
AGH University of Science and Technology
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Faculty of Computer Science, Elelctronics and Telecommunications
DEPARTMENT OF ELECTRONICS
ELECTRONIC
DEVICES
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DIODES
more details …
LEDs
varactors
Zener diodes
tunneling diodes
EiT PD
Electronic devices - diodes
2

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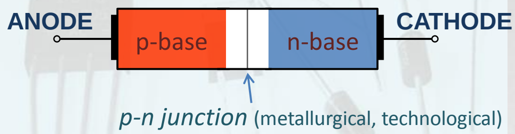
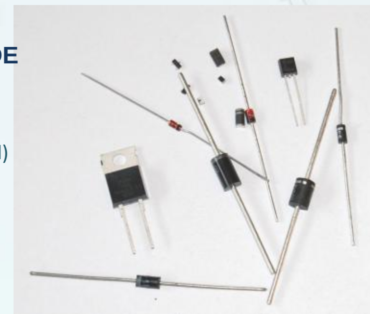
DIODE

It is

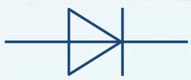
p-n junction

formed and sealed within the housing with contacts





symbol:



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DIODE IN DC CURRENT CIRCUIT

EXAMPLE

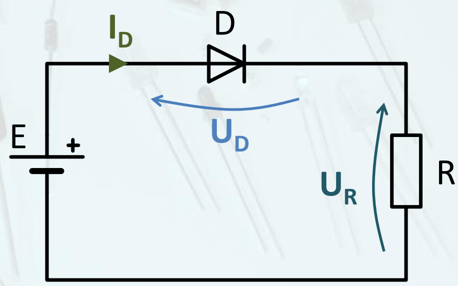
Data:

E=3V, R=10kΩ, I_S=0,1pA, T=300K, D – diode

Looking for:

I_D=?

U_D=?



DIODE IN DC CURRENT CIRCUIT

SOLUTION

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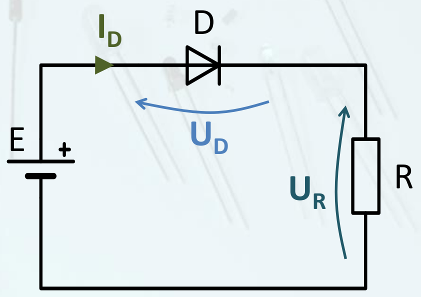
Equation based II Kirchhoff's law: ...

The diode current I_D, Shockley's formula: ...

Substitution of I_D: ...

Finally we can calculate: ...



DIODE IN DC CURRENT CIRCUIT

SOLUTION II

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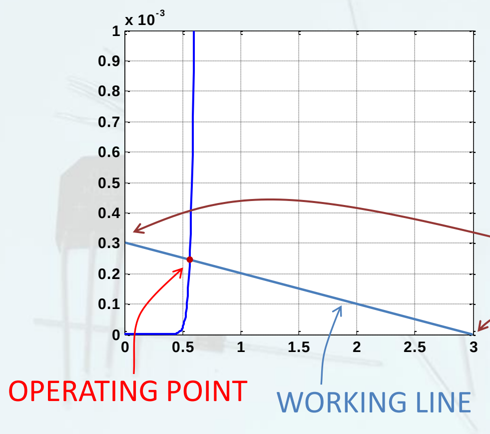
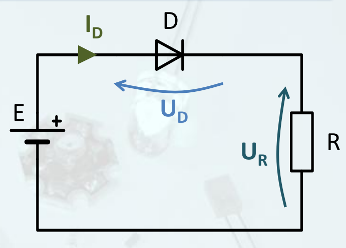
I_S=0,1pA, T=300K, D – diode





Data: E=3V, R=10kΩ

I_{Dmax} = E/R =3V/10kΩ = 0,3mA (when U_D = 0)

U_{Dmax} = E (when I_D = 0)

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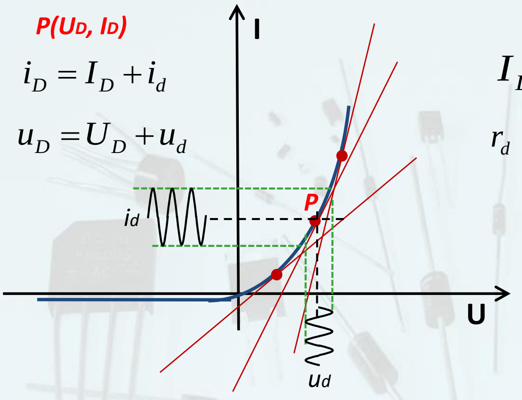
DIODES
DYNAMIC RESISTANCE

P(UD, ID)

$$i_D = I_D + i_d$$

$$u_D = U_D + u_d$$

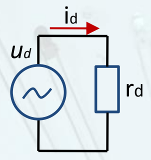


$$I_D = I_S e^{\frac{U_D}{U_T}}$$

U_T – electrothermal potential

$$r_d = \frac{du_D}{di_D} \approx \frac{U_T}{I_D}$$

Small-signal scheme of a diode



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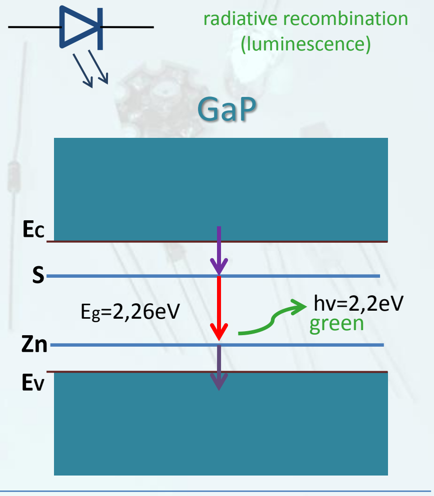
DIODES
LED

III	IV	V
B	C	P
Al	Si	As
Ga	Ge	Sb
In	Sn	

III-V
AlP
AlAs
GaP
GaAs
GaSb

radiative recombination (luminescence)



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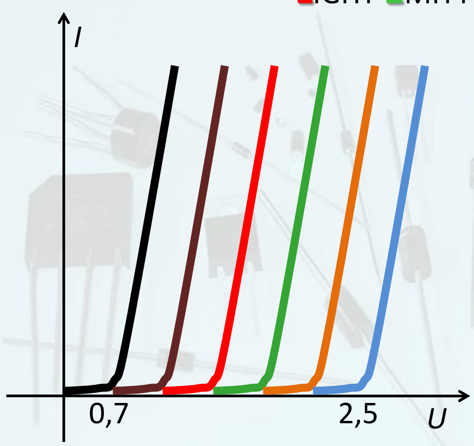
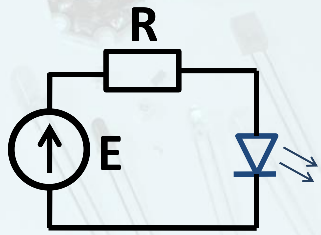
DIODES
LED

LIGHT EMITTING DIODE





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… MORE DETAILS ….

I vs. U characteristic of the P-N junction (real diode)

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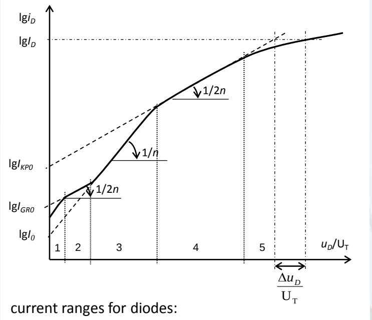
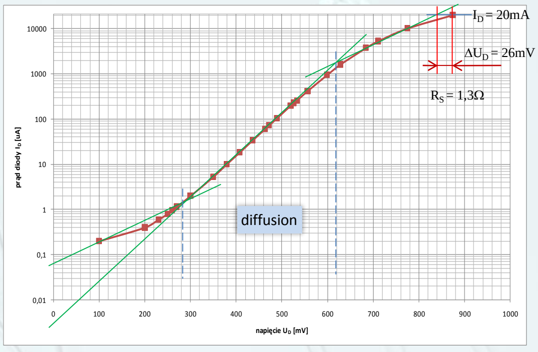
Lab exercise no. 2



current ranges for diodes:
1 - small currents, 2 - recombination, 3 - diffusion,
4 - drift, 5 - ohm

$$i_D = I_{GR0}\left(e^{\frac{u_D - i_D r_S}{2U_T}} - 1\right) + I_0\left(e^{\frac{u_D - i_D r_S}{U_T}} - 1\right)$$



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I_0 – saturation current of minority carriers (I_S)

SEMICONDUCTOR IN A STATE OF THERMODYNAMIC IMBALANCE

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- The law of mass does not apply:

$$np \neq n_i^2$$

- Carrier generation rate is not equal to the recombination rate:

$$G \neq R$$

- Electrical neutrality can be disrupted:

$$\rho = q(N_D - N_A + p_0 - n_0) \neq 0$$

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SEMICONDUCTOR IN A STATE OF THERMODYNAMIC IMBALANCE

INJECTION, EXCTRACTION

- INJECTION – supplying carriers to the semiconductor region: $np > n_i^2$
- EXCTRACTION – removing carriers from the semiconductor region: $np < n_i^2$

Accumulation of carriers:

$$n = n_0 + n', \qquad p = p_0 + p'$$

Carriers concentrations at thermodynamic equilibrium (n_0, p_0)

additional carrier concentration - excess carriers (n', p')

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SEMICONDUCTOR IN A STATE OF THERMODYNAMIC IMBALANCE

INJECTION – introduces imbalance

- Small levels of injection :

$p' << n_n$ injection of holes to **N**

$n' << p_p$ injection of electrons to **P**

small disturbance of equilibrium: $n' \approx p'$

quasi-indifferential *state*

- Large levels of injections:

$$\left.\begin{array}{l} p' \geq n_n \\ n' \geq p_p \end{array}\right\} \Rightarrow \text{internal electric field}$$

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SEMICONDUCTOR IN A STATE OF THERMODYNAMIC IMBALANCE

GENERATION and RECOMBINATION

- GENERATION – transition of an electron from the valence band to the conduction one
- RECOMBINATION –"return" transition of an electron from the conduction band to the valence
  - Direct recombination
  - Indirect recombination: passage through the quantum states in the band gap resulting from defects in the crystal lattice of atoms or other impurities (gold) - generation-recombination centers
  - Surface recombination: passage through the quantum states in the band gap corresponding to surface states – „the edge" of crystal („collapse" in periodicity of the crystal structure)

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SEMICONDUCTOR IN A STATE OF THERMODYNAMIC IMBALANCE

GENERATION and RECOMBINATION – return to the equilibrium

- Equilibrium:

The rate is proportional to the amount of carriers

resultant rate of recombination-generation processes :

$$V_{RG} = R - G_{th}, \quad R = Cnp, \quad G_{th} = Cn_i^2$$ C – recombination coefficient

$$V_{RG} = C(np - n_i^2)$$

- Imbalance:

$$V_{RG} = C(n_0 p' + p_0 n' + n' p')$$ when: $n = n_0 + n', \ p = p_0 + p'$

for a low level of disturbance (injection) we have: $n' << n_0 + p_0$

therefore: $V_{RG} = C(n_0 + p_0)n'$

or otherwise: $V_{RG} = \frac{n'}{\tau}$

τ - ***lifetime of excess carriers***

the average duration of their existence in the semiconductor

$$\tau = \frac{1}{C(n_0 + p_0)}$$ for n: $\tau \approx \frac{1}{CN_A}$ for p: $\tau \approx \frac{1}{CN_D}$

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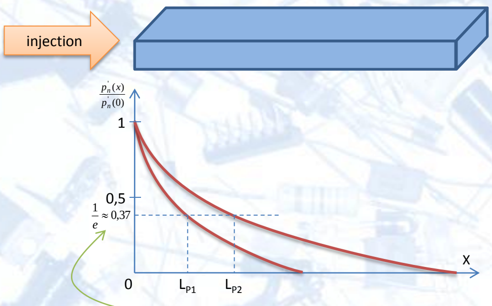
SEMICONDUCTOR IN A STATE OF THERMODYNAMIC IMBALANCE

CARRIERS CONCENTRATION at ESTABLISHED LEVEL of INJECTION or EXTRACTION



Change of the carrier concentration is a result of diffusion :

$$\frac{\partial p_n}{\partial t} = D_p \frac{\partial^2 p_n}{\partial x^2}$$

in a steady state, taking into account recombination, we have :

$$D_p \frac{\partial^2 p_n}{\partial x^2} = \frac{p_n - p_{n0}}{\tau}$$

The solution with the boundary conditions : $p_n(0) = const, \quad p_n(\infty) = p_{n0}$

when injection is considered:

$$p_n'(x) = p_n'(0)\exp(-x/L_p)$$

$L_p = \sqrt{D_p \tau_p}$ ***- diffusion way***

Per analogy, for extraction we have:

$$p_n'(x) = p_n'(\infty)(1-\exp(-x/L_p))$$

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I vs. U characteristic of the P-N junction (going into details)

GENERATION and RECOMBINATION in DEPLETION AREA

for reverse bias

as a result of generation in the depletion layer, the number of minority carriers drifted by the electric field increases – *electrical current under reverse bias increases*

density of generation current: $J_g = qGl_d$

G – rate of generation, l_d – width of depletion layer

$$G = n_i / 2\tau$$

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

After substitution: $J_g = \frac{1}{2} q \frac{n_i}{\tau} \sqrt{\frac{2\varepsilon_s (N_D + N_A)(\varphi_B - U)}{qN_D N_A}}$

for asymmetric junction p^+-n: $N_A >> N_D$ density of saturation current: $J_S \approx q n_i^2 \sqrt{D_p / \tau} \frac{1}{N_D}$

and : $J_g = J_s \frac{1}{2n_i} \sqrt{\frac{2\varepsilon_s}{q} \frac{N_D}{D_p \tau_p} (\varphi_B - U)}$ or: $\frac{J_g}{J_S} = \frac{N_D l_d}{2n_i L_p}$

I vs. U characteristic of the P-N junction (details)

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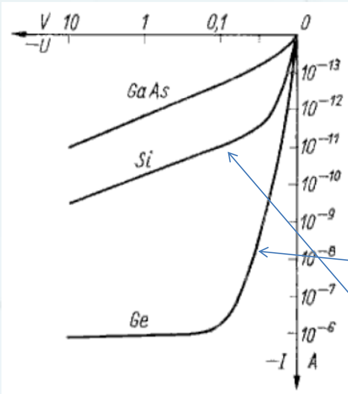
GENERATION and RECOMBINATION in DEPLETION AREA

for reverse bias



Comparison of current-voltage characteristics for reverse bias direction

$$\frac{J_g}{J_S} = \frac{N_D l_d}{2 n_i L_p}$$

The effect of the intrinsic concentration:

$E_g \nearrow$ then $n_i \searrow$ and $J_g/J_S \nearrow$

$$n_i = \sqrt{N_C N_V}\, e^{-\frac{E_g}{2kT}}$$

For *Ge* we can neglect J_g

For *Si* and *GaAs* **we can NOT neglect** J_g

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

I vs. U characteristic of the P-N junction (details)

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GENERATION and RECOMBINATION in DEPLETION AREA

for forward bias

part of majority carriers diffusing through a depletion layer recombine – electrical current in forward direction decreases

density of recombination current: $J_r = qRl_d$

R – rate of recombination , l_d – width of depletion layer

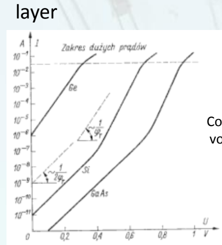
$$R_0 = n_i/2\tau = \sqrt{np}/2\tau$$

$$np = n_i^2 \exp(U/\varphi_T)$$

$$R = \frac{n_i}{2\tau}\exp(U/2\varphi_T)$$

after substitution: $J_r = \frac{1}{2} q \frac{n_i}{\tau} l_d \exp(U/2\varphi_T)$

and: $$\frac{J_r}{J_d} = \frac{1}{2}\frac{N_D}{n_i}\frac{l_d}{L_p}\exp(-U/2\varphi_T)$$



Comparison of current-voltage characteristics for forward bias direction

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

I vs. U characteristic of the P-N junction (details)

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HIGH LEVEL OF INJECTION

Concentration of excess minority carriers becomes comparable to or greater than the dopant concentration in the base of the junction (eg. for p^+-n it is: $p'_n \geq N_D$).

There are also majority carrier concentration inreases – the conductivity modulation in the base appears.

Furthermore, the electric field occurs from the injected charge carriers.

Finally:

$$J \sim \exp(U/2\varphi_T)$$

I vs. U characteristic of the P-N junction (details)

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SERIAL RESISTANCE

With the increase in current (forward bias) we observe an increasing impact of resistance of a semiconductor areas in the immediate vicinity of the junction – ***serial resistance***

therefore:

$$U = U_J + I_D r_s$$

voltage drop over a diode (U)

voltage drop over a junction (U_J)

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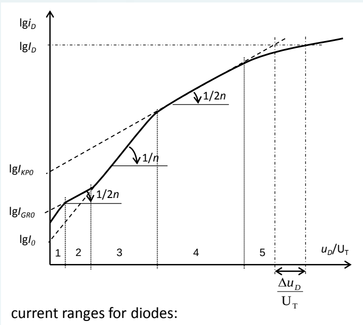
I vs. U characteristic of the P-N junction (real diode)

Lab exercise no. 2



current ranges for diodes:
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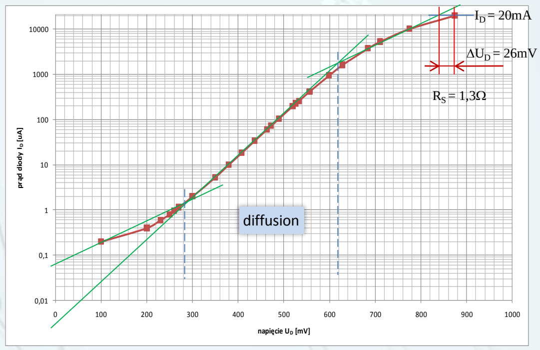
$$i_D = I_{GR0}\left(e^{\frac{u_D - i_D r_S}{2U_T}} - 1\right) + I_0\left(e^{\frac{u_D - i_D r_S}{U_T}} - 1\right)$$



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I_0 – saturation current of minority carriers (I_S)

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VARICAP DIODE AS CAPACITOR

CAPACITANCES IN DIODES
JUNCTION CAPACITANCE

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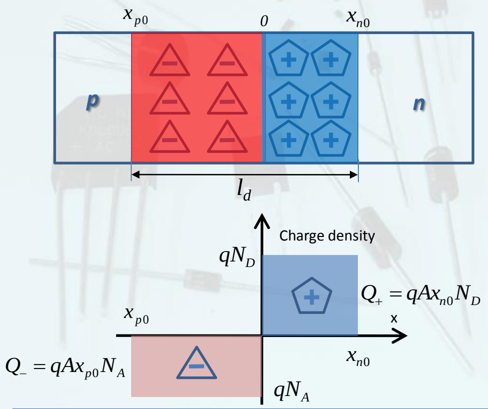
Junction capacitance
is created in the depletion area, therefore it dominates at reverse bias mode



$$l_d = \left[\frac{2\varepsilon\varphi_B}{q}\left(\frac{N_A+N_D}{N_AN_D}\right)\right]^{\frac{1}{2}}$$ *in equilibrium, in the absence of external polarization*

$$l_d = \left[\frac{2\varepsilon(\varphi_B - U)}{q}\left(\frac{N_A+N_D}{N_AN_D}\right)\right]^{\frac{1}{2}}$$ *the polarity of the external voltage U*

$$|Q| = qAx_{n0}N_D = qAx_{p0}N_A$$

$$x_{n0} = \frac{N_A}{N_A+N_D}l_d \qquad x_{p0} = \frac{N_D}{N_A+N_D}l_d$$

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l_d – width of depletion area
A – cross-section area of the junction

CAPACITANCES IN DIODES
JUNCTION CAPACITANCE

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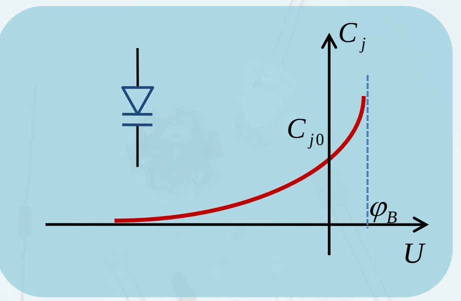
$$|Q| = qA\frac{N_AN_D}{N_A+N_D}l_d = A\left[2\varepsilon(\varphi_B - U)\frac{N_AN_D}{N_A+N_D}\right]^{\frac{1}{2}}$$

$$C = \left|\frac{dQ}{du}\right|$$

$$C_j = \left|\frac{dQ}{d(\varphi_B - U)}\right| = \frac{A}{2}\left[\frac{2q\varepsilon}{(\varphi_B - U)}\frac{N_AN_D}{N_A+N_D}\right]^{\frac{1}{2}}$$

$$C_j = \frac{\varepsilon A}{l_d}$$

How do we know it?



For junction (p^+-n) $N_A >> N_D$, therefore $x_{n0} \approx l_d$, $x_{p0} \approx 0$, then:

$$C_j = \frac{A}{2}\left[\frac{2q\varepsilon}{(\varphi_B - U)}N_D\right]^{\frac{1}{2}}$$

$$C_j(U) = \frac{C_{j0}}{\left(1 - \frac{U}{\varphi_B}\right)^m}$$

$m = \frac{1}{2}$ *for abrupt junctions*

$m = \frac{1}{3}$ *for linear junctions*

***conclusion:** by measuring the capacitance of the junction, we can determine the concentration of the less-doped region*

CAPACITANCES IN DIODES
DIFFUSION CAPACITANCE

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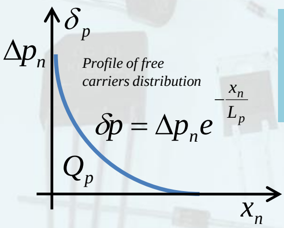
Diffusion capacitance

it appears when the junction is forward biased, it results from a voltage delay against current

Let's assume junction (p⁺-n), so: $N_A >> N_D$*, therefore* $x_{n0} \approx l_d$, $x_{p0} \approx 0$



$$Q_p = qA\int_0^{\infty} \delta p(x_n)dx_n$$

The entire distribution profile of free carriers is renewed by injecting charges by the flowing current. Otherwise, this distribution profile would disappear as a result of recombination after the period τ_p *– the mean lifetime of holes in n-type material.*

$$Q_p = Q_D = I_D \cdot \tau_p$$

$$C_d = \frac{dQ_D}{dU_D} = \tau_p \frac{dI_D}{dU_D} = \tau_p \frac{I_D}{U_T}$$

How do we know it?

CAPACITANCES IN DIODES

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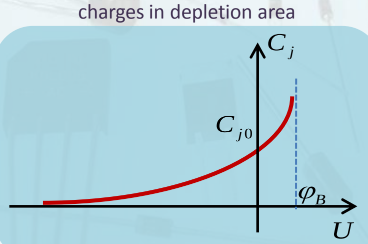
polarization

reverse	**forward**
Junction capacitance prevails $C_j > C_d$ It is related to accumulation of charges in depletion area	Diffusion capacitance prevails $C_d >> C_j$ It is related to the current flowing through the junction



$$C_j(U) = \frac{C_{j0}}{\left(1 - \frac{U}{\varphi_B}\right)^m}$$

$$C_d = \frac{dQ_D}{dU_D} = \tau_p \frac{dI_D}{dU_D} = \tau_p \frac{I_D}{U_T}$$

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DIODE MODELS

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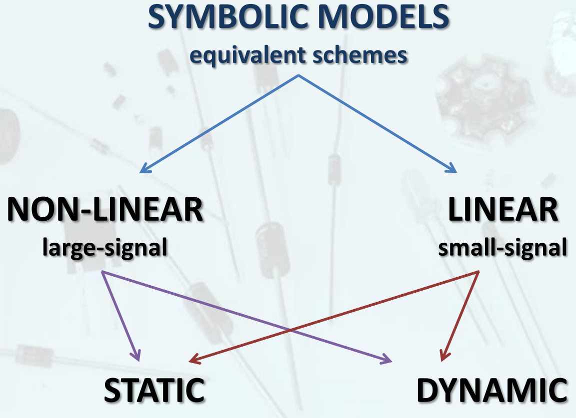
DIODE MODELS



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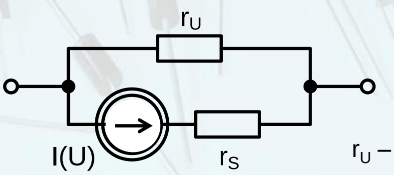
DIODE MODELS
LARGE-SIGNAL MODEL, STATIC

Shockley's formula: $$I_D(U_D) = I_S\left(e^{\frac{U_D}{\varphi_T}} - 1 \right)$$

or: $$I_D(U_D) = I_{GR0}\left(e^{\frac{U_D - I_D r_S}{2U_T}} - 1 \right) + I_S\left(e^{\frac{U_D - I_D r_S}{U_T}} - 1 \right)$$

It is NON-LINEAR relationship between current and voltage



Controlled current source
(according to the equations above-mentioned)

r_U – leakage resistance
(for reverse bias)

r_S – series resistance

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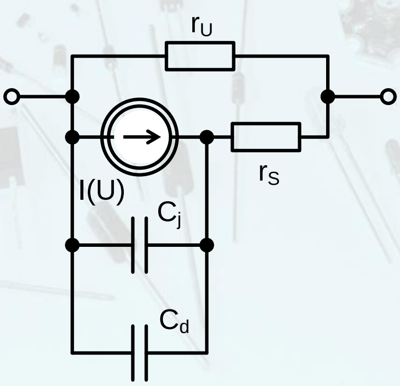
DIODE MODELS
LARGE-SIGNAL MODEL, DYNAMIC

dynamic phenomena are represented by:
junction capacitance C_j and diffusion capacitance C_d



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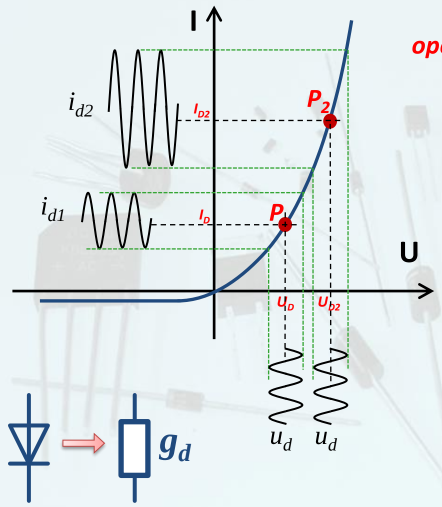
DIODE

CONTROLLED CONDUCTANCE



operating point $P(U_D, I_D)$

$$i_D = I_D + i_d$$

$$u_D = U_D + u_d$$

constant component

variable component

$$g_d = \frac{\Delta i_D}{\Delta u_D} = \frac{i_d}{u_d}$$

$$g_{d1} = \frac{i_{d1}}{u_d} \qquad g_{d2} = \frac{i_{d2}}{u_d}$$

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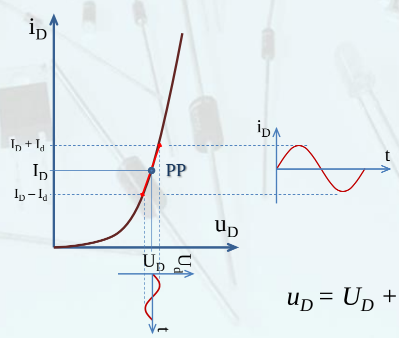
DIODE MODELS

SMALL-SIGNAL MODEL, LINEAR

NOTE:

if the voltage and diode current are small then NON-LINEAR characteristic can be

LINEARIZED locally arround the operation point



$$u_D = U_D + U_d \sin(\varpi t)$$

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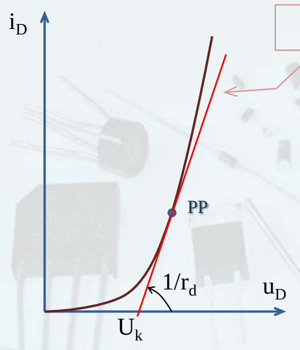
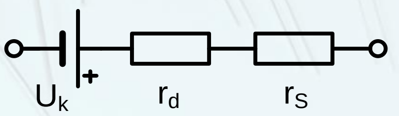
DIODE MODELS
SMALL-SIGNAL MODEL, LINEAR



$$i_D = I_S\left(e^{\frac{u_D}{n\varphi_T}} - 1 \right)$$

$$r_d \equiv \left.\frac{du_D}{di_D}\right|_{(U_D, I_D)} = \frac{n\varphi_T}{I_D + I_S} \approx \frac{n\varphi_T}{I_D}$$

usually $n = 1$ and $r_d = \dfrac{\varphi_T}{I_D}$



model for forward bias

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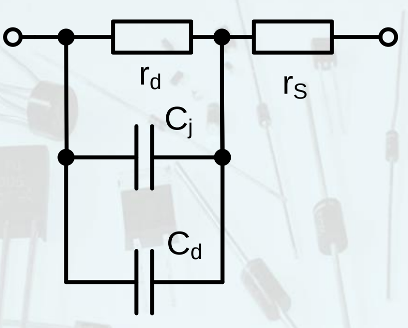
DIODE MODELS
SMALL-SIGNAL MODEL, DYNAMIC



r_d – dynamic resistance
r_S – series resistance
C_j – junction capacitance
C_d – diffusion capacitance

limiting pulsation

$$\varpi_{gr} = \frac{1}{r_S C_j}$$

occurs when the voltage drop across the junction is comparable with the voltage drop on the series resistance (r_S)

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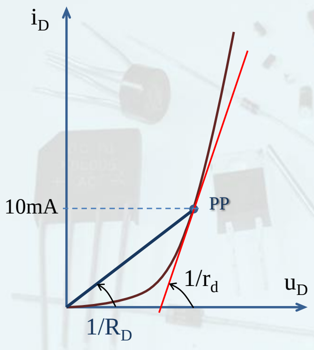
DIODE MODELS
SMALL-SIGNAL MODEL, LINEAR (EXAMPLE)

A silicon diode operates at a current I_D = 10mA. Calculate the static and dynamic resistances.



Static resistance: $R_D = \frac{U_D}{I_D}$

Dynamic resistance: $r_d = \frac{\varphi_T}{I_D}$

For a silicon diode we can assume U_D = 0,6V and electrothermal potential 26mV for T=300K.
therefore: R_D = 0,6V/10mA = 60Ω,
r_d = 26mV/10mA = 2,6 Ω.

How would the R_D/r_d look like against U_D ?

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JUNCTION BREKADOWN

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BREAKDOWN of *p-n* JUNCTION

The sudden rise in current above a certain voltage of reverse biased junction

- ***Zener breakdown***
- ***Avalanche breakdown***
- *Thermal breakdown*

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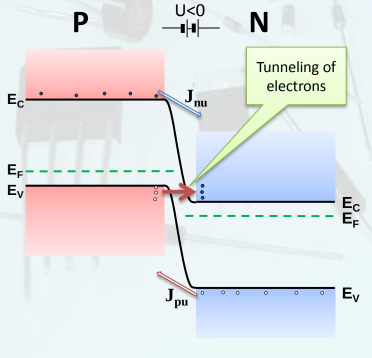
ZENER BREAKDOWN

The electric field in the thin depletion layer can break the covalent bond of atoms of the crystal lattice

electrostatic ionization – *internal emission (Zener effect).*



$$l_d = \sqrt{\frac{2\varepsilon_s(\varphi_B - U)}{qN_D}}$$ p^+-n: $N_A >> N_D$

increase in the concentration of dopants - the narrower the depletion layer

smaller width of the potential barrier - easier tunneling of carriers

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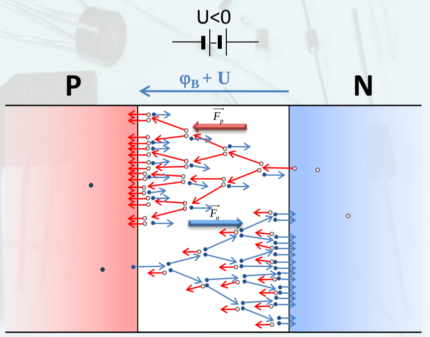
AVALANCHE BREAKDOWN

The strong electric field accelerates the free carriers to the speed allowing the breakage of covalent bonds in the lattice – **collision ionization** – *avalanche multiplication.*



The intensity of the electric field has to be of the order 10^6V/cm

Coefficient of avalanche multiplication:

$$M = \frac{1}{1-\left(\frac{U}{U_{BR}}\right)^m}$$

U_{BR} – breakdown voltage
m – for Si: 2…6

Current density: $J = J_0 M$

J_0 – current density before breakdown

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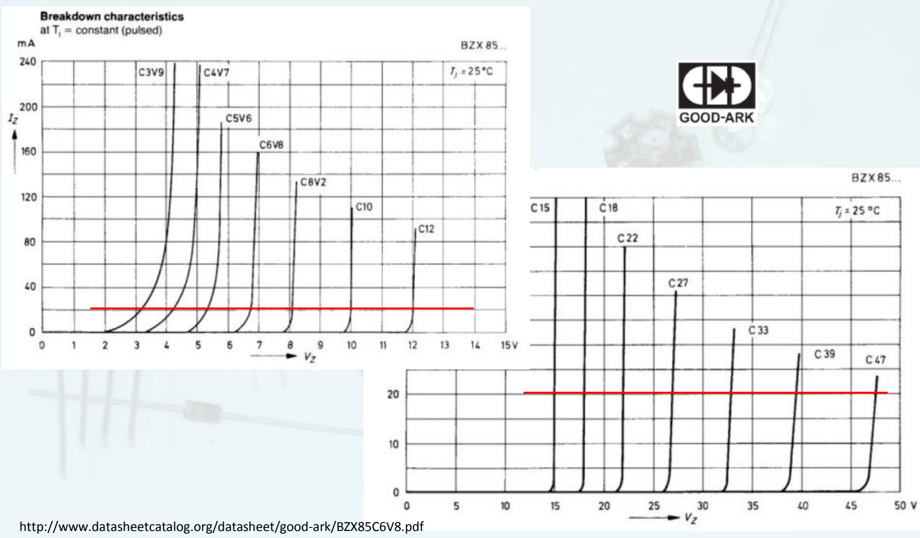
STABILIZING DIODE
dynamic resistance



GOOD-ARK

http://www.datasheetcatalog.org/datasheet/good-ark/BZX85C6V8.pdf

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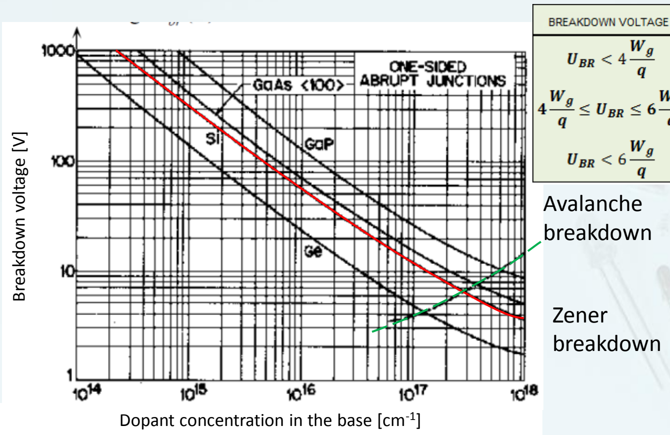
BREAKDOWN of *p-n* JUNCTION



BREAKDOWN VOLTAGE	FOR SILICON	KIND OF BREAKDOWN
$U_{BR} < 4\frac{W_g}{q}$	$U_{BR} < 5V$	ZENER
$4\frac{W_g}{q} \leq U_{BR} \leq 6\frac{W_g}{q}$	$5V < U_{BR} < 7V$	ZENER / AVALANCHE
$U_{BR} < 6\frac{W_g}{q}$	$U_{BR} > 7V$	AVALANCHE

Source: Figure 26 in *Physics of Semiconductor Devices, Second Edition,* S.M. Sze, John Wiley and Sons, New York, 1981, p.101

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STABILIZING DIODE

It uses reversible breakdown of the junction (Zener and / or avalanche)

Parameters:

- Stabilizing voltage U_Z (called Zener voltage)
- Temperature coefficient of voltage stabilization
- Dynamic resistance r_z
- Maximum power dissipation P_{max}
- thermal resistance R_{th}
- maximum junction temperature T_{jmax}

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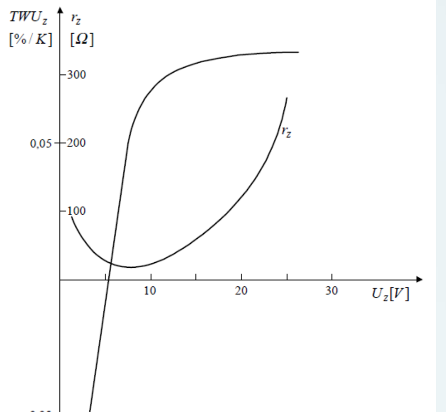
STABILIZING DIODE
dynamic resistance

$$r_Z = \left.\frac{\Delta U_Z}{\Delta I_Z}\right|_{(U_Z, I_Z)}$$

Specifies the stabilizing properties of Zener diodes - the slope of the characteristic breakdown region



The relationship of TWUZ and the dynamic resistance against breakdown voltage

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

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STABILIZING DIODE
permissible power dissipation P_{max}

P_{max} determines the maximum power that can be dissipated in the diode at a specified temperature.

Usually, in datasheets, it is quoted at ambient temperature T_{amb}=25°C

$$P_{\max} = \frac{T_{j\max} - T_{amb}}{R_{th}}$$

Exceeding the maximum power of the junction most commonly causes destruction of a diode resulting from overheating

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INFLUENCE OF TEMPERATURE ON JUNCTIONS

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THERMAL BREAKDOWN

higher temperature increases the reverse current in junction

↓

heating and further increase in current

↓ **positive feedback**

destruction of junction resulting from overheating

I vs U CHARACTERISTIC
INFLUENCE OF TEMPERATURE

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Reverse bias

- Temperature coefficient of reverse saturation current of minority carriers : $TWI_0 \equiv \frac{1}{I_0}\frac{dI_0}{dT} = \frac{d}{dT}(\ln I_0)$

$$n_i^2 = AT^3 \exp(-E_{g0}/kT) \qquad TWI_0 = \frac{d}{dT}\left(\ln A + 3\ln T - \frac{E_{g0}}{kT}\right) = \frac{1}{T}\left(3 + \frac{E_{g0}}{kT}\right)$$

For silicon E_g=1,21eV at T=300K we get: $TWI_0 \approx 15$ %/K

- Temperature coefficient of generation-recombination current:

$$TWI_{GR0} = \frac{1}{2T}\left(3 + \frac{E_{g0}}{kT}\right)$$

For silicon E_g=1,21eV at T=300K we get : $TWI_{GR0} \approx 7{,}5$ %/K

The relative change of total reverse current usually is not more than 9 %/K

For every 10K reverse current doubles

I vs U CHARACTERISTIC
INFLUENCE OF TEMPERATURE

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Forward bias

Diffusion current range, when $n \approx 1$ ($U_D = U_F$), then: $I_D \cong I_0 \exp\left(\frac{U_F}{nU_T}\right) \approx I_0 \exp\left(\frac{qU_F}{kT}\right)$

therefore: $TWI_D = TWI_0 + \frac{U_F}{U_T}\left(\frac{dU_F}{U_F dT} - \frac{dU_T}{U_T dT}\right) = TWI_0 + \frac{U_F}{U_T}\left(TWU_F - \frac{1}{T}\right)$

Temperature coefficient of forward voltage

$$TWU_F \equiv \frac{dU_F}{U_F dT}$$

$$\left.\frac{dU_F}{dt}\right|_{I_D = const} = -\left(\frac{3nk}{q} + \frac{U_{g0} - U_F}{T}\right) \approx -2mV/K$$

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Diode as thermometer

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INFLUENCE OF TEMPERATURE ON BREAKDOWN VOLTAGE

- Zener breakdown

$$T \nearrow \Rightarrow E_g \searrow \Rightarrow I_{tunneling} \nearrow$$

- Avalanche breakdown

$$T \nearrow \Rightarrow \text{vibration amplitude of atoms} \nearrow$$

$$\text{the probability of collisions} \nearrow$$

$$\text{free path} \searrow \Rightarrow \text{kinetic energy of the carriers} \searrow$$

$$\text{avalanche multiplication} \searrow \Rightarrow I_{avalanche} \searrow$$

INFLUENCE OF TEMPERATURE ON BREAKDOWN VOLTAGE

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Temperature coefficient of breakdown voltage

$$TWU_Z = \frac{1}{U_Z}\frac{\Delta U_Z}{\Delta T}$$

defines the relative change in the breakdown against temperature

INFLUENCE OF TEMPERATURE ON BREAKDOWN VOLTAGE

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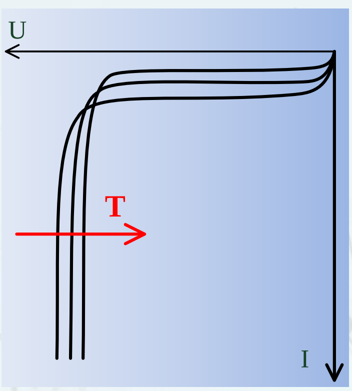
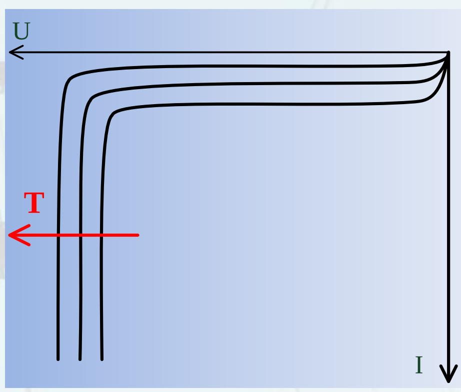
Zener breakdown



Avalanche breakdown



$TWU_Z < 0$

$TWU_Z > 0$

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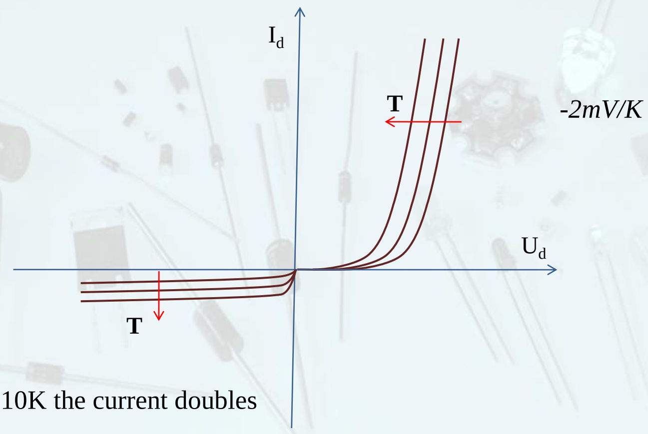
I vs U CHARACTERISTIC
INFLUENCE OF TEMPERATURE



for each 10K the current doubles

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TUNNELING DIODE

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TUNNELING DIODE

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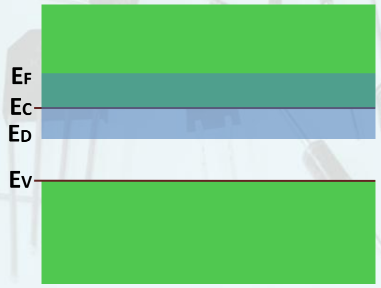
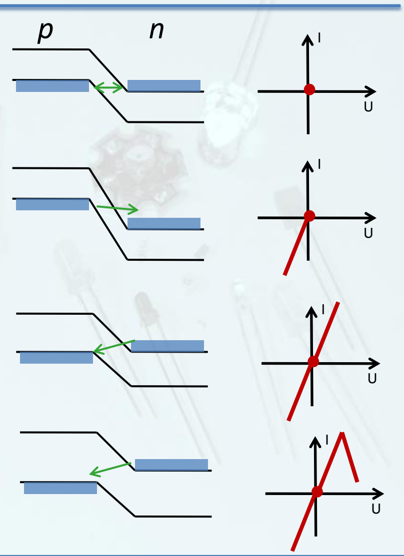
Tunneling diode is created by a junction formed with two „degenerate" semiconductors $p^{++}n^{++}$. Degenerate semiconductor is one in which the dopant concentration level is approaching the atom concentration of the material.





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TUNNELING DIODE

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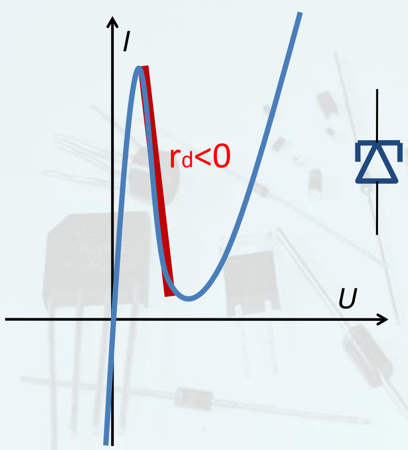

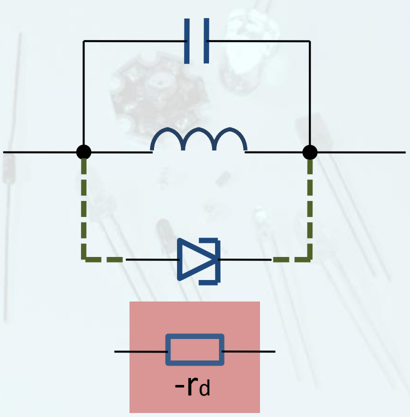

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APPLICATIONS OF DIODES

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DIODES IN ELECTRONIC CIRCUITS

SIGNAL FORMING CIRCUITS

PEAK DETECTOR

DIODE GATES

VOLTAGE CLIPPER

RECTIFIERS

CHARGE PUMPS

VOLTAGE MULTIPLIER

APPLICATIONS OF DIODES

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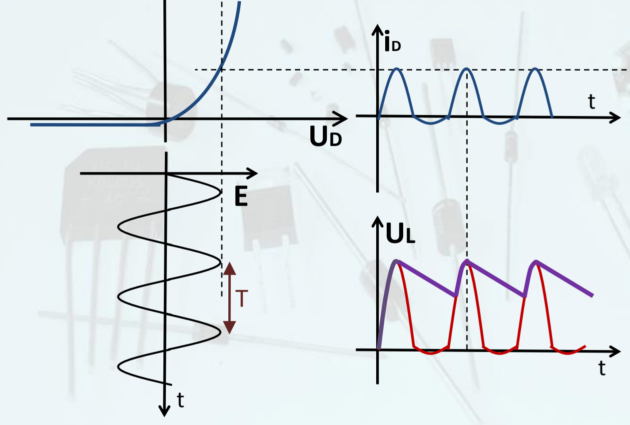
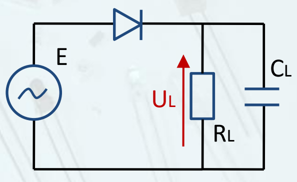
SIMPLE RECTIFIER

Low ripple amplitude:
When following condition is fulfilled : $R_L C_L >> T$





APPLICATIONS OF DIODES

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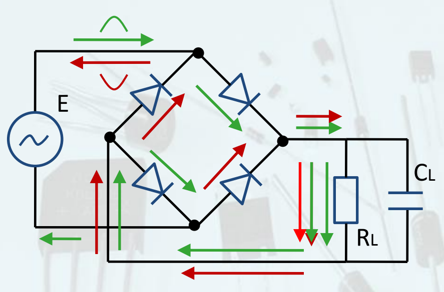
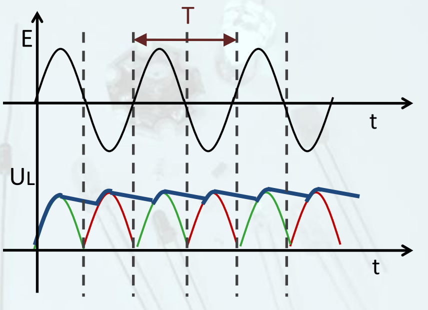
FULL-WAVE RECTIFIER





APPLICATIONS OF DIODES

SIGNAL FORMING CIRCUIT

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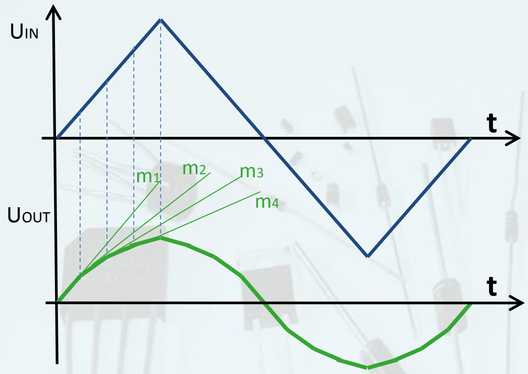

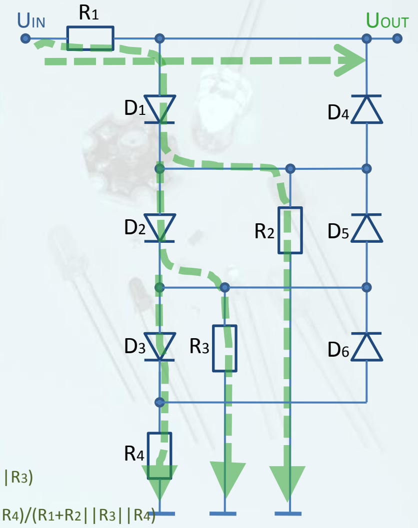

m1: current flows through (R1) → m1=1

m2: current flows through (R1, D1, R2) → m2=(R2)/(R1+R2)

m3: current flows through (R1, D1, D2, R2, R3) → m3=(R2||R3)/(R1+R2||R3)

m4: current flows through (R1, D1, D2, D3, R2, R3, R4) → m4=(R2||R3||R4)/(R1+R2||R3||R4)

APPLICATIONS OF DIODES

VOLTAGE CLIPPER

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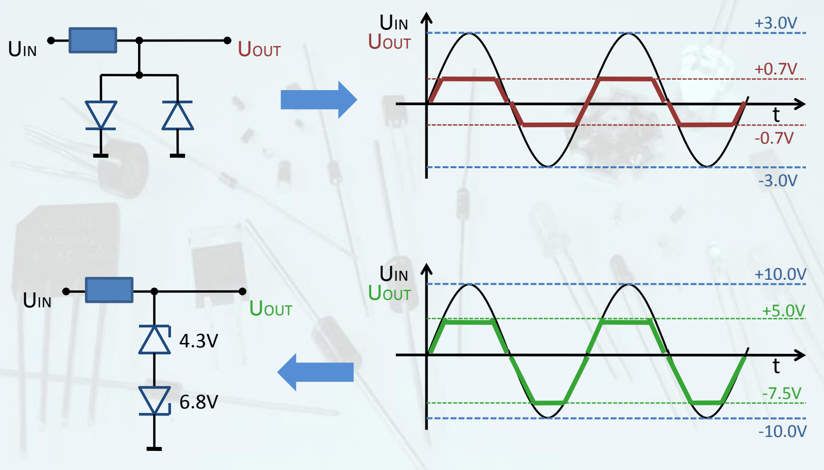

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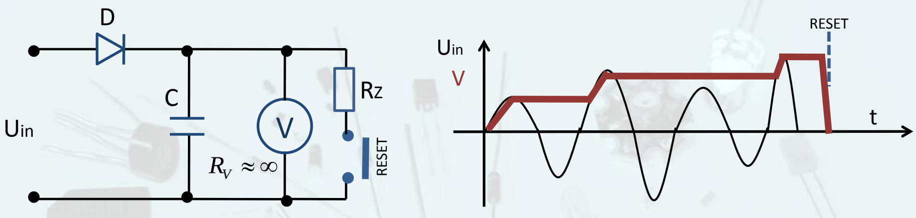
APPLICATIONS OF DIODES
PEAK DETECTOR



By means of peak detector DC voltmeter can measure amplitude of variable waveforms.

Capacitor C is charged via a diode, a large voltmeter internal resistance prevents its rapid discharge. Short-circuit with RESET button discharges capacitor with very small time constant $\tau=R_Z C$ thus, new measurements can be taken.

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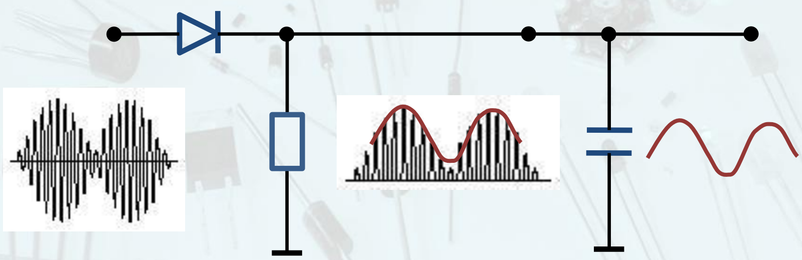
APPLICATIONS OF DIODES
AM DEMODULATION



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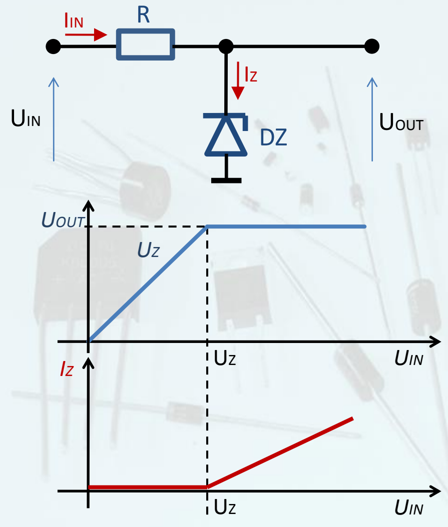
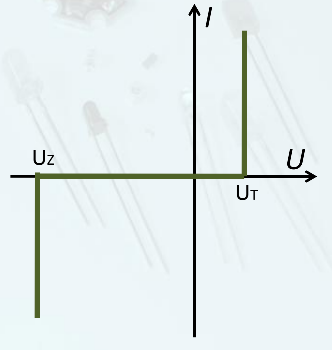
APPLICATIONS OF DIODES

PARAMETRIC VOLTAGE REGULATOR

Parametric voltage regulator without a load



Ideal characteristic of a Zener diode



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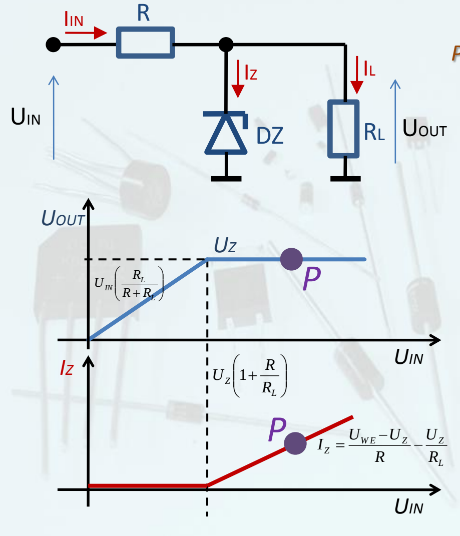
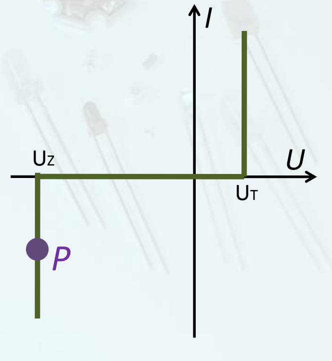
APPLICATIONS OF DIODES

PARAMETRIC VOLTAGE REGULATOR

Parametric voltage regulator with a load



Ideal characteristic of a Zener diode



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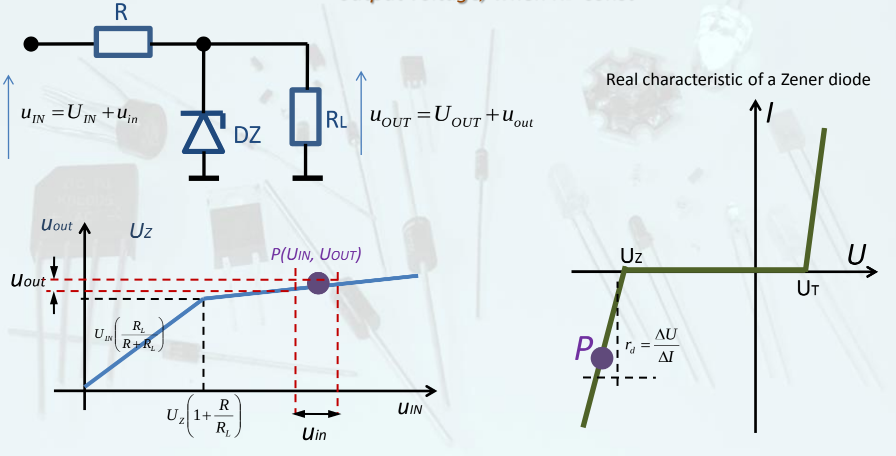
APPLICATIONS OF DIODES
PARAMETRIC VOLTAGE REGULATOR

Effect of changes in input voltage to the output voltage, when R_L=const



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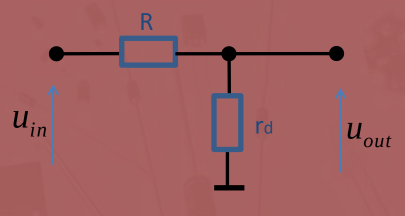
APPLICATIONS OF DIODES
PARAMETRIC VOLTAGE REGULATOR

Effect of changes in input voltage to the output voltage



$$u_{out} = \frac{r_d}{r_d + R} \cdot u_{in}$$

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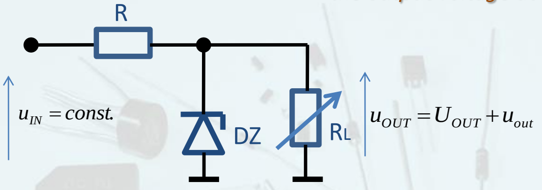
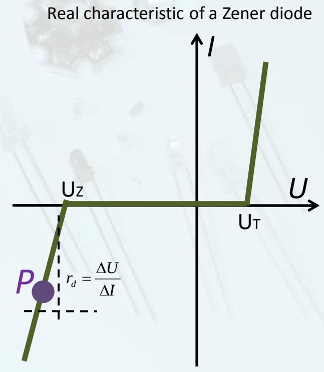
APPLICATIONS OF DIODES
PARAMETRIC VOLTAGE REGULATOR

Effect of changes in load resistance R_L on the output voltage at U_{WE}=const.





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METAL-SEMICONDUCTOR JUNCTION

Combination of the silicon die with the element terminals (leads)

it should be

- low resistance
- not influencing on DC I vs U characteristic

it is

- in some cases there may appear a junction

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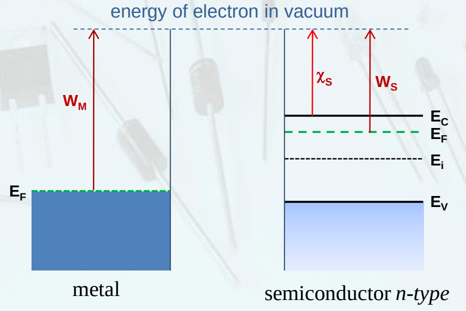
M-S JUNCTION

(METAL-SEMICONDUCTOR)

- Work function W – the energy required to transfer an electron from the Fermi level to infinity (W_∞ - W_F)
- Electron affinity χ - the work function from the minimum energy level in the conduction band E_C



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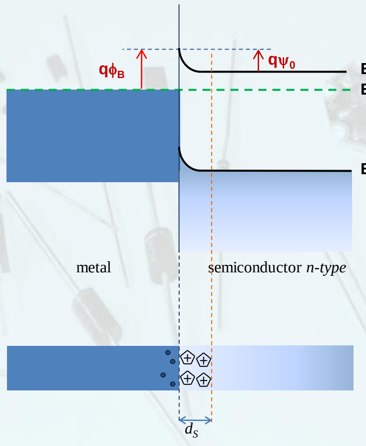
M-S JUNCTION

ϕ_B – barrier potential

ψ_0 – contact potential



From Poissona eq.

$$d_S = \sqrt{\frac{2\varepsilon_S \psi_0}{qN_D}}$$

Rectifying junction – Schottky diode

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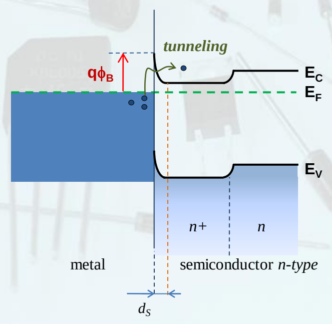
M-S JUNCTION

In case of external polarization U:

$$d_S = \sqrt{\frac{2\varepsilon_S(\psi_0 - U)}{qN_D}}$$



$$N_D \nearrow \Rightarrow d_S \searrow$$

tunneling can occur - the loss of rectifying properties

to make the ohmic contact, there must be sufficient dopants concentration

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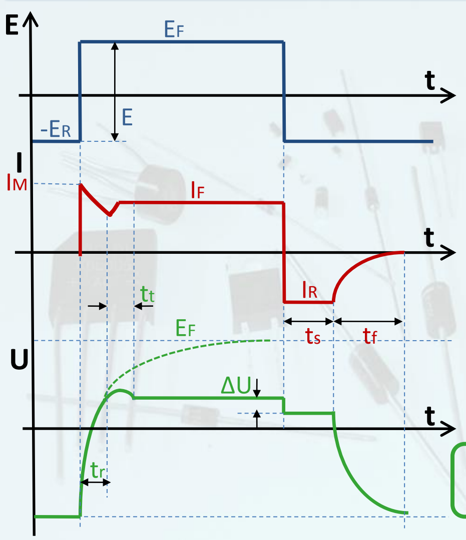
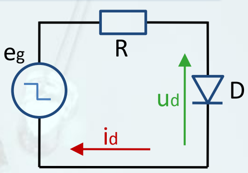
SWITCHING THE DIODE

DYNAMIC EFFECTS



„current" switching:

$R >> r_d + r_s$



$$I_M = \frac{E_F + E_R}{R}$$

$$t_r = RC_j \ln\frac{E}{E_F - 0.7V} \approx RC_j \ln 2 = 0.69\,RC_j$$

If E_F>>0.7V and E_F=E_R

rise time

$t_r = 1{,}58\,RC_{j0}$ for m=1/2 $t_r = 1{,}125\,RC_{j0}$ for m=1/3

$$I_F = \frac{E_F - 0.7V}{R + r_d} \approx \frac{E_F - 0.7V}{R}$$

$$I_R = \frac{-E_R + 0.7V}{R}$$

$$\Delta U = r_s(I_F + I_R)$$

$$t_s = t_t \ln\left(1 + \frac{I_F}{I_R}\right)$$

storage time

$$t_{off} = t_s + t_f$$

$$t_f = 2.2RC_j$$

falling time