Budapest University of Technology and Economics
Department of Electron Devices

Microelectronics, BSc course

Operation of PN junctions: Electrostatic conditions

Diodes: basics

- What are they? Data sheets
- How are they made?
- How do they work?

Diodes: what are they? We learnt:

- …as diodes are presented in vendors' data sheets:

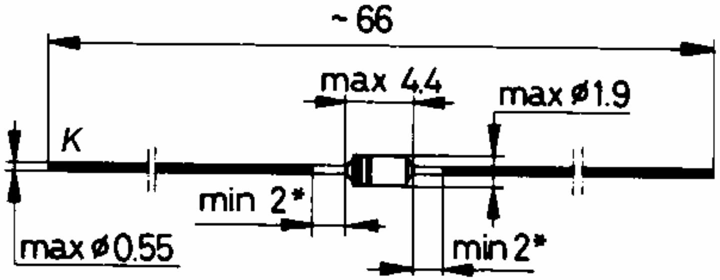
1N 4151 (BAY 95), 1N 4154 (BAY 94)

Silicon Epitaxial Planar Low-Capacitance Diodes

for very fast switching applications.

Dimensions in mm

Band: cathode



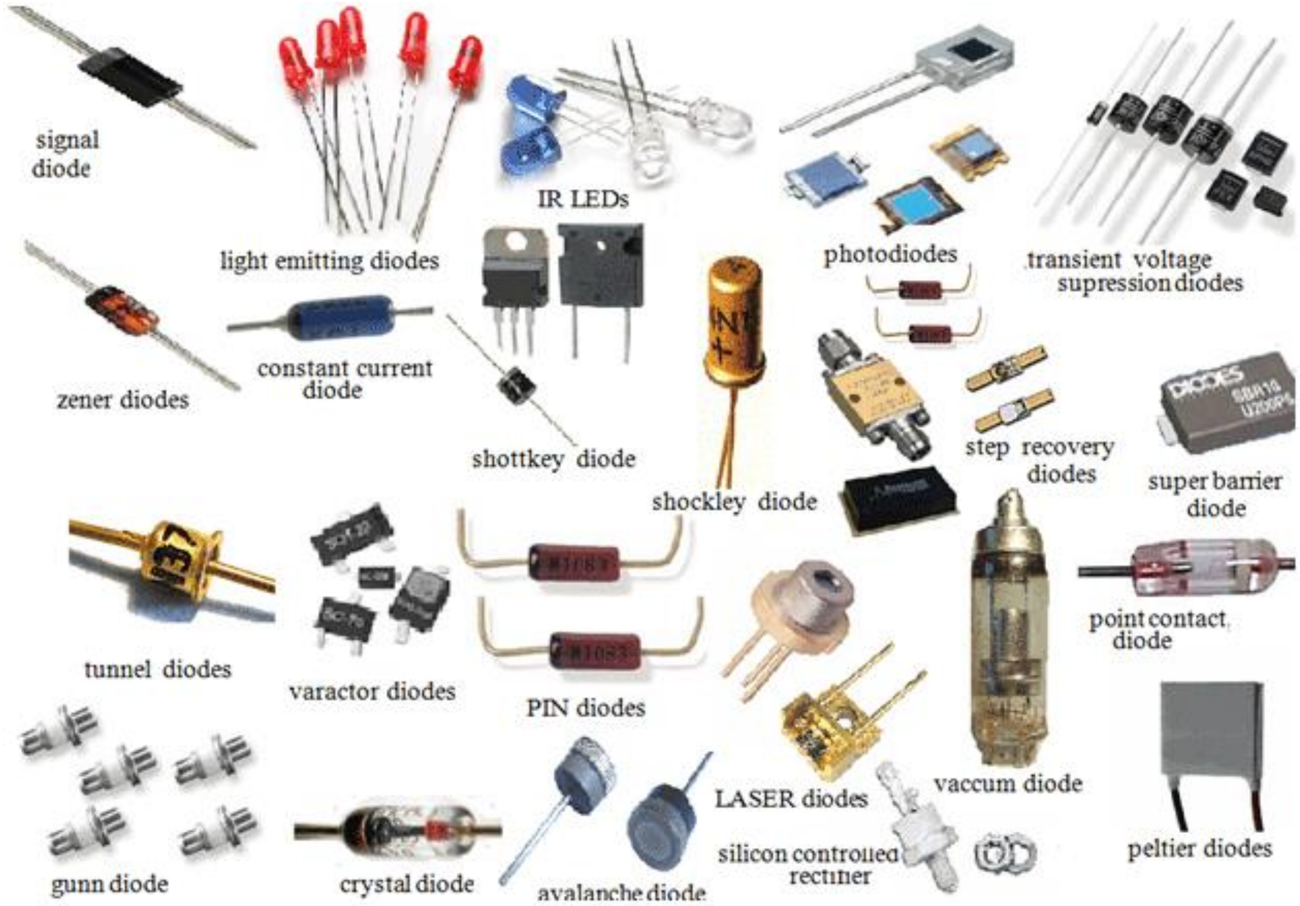
* not tinned

Case: DO-35

Mass: approx. 0.15 g

Diodes: what are they? We learnt:

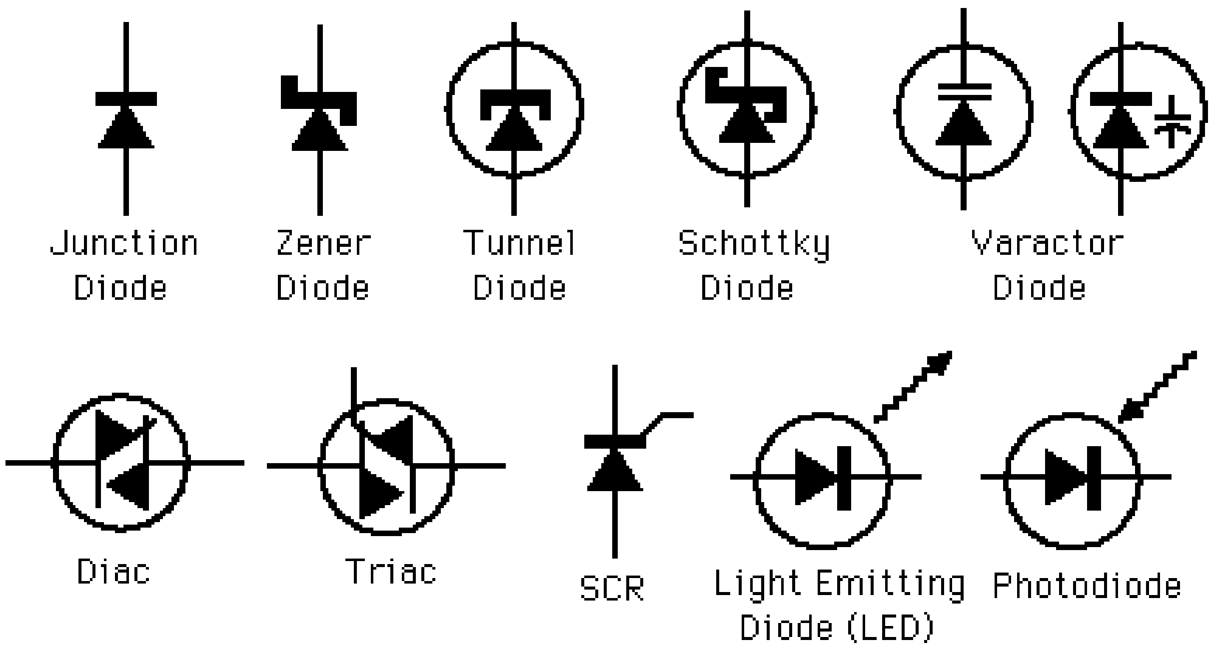
- …as they are actually look like:



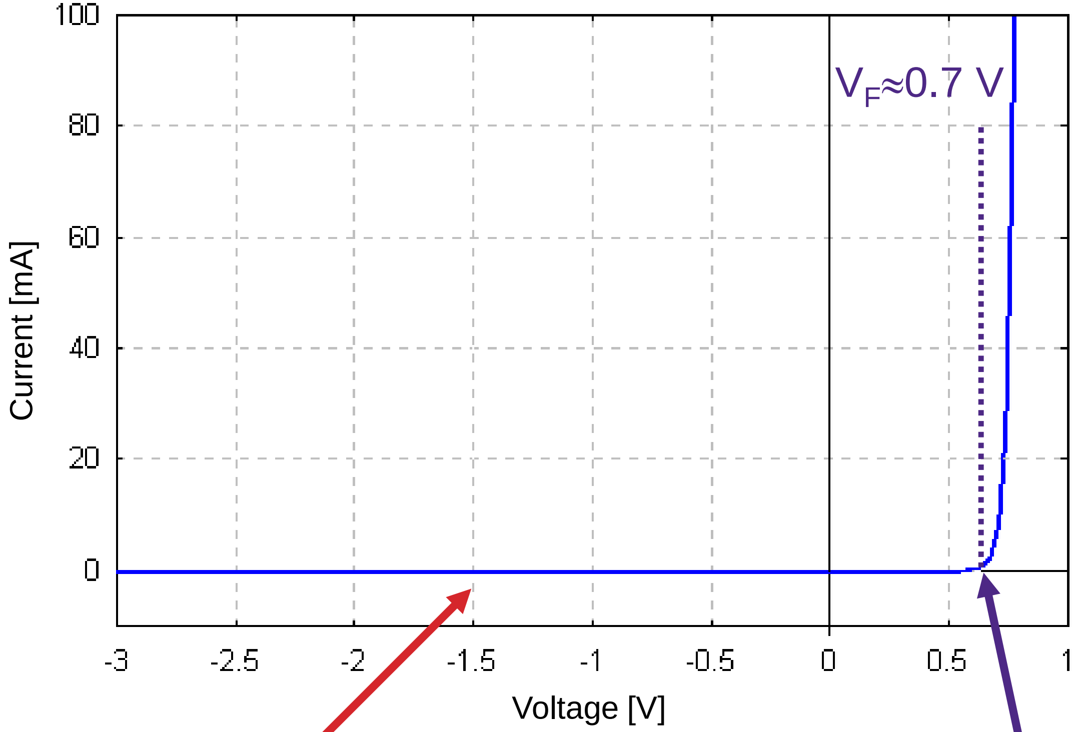
Types of Diode

Diodes: what are they? We learnt:

- …and their symbols:



Main features



Rectifies

The characteristic:

$$I = f(V)$$

Reverse region

$I \sim 10^{-12}$ A/mm^2

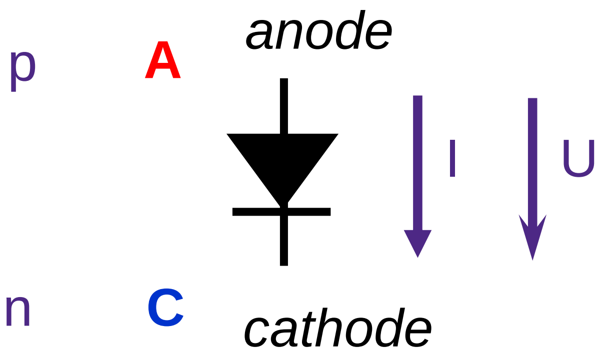
(Si, T=300 K)

Forward region

$I \sim \exp(V/V_T)$

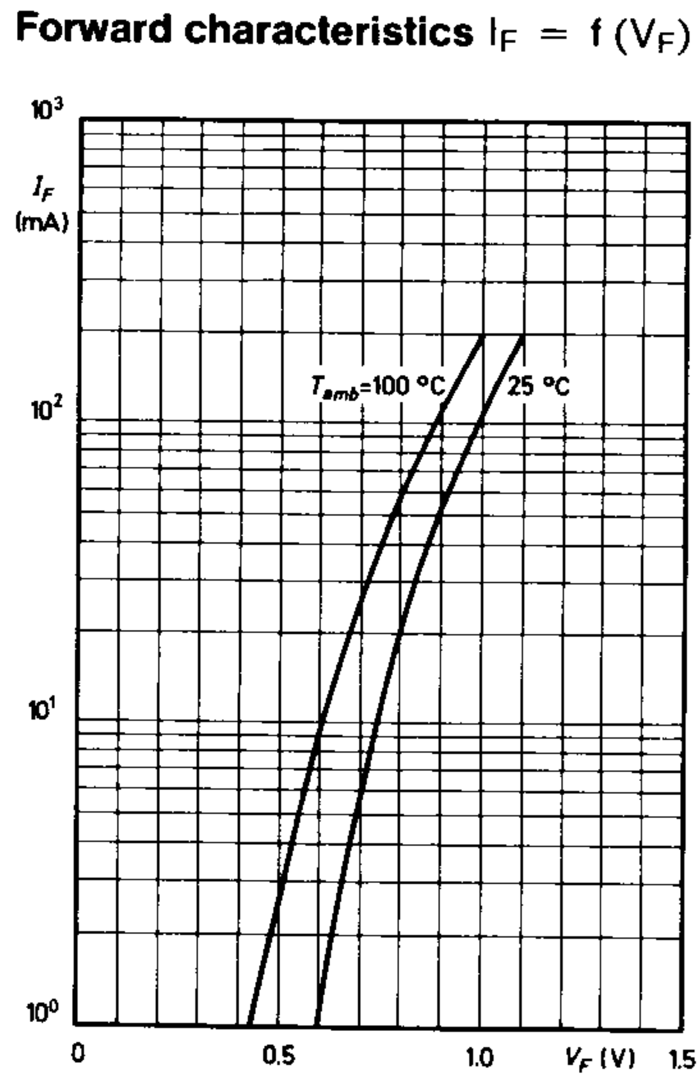
Main features

Symbol, reference directions



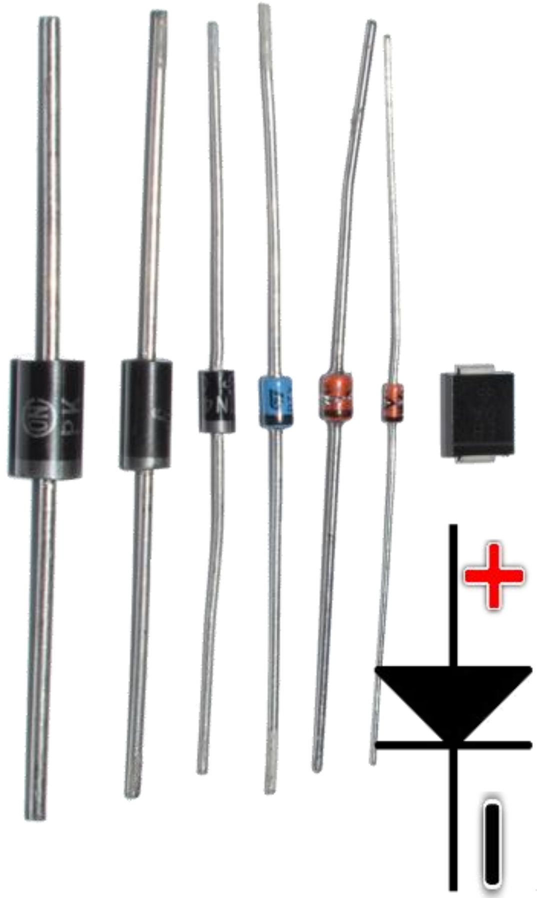
U_F or V_F forward voltage

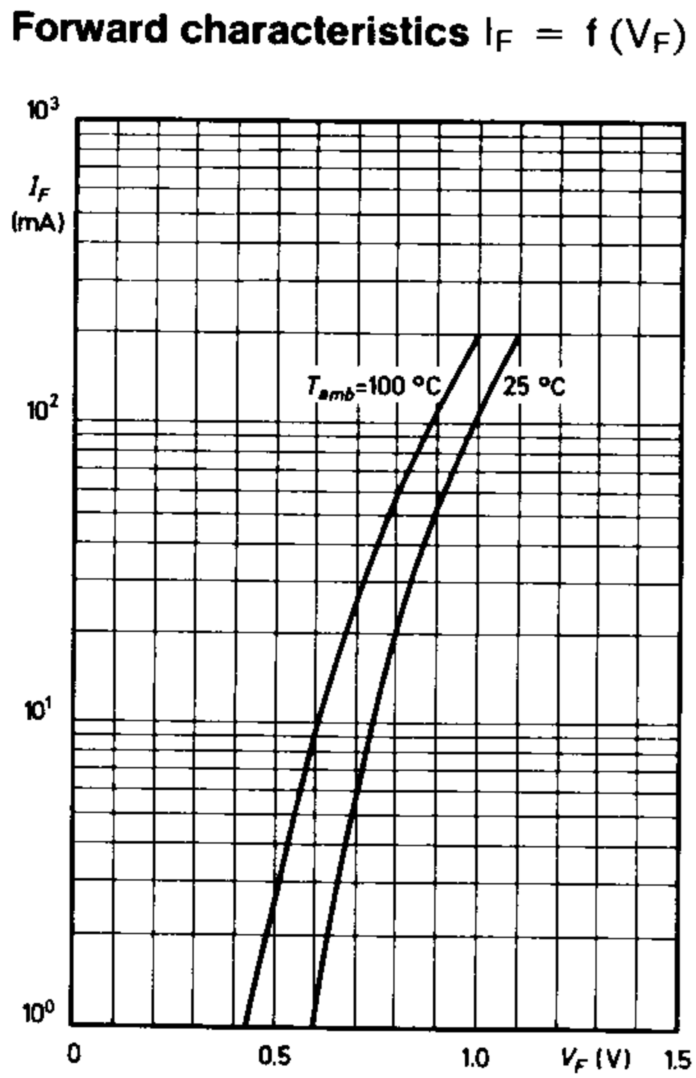
I_F forward current



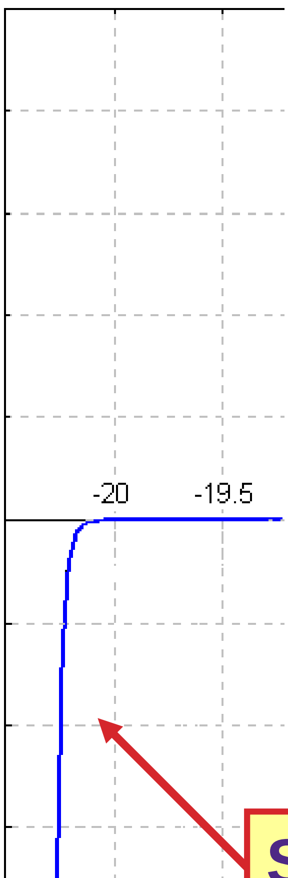
Main features

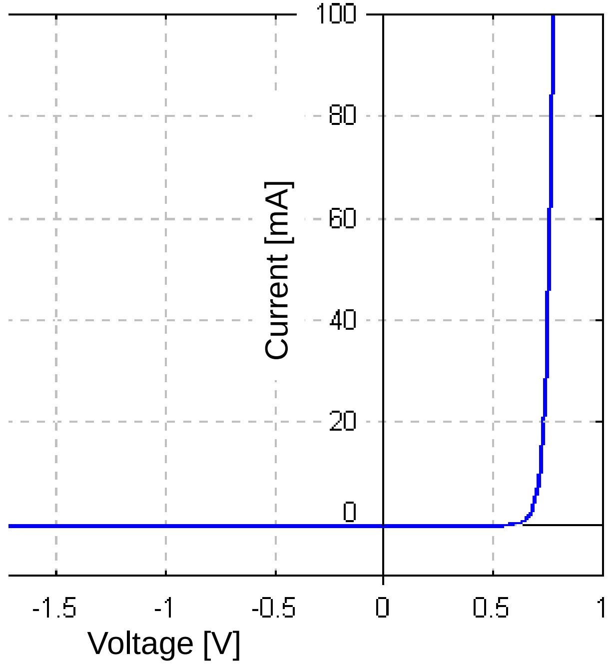
Symbol, reference directions





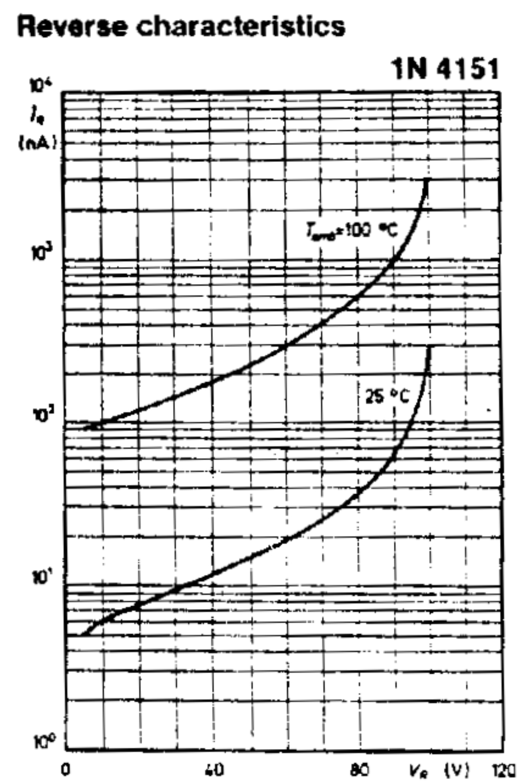
Main features





Dynamic properties:

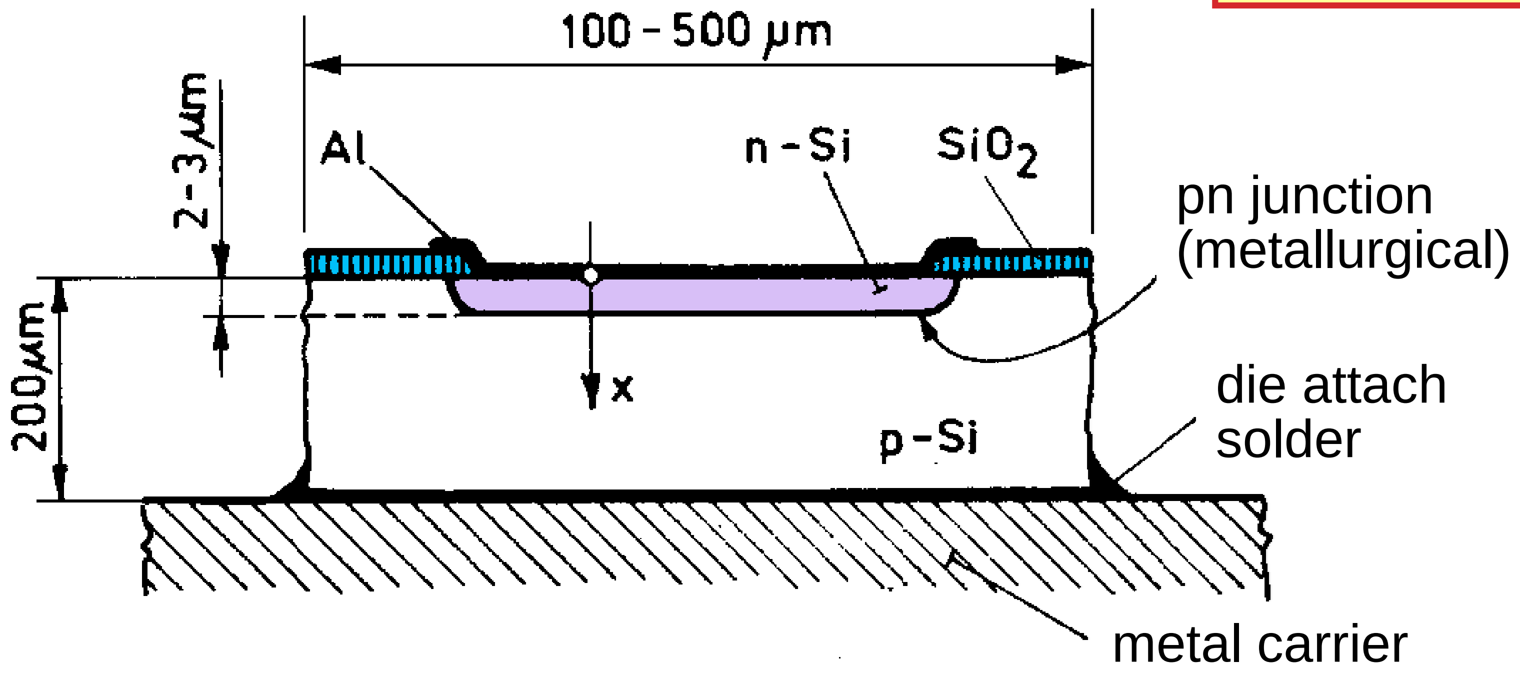
capacitance, finite speed of operation



Secondary effects such as breakdown

How does it look like?

"pn junction"

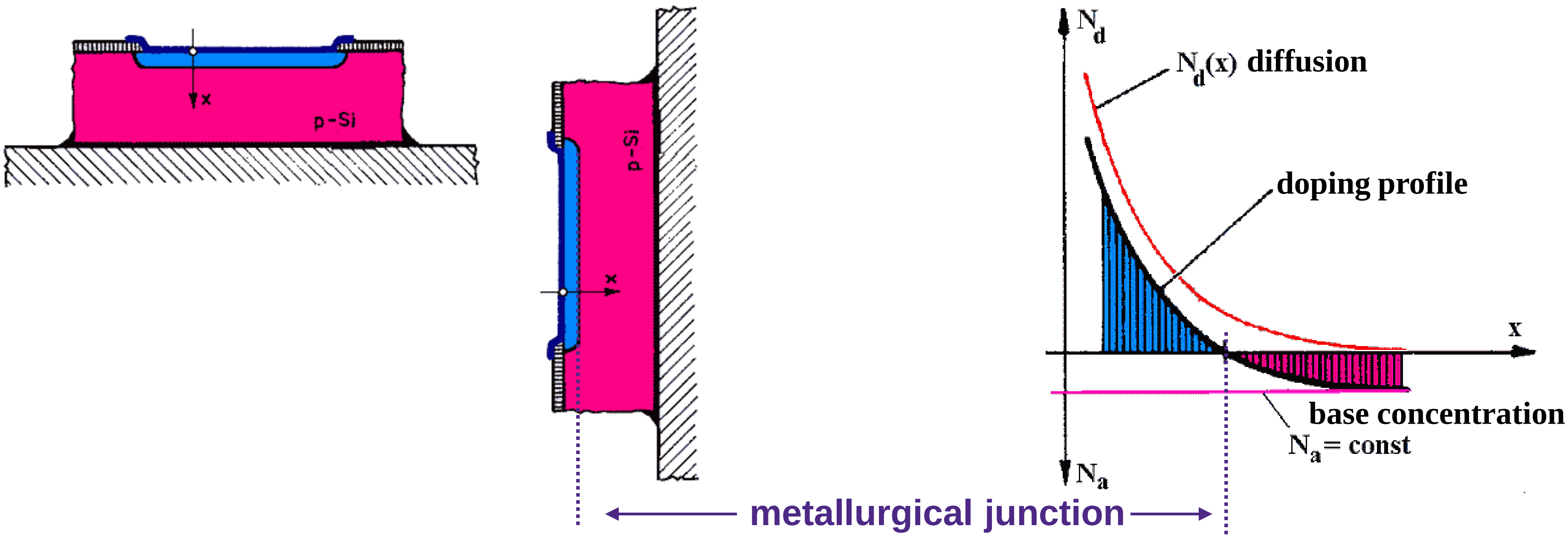


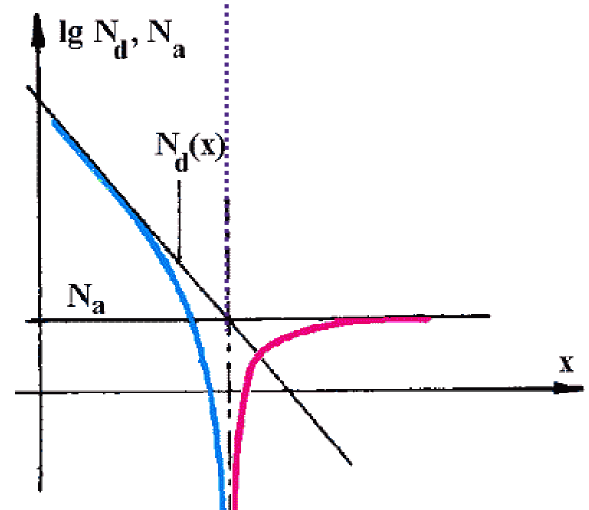
Start from: single crystalline Si wafer

Oxidation, window opening, n diffusion, metallization

Dicing, die attach soldering, packaging

Diode – doping profile





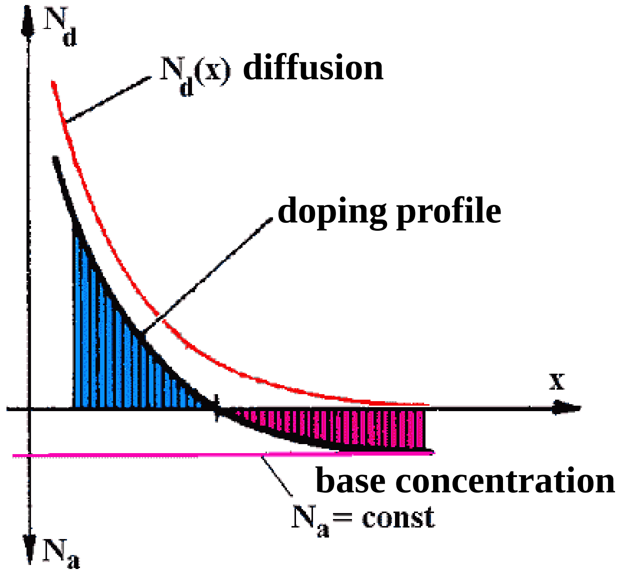
Doping profile: **dopant concentration as function of depth**

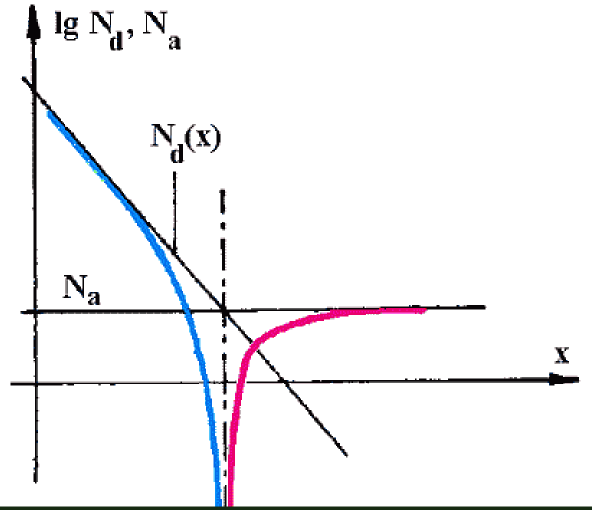
Diode – doping profile

Doping profile: doping density as a function of depth

The doping profile depends on the manufacturing technology and of the application of the diode!

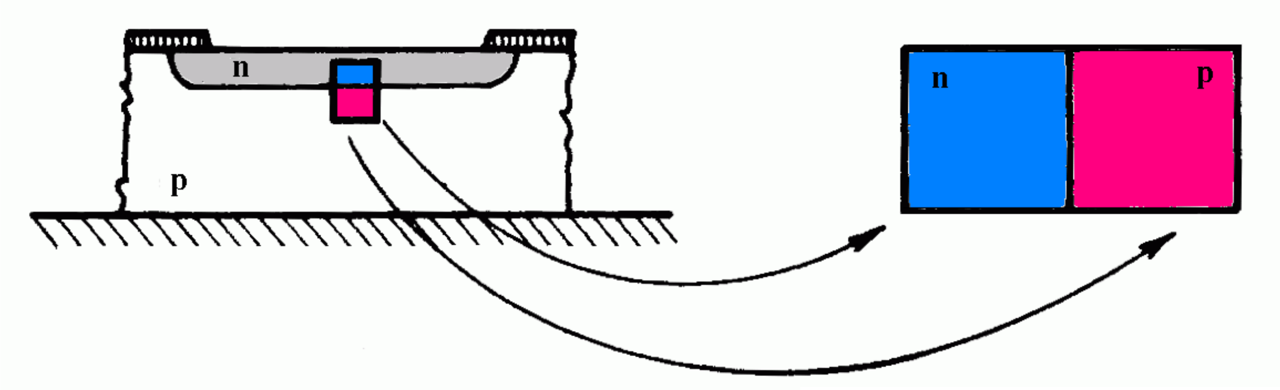
- **<u>diffusion (exponential profile)</u>**
- **epitaxial layer growth (sudden/abrupt transition, within 0.1um distance p doping is changed to n, homogeneous doping)**
- **ion-implantation (sudden transition, possibility of homogeneous doping)**





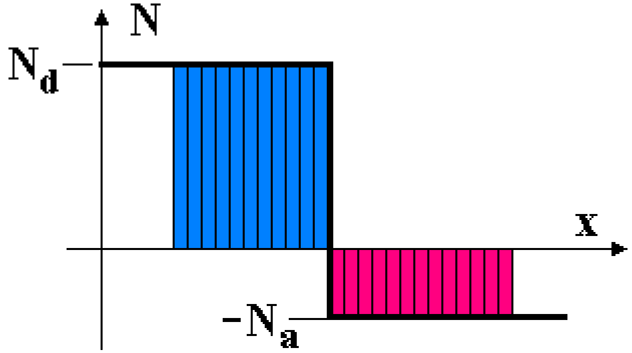
Our method of study

1. 1D analysis, internal PN-junction only



2. Homogeneous doping

“abrupt” profile



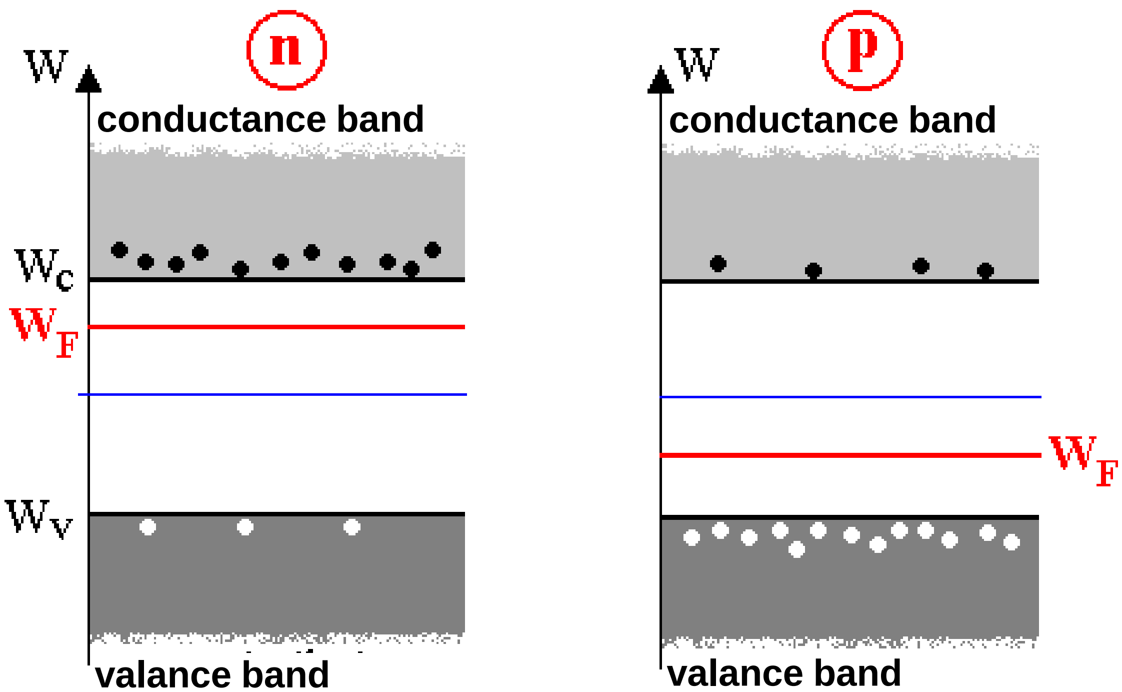
3. One side is more heavily doped than the other side

(Let it be the n-side)

$\boxed{N_d >> N_a}$

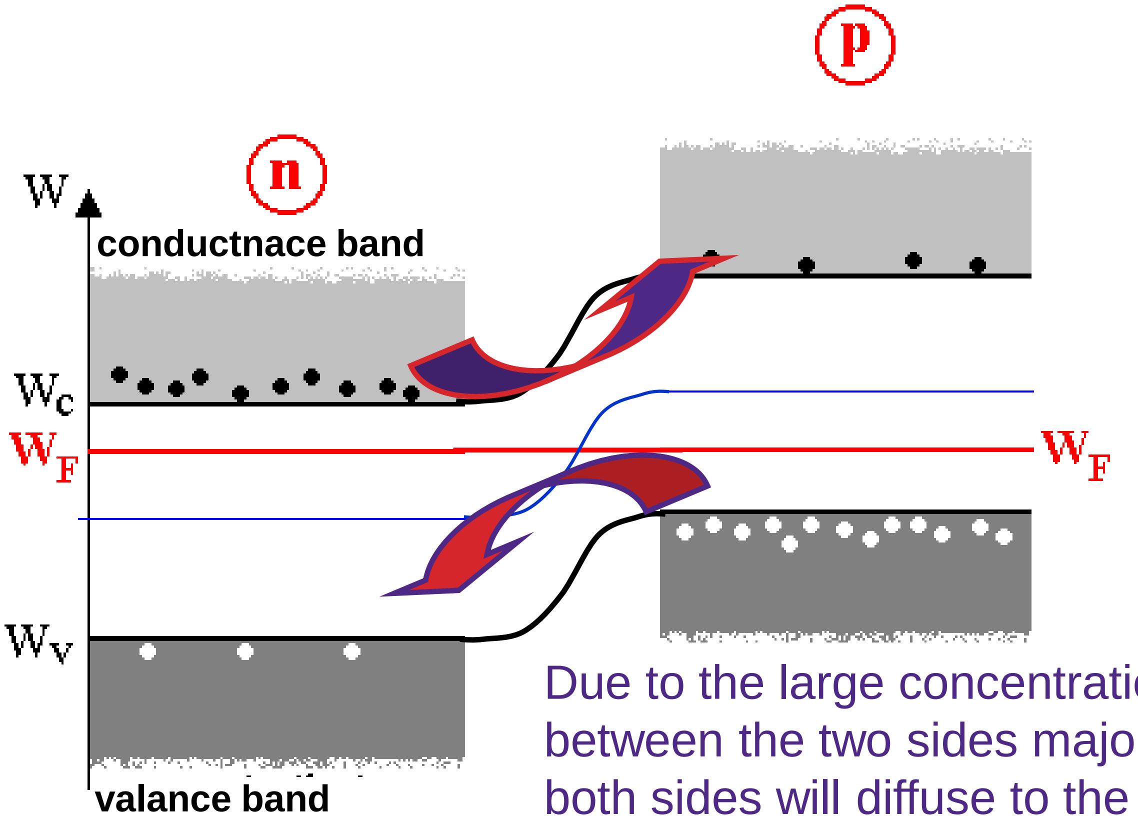
Two separate pieces of doped Si

- The Fermi-levels shift from the intrinsic level according to the doping:



PN junction

- A potential step develops between the p and n sides. This will be so high that the Fermi-levels of both sides will be equal:

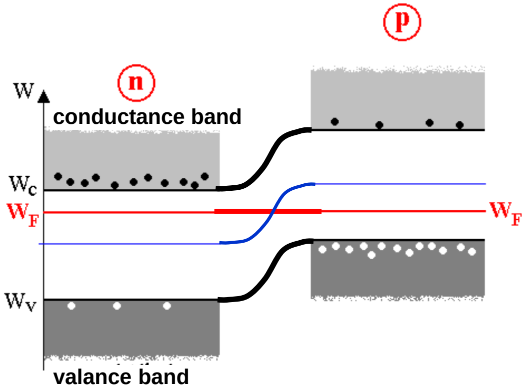


Due to the large concentration gradient between the two sides majority carriers of both sides will diffuse to the other side until the Fermi-levels get equal.

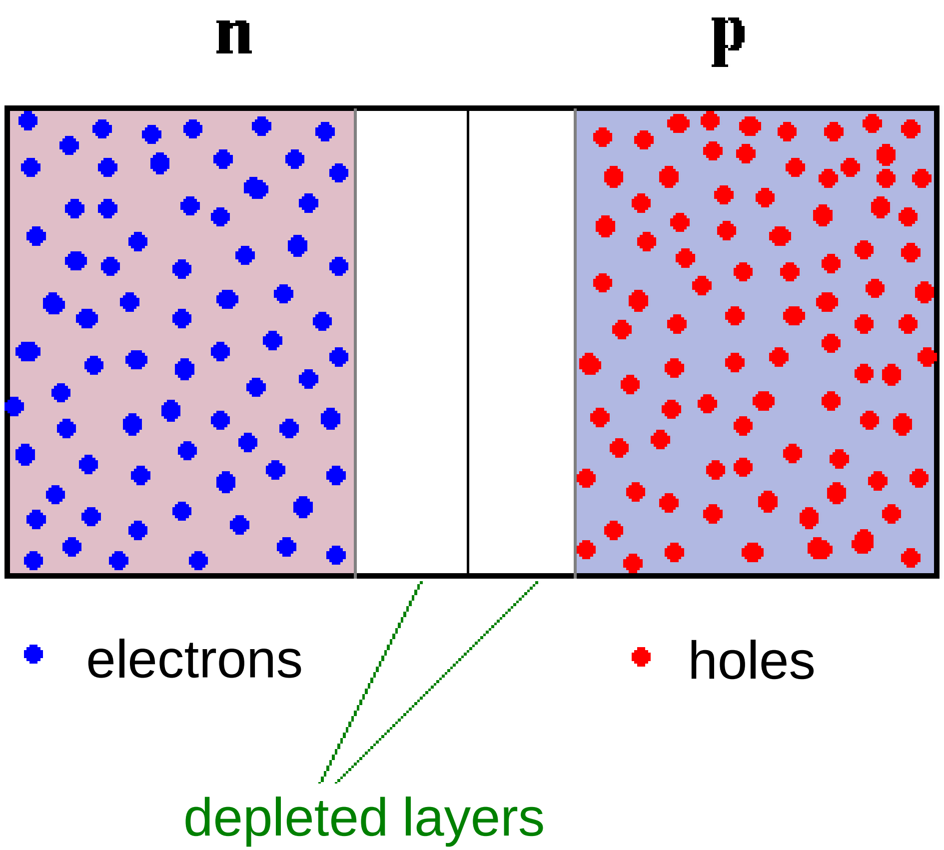
PN junction

- Significant difference of carriers between the two sides
- In the n side e^--s, in the p side holes are the majority
- The density gradient (grad n) causes diffusion current
- Holes flow from the p side, e^- flow from the n side (same direction!)
- Opposite effect is needed for the balance!
- $\bar{E}$ is needed for the drift current!
- A potential step must be developed (*contact potential, contact pot. difference*)

$$J_n(x) = -qD_n \frac{dn}{dx}$$



Electrostatic conditions



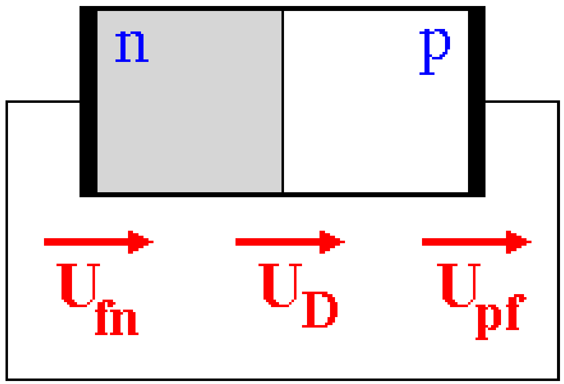
Depleted layers (space charge layers)

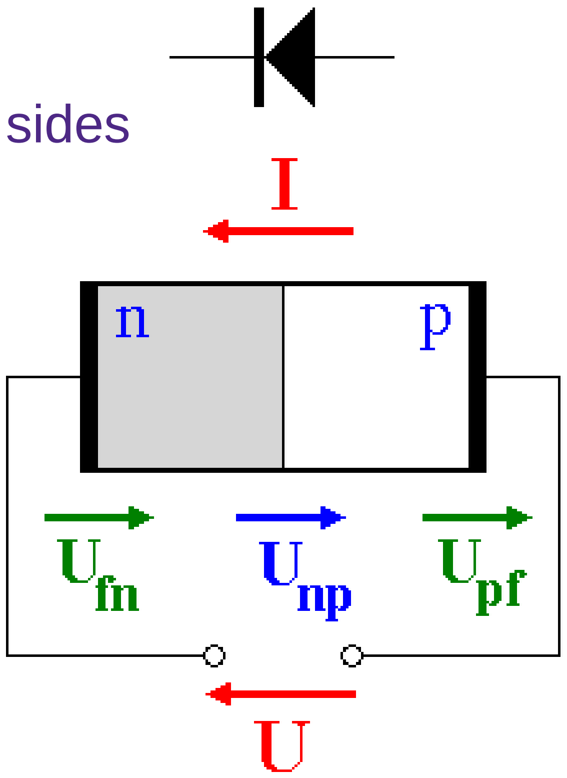
Contact & diffusion potentials

U_{fn} metal – n-Si contact potential

U_D diffusion potential between p & n sides

U_{pf} p-Si – metal contact potential





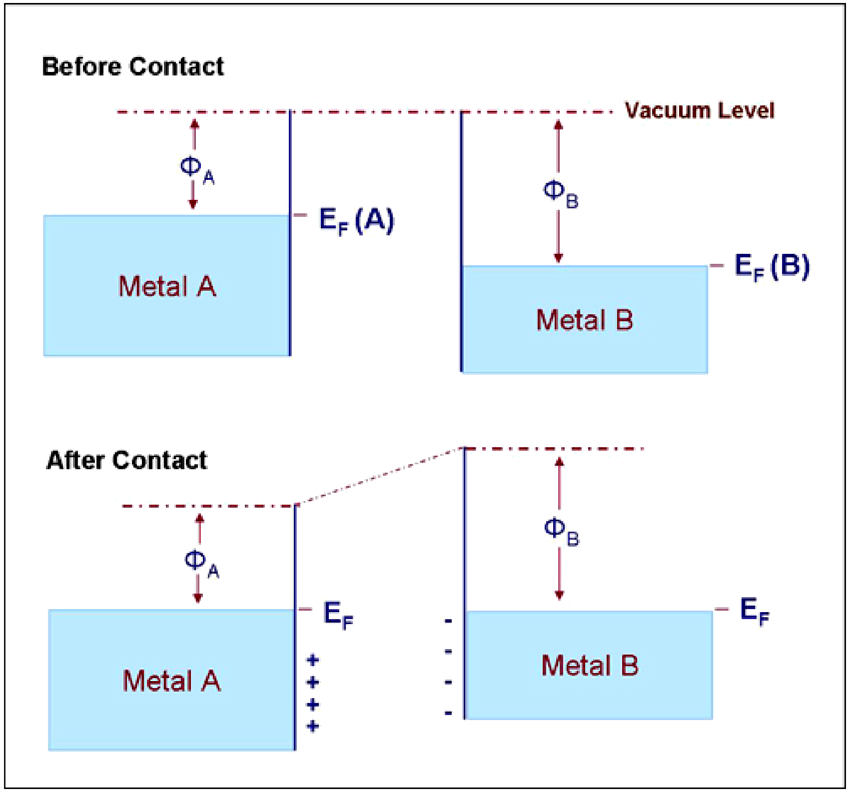
According to Kirchoff's voltage law:

$$U_D + U_{fn} + U_{pf} = 0$$

$$U_{np} + U_{fn} + U_{pf} = -U$$

$$\boxed{U_{np} = U_D - U}$$

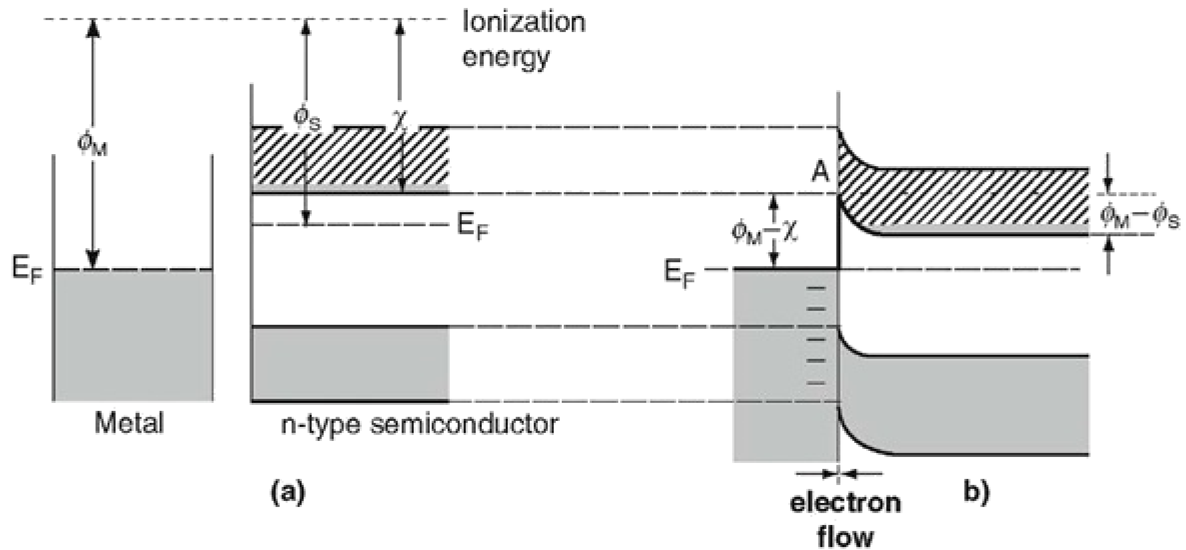
Contact potential metal-metal



- Temperature sensor
  Peltier, Seebeck eff.
- Before contacting the metals have different work functions
  Einstein formula: $E = h \cdot \nu = \phi_A + \frac{1}{2}mv^2$
- Different Fermi-levels
- Contact → e^- current
- Metals with smaller ϕ_A: e^- deficit, apparent positive surplus, E_f decrease
- Potential of the other metal becomes more negative, E_f increases

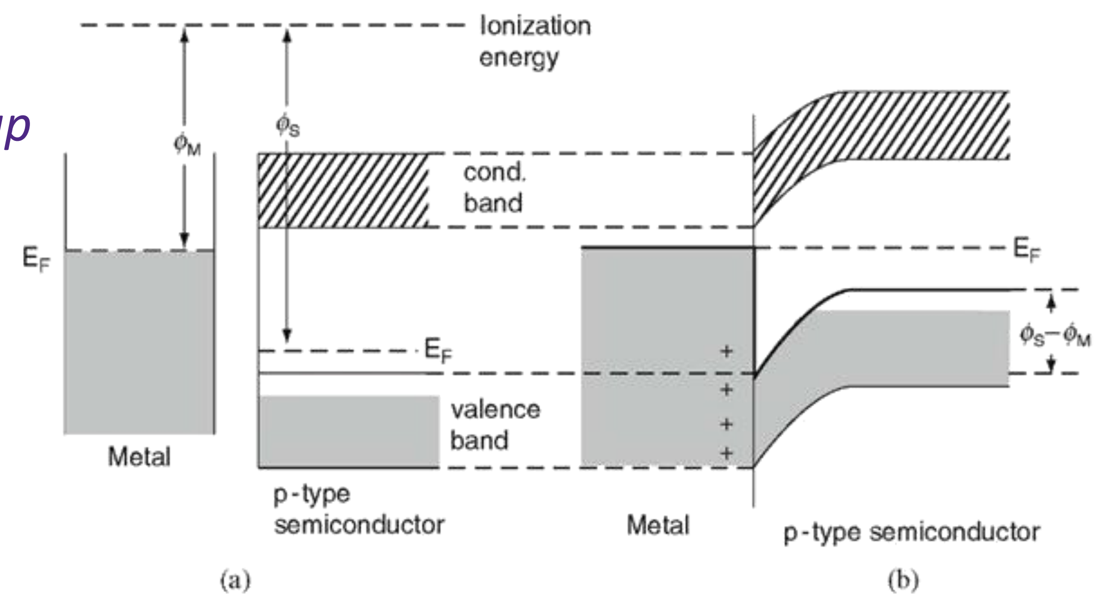
Contact potential metal-semicond.

- n type semiconductor, e⁻ current into the metal
- Metal: e⁻ surplus, apparent negative potential
- Semiconductor: e⁻ shortage, band bending!
- Potential barrier: $\Phi_b = \Phi_M - X$
- X electron affinity



Contact potential metal-semicond.

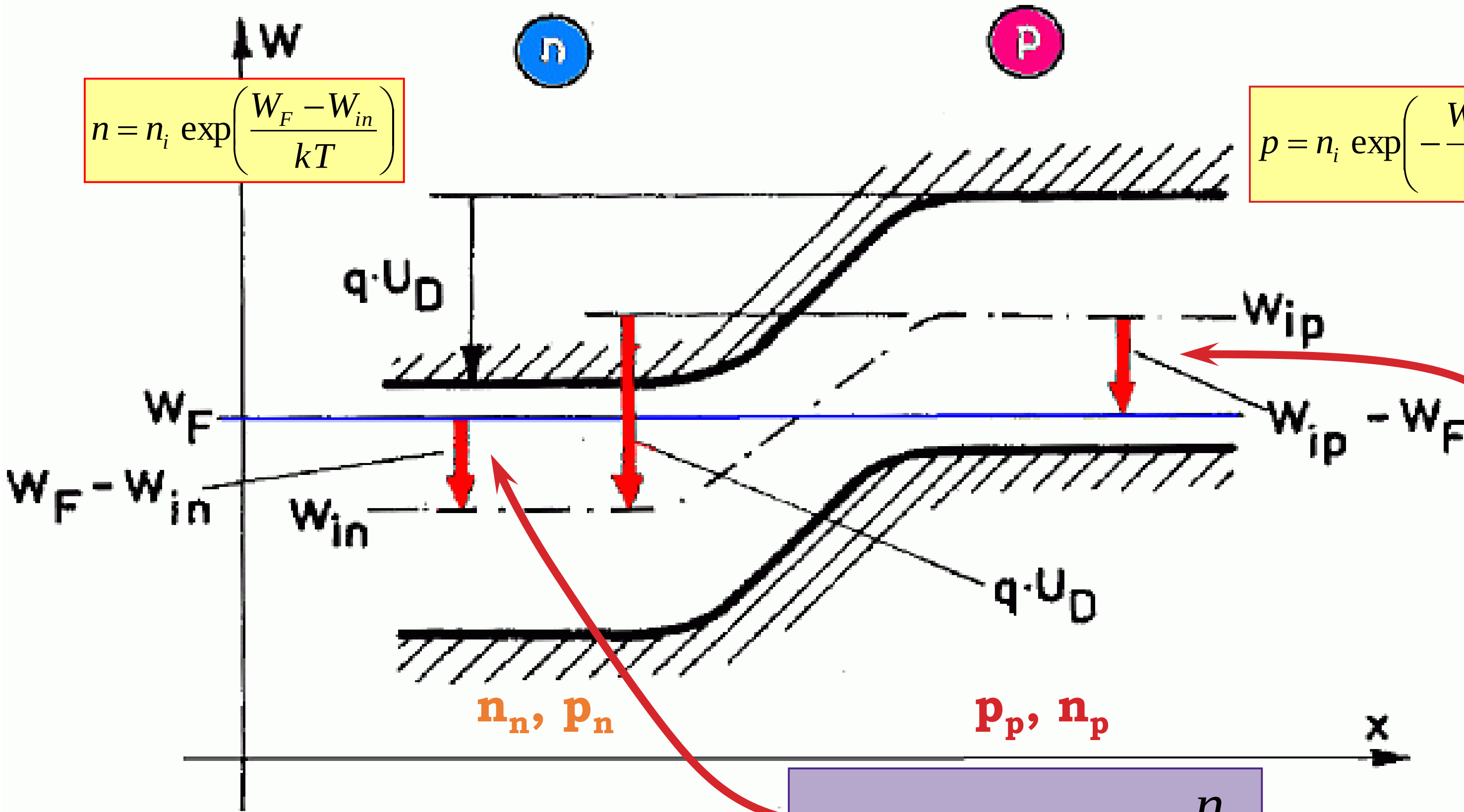
- p type semiconductor, e^- current into the semicond.
- Metal: e^- shortage, apparent positive potential
- Semiconductor: e^- surplus, band bending!
- Potential barrier:: $\Phi_b = E_g - (\Phi_M - X)$
- Influenced by:
  - Surface states
    Energy levels in the band gap
  - Thicknes of the surface layers



Calculation of the diffusion potential

$$n = n_i \exp\left(\frac{W_F - W_{in}}{kT}\right)$$

$$p = n_i \exp\left(-\frac{W_F - W_{ip}}{kT}\right)$$

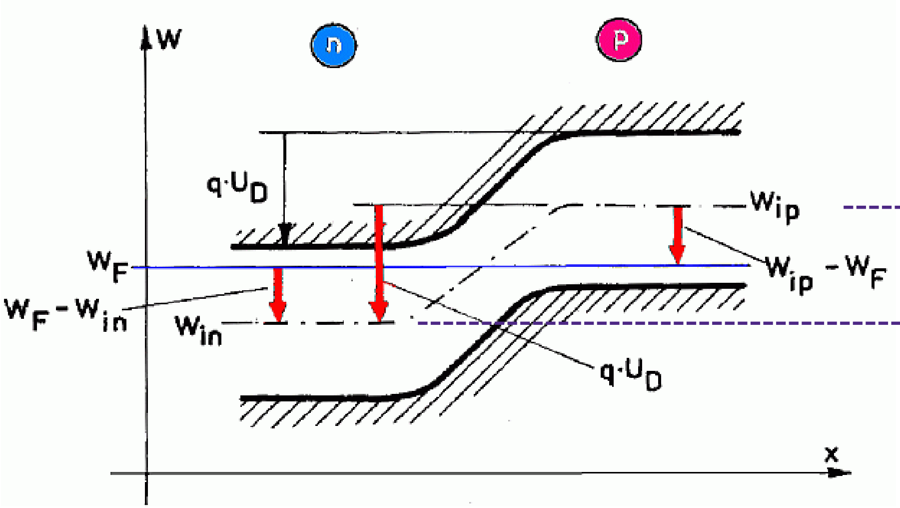


$$n_n = n_i \exp\left(\frac{W_F - W_{in}}{kT}\right)$$

$$W_F - W_{in} = kT \ln \frac{n_n}{n_i}$$

$$W_F - W_{ip} = kT \ln \frac{n_p}{n_i}$$

Calculation of the diffusion potential



$$W_F - W_{in} = kT \ln \frac{n_n}{n_i}$$

$$W_F - W_{ip} = kT \ln \frac{n_p}{n_i}$$

$$W_{ip} - W_{in} = kT \ln \frac{n_n}{n_p}$$

$$U_D = \frac{W_{in} - W_{ip}}{-q} = \frac{kT}{q} \ln \frac{n_n}{n_p} = \frac{kT}{q} \ln \frac{n_n p_p}{n_i^2}$$

$$n_p = n_i^2 / p_p$$

mass effect law

$$\boxed{U_D = U_T \ln \frac{N_d N_a}{n_i^2}}$$

„built-in” voltage

Calculation of the diffusion potential

$$U_D = U_T \ln \frac{N_d N_a}{n_i^2}$$

Problem

Doping levels of an abrupt Si diode: $N_d=10^{18}/cm^3$, $N_a=10^{16}/cm^3$.

Let us calculate the diffusion potential at room temperature!

$$U_D = 0.026 \cdot \ln \frac{10^{18} \cdot 10^{16}}{10^{20}} = 0.026 \cdot \ln 10^{14} = 0.838\ V$$

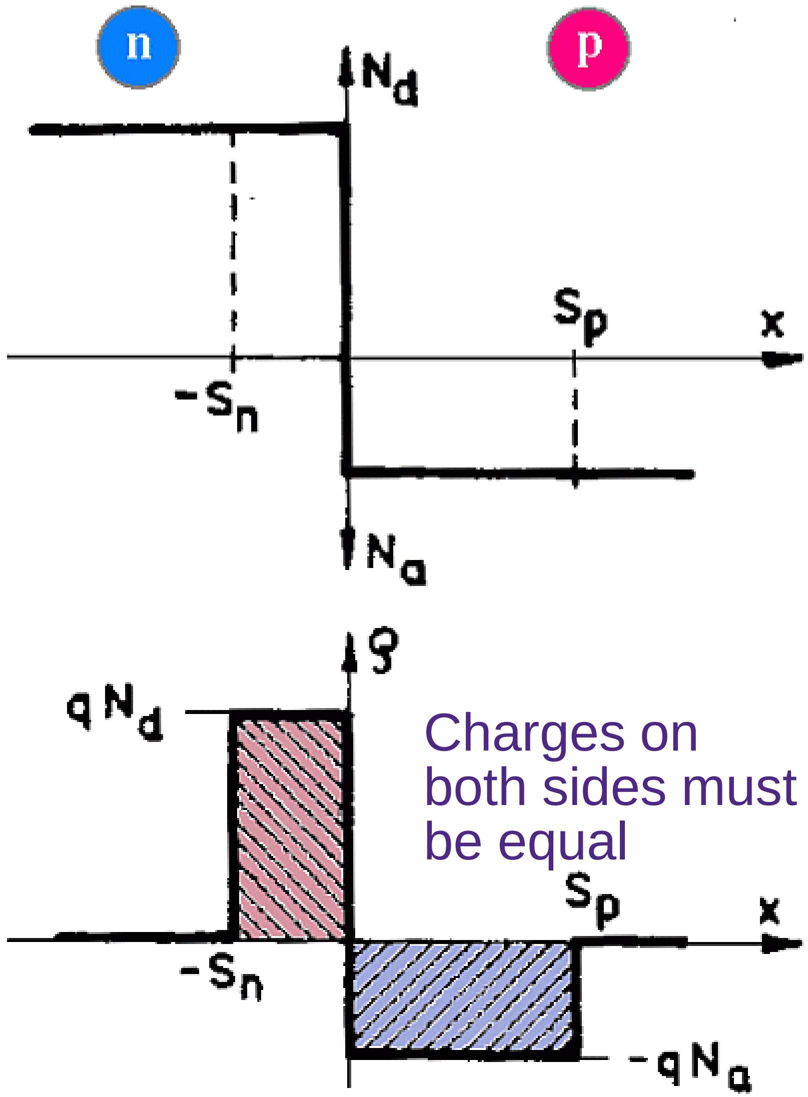
Obviously $U_D < U_{g,}$, U_D is usually 70-80% of U_g

Calculations for the depletion layer

$$q\,S_n N_d = q\,S_p N_a$$

$$\boxed{\frac{N_a}{N_d} = \frac{S_n}{S_p}}$$

The depletion layer is wider on the less doped side.



Charges on both sides must be equal

Calculations for the depletion layer

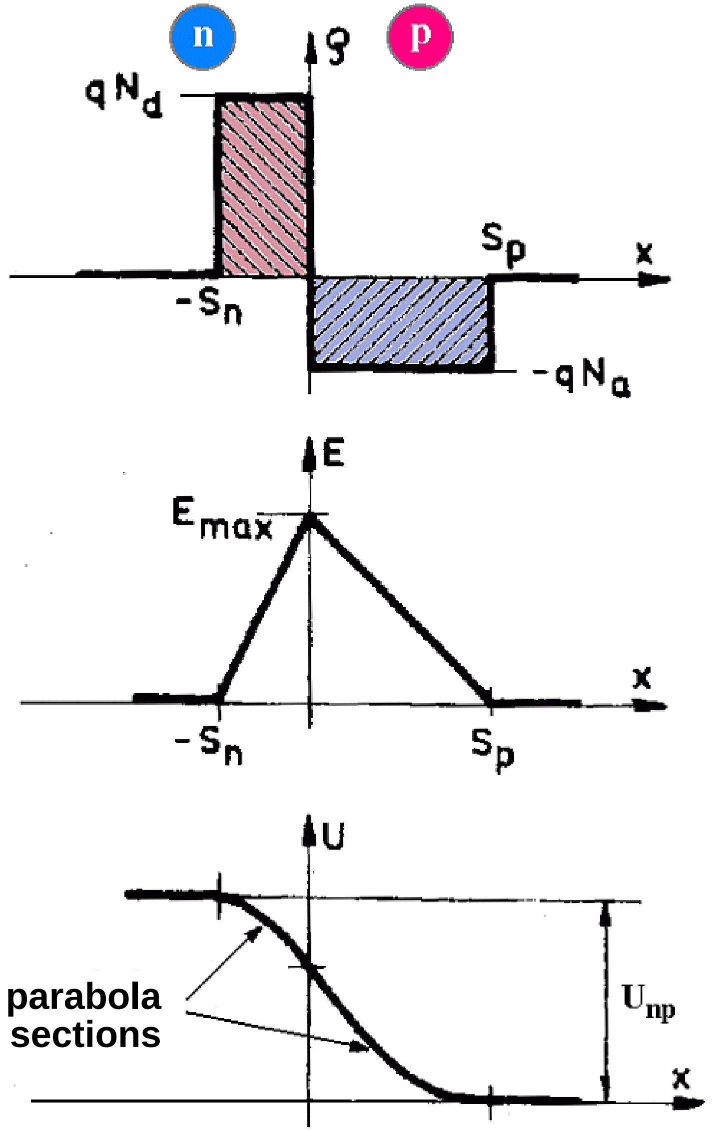
Poisson eq.:

$$\frac{dE}{dx} = \frac{\rho(x)}{\varepsilon}$$

$$E(x) = \frac{1}{\varepsilon} \int_{-\infty}^{x} \rho(\xi)\, d\xi$$

$$E_{\max} = \frac{1}{\varepsilon} \int_{-S_n}^{0} q \cdot N_d \, dx$$

$$E_{\max} = \frac{q\, N_d S_n}{\varepsilon} = \frac{q\, N_a S_p}{\varepsilon}$$



Calculations for the depletion layer

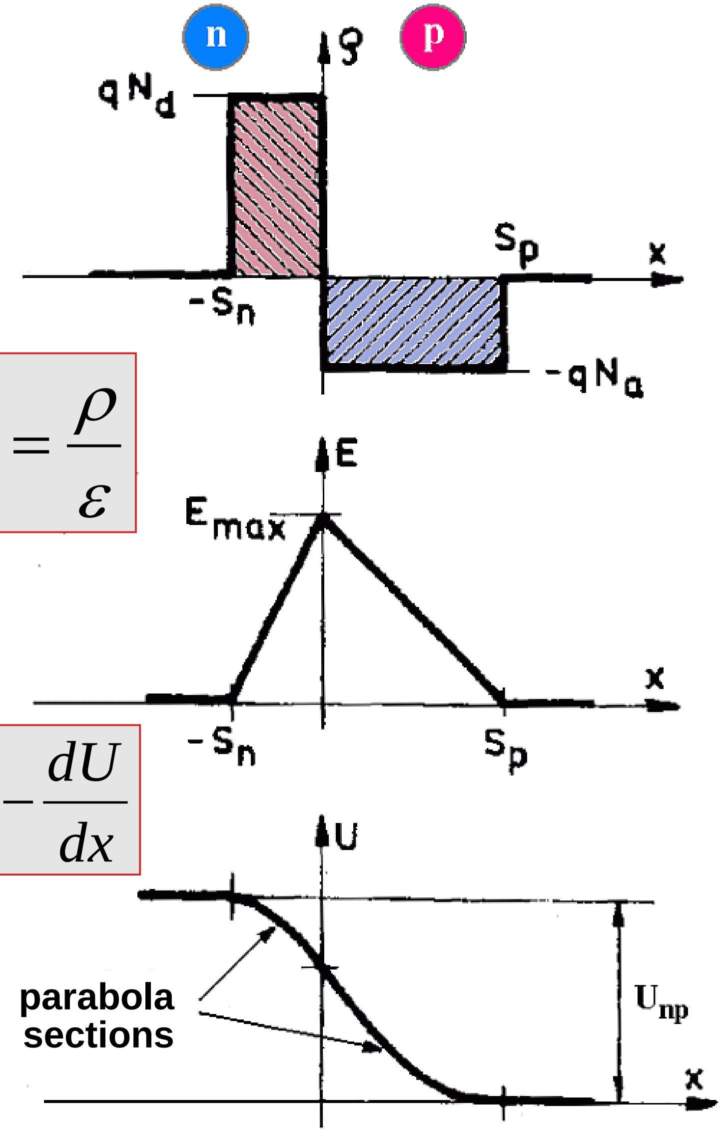
$$E_{\max} = \frac{qN_a}{\varepsilon} S_p$$

$$\frac{dE}{dx} = \frac{\rho}{\varepsilon}$$

$$U_{np} = \frac{1}{2} E_{\max} \left(S_n + S_p\right) \cong \frac{1}{2} E_{\max} S_p$$

$$E = -\frac{dU}{dx}$$

$$U_{np} = \frac{1}{2} \frac{qN_a}{\varepsilon} S_p^2$$



Calculations for the depletion layer

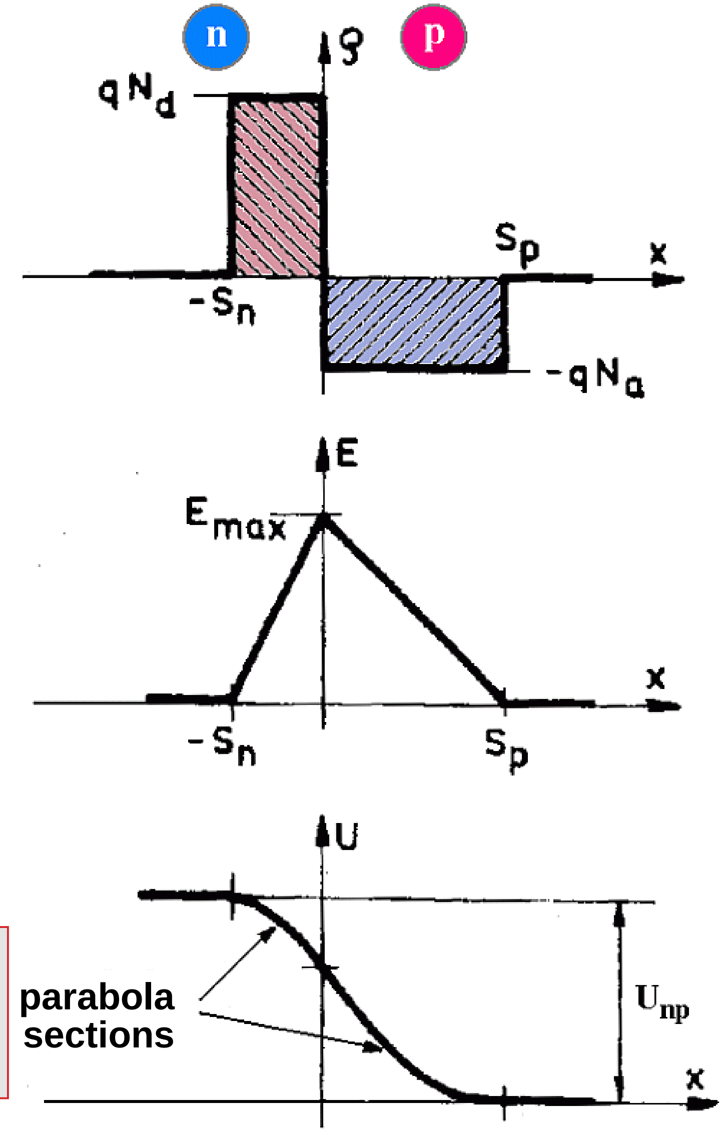
$$U_{np} = \frac{1}{2}\frac{qN_a}{\varepsilon}S_p^2$$

$$S_p = \sqrt{\frac{2\varepsilon}{qN_a}}\sqrt{U_{np}} = \sqrt{\frac{2\varepsilon}{qN_a}}\sqrt{U_D - U}$$

$$S_n = \frac{N_a}{N_d}S_p$$

$$E_{\max} = \frac{qN_a}{\varepsilon}S_p$$

$$E_{\max} = \frac{qN_a}{\varepsilon}\sqrt{\frac{2\varepsilon}{qN_a}}\sqrt{U_D - U} = \sqrt{\frac{2qN_a}{\varepsilon}}\sqrt{U_D - U}$$



Calculations for the depletion layer

$$S_p = \sqrt{\frac{2\varepsilon}{qN_a}}\sqrt{U_{np}} = \sqrt{\frac{2\varepsilon}{qN_a}}\sqrt{U_D - U}$$

$$S_n = \frac{N_a}{N_d} S_p$$

Problem

Doping data of an abrupt Si diode:

$N_d = 10^{18}/cm^3$, $N_a = 10^{16}/cm^3$.

Calculate the widths of the depletion layers!

($\varepsilon_r = 11.8$, U=0V)

$$S_p = \sqrt{\frac{2 \cdot 11.8 \cdot 8.86 \cdot 10^{-12}}{1.6 \cdot 10^{-19} \cdot 10^{22}}}\sqrt{0.838} = 0.331\,\mu m$$

$$S_n = 0.003\,\mu m$$

And if U= -100V ?

$$S_p = 0.331 \cdot \sqrt{\frac{0.838 + 100}{0.838}} = 3.63\,\mu m$$