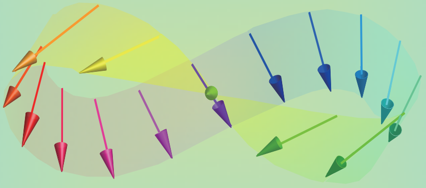
Semiconductor Devices

23



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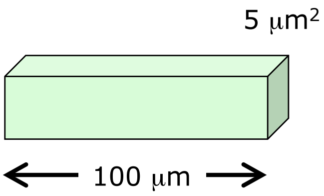
Exercise 2

For the Silicon material with doping, estimate the dopant concentration (N_D) needed to manufacture a 1 MΩ resister measuring 100 μm in length and 5 μm^2 in cross section.



Assume that the transport of current will be carried out by majority carriers and that for Silicon,
intrinsic carrier density: $n_i = 10^{16}$ m^{-3},
mobility of electrons: $\mu_e = 0.135$ m^2/V·s
and mobility of holes: $\mu_h = 0.05$ m^2/V·s.

Answer to Exercise 2

Resistance can be defined by

$$R = \frac{(\text{Length})}{(\text{Cross section})} \times \rho$$

where ρ is resistivity:

$$\rho = \frac{1}{\sigma}$$

$$= \frac{1}{q(p \cdot \mu_h + n \cdot \mu_e)}$$

Here, n and p can be calculated as

$$n \cdot p = n_i^2$$

For an n-doped semiconductor, $n = N_D$ and hence p can be derived as

$$p = \frac{n_i^2}{N_D} << n = N_D$$

$$\rho = \frac{1}{q \cdot N_D \cdot \mu_e}$$

Answer to Exercise 2 (Cont'd)

By substituting the given values for Silicon, resistance is calculated to be

$$1[\mathrm{M\Omega}] = \frac{100[\mu\mathrm{m}]}{5[\mu\mathrm{m}^2]} \times \frac{1}{1.6 \times 10^{-19}[\mathrm{C}] \times N_D \times 0.135[\mathrm{m}^2/\mathrm{V} \cdot \mathrm{s}]}$$

$$1 \times 10^6[\Omega] = \frac{100 \times 10^{-6}[\mathrm{m}]}{5 \times 10^{-12}[\mathrm{m}^2]} \times \frac{1}{1.6 \times 10^{-19}[\mathrm{C}] \times N_D \times 0.135[\mathrm{m}^2/\mathrm{V} \cdot \mathrm{s}]}$$

$$0.135 N_D = 1.25 \times 10^{20}$$

$$N_D = 9.259 \cdots \times 10^{21}$$

Hence, $N_D = 9.3 \times 10^{21}$ [m^{-3}].

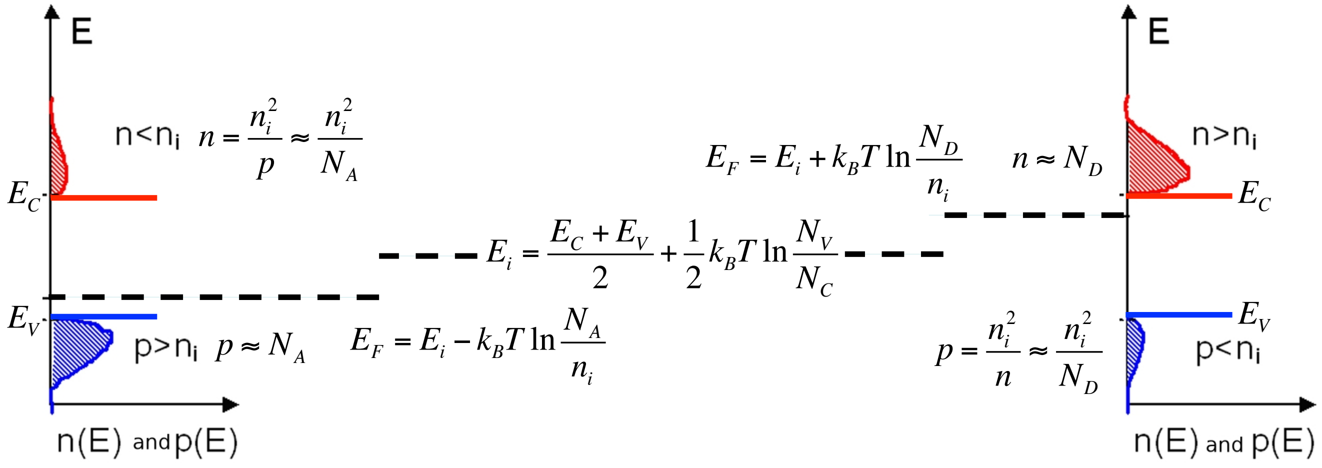
23 *p-n* Junction

- Depletion layer
- Built-in potential
- Drift current
- Current-voltage characteristics

Carrier Densities of Extrinsic Semiconductors

p-type band structure :

n-type band structure :



n<n$_i$ $n = \frac{n_i^2}{p} \approx \frac{n_i^2}{N_A}$

p>n$_i$ $p \approx N_A$

$$E_F = E_i - k_B T \ln \frac{N_A}{n_i}$$

$$E_i = \frac{E_C + E_V}{2} + \frac{1}{2} k_B T \ln \frac{N_V}{N_C}$$

$$E_F = E_i + k_B T \ln \frac{N_D}{n_i}$$

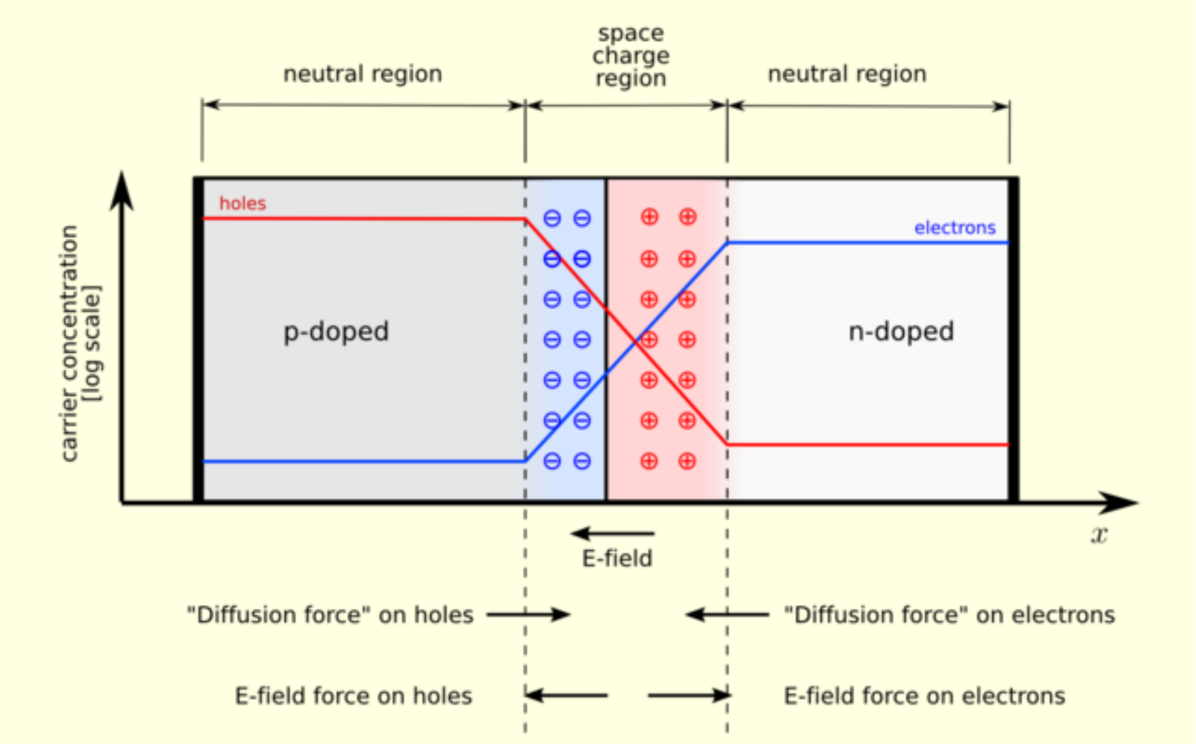
$n \approx N_D$ n>n$_i$

$p = \frac{n_i^2}{n} \approx \frac{n_i^2}{N_D}$ p<n$_i$

* http://www.optique-ingenieur.org/en/courses/OPI_ang_M05_C02/co/Contenu_04.html

By attaching *p*- and *n*-Type Semiconductors

p-*n* junctions :



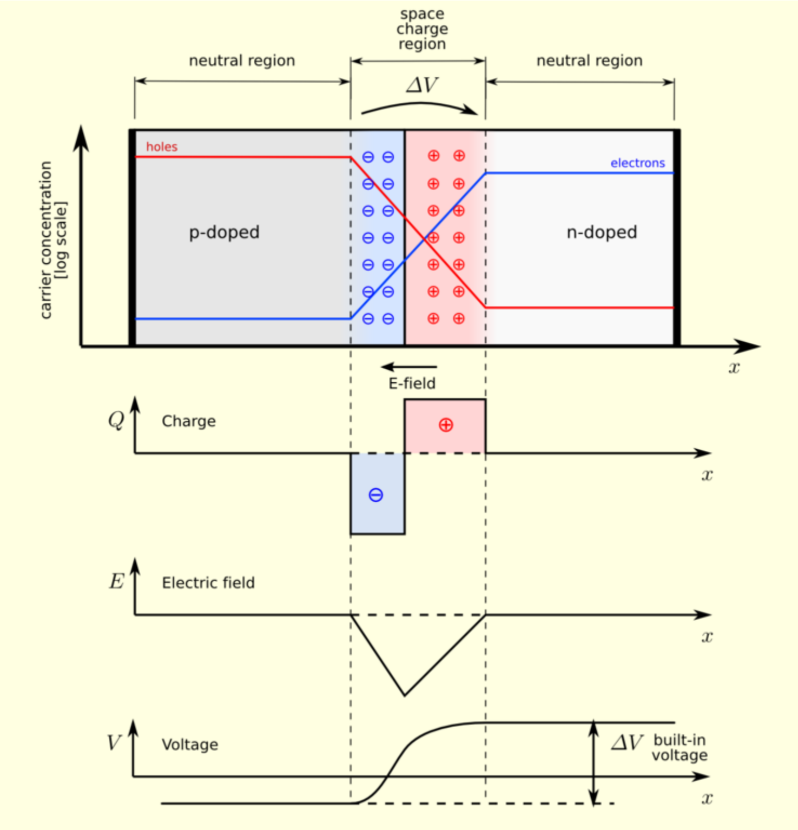
* http://www.wikipedia.org/

Fundamentals of *p*-*n* Junctions

* https://www.youtube.com/watch?v=JBtEckh3L9Q

Carrier Concentrations at the Interface

Thermal equilibrium state :



* http://www.wikipedia.org/

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p-*n* Junction

Fabrication method :

- Annealing method :

  n-type : Spread P_2O_5 onto a Si substrate and anneal in forming gas.

  p-type : Spread B_2O_3 onto a Si substrate and anneal in forming gas.

- Epitaxy method (“epi” = on + “taxy” = arrangement) :

  Oriented overgrowth

  n-type : thermal deformation of SiH_4 (+ PCl_3) on a Si substrate

  p-type : thermal deformation of SiH_4 (+ BBr_3) on a Si substrate

p-n Junction Interface

By connecting *p*- and *n*-type semiconductors,

p : Most of accepters become - ions

→ Holes are excited in E_V.

n : Most of donors become + ions

→ Electrons are excited in E_C.

Fermi level E_F needs to be connected.

→ Built-in potential : $qV_d = E_{fn} - E_{Fp}$

Electron currents balances

$p \rightarrow n = n \rightarrow p$

Majority carriers :

p : holes, *n* : electrons

Minority carriers :

p : electrons, *n* : holes

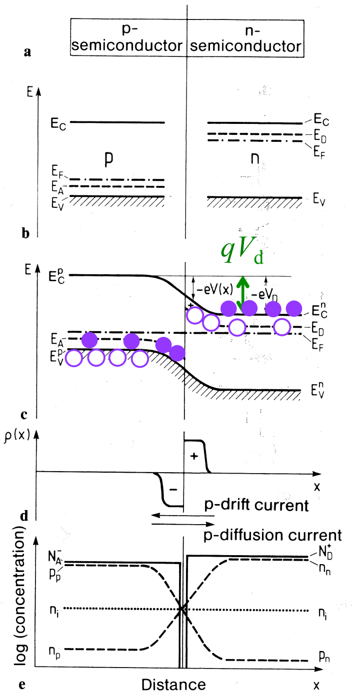
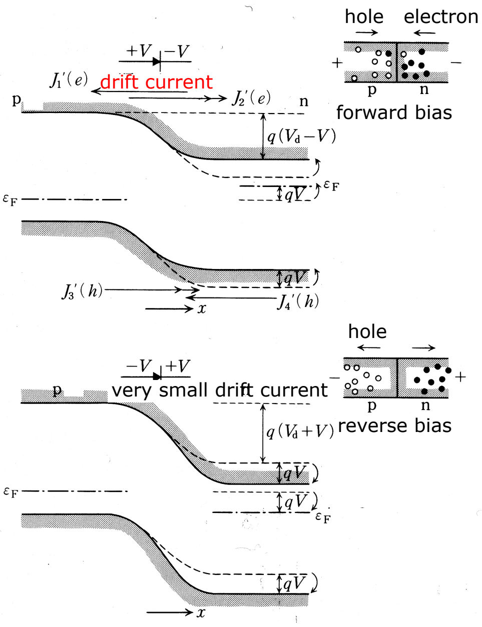


Fig. 12.16a–e. Schematic representation of a *p–n* junction in thermal equilibrium: (**a**) a semiconductor crystal doped on one side with acceptors (N_A) and on the other side with donors (N_D); (**b**) band scheme for the *n* and *p* sides for the imaginary case of total decoupling of the two sides. E_A and E_D indicate the ground states of the acceptors and donors; E_F is the Fermi level; (**c**) band scheme of the *p–n* junction when the two sides are in thermal equilibrium with one another. The transition from the *p* to the *n* doping is assumed to be abrupt. The position of conduction and valence band edges are denoted E_C^p and E_V^p deep in the *p* region, and E_C^n and E_V^n deep in the *n* region. V_D is the diffusion voltage. In the region of the *p–n* junction, a so-called macropotential $V(x)$ is induced; (**d**) the fixed space charge $\varrho(x)$ in the region of the *p–n* junction due to the ionized impurities; (**e**) qualitative behavior of the concentrations of acceptors N_A, donors N_D, holes *p* and free electrons *n*. The intrinsic carrier concentration is n_i and p_p and p_n denote the hole concentrations deep in the *p* and *n* regions, respectively (and similarly for n_p and n_n). Considered here is the frequently occurring case in which almost all of the donors and acceptors in the interior of the crystal are ionized

* H. Ibach and H. Lüth, *Solid-State Physics* (Springer, Berlin, 2003).

Rectification in a *p-n* Junction

Under an electrical field ***E***,



Current rectification :

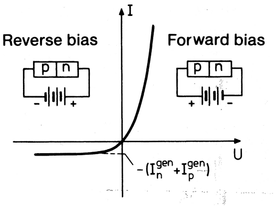


Fig. 12.18. Schematic representation of the current voltage (*I–U*) characteristic of a *p–n* junction, together with the corresponding circuit. The maximum current in the reverse direction is given by the sum of the generation currents for electrons and holes

* M. Sakata, *Solid State Physics* (Baifukan, Tokyo, 1989).
** H. Ibach and H. Lüth, *Solid-State Physics* (Springer, Berlin, 2003).

Built-In Potential

In the *p*-doped region, hole carrier density can be defined by

$$p_p = n_i \cdot \exp\left(\frac{E_{ip} - E_F}{k_B T}\right) = N_A$$

This leads to the energy level:

$$E_{ip} - E_F = k_B T \cdot \ln\left(\frac{N_A}{n_i}\right)$$

In the *n*-doped region, electron carrier density can be defined by

$$n_n = n_i \cdot \exp\left(\frac{E_F - E_{in}}{k_B T}\right) = N_D$$

This leads to the energy level:

$$E_F - E_{in} = k_B T \cdot \ln\left(\frac{N_D}{n_i}\right)$$

By taking the difference between the energy levels,

$$\begin{aligned} qV_{bi} &= E_{ip} - E_{in} \\ &= k_B T \cdot \ln\left(\frac{N_A}{n_i}\right) + k_B T \cdot \ln\left(\frac{N_D}{n_i}\right) \end{aligned}$$

Built-In Potential (Cont'd)

$$\begin{aligned} qV_{bi} &= E_{ip} - E_{in} \\ &= k_B T \cdot \ln\left(\frac{N_A}{n_i}\right) + k_B T \cdot \ln\left(\frac{N_D}{n_i}\right) \\ &= k_B T \cdot \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right) \end{aligned}$$

Therefore, the built-in potential is derived as

$$V_{bi} = \frac{k_B T}{q} \cdot \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)$$

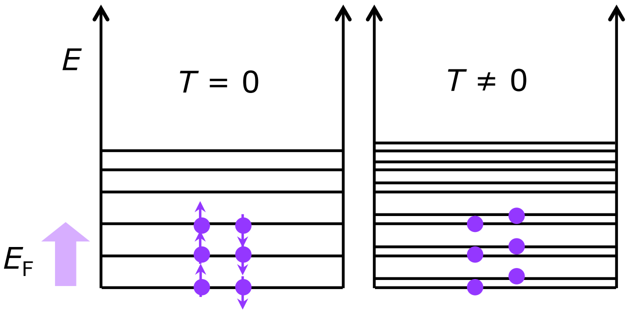
→ Internal potential at the *p*-*n* interface.

→ Cannot extract as an external voltage.

→ Suppress carrier diffusion across the interface.

Fermi Energy

Fermi-Dirac distribution :



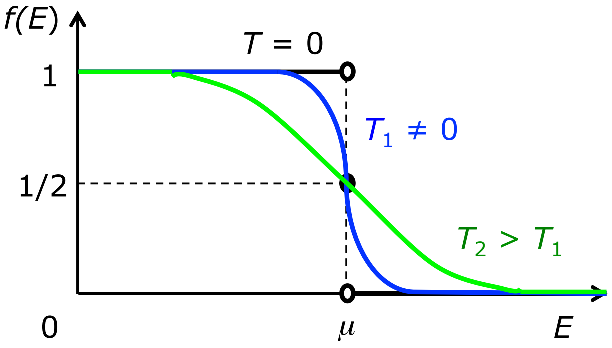
Pauli exclusion principle

At temperature T, probability that one energy state E is occupied by an electron :

$$f(E) = \frac{1}{\exp\left[(E-\mu)/k_B T\right]+1}$$

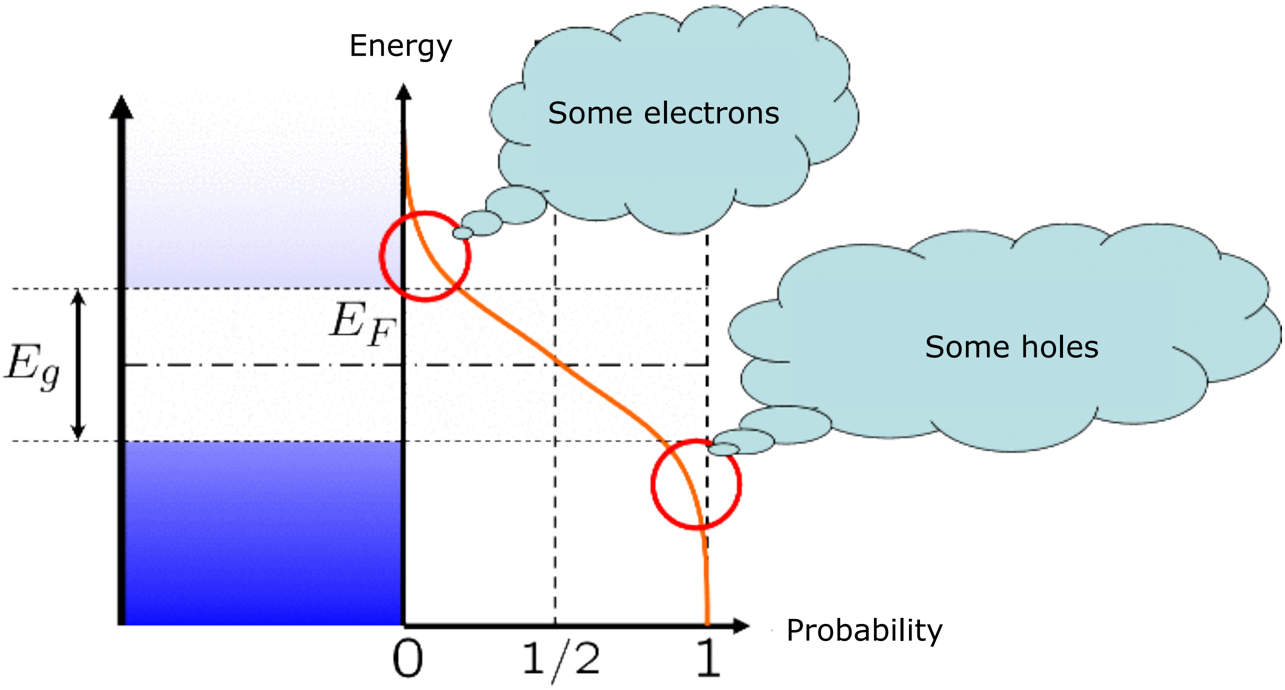
μ : chemical potential
(= Fermi energy E_F at T = 0)

k_B : Boltzmann constant



Intrinsic Semiconductors

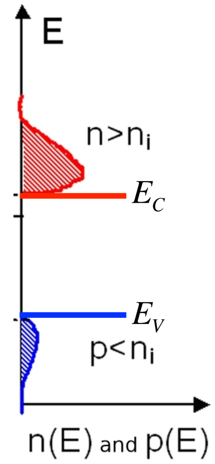
Band structures :



* http://hooktail.sub.jp/solid/shino-PNI-typeSemiconductor-upp

Exercise 1

Find the probability of occupation of a level of 0.05 eV above the conduction band edge of a Silicon device if the Fermi level is 0.7 eV above the valence band edge.



Assume the bandgap (E_g) of Silicon is 1.1 eV and the effective mass of electron in Silicon is

$$0.40 \times (0.91 \times 10^{-30}\ \text{kg}).$$

The Boltzmann constant (k_B) is 1.4×10^{-23} J/K,
the Planck constant is 6.6×10^{-34} J·s and
the temperature is 300K.
Use the conversion ratio: 1 eV = 1.6×10^{-19} J.

Answer to Exercise 1

Probability of electron occupation can be given by the Fermi-Dirac distributions :

$$f(E) = \frac{1}{\exp\left[\left(E - E_F\right)/k_B T\right] + 1}$$

Here, the energy level is 0.05 eV above E_C,

$$\begin{aligned} E &= E_C + 0.05 \\ &= \left(E_V + 1.1\right) + 0.05\left[\text{eV}\right] \end{aligned}$$

Since $E_F = E_V + 0.7$ [eV],

$$\begin{aligned} E - E_F &= \left(E_V + 1.1 + 0.05\right) - \left(E_V + 0.7\right) \\ &= 0.45\left[\text{eV}\right] \\ &= 0.45 \times 1.6 \times 10^{-19}\left[\text{J}\right] \\ &= 7.2 \times 10^{-20}\left[\text{J}\right] \end{aligned}$$

Hence, the probability is calculated to be

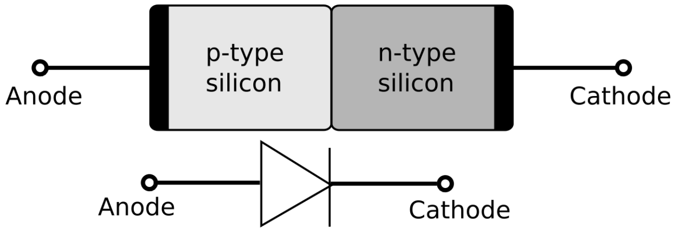
$$\begin{aligned} f(E) &= \frac{1}{\exp\left[7.2 \times 10^{-20} / 1.4 \times 10^{-23} \times 300\right] + 1} \\ &= \frac{1}{\exp\left[17.1\cdots\right] + 1} \\ &= 3.59\cdots \times 10^{-8} \end{aligned}$$

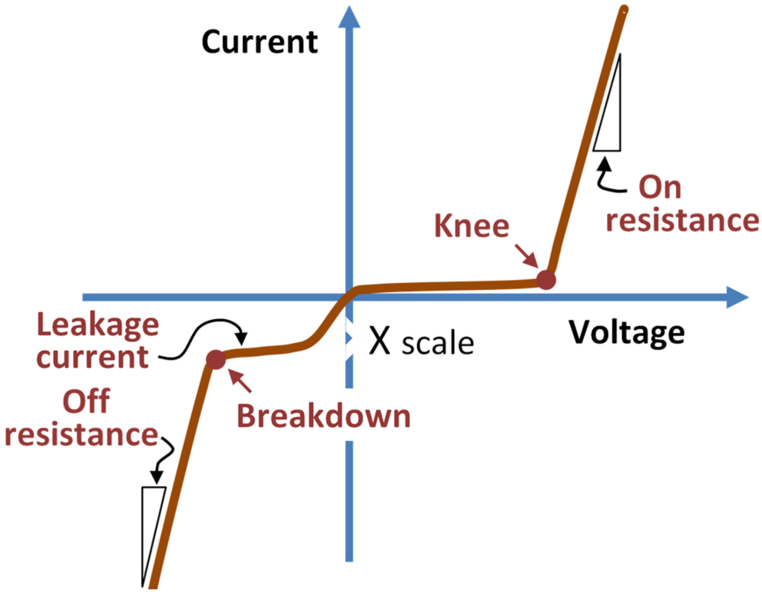
p-n Diode

A junction made by attaching *p*- and *n*-doped semiconductors :

Widely used to insulate transistors.

Common circuit to convert ac to dc in a battery charger.





* http://www.wikipedia.org/

Exercise 3

Calculate the built-in potential of an abrupt *p*-*n* junction diode which is made from Silicon and has the following properties:

p-region: doping density of $N_A = 2 \times 10^{21}$ m^{-3}

n-region: doping density of $N_D = 1 \times 10^{21}$ m^{-3}

intrinsic concentration of electrons:

$n_i = 1.2 \times 10^{16}$ m^{-3}

and assume $k_B T / q = 25$ mV.