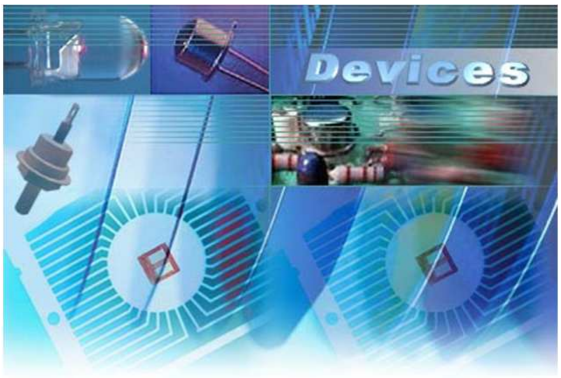
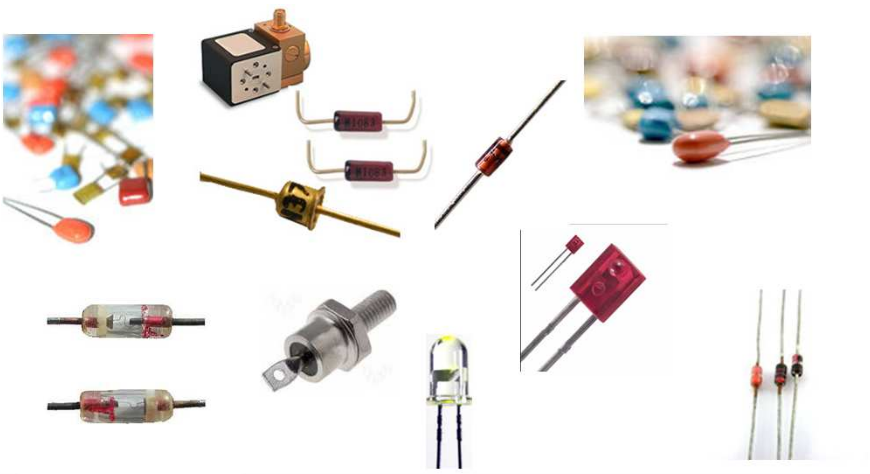
PN Junction Diode

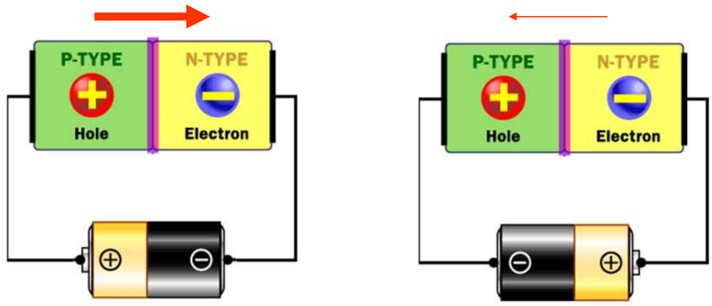


Semiconductor Elements

Diode Cases



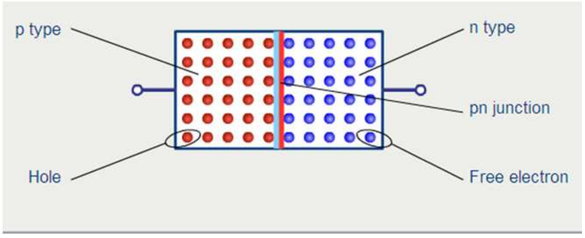
Basic Diode Feature



The essential feature of a diode is that the magnitude of the current greatly depends on the **polarity of applied voltage**.

Basicaly the diode conducts current in **only one direction**. It is applied in rectifiers for converting an alternating current into a dirrect current.

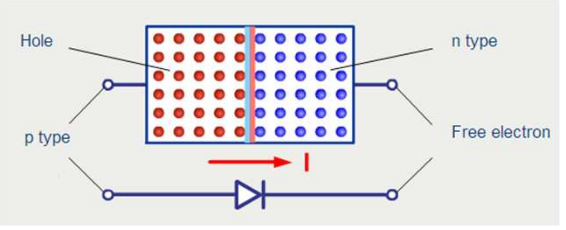
PN Junction Diode Structure



An ideal diode can only conduct current in one direction.

Diode specific electrical properties depends on it's structure.

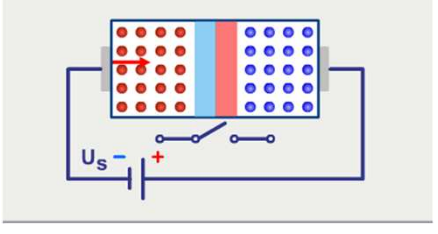
Junction Diode Schematic Symbol

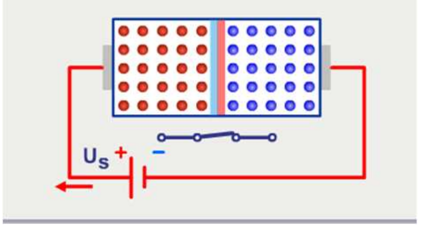


A diode is a nonlinear semiconductor device with two electrodes: an anode and a cathode.

An arrow points from the anode to the cathode to remind that the current will only flow easily in this direction.

Diode's Mode of Operation

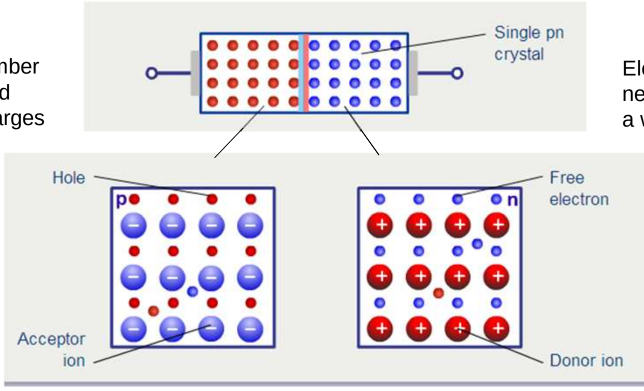




A diode's mode of operation depends on the various conditions possible at the pn junction. They are caused by the polarity of the applied voltage.

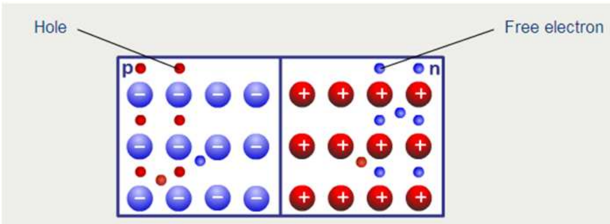
Unibiased Diode

Equal number of plus and minus charges



Electrically neutral as a whole

PN Junction Formation

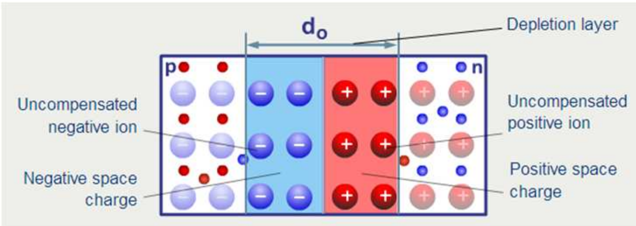


Majority carriers – free electrons and holes, diffuse (spread) across the junction because difference in concentration in both side of the crystal.

Unlike the free carriers, the ions will never move. They remains fixed due to their covalent bonds in the crystal structure.

Depletion Layer

almost completely depleted of mobile charge carriers

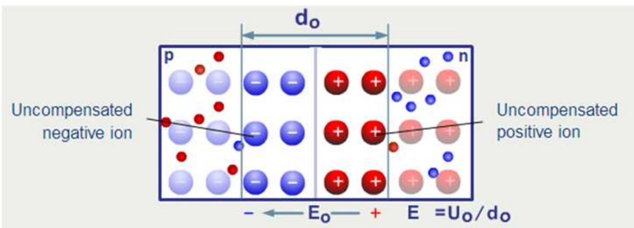


When an electron leaves the *n* side, it will leave behind an uncompensated positive ion. A positive space charge is created to the right of the junction in the *n*-region.

Similarly a negative space charge will be created to the left of the junction in the *p*-region.

Barrier Potential & Electric Field

Diffusion current I_D → I_D *Majority carriers*

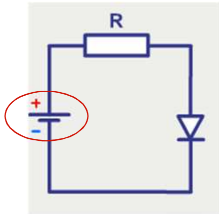


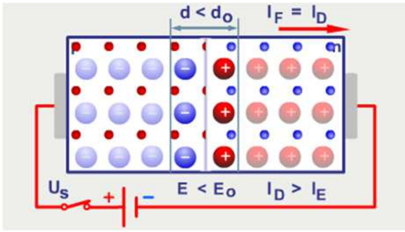
Drift current I_E ← I_E *Minority carriers*

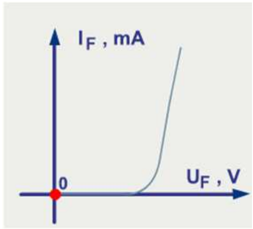
The uncompensated positively- and negatively-charged ions that are within the depletion layer generate an **electric field E_o** the **barrier potential U_o**.

At room temperature (25 ºC) the barrier potential has for Si diodes a voltage of approximately 0.7V and for Ge diodes a voltage of about 0.3V.

Forward Bias





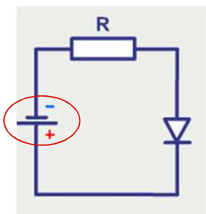


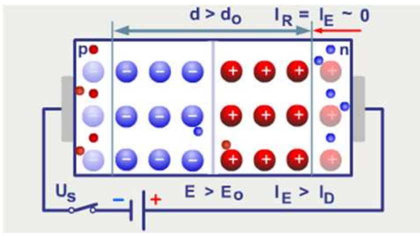
The barrier potential will reduce to U_o - U_s and the electric field to $E < E_o$.

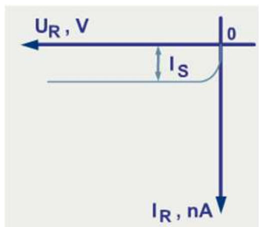
A forward current is always composed of majority carriers whose energies are sufficient to overcome the barrier potential.

Current will easily flow in forward-biased diode.

Reverse Bias



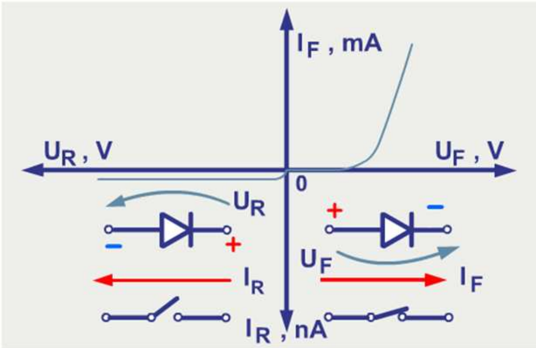




The barrier potential will increase to U_o + U_s and the electric field to $E > E_o$.
The diffusion of majority carriers across the junction has been greatly diminished.

A very small reverse current I_R, composed of thermally produced minority carriers still cross the junction. This makes the reverse current I_R independent from the direction of the voltage polarity and of the barrier potential.

VA Characteristic



A diode is a **nonlinear** device. It conducts in **only one direction**.
An ideal diode functions like a switch – open and closed.

In forward-biased diode, the current increases very rapidly with *U*.
The reverse current is very small.

Ideal Diode Equation

$$I = I_s(e^{\frac{U}{\varphi_T}} - 1)$$

$$I_s = SJ_s$$

I_S - Saturation current

J_S - Current density

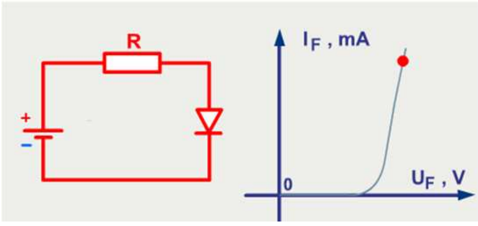
S - Junction area

φ_T - Thermal potential

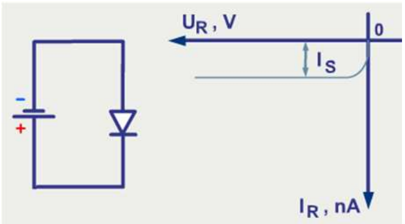
$$\varphi_T = \frac{kT}{q} \qquad \varphi_T = \frac{T(K)}{11600} \qquad \varphi_T = 0.0258 \text{ V } \textit{for } T = 25\ ^oC$$

$$U = \varphi_T \ln\left(\frac{I}{I_S} + 1\right)$$

Ideal Diode Equation



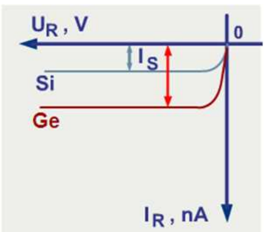
$$I = I_s e^{\frac{U}{\varphi_T}}$$

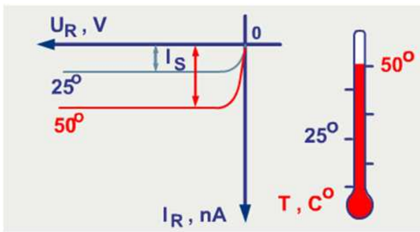


$$I = -I_s$$

Saturation Current

$$I_s = f(\Delta W, T, S)$$





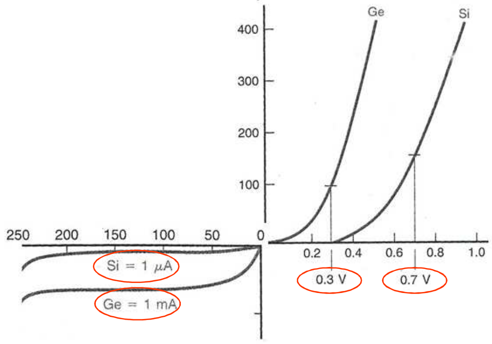
A *Si* diode has a much smaller I_S than a *Ge* diode.

There are fewer minority carriers in *Si* diodes than in *Ge* diodes.

I_S doubles with every *10°C* increase.

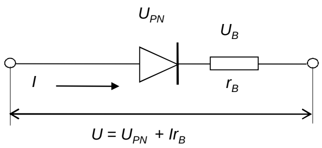
Because the reverse current is caused by thermally created minority carriers, it will also be highly sensitive to temperature changes.

VA Characteristics of Si and Ge Diode

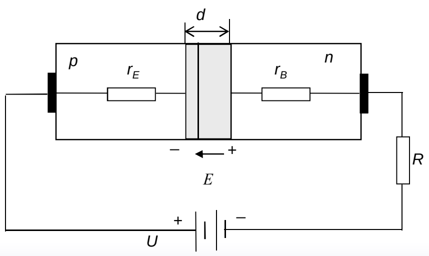


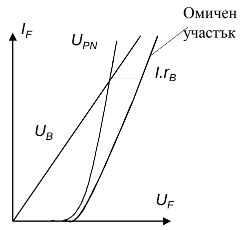
Real Diode – Forward Region

Recombination current, base ohmic resistance r_B, $r_B = f(I)$ are considered.



$$I = I_S\left(e^{\frac{U - Ir_B}{m\varphi_T}}\right)$$



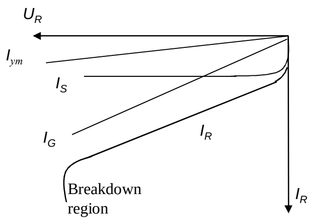


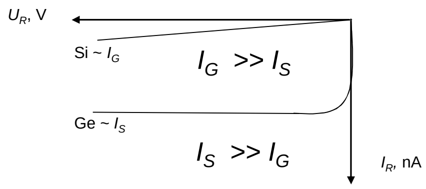
Real Diode – Reverse Region

Generation current, leakage current and breakdown are considered.

$$I_R = I_S + I_G + I_{ym} + I_{BR}$$

$I_G \approx \sqrt{U}$





Si diode $I_R = I_S + I_{ym}$ $(I_G >> I_S)$,

Ge diode $I_R = I_G + I_{ym}$ $(I_S >> I_G)$

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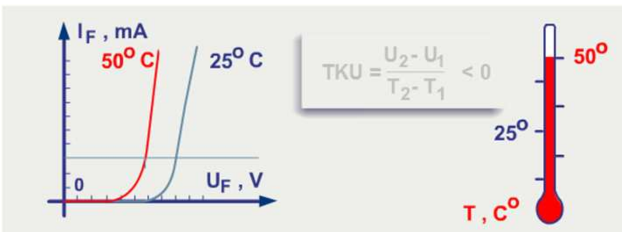
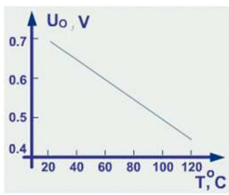
Forward Voltage and Temperature



$$TKU_F = \frac{dU}{dT} \approx \frac{\Delta U}{\Delta T}\Big| I = const$$



$TKU_F \approx -2$ mV/ °C

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Diode Ratings

- Max junction temperature $T_{jmax} < T_i$, where $n=p=n_i$
- Max power P_{jmax}

$P = UI$ Power dissipated in diode

$$P = \frac{T_j - T_a}{R_{th}}$$

Power conducted into the ambient surroundings

$$UI = \frac{T_j - T_a}{R_{th}}$$

$$P_{\max} = \frac{T_{i\max} - T_a}{R_{th}}$$

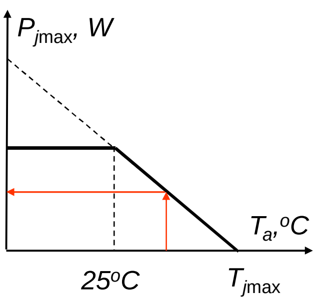
$$P_{\max} = -\frac{1}{R_{th}} T_a + \frac{1}{R_{th}} T_{j\max}$$

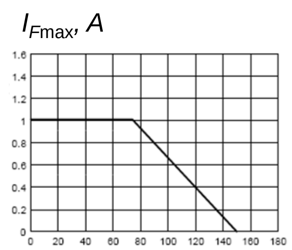
Max Power & Max Current

$$P_{\max} = -\frac{1}{R_{th}} T_a + \frac{1}{R_{th}} T_{j\max}$$

$$U_F I_{F\max} = P_{\max} = \frac{T_{j\max} - T_a}{R_{th}}$$

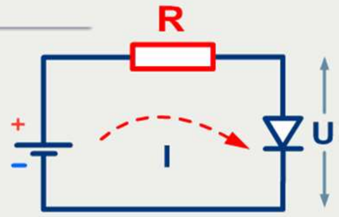
$$\frac{T_{j\max}}{R_{th}}$$





Current-Limiting Resistor

$$I = \frac{E - U_F}{R} < I_{F\max}$$



The **current-limiting resistor** has the function to keep the diode current **smaller than the maximum rating**.

Heat Removal

R_{th} indicates efficiency in removing heat from the transistor in units °*K*/*W*.

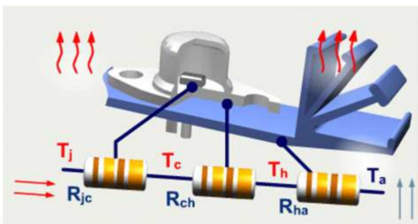
$$R_{th} = R_{th_{jc}} + R_{th_{ca}} \qquad R_{th_{ca}} >> R_{th_{jc}}$$

The **less thermal resistance** the **higher power rating**.

Thermal energy can be easily reduced through conduction and radiation from the device's case.

$$R_{th} = R_{th_{jc}} + R_{th_{ch}} + R_{th_{ha}}$$

Heat sink



Reverse Breakdown

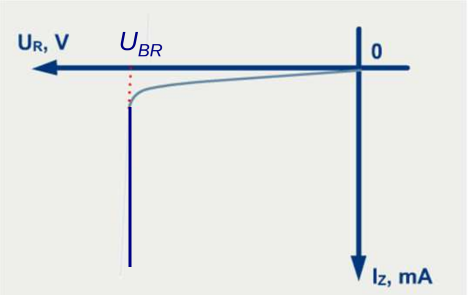
At a **reverse breakdown voltage** U_{BR}, the current will rapidly increase with only small changes in the voltage.

Thermal breakdown

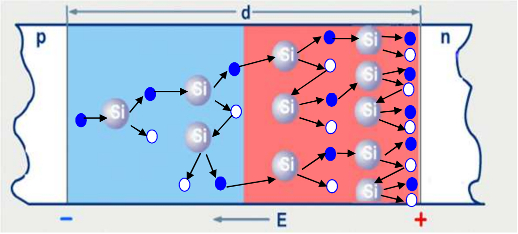
Electrical breakdown

Avalanche breakdown

Zener breakdown



Avalanche Breakdown

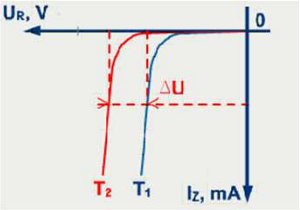


$$M = \frac{I_{BR}}{I_R} = \frac{1}{1 - \left(\frac{U_R}{U_{BR}} \right)^n}$$

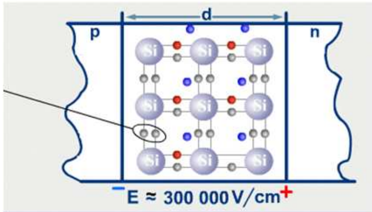
Minority carriers can be accelerated by the field and generate another two electron- hole pairs on collisions with crystal atoms. The process may continue, causing the increase of the current.

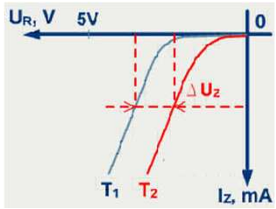
$U_{BR} > 7V$

Avalanche breakdown occurs in wide depletion layers with a reverse bias **higher than 7V**.



Zener Breakdown





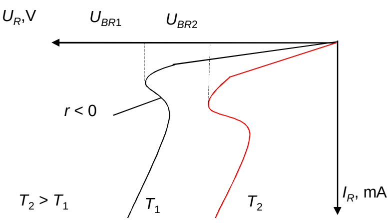
When an electric field of the barrier potential is large enough to break the covalent bonds additional free electrons and holes are created. Such effect is called Zener effect or Zener breakdown. This requires high electric fields on the order of 300 000 V/cm.

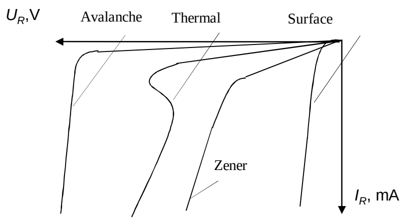
Zener breakdown occurs in very narrow depletion layers with a reverse bias **less than 5V**.

Thermal Breakdown

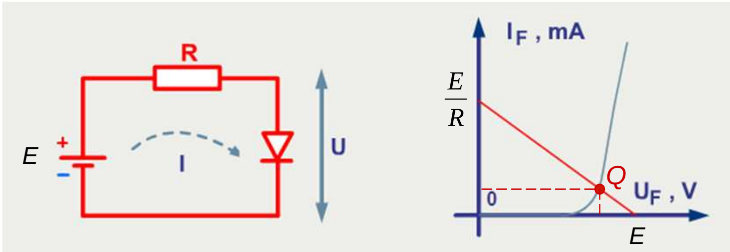
This breakdown occurs if

$$U_R I_R > \frac{T_j - T_a}{R_{th}}$$



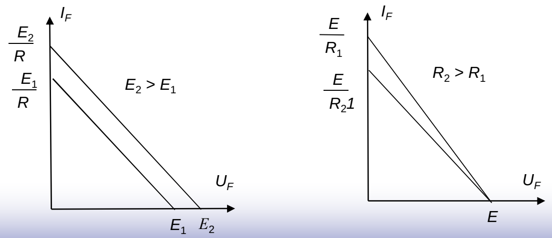


Load Line and Operating Point



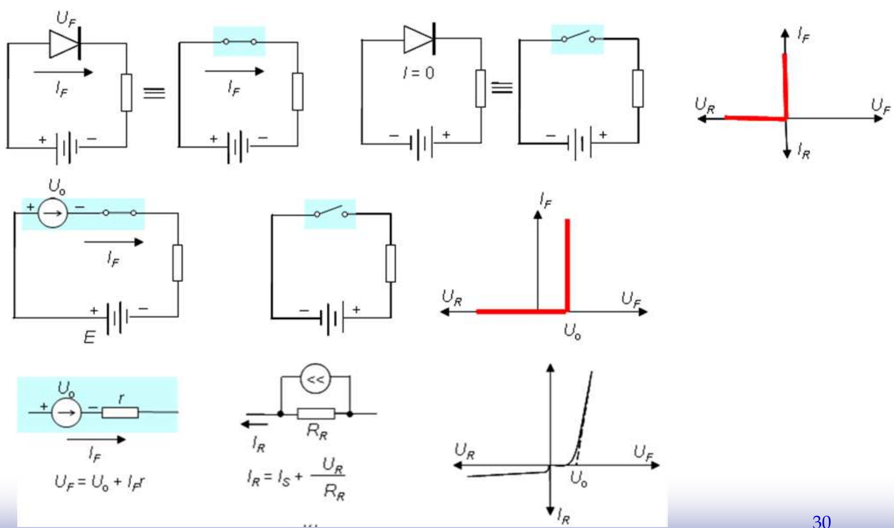
$$R_Q = \frac{U_Q}{I_Q}$$

$E = U + IR$



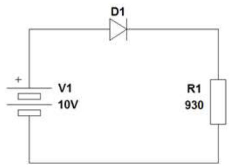
$$I = -\frac{1}{R}U + \frac{E}{R}$$

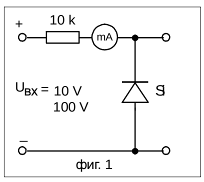
Equivalent Circuits



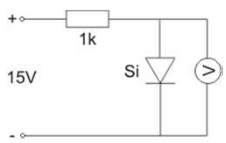
Diode Testing

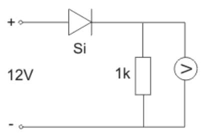
Examples

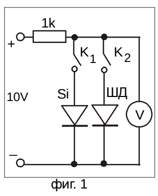




I=?



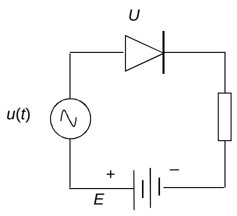


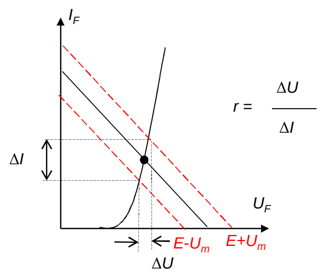


V=?

Work with ac Signal

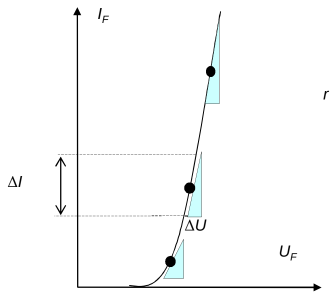
- Dynamic resistance



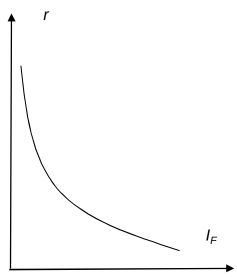


$$r = \frac{dU}{dI} = \frac{\varphi_T}{I + I_s}$$

Graphical calculation of r_B

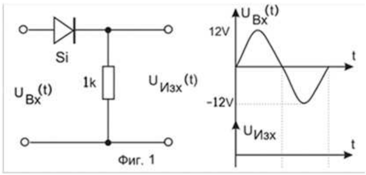


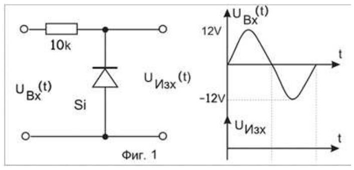
$r = \frac{\Delta U}{\Delta I}$

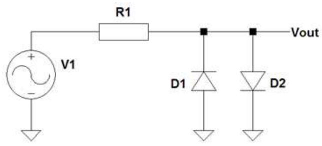


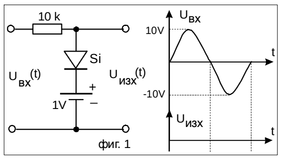
Values of dynamic parameters are valid in **operation point only**. W hen the position of operating point changes the value of the dynamic parameter also changes. The value of forward dynamic resistor is very small (less than 100 ohms), but in reverse direction is very large (around Mohms)

Examples


Si
1k
U Вх(t)
U Изх (t)
12V
-12V
U Вх(t)
U Изх
t
Фиг. 1


10k
Si
U Вх(t)
U Изх (t)
12V
-12V
U Вх(t)
U Изх
t
Фиг. 1


R1
V1
Vout
D1
D2


10 k
Si
1V
U вх(t)
U изх(t)
10V
-10V
U вх
U изх
t
фиг. 1