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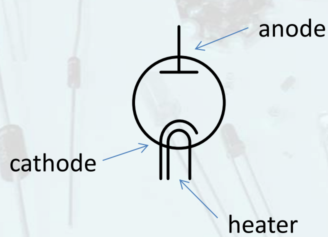
p-n JUNCTION
JUNCTION DIODE
EiT PD
Electronic devices - pn junction
2

Semiconductors, and what's next ?

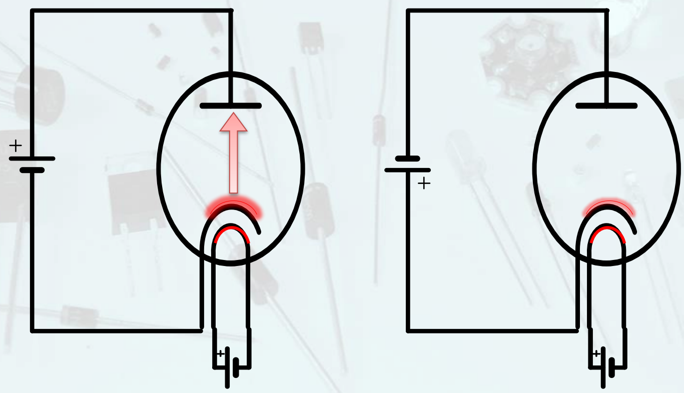
- What do we need semiconductors for?
- Why do we need two types of semiconducting materials?
- What can we make of them?

TUBE DIODE



TUBE DIODE – how does it works ?

DIODE – one-way valve



current

no current

TUBE DIODE vs. SEMICONDUCTOR DIODE

Tube diode – mostly drawbacks:

- large,
- glass,
- heater,
- high voltage,
- difficult to miniaturize

Semiconductor diode – benefits:

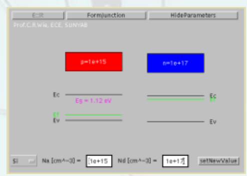
- small,
- large range of voltages and currents,
- it can be integrated and miniaturized
- resistant to shocks

Let's make a semiconductor diode

A few questions:

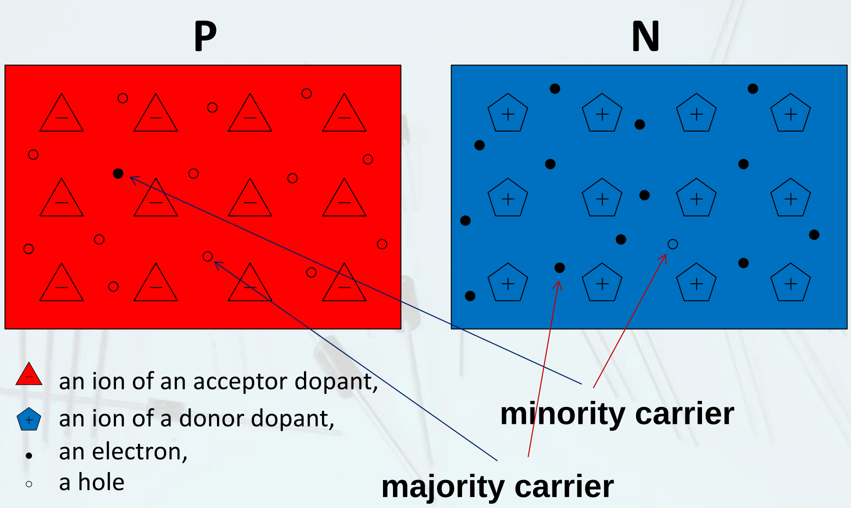
- What will we need to make a tiny diode?
- What kind of semiconductors?
- What is a p-n junction?
- **What are design steps?**

The answer:



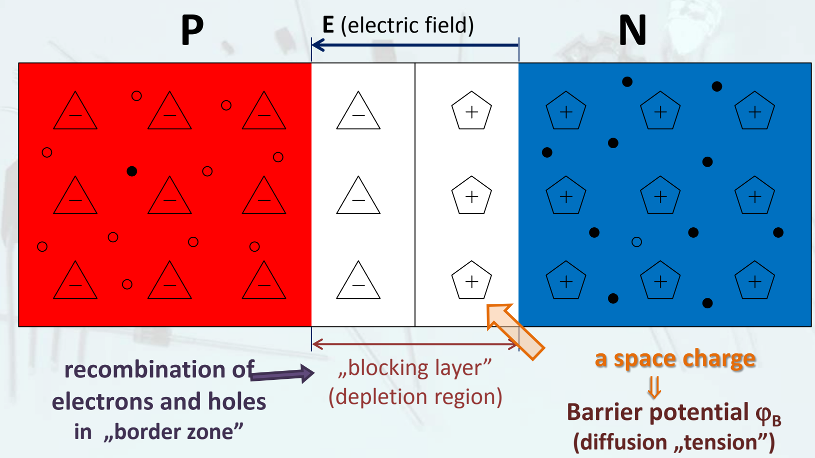
http://www.acsu.buffalo.edu/~wie/applet/pnformation/pnformation.html

p-n JUNCTION- „components"



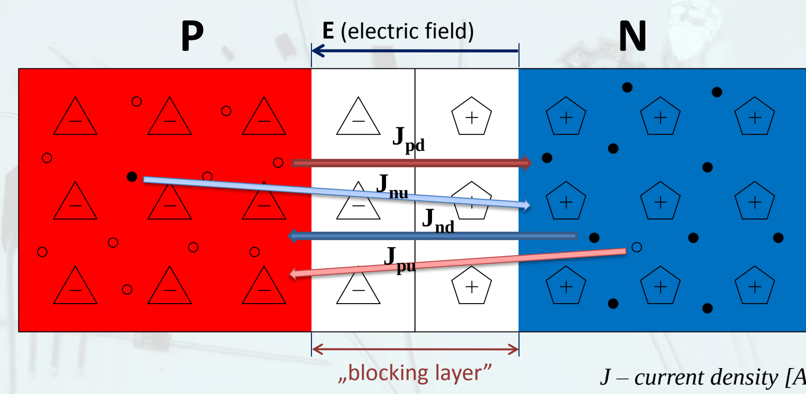
p-n JUNCTION- „merging the components”

An experiment: „merging” *p* and *n* semiconductors



p-n JUNCTION

THERMODYNAMIC EQUILIBRIUM

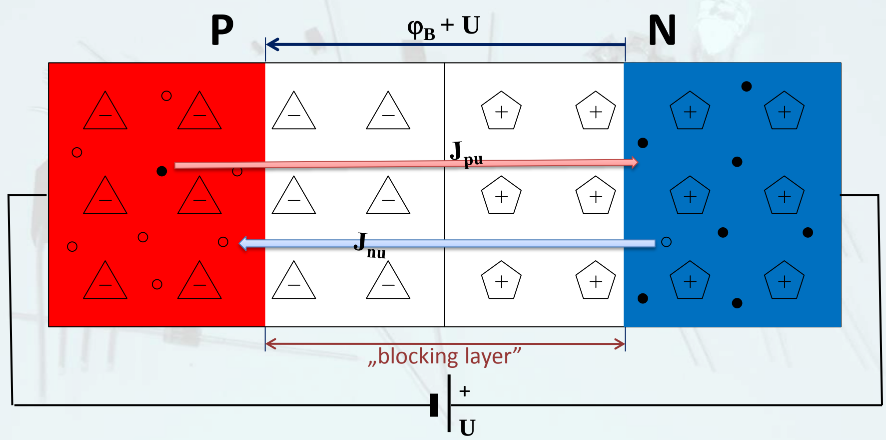


J – current density [A/m²]

$$J_{pd} - J_{pu} = 0, J_{nd} - J_{nu} = 0$$

p-n JUNCTION

REVERSE BIAS POLARIZATION



ZŁĄCZE *p-n*

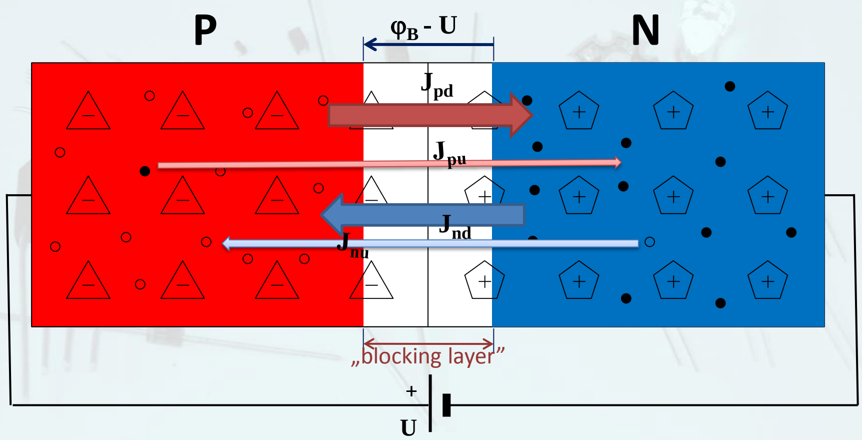
REVERSE BIAS POLARIZATION

Increased potential barrier (ψ_B+U) results in complete disappearance of the majority carriers diffusion currents.

There exist only drift currents of minority carriers that are independent of the voltage.

p-n JUNCTION

FORWARD BIAS POLARIZATION



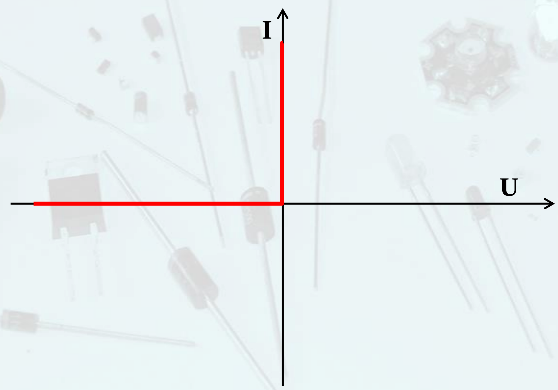
ZŁĄCZE *p-n*

FORWARD BIAS POLARIZATION

Reduced potential barrier (ψ_B-U) causes **large** <u>diffusion</u> currents flow of majority carriers and low drift current of minority carriers.

I vs. U characteristic of the junction

IDEAL DIODE – electronic valve

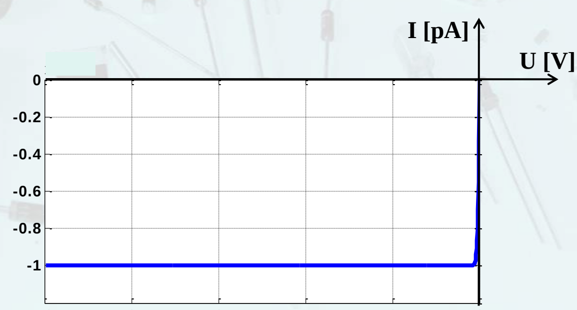


I vs. U characteristic of the junction

first approach

For the reverse bias polarization, there is a constant current associated with drift of minority carriers (J_u).

Its value is independent of the value of the biasing voltage.



I vs. U characteristic of the junction

first approach

*For **forward bias** polarization*

according to the Maxwell-Boltzmann statistics, probability of particles transition over the energy barrier W is: ***f(W)=exp(-W/kT)***

energy barrier for the diffusing majority carriers : $W=q(\varphi_B-U)$

Therefore,

$$J_d = ae^{\frac{-q(\varphi_B-U)}{kT}}$$

- diffusion current density (proportional to the number of carriers with energies greater than ***W***

a – proportionality factor

for *U=0* $J_d = J_u$

$$J_d = J_u = ae^{\frac{-q\varphi_B}{kT}} \Rightarrow a = J_u e^{\frac{q\varphi_B}{kT}}$$

I vs. U characteristic of the junction

first approach

For forward bias polarization cont.

After substituting: $J_d = J_u e^{\frac{q\varphi_B}{kT}} e^{\frac{-q(\varphi_B-U)}{kT}} = J_u e^{\frac{q\varphi_B-q\varphi_B+qU}{kT}}$

and finally: $J_d = J_u e^{\frac{qU}{kT}} = J_u e^{\frac{U}{\varphi_T}}$

$\varphi_T = \frac{kT}{q}$ electrothermal potential (denoted as U_T)

knowing that: $J = J_d - J_u$ we obtain: $J = J_u e^{\frac{U}{\varphi_T}} - J_u$

After all:

$$J = J_u\left(e^{\frac{U}{\varphi_T}} - 1 \right)$$

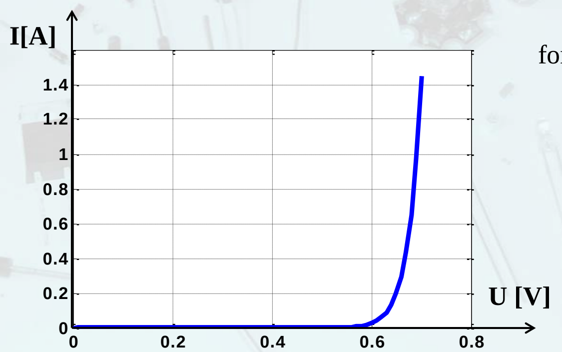
Shockley's equation

http://www.magnet.fsu.edu/education/tutorials/pioneers/shockley.html

I vs. U characteristic of the junction

first approach

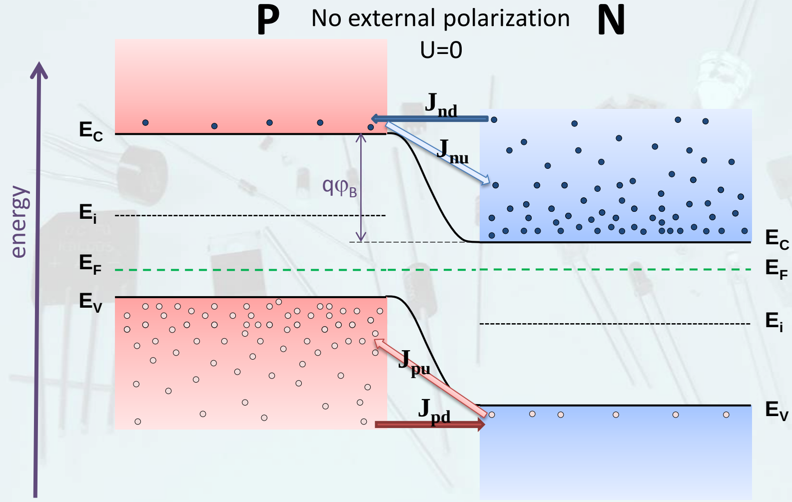
$$J = J_u \left(e^{\frac{U}{\varphi_T}} - 1 \right)$$



for J_u = 1pA

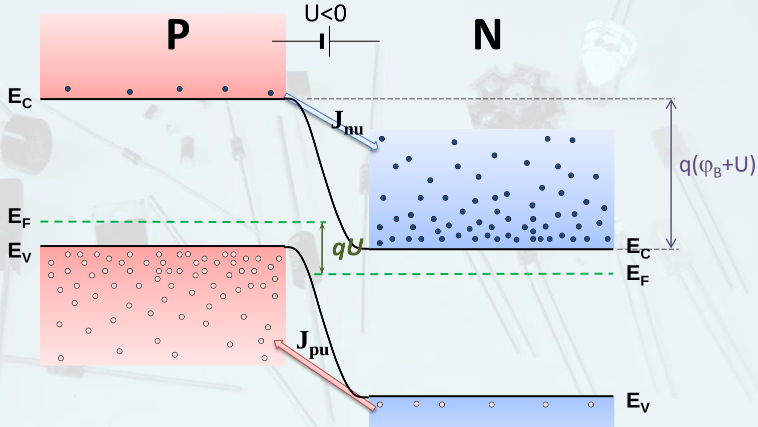
ENERGY BAND MODEL OF PN JUNCTION

P No external polarization U=0 **N**



ENERGY BAND MODEL OF PN JUNCTION

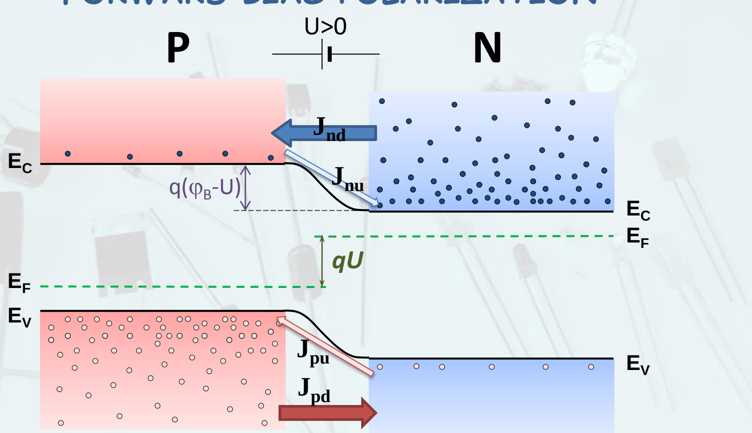
REVERSE BIAS POLARIZATION



Increased potential barrier (ψ_B+U) results in a complete disappearance of the majority carriers diffusion currents. There only remain drift currents of minority carriers, independent of the voltage.

ENERGY BAND MODEL OF PN JUNCTION

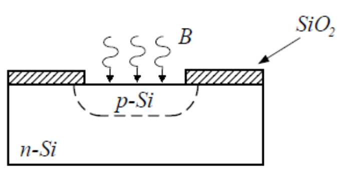
FORWARD BIAS POLARIZATION



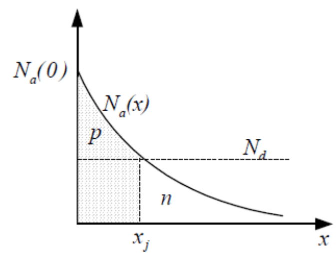
Decreased potential barrier (ψ_B-U) causes large diffusion currents flow of majority carriers and small drift currents of minority carriers

HOW IS PN JUNCTION CREATED?

- Diffusion junction – diffusion of donor or acceptor atoms



Diffusion of boron atoms through a window in silicon oxide



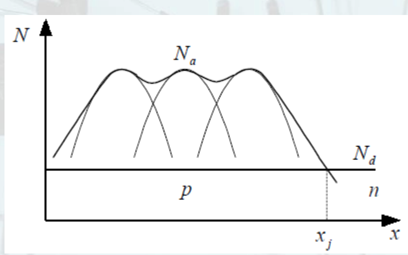
The distribution of the acceptor dopant concentration for diffusion from a source with an unlimited capacity

LINEAR JUNCTION $N(x) = N_a - N_d \approx -ax$

Figures from: S. Kuta „Elementy i układy elektroniczne", AGH 2000

HOW IS PN JUNCTION CREATED?

- Implant junction – „bombardment" of Si crystal by dopant ions with very high energy (hundreds of keV)



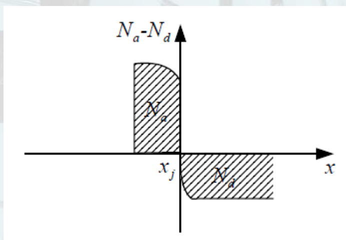
The distribution of the acceptor dopant introduced into the semiconductor by multiple implantation

ABRUPT JUNCTION

Figure from:S. Kuta „Elementy i układy elektroniczne", AGH 2000

HOW IS PN JUNCTION CREATED?

- Epitaxial junction – semiconductor epitaxial layer deposition from the atmosphere enriched with elements of dopants

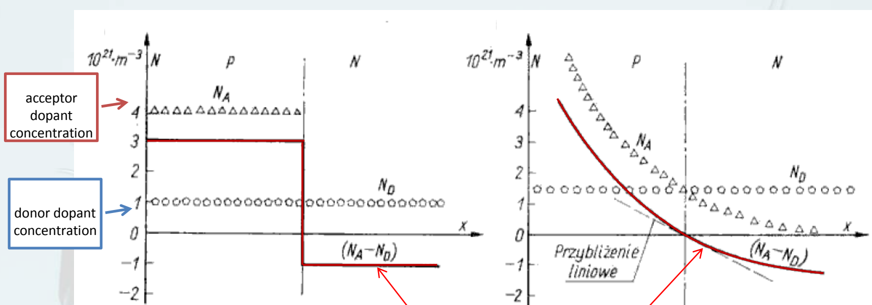


The distribution of dopant concentration for an example of the abrupt junction, obtained by epitaxial deposition

ABRUPT JUNCTION

Figures from: S. Kuta „Elementy i układy elektroniczne", AGH 2000

ABRUPT AND LINEAR JUNCTION



Dopant concentration distribution **in an abrupt junction**

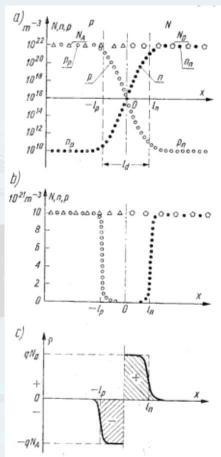
Dopant concentration distribution **in a linear junction**

Effective distribution of dopant concentration determining the type of a semiconductor

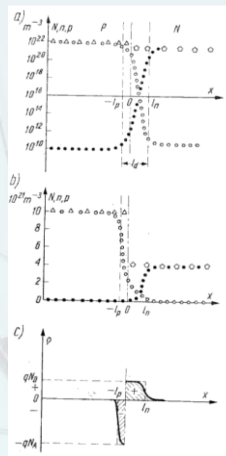
Figures from: W. Marciniak „Przyrządy półprzewodnikowe i układy scalone", WNT 1979

ABRUPT PN JUNCTION

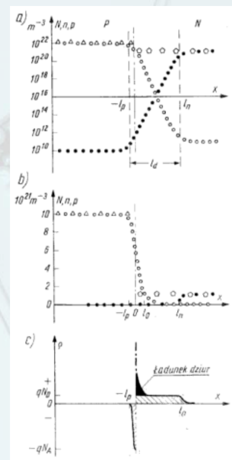
charge density distribution   distribution of dopant concentration



symmetrical abrupt junction



asymmetric abrupt junction

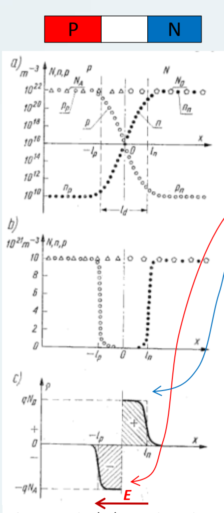


abrupt junction strong asymmetric

Figures from: W. Marciniak „Przyrządy półprzewodnikowe i układy scalone", WNT 1979

DEPLETION AREA

ANALYSIS



Symmetrical abrupt junction

The distribution of the electric field $\underline{E(x)}$, potential $\varphi(x)$ and width of the depletion area can be found from the Poisson equation :

$$\frac{d^2\varphi}{d^2x} = -\frac{\rho(x)}{\varepsilon_s}$$

ε_S – absolute permittivity of the semiconductor

Space charge density ρ in depletion area :

$\rho_A(x) = -qN_A$ for acceptor area

$\rho_D(x) = qN_D$ for donor area

Integrating the Poisson equation and bearing in mind that the the electric field $E = d\varphi/dx$ we get:

$$E = -\frac{1}{\varepsilon_S}\int \rho(x)dx$$

PN junction as a whole, maintains electrical indifference - dipole layer with equal positive and negative charges ($-qN_A l_p + qN_D l_n = 0$). Thus, there is no electric field outside the depletion layer ($E=0$ for $x \le -l_p$ i $x \ge l_n$). Under these conditions and charge densities in the different areas, as well as E directed to the left, after integration we get:

$$E_A(x) = \frac{qN_A}{\varepsilon_S}(-x - l_p), \quad E_D(x) = \frac{qN_D}{\varepsilon_S}(x - l_n)$$

E_A – in acceptor area ,
E_D – in donor area

DEPLETION AREA
ANALYSIS

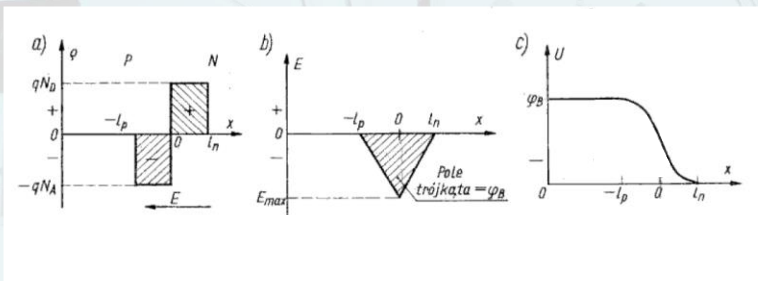
The electric field preserves continuity at the transition between acceptor and donor areas : $E_A(0)=E_D(0)$. Furthermore, at this point its maximum is:

$$E_{\max} = \frac{-qN_A l_p}{\varepsilon_S} = \frac{qN_D l_n}{\varepsilon_S}$$

Potential distribution $\varphi(x)$ can be calculated by integrating the electric field $E(x)$ within $-l_p$ to l_n (figure below). In contrast, the potential difference is the potential barrier φ_B (diffusion voltage):

$$\varphi_B = \frac{1}{2} E_{\max} l_d \qquad l_d = l_p + l_n$$

l_d – width of the depletion area



Rysunki zaczerpnięto z W. Marciniak „Przyrządy półprzewodnikowe i układy scalone", WNT 1979

DEPLETION AREA
ANALYSIS

Using the above equations and the "leverage law" ($N_A l_p = N_D l_n$), width of the depletion layer l_d, can be shown as:

$$l_d = \frac{2\varphi_B}{E_{\max}} = \sqrt{\frac{2\varepsilon_s (N_D + N_A)\varphi_B}{qN_D N_A}}$$

Using the fact that in a state of thermodynamic equilibrium, drift current is equal to the diffusion current ($J_u = J_d$), one can determine the value of the potential barrier.

For example, for holes:

$$qD_p \frac{dp}{dx} = q\mu_p pE$$

using Einstein's equations ($kT/q=D/\mu$) and ($\varphi_T = kT/q$) we can write:

$$\varphi_T \frac{dp}{p} = Edx$$

Integrating the concentration of holes and length of depletion layer :

$$\varphi_T \int_{p_p}^{p_n} \frac{dp}{p} = \int_{-l_p}^{l_n} Edx = -\varphi_B$$

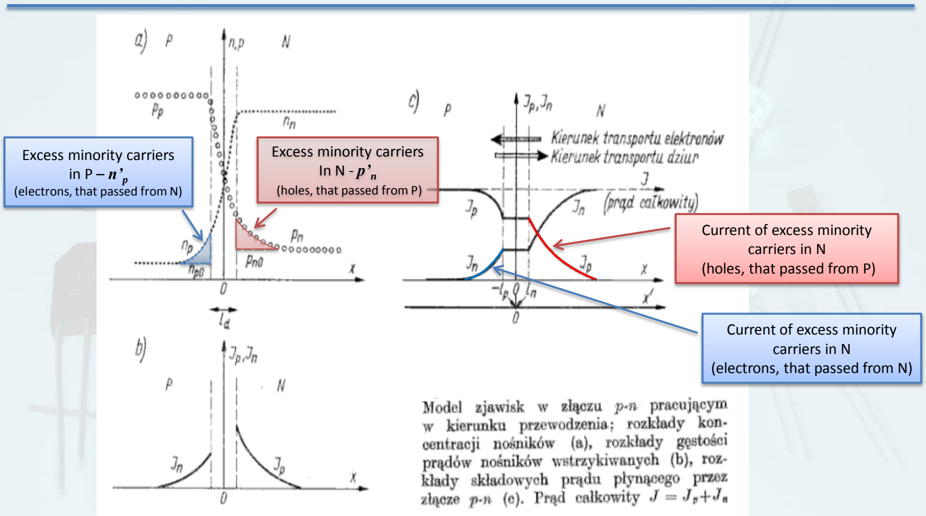
we get: $\varphi_B = \varphi_T \ln(p_p / p_n)$

or for electrons: $\varphi_B = \varphi_T \ln(n_n / n_p)$

Taking into account: $n_n \approx N_D$ i $p_p \approx N_A$ and $np = n_i^2$ we get:

$$\varphi_B = \varphi_T \ln(N_D N_A / n_i^2)$$

I vs. U CHARACTERISTIC



Figures from: W. Marciniak „Przyrządy półprzewodnikowe i układy scalone", WNT 1979

I vs. U CHARACTERISTIC

Total current (for simplicity we omitted depleted layer – x' axix):

$$J = J_{dn|x'=0} + J_{dp|x'=0}$$

only diffusion components:

$$J_{dn} = qD_n \frac{dn_p}{dx'}\bigg|_{x'=0}$$ for electrons

$$J_{dp} = -qDp \frac{dp_n}{dx'}\bigg|_{x'=0}$$ for holes

The concentration of the injected carriers through the depletion area :

$$n_p = n_{p0} + n'_p(0)\exp(-x/L_n), \quad p_n = p_{n0} + p'_n(0)\exp(-x/L_p)$$

n_{p0}, p_{n0} – concentration of minority carriers in thermodynamic equilibrium ,
$n'_p(0), p'_n(0)$ – Concentrations of excess minority carriers for $x=0$

finally:

$$J = q\left[\frac{D_n n_{p0}}{L_n} + \frac{D_p n_{n0}}{L_p}\right](e^{\frac{U}{\varphi_T}} - 1)$$

„diffusion diode"

J_s – saturation current density

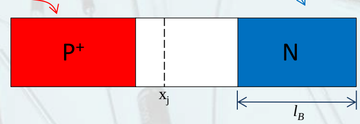
$$I_D = I_S(e^{\frac{U}{\varphi_T}} - 1) \qquad I_S = qA\left[\frac{D_n n_{p0}}{L_n} + \frac{D_p n_{n0}}{L_p}\right]$$

current $I_S = J_S A$, where: A this junction cross-sectional area

BASE AND EMITTER OF PN JUNCTION

In the case of asymmetrical junctions :

- ***junction base*** – less doped area
- ***junction emitter*** – heavily doped layer



$N_A >> N_D$

junction with very narrow base: $l_B < L_n$