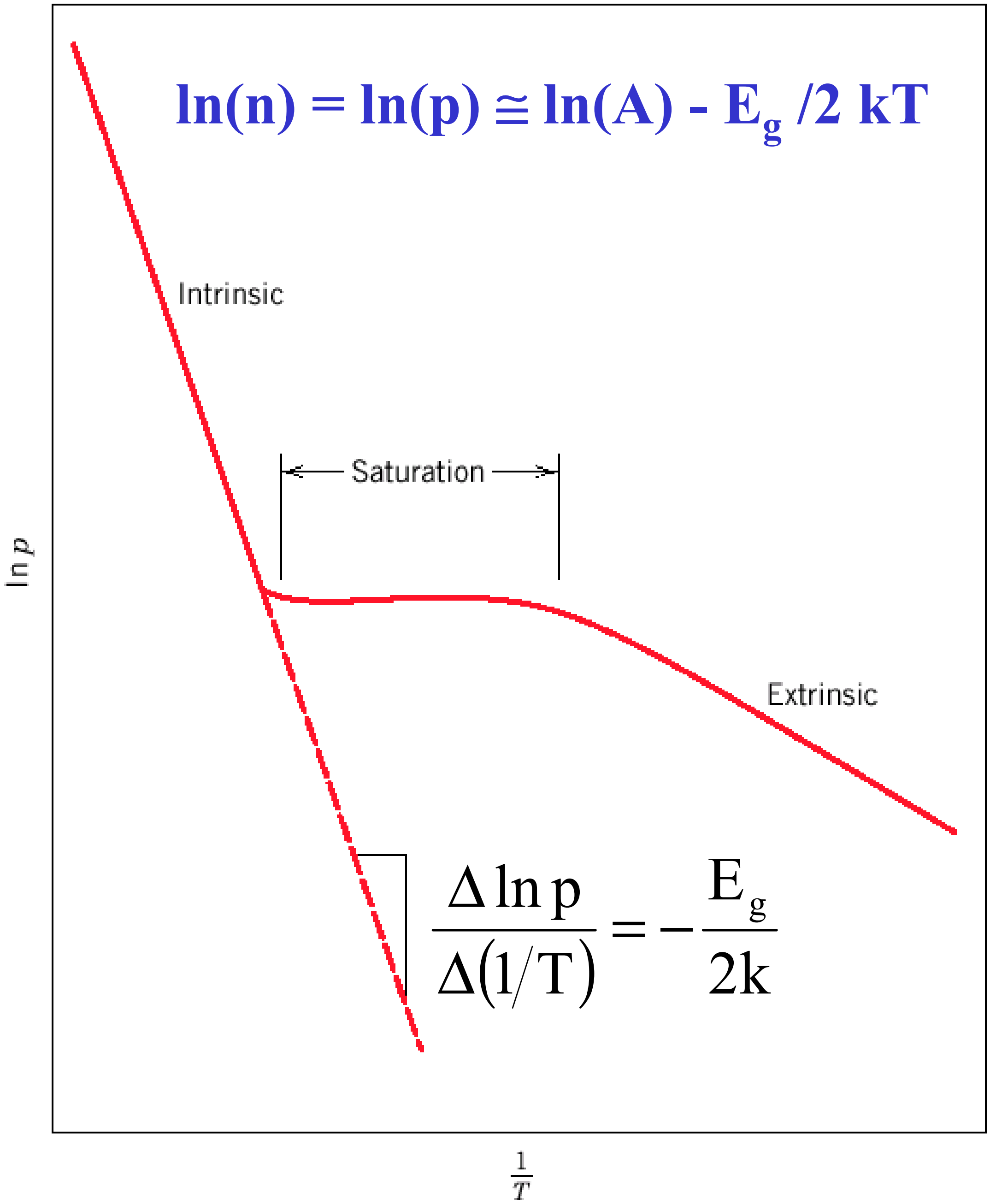
$$n = p \cong A \exp(-E_g/2kT) \qquad \sigma \cong C \exp(-E_g/2kT)$$



Temperature variation of conductivity (II)

$$n = p \cong A \exp(-E_g/2kT) \qquad \sigma \cong C \exp(-E_g/2kT)$$

Plotting ln(σ), ln(p), or ln(n) vs. 1/T produces a straight line of slope $E_g/2k$ from which the band gap energy can be determined.



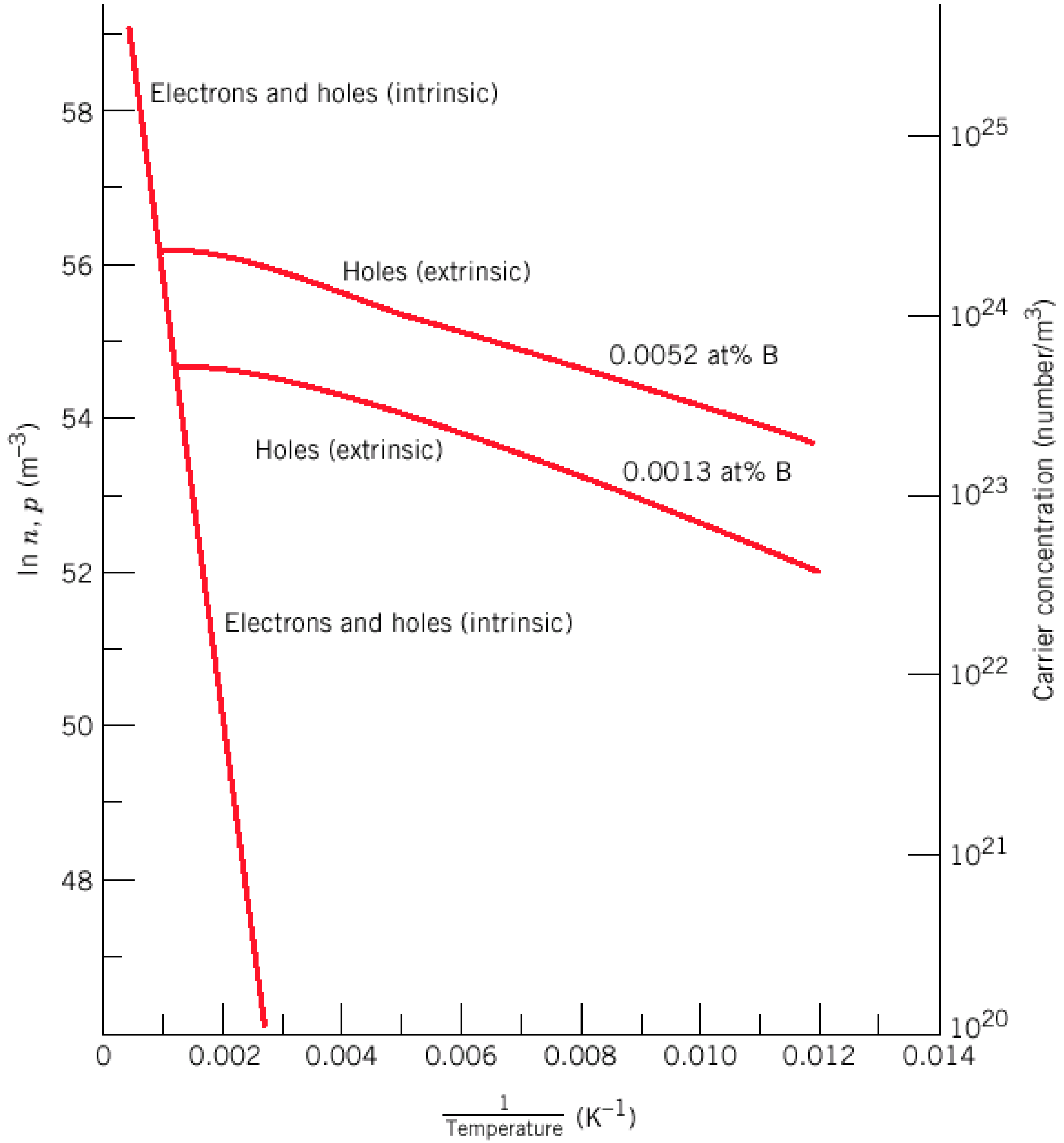
$$\ln(n) = \ln(p) \cong \ln(A) - E_g/2kT$$

$$\frac{\Delta \ln p}{\Delta(1/T)} = -\frac{E_g}{2k}$$

Temperature variation of conductivity (III)

Extrinsic semiconductors

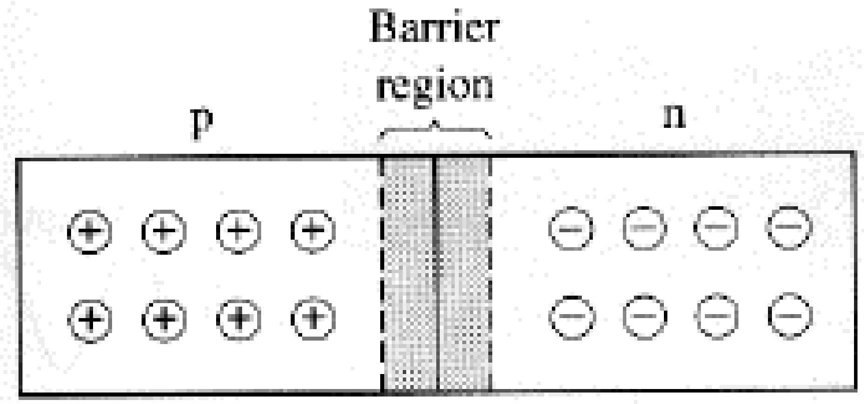
- low T: all carriers are due to the extrinsic excitations
- mid T: most dopants are ionized (saturation region)
- high T: intrinsic generation of carriers dominates



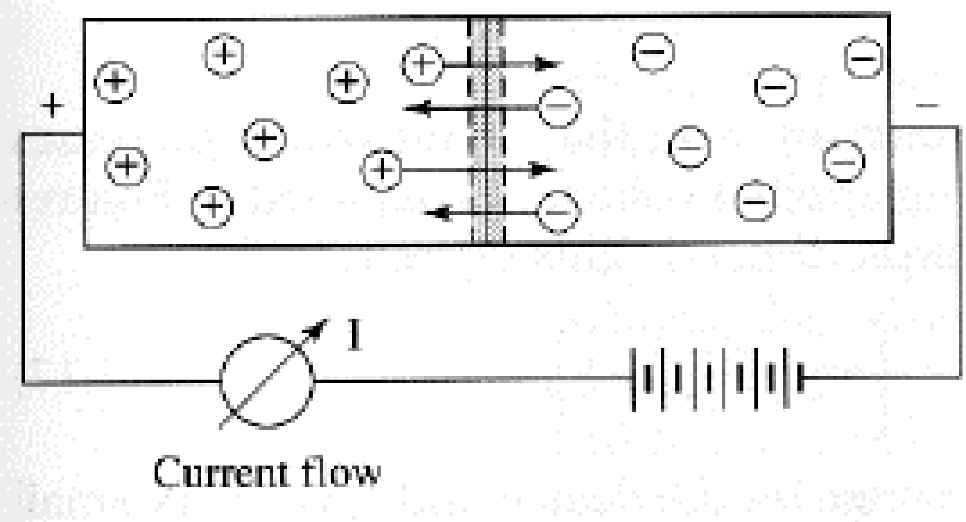
Semiconductor Devices. Diode (I)

A rectifier or **diode** allows current flow in one direction only

p-n junction diode consists of adjacent p- and n-doped semiconductor regions

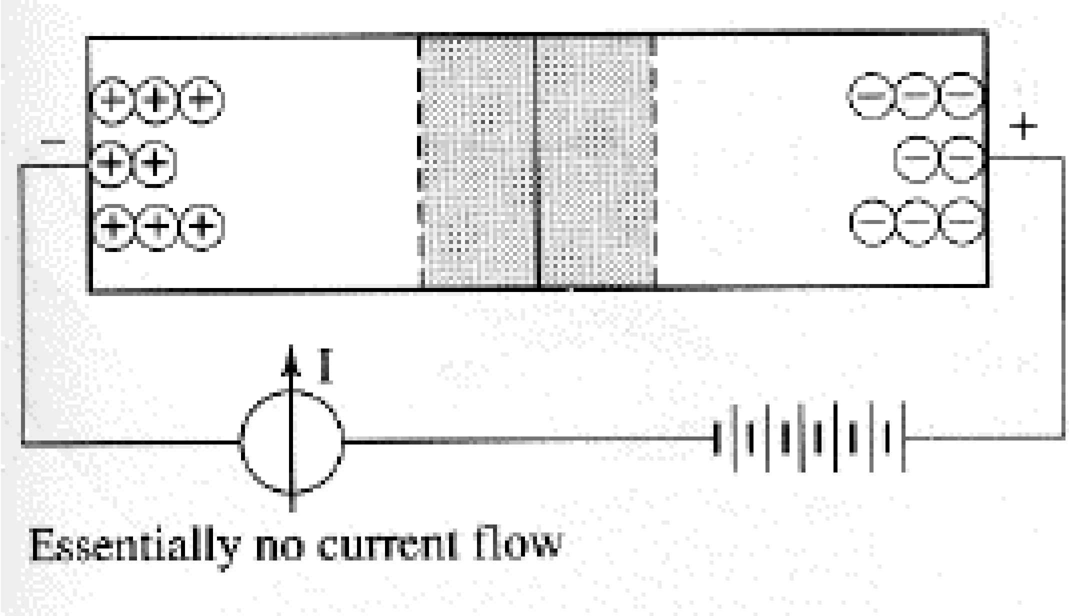


If the positive side of a battery is connected to the p-side (**forward bias**) a large amount of current can flow since holes and electrons are pushed into the junction region, where they recombine (annihilate).



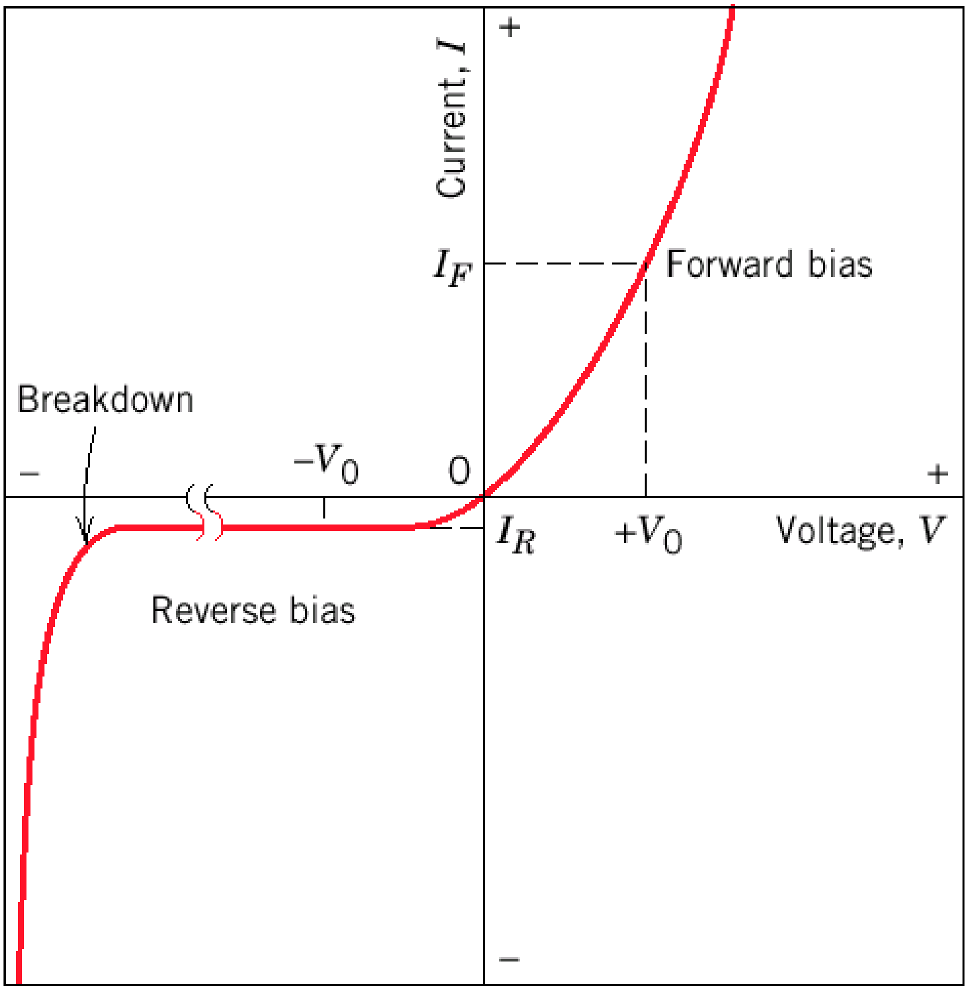
Semiconductor Devices. Diode (II)

If the polarity of the voltage is flipped, the diode operates under **reverse bias**. Holes and electrons are removed from the region of the junction, which therefore becomes depleted of carriers and behaves like an insulator.



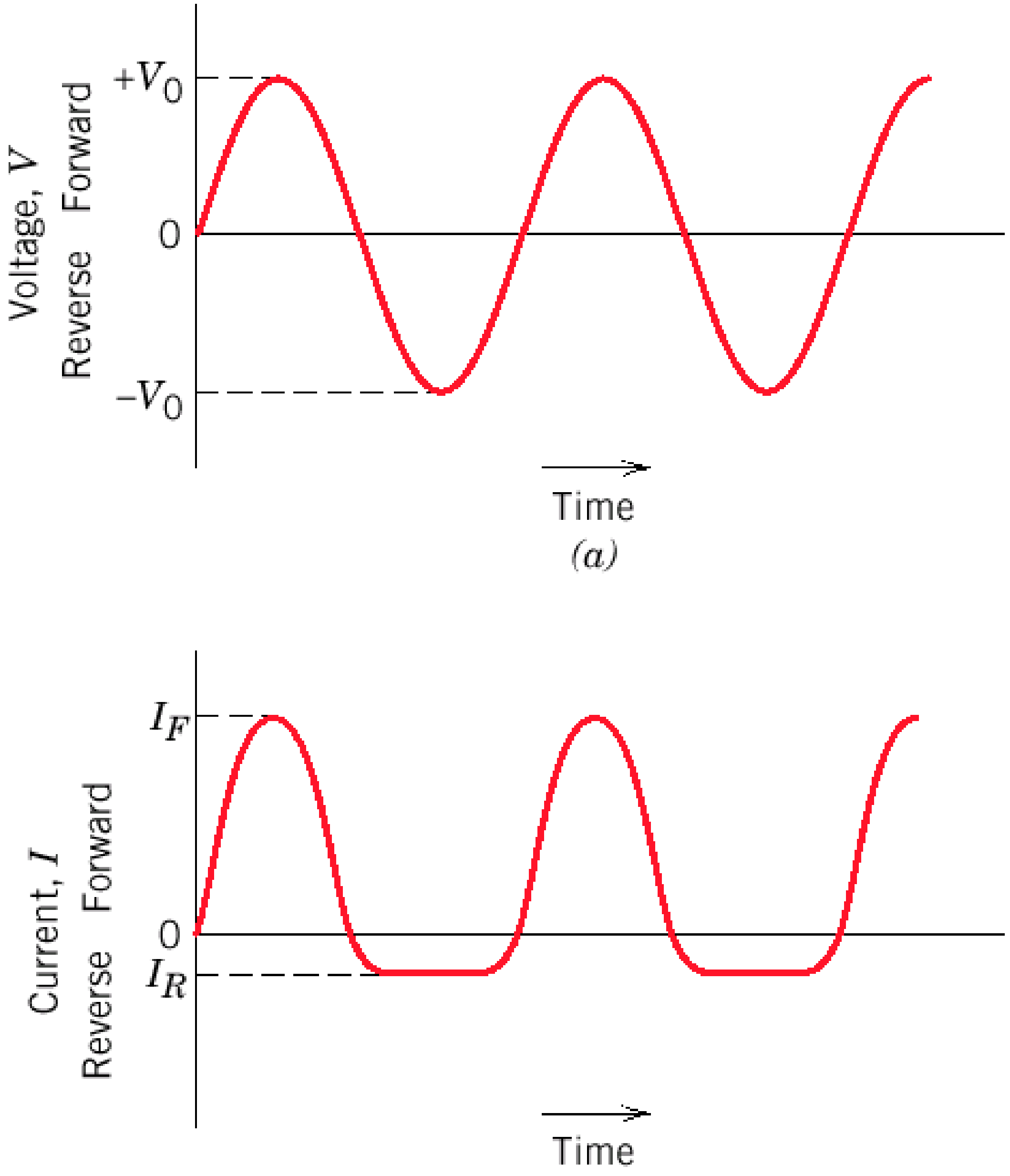
Semiconductor Devices. Diode (III)

For reverse bias, both holes and electrons are drawn away from the junction, leaving the junction region depleted of free carriers ⇒ the current is very small.



Semiconductor Devices. Diode (IV)

The asymmetric current-voltage characteristics of diodes is used to convert alternating current into direct current (**rectification**).



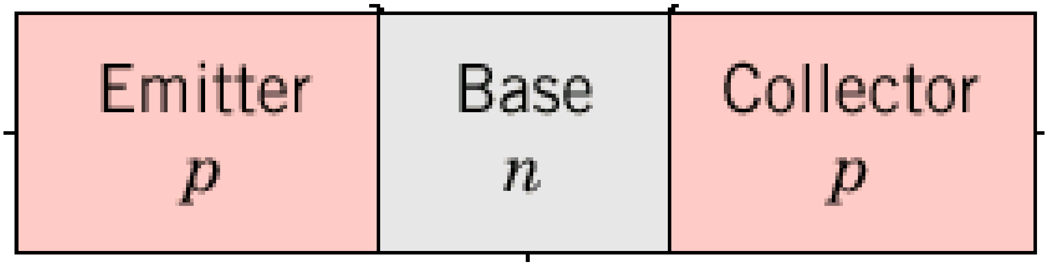
Semiconductor Devices. Transistors.

Transistors are used to amplify an electric signal and as switching devices in computers.

Two major types of transistors are **junction** (or bimodal) transistor and **MOSFET** transistor.

p-n-p (or n-p-n) junction transistor

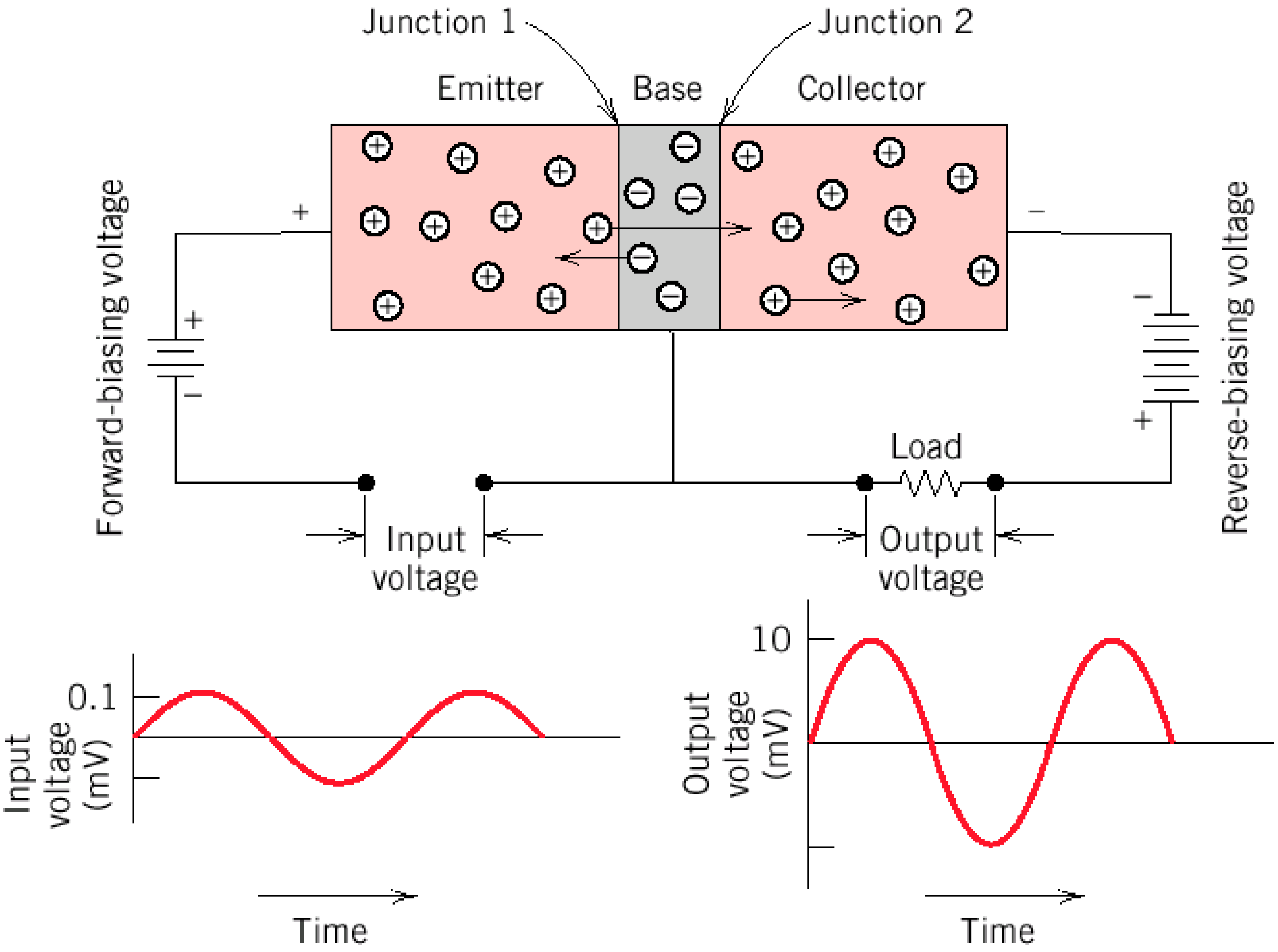
junction transistor contains two diodes back-to-back. The central region (**base**) is very thin (~ 1 micron or less) and is sandwiched in between **emitter** and **collector** regions.



Junction transistor

Emitter-base junction is forward biased and holes are pushed across junction. Some recombine with electrons in the base, but most cross the base as it is so thin. They are then swept into the collector.

A small change in base-emitter voltage causes a relatively large change in emitter-base-collector current, and hence a large voltage change across output ("load") resistor - voltage amplification

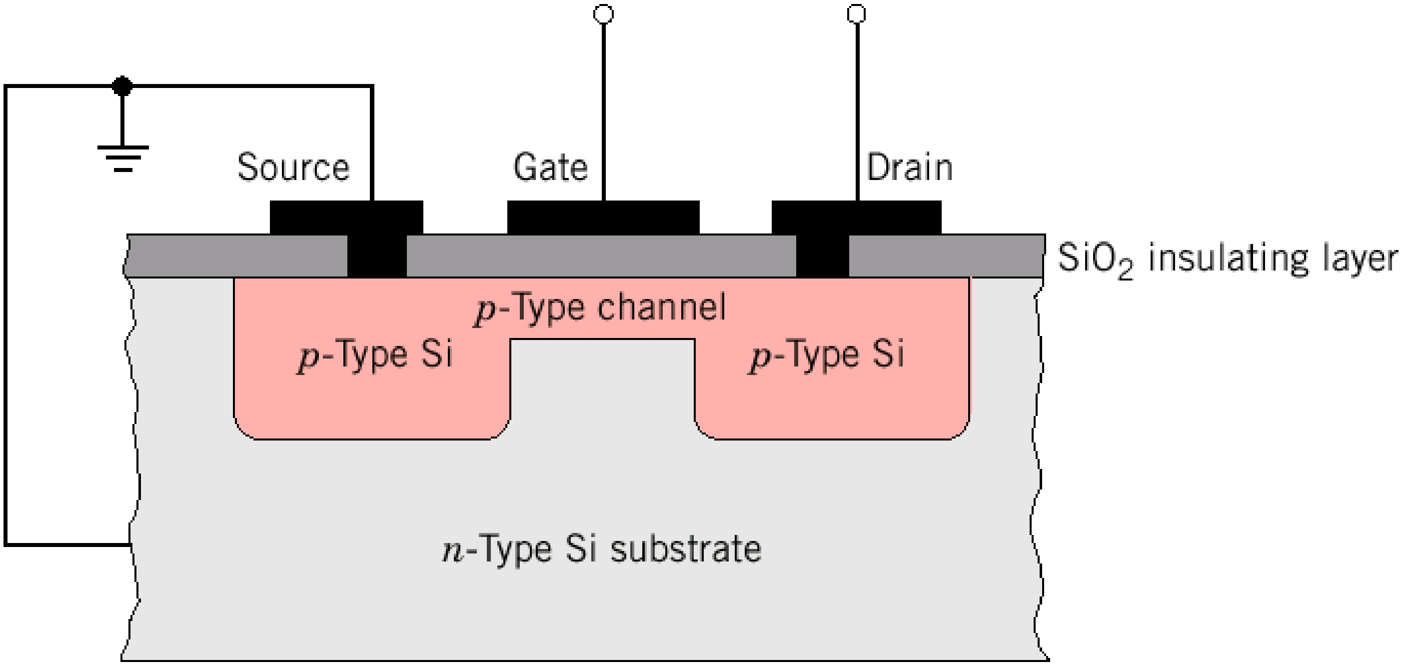


MOSFET
(Metal-Oxide-Semiconductor Field Effect Transistor)

MOSFET transistor: consists of two small islands of p-type semiconductor created within n-type silicon substrate. The islands are connected by a narrow p-type channel.

Metal contacts are made to the islands (source and drain), one more contact (gate) is separated from the channel by a thin (< 10 nm) insulating oxide layer.

The gate serves the function of the base in a junction transistor (the electric field induced by the gate controls the current through the transistor)

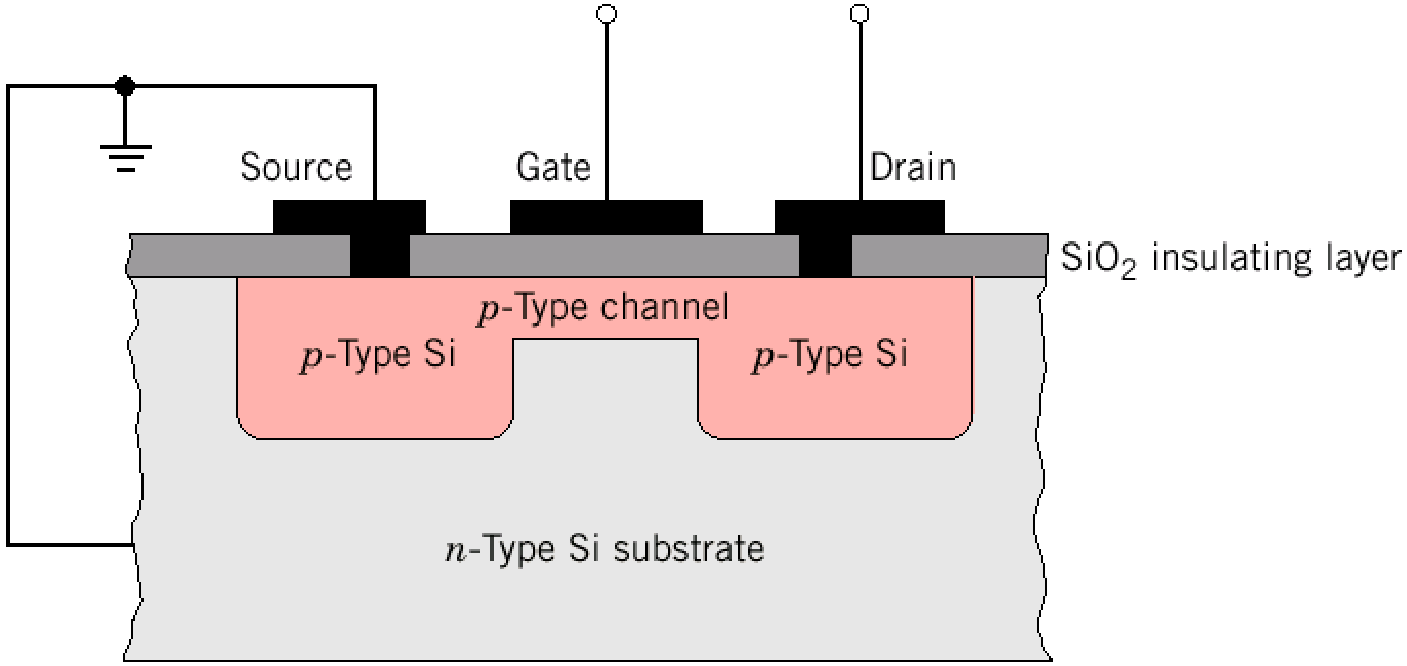


MOSFET
(Metal-Oxide-Semiconductor Field Effect Transistor)

Voltage applied from source encourages carriers (holes in the case shown below) to flow from the source to the drain through the narrow channel.

Width (and hence resistance) of channel is controlled by intermediate gate voltage. For example, if positive voltage is applied to the gate, most of the holes are repelled from the channel and conductivity is decreasing.

Current flowing from the source to the drain is therefore modulated by the gate voltage (amplification and switching)



Transistors and microelectronic devices

- The MOSFET dominates the microelectronic industry (memories, microcomputers, amplifiers, etc.)
- Large Si single crystals are grown and purified. Thin circular wafers ("chips") are then cut from the crystals
- Circuit elements are then constructed by selective introduction of specific impurities (diffusion or ion implantation)
- A single 8" diameter wafer of silicon can contain as many as 10^{10} - 10^{11} transistors in total
- Cost to consumer ~ 0.00001c each.

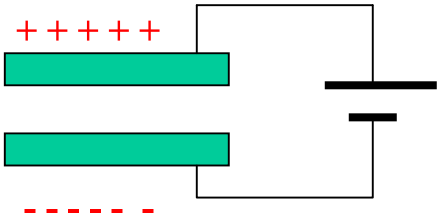
Dielectric Materials

- A **dielectric material** is an insulator which contains electric dipoles, that is where positive and negative charge are separated on an atomic or molecular level

- When an electric field is applied, these dipoles align to the field, causing a net dipole moment that affects the material properties.

Capacitance

- Capacitance is the ability to store charge across a potential difference. Example: parallel conducting plates



- Magnitude of the capacitance, C is related to the charge stored on either plate, Q:

$$\mathbf{C = Q / V} \quad \text{[Farads]}$$

- For a parallel- plate capacitor, C depends on geometry of plates and material between plates

$$\mathbf{C = \varepsilon_r \varepsilon_o A / L = \varepsilon A / L}$$

where A is the area of the plates, L is the distance between plates, ε is the permittivity of the dielectric medium, ε_o is the permittivity of a vacuum ($8.85\text{x}10^{-12}$ F/m^2), and ε_r is relative permittivity (or dielectric constant) of the material, $\varepsilon_r = \varepsilon / \varepsilon_o$