AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY
IM. STANISŁAWA STASZICA W KRAKOWIE
Faculty of Computer Science, Electronics and Telecommunications
DEPARTMENT OF ELECTRONICS

# ELECTRONIC DEVICES

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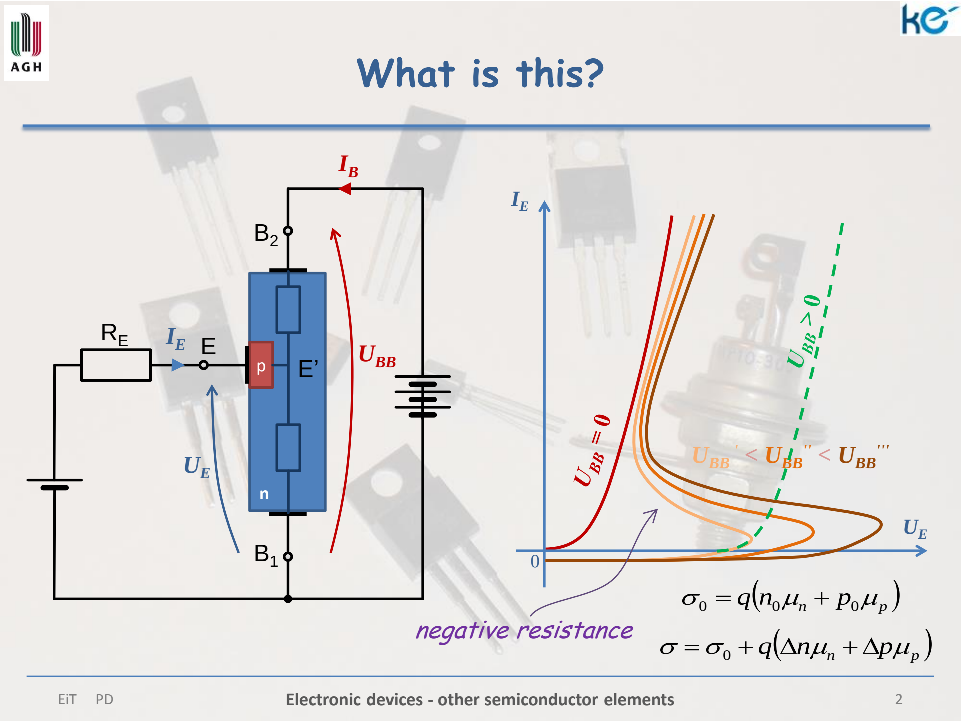
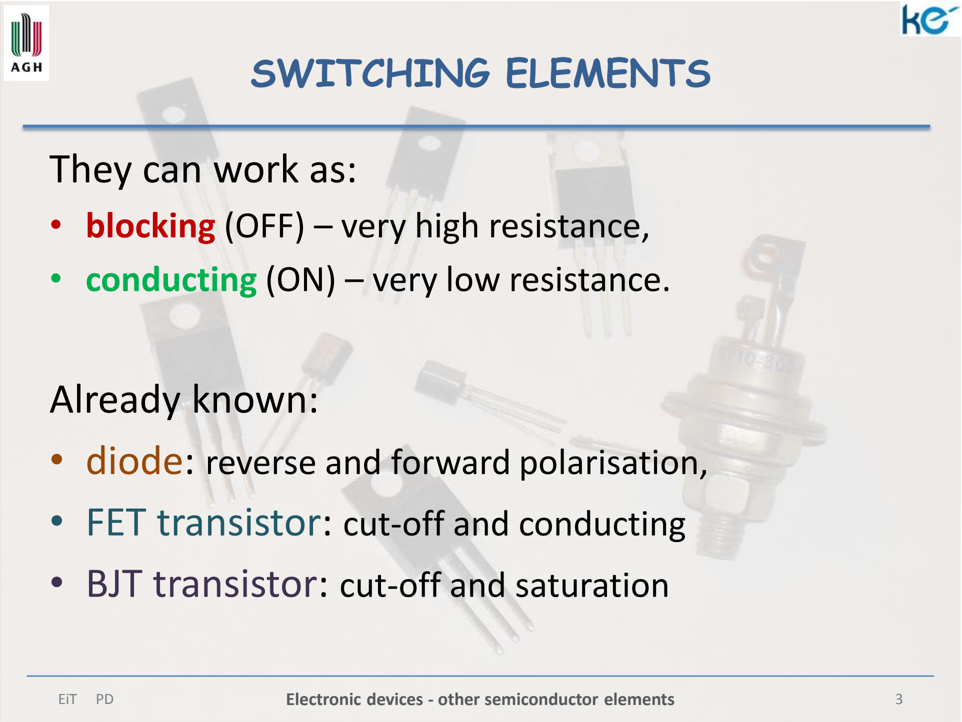


## What is this?

$$\sigma_0 = q(n_0\mu_n + p_0\mu_p)$$

$$\sigma = \sigma_0 + q(\Delta n\mu_n + \Delta p\mu_p)$$



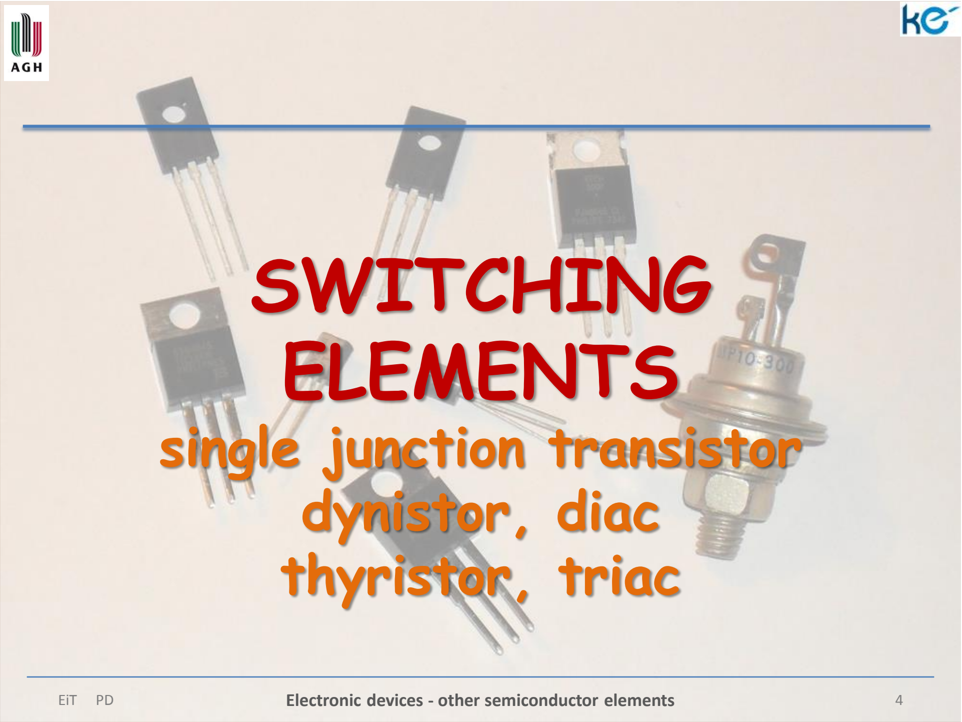
## SWITCHING ELEMENTS

They can work as:

- **blocking** (OFF) – very high resistance,
- **conducting** (ON) – very low resistance.

Already known:

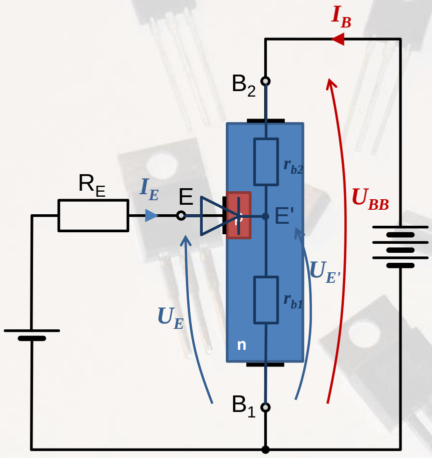
- diode: reverse and forward polarisation,
- FET transistor: cut-off and conducting
- BJT transistor: cut-off and saturation



# SWITCHING ELEMENTS

## single junction transistor
## dynistor, diac
## thyristor, triac

# SINGLE JUNCTION TRANSISTOR

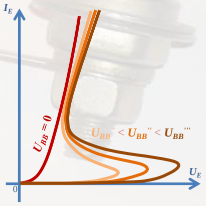


When the diode is OFF ($I_E$=0):

$$U_{E'} = I_B r_{B1} = U_{BB}\left(\frac{r_{B1}}{r_{B1}+r_{B2}}\right) = \eta U_{BB}$$

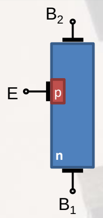
$$\boxed{\eta = \frac{r_{B1}}{r_{B1}+r_{B2}}}$$

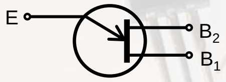
internal partition coefficient



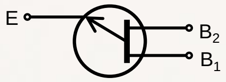
$$I_E \nearrow \;\rightarrow r_{b1} \searrow \;\rightarrow\; U_j \nearrow \;\rightarrow\; I_E \nearrow \rightarrow U_{RE} \nearrow \rightarrow U_E \searrow$$

# SINGLE JUNCTION TRANSISTOR

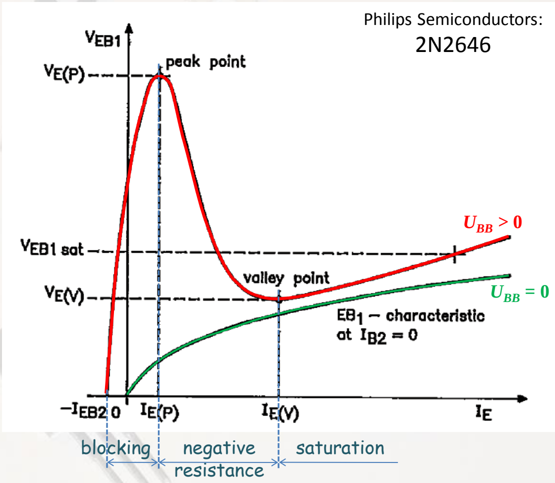




emitter type ***p***



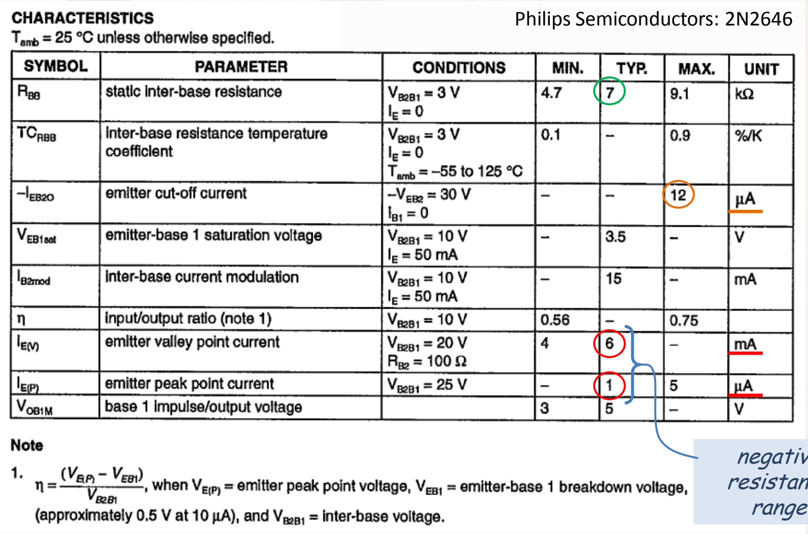
emitter type ***n***



Philips Semiconductors:
2N2646

# SINGLE JUNCTION TRANSISTOR

## PARAMETERS



Philips Semiconductors: 2N2646

**CHARACTERISTICS**

$T_{amb}$ = 25 °C unless otherwise specified.

| SYMBOL | PARAMETER | CONDITIONS | MIN. | TYP. | MAX. | UNIT |
|---|---|---|---|---|---|---|
| $R_{BB}$ | static inter-base resistance | $V_{B2B1} = 3$ V<br>$I_E = 0$ | 4.7 | 7 | 9.1 | kΩ |
| $TC_{RBB}$ | inter-base resistance temperature coefficient | $V_{B2B1} = 3$ V<br>$I_E = 0$<br>$T_{amb} = -55$ to 125 °C | 0.1 | – | 0.9 | %/K |
| $-I_{EB2O}$ | emitter cut-off current | $-V_{EB2} = 30$ V<br>$I_{B1} = 0$ | – | – | 12 | µA |
| $V_{EB1sat}$ | emitter-base 1 saturation voltage | $V_{B2B1} = 10$ V<br>$I_E = 50$ mA | – | 3.5 | – | V |
| $I_{B2mod}$ | inter-base current modulation | $V_{B2B1} = 10$ V<br>$I_E = 50$ mA | – | 15 | – | mA |
| η | input/output ratio (note 1) | $V_{B2B1} = 10$ V | 0.56 | – | 0.75 | |
| $I_{E(V)}$ | emitter valley point current | $V_{B2B1} = 20$ V<br>$R_{B2} = 100\ \Omega$ | 4 | 6 | – | mA |
| $I_{E(P)}$ | emitter peak point current | $V_{B2B1} = 25$ V | – | 1 | 5 | µA |
| $V_{OB1M}$ | base 1 impulse/output voltage | | 3 | 5 | – | V |

**Note**

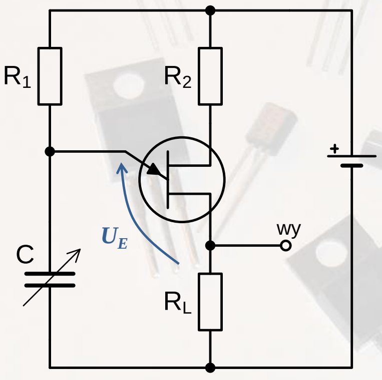
1. $\eta = \frac{(V_{E(P)} - V_{EB1})}{V_{B2B1}}$, when $V_{E(P)}$ = emitter peak point voltage, $V_{EB1}$ = emitter-base 1 breakdown voltage, (approximately 0.5 V at 10 µA), and $V_{B2B1}$ = inter-base voltage.

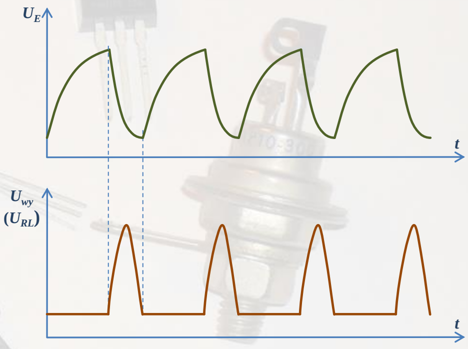
*negative resistance range*

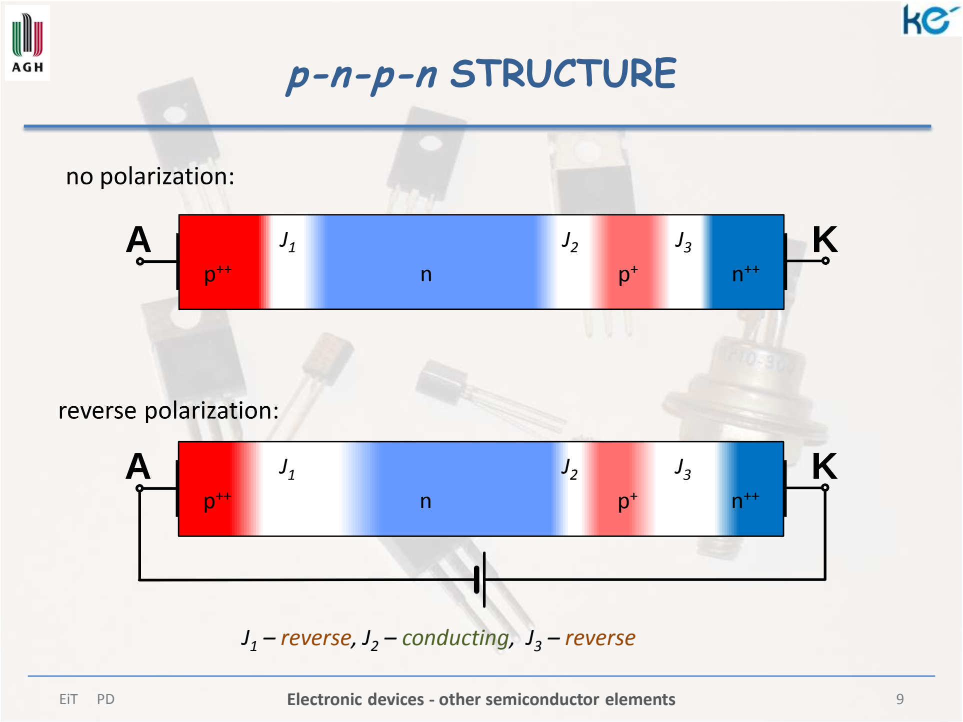
# SINGLE JUNCTION TRANSISTOR

## APPLICATIONS

Oscillator – the use of negative resistance





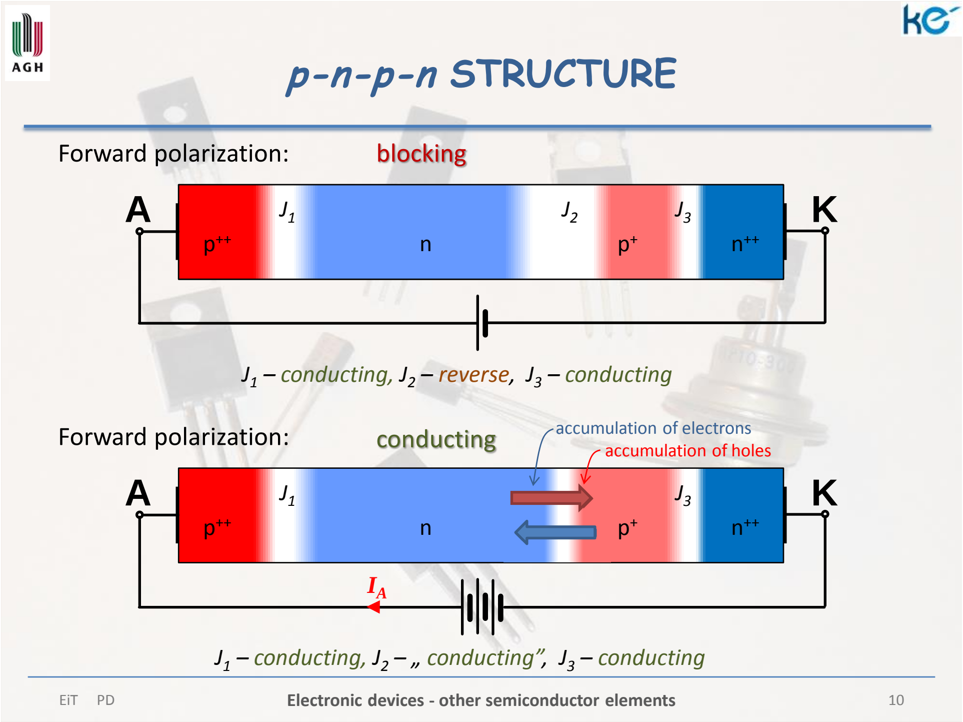


## *p-n-p-n* STRUCTURE

no polarization:

reverse polarization:

$J_1$ – *reverse*, $J_2$ – *conducting*, $J_3$ – *reverse*



## *p-n-p-n* STRUCTURE

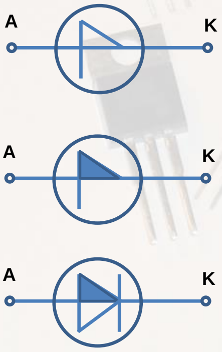
Forward polarization: blocking

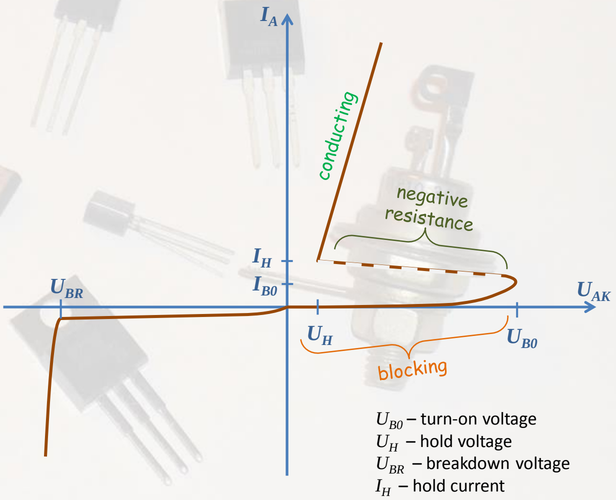
$J_1$ – *conducting*, $J_2$ – *reverse*, $J_3$ – *conducting*

Forward polarization: conducting

$J_1$ – *conducting*, $J_2$ – *„ conducting”*, $J_3$ – *conducting*

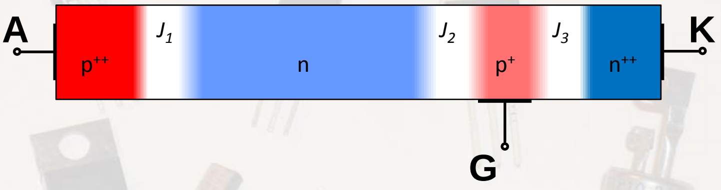
# DYNISTOR





$U_{B0}$ – turn-on voltage
$U_H$ – hold voltage
$U_{BR}$ – breakdown voltage
$I_H$ – hold current

# *p-n-p-n* STRUCTURE with a GATE

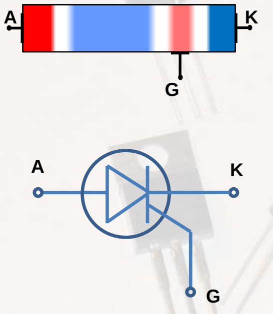


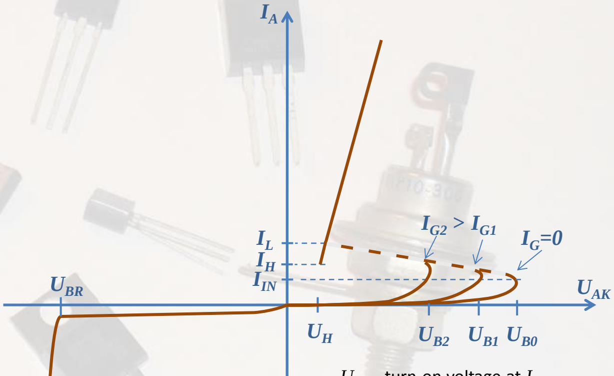
Gate current $I_G$ followed by the injection of electrons from the cathode through the junction $J_3$, causes avalanche breakdown in junction $J_2$ before voltage $U_{AK}$ reaches $U_{B0}$ – ***turn-on*** of the thyristor

**controlled dynistor ⟶ thyristor**

Once turned-on thyristor can not be turned-off by the gate current.
Turn-off is followed by disappearance of the anode current, or change of $U_{AK}$ polarisation.

# THYRISTOR





$U_{Bx}$ – turn-on voltage at $I_{gx}$
$U_H$ – hold voltage
$U_{BR}$ – breakdown voltage
$I_H$ – hold current
$I_L$ – current of inevitable turn-on
$I_{IL}$ – turn-on current at $U_{B0}$

# THYRISTOR

## APPLICATIONS

- high current and high voltage circuits

  electric power, electric drives, electrical traction, control systems operating at high power

- converters with phase control

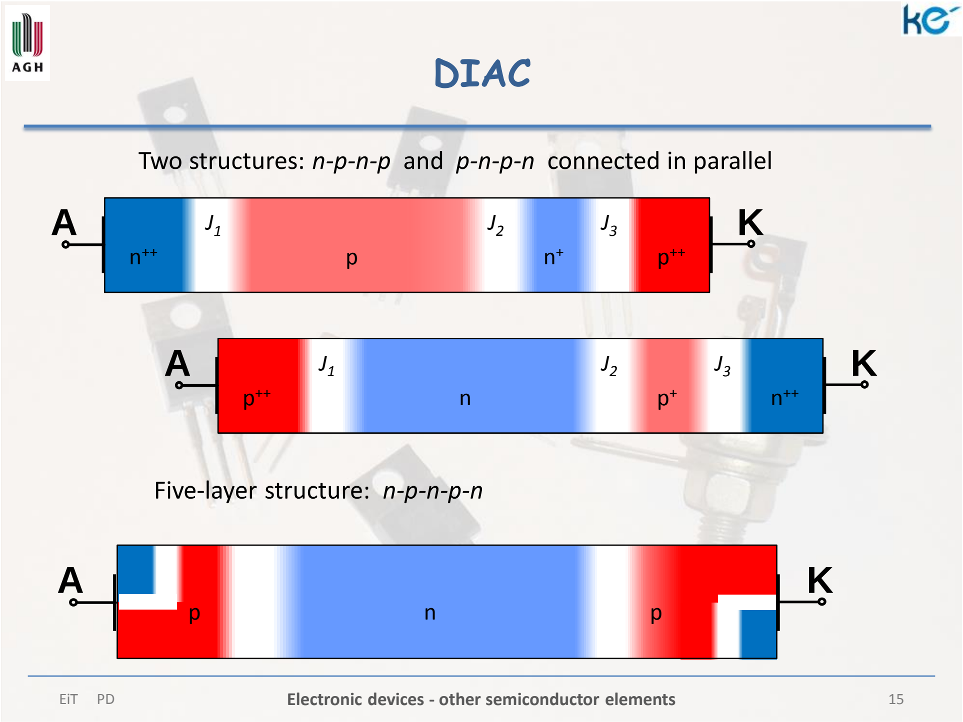
  AC voltage controllers, voltage controlled rectifiers, inverters

- electrothermal systems to control the heating power
- in electrical cars

  thyristor ignition systems are replacing relay systems

- lighting control

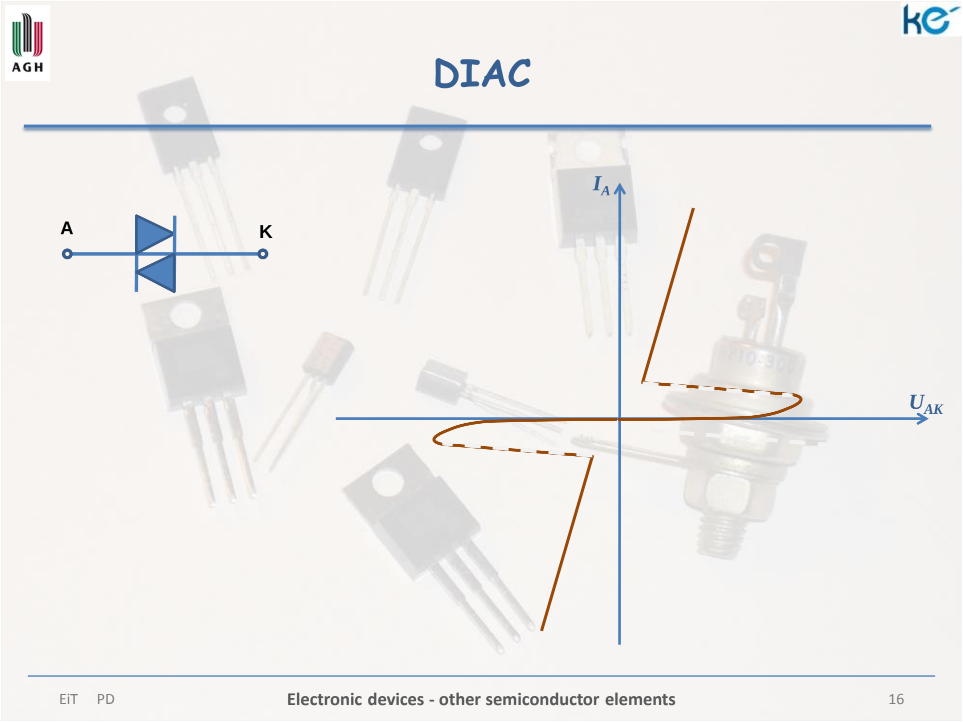
  thyristor lighting controllers, dimmers



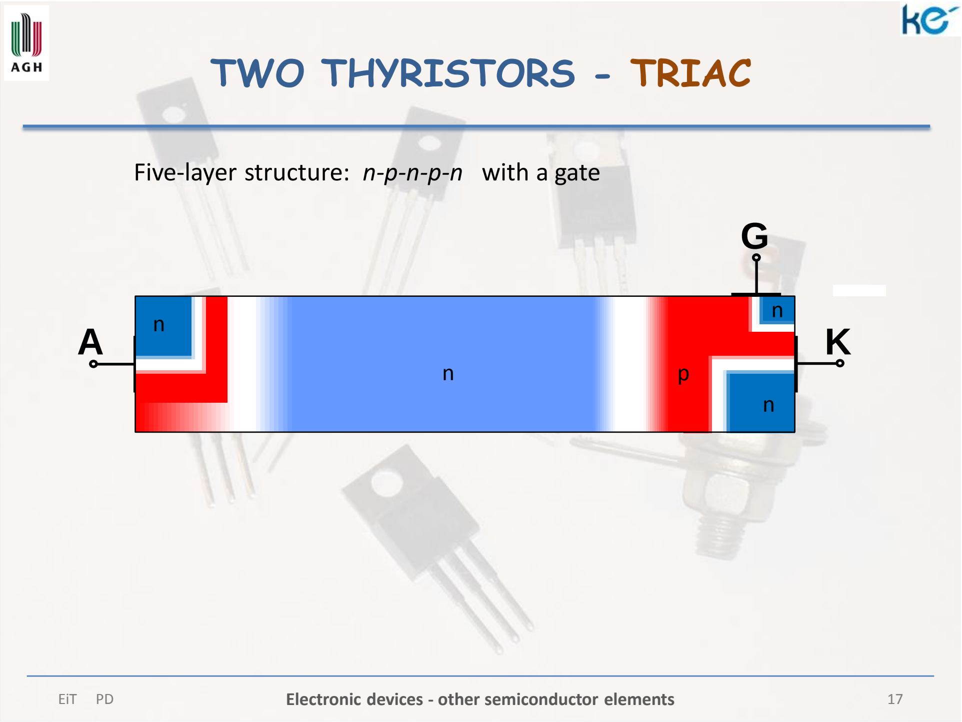
## DIAC

Two structures: *n-p-n-p* and *p-n-p-n* connected in parallel

Five-layer structure: *n-p-n-p-n*

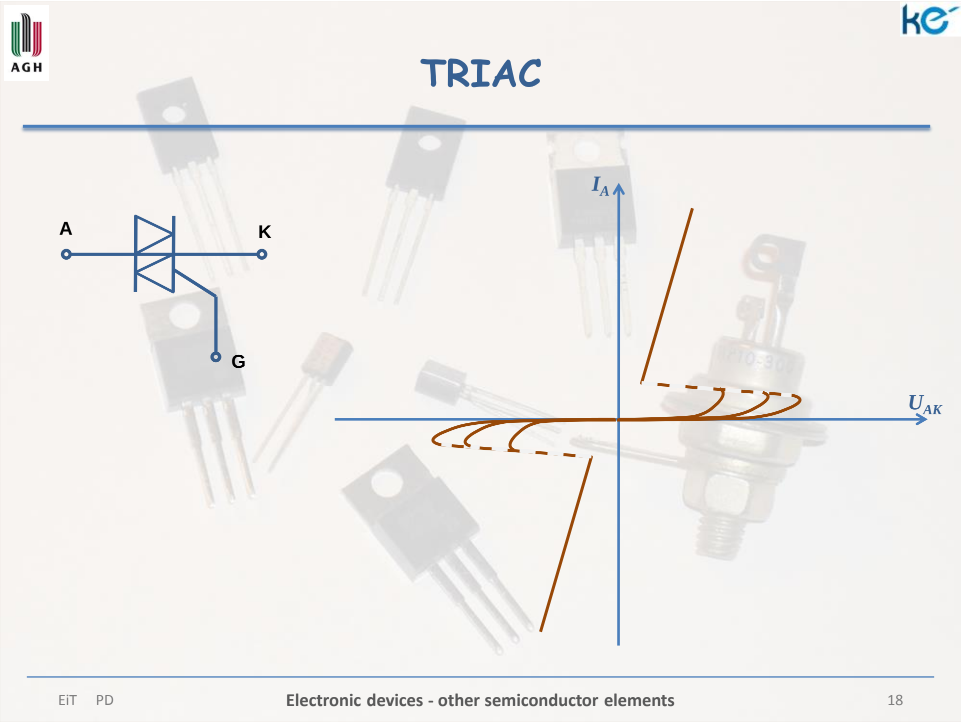


## DIAC



# TWO THYRISTORS - TRIAC

Five-layer structure: *n-p-n-p-n* with a gate



# TRIAC

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# JUNCTIONLESS SEMICONDUCTOR COMPONENTS

## varistor, thermistor, photoresistor, piezoresistor, piezoelectric resonator, hallotron, magnetoresistor

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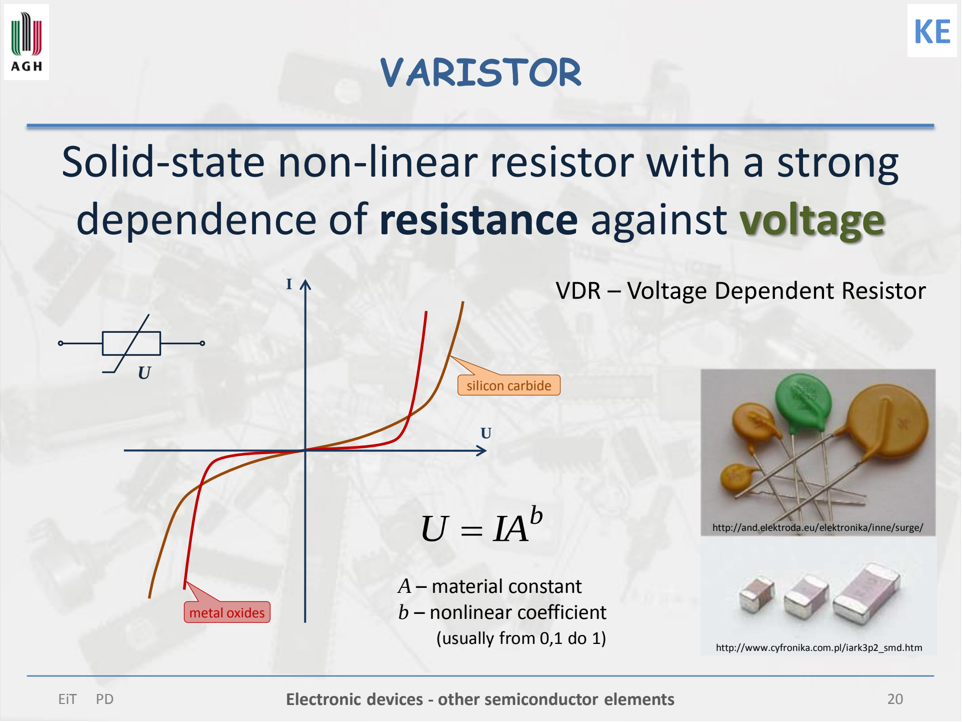

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# VARISTOR

Solid-state non-linear resistor with a strong dependence of **resistance** against **voltage**

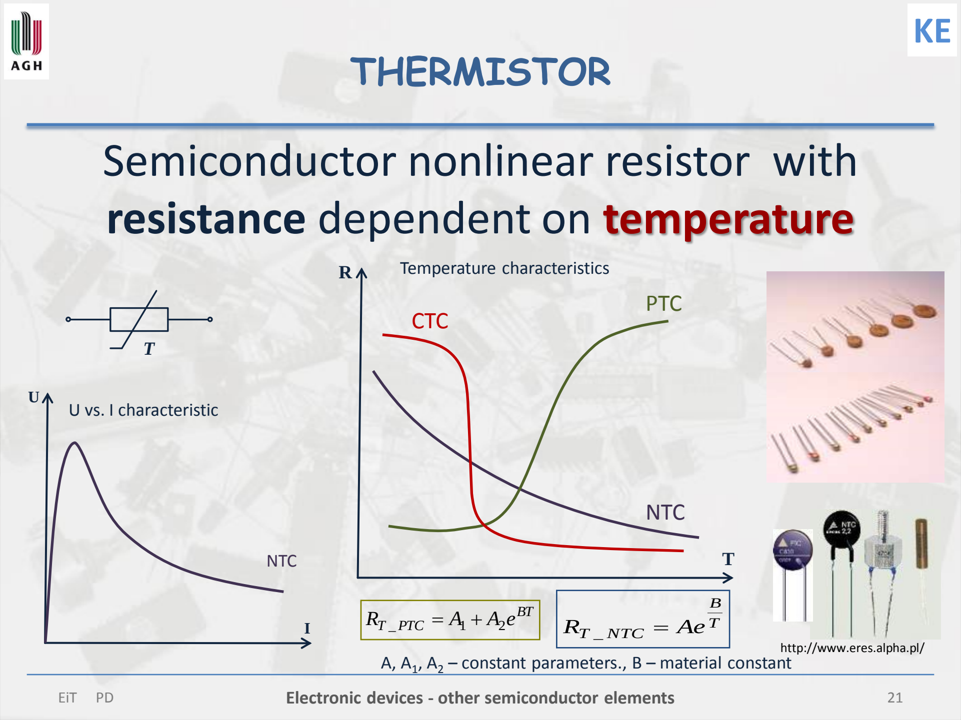
VDR – Voltage Dependent Resistor

$$U = IA^b$$

$A$ – material constant
$b$ – nonlinear coefficient
(usually from 0,1 do 1)

http://and.elektroda.eu/elektronika/inne/surge/

http://www.cyfronika.com.pl/iark3p2_smd.htm



# THERMISTOR

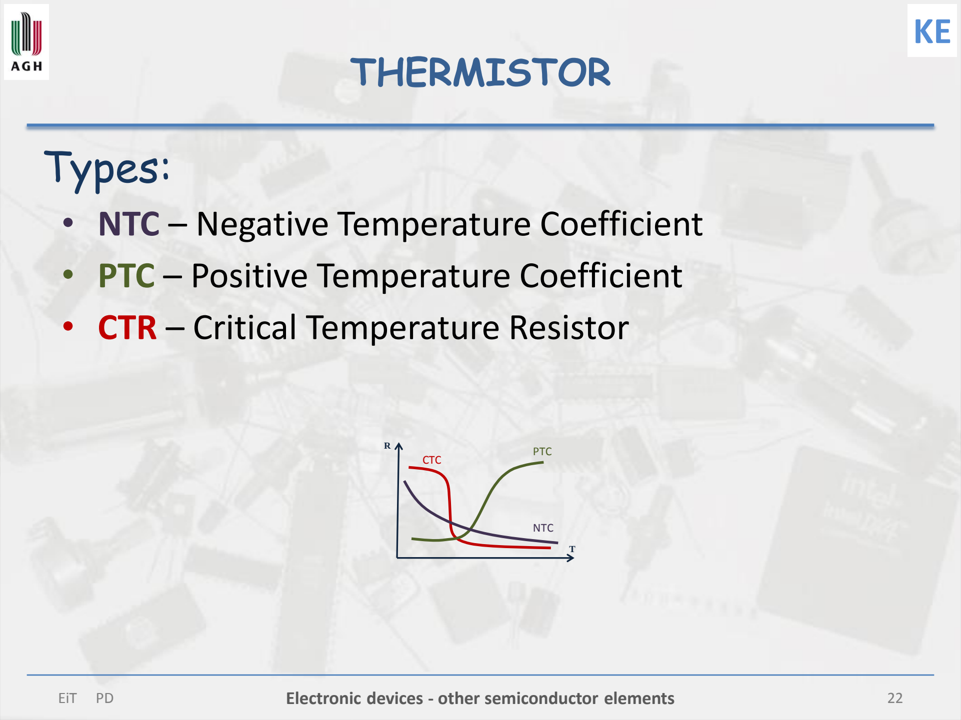
Semiconductor nonlinear resistor with **resistance** dependent on **temperature**

$R_{T\_PTC} = A_1 + A_2 e^{BT}$

$R_{T\_NTC} = A e^{\frac{B}{T}}$

A, $A_1$, $A_2$ – constant parameters., B – material constant

http://www.eres.alpha.pl/



# THERMISTOR

Types:

- **NTC** – Negative Temperature Coefficient
- **PTC** – Positive Temperature Coefficient
- **CTR** – Critical Temperature Resistor

## How does thermistor work?

in $1mm^3$ we can find
15 millions of free electrons !!!
and the same number of holes ;))

$$n_i(T) = AT^{\frac{3}{2}}e^{-\frac{E_g}{2kT}}$$

$$n_i(300K) = 1.5 \cdot 10^{10}\,cm^{-3}$$

What is the sensitivity of free electrons and holes concentration changes in the intrinsic silicon at the ambient temperature T = 300K?

**The conductivity of intrinsic semiconductor (undoped) is strongly dependent on temperature**

we should calculate :

$$\gamma_i = \frac{\frac{dn_i}{dT}}{n_i} = \frac{3}{2T} + \frac{E_g}{2kT^2}$$

$$\rho = AT^b e^{\frac{E_g}{2kT}}$$

after substituting the data
we obtain :

$$\gamma_i(300K) = 8.3\%$$

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## THERMISTOR

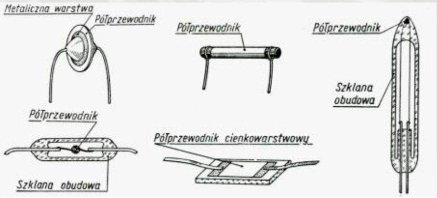
### Construction:

A solid semiconductor structure properly selected, with leads.

A mixture of powdered semiconductor materials (oxides of manganese, nickel, cobalt and copper), linked by a suitable adhesive, pressed and sintered at high temperature.

***They can be made as:***

sticks, rings, cylinders, thin layers deposited substrates, etc.



A. Świt, J. Pułtorak, „Przyrządy półprzewodnikowe", WNT, Warszawa, 1979

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# THERMISTOR

## *Parameters:*

- **nominal resistance** ($R_{25}$) – value of resistance at 25°C
- **temperature coefficient of resistance** (TWR, $\alpha_T$)
- **permissible power loss**
- **tolerance**

$$\alpha_T = \frac{1}{R_T}\frac{\Delta R}{\Delta T}$$

## *Applications:*

- measurement and temperature control
- temperature compensation of other components
- delay circuits and limiting the starting current
- current limiters
- stabilization of voltage and the amplitude of vibration

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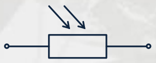
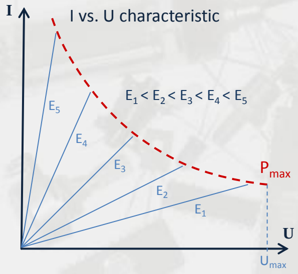
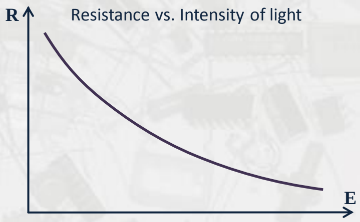
# PHOTORESISTOR

Semiconductor nonlinear resistor
with **resistance** dependent on **light**
(the intensity of visible and invisible)

LDR – Light Dependent Resistor







http://www.cyfronika.com.pl

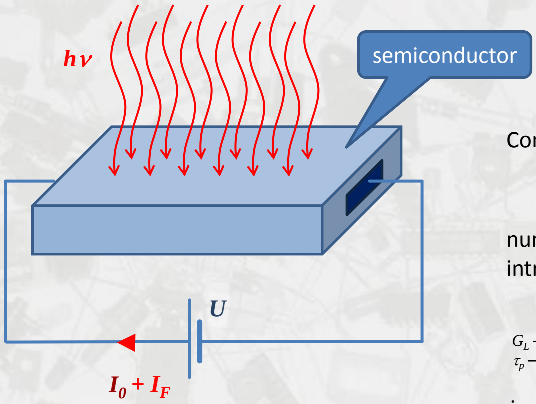
$$I = I_0 + I_F$$

$I_0$ – dark current
$I_F$ – photoelectric current

$$R_E = R_0\left(\frac{E_0}{E}\right)^{\gamma}$$

$R_E$ – photoresistor resistance
E – intensity of light
$R_0$ – resistance at intensity $E_0$
$\gamma$ – material coefficient
for CdS $\gamma = 0,5 \div 1$

# PHOTORESISTOR



Conductivity:

$$\sigma = q(\mu_n n_0 + \mu_p p_0)$$

number of excess intrinsic carriers:

$$\Delta n = \Delta p = G_L \tau_p$$

$G_L$ – rate of generation
$\tau_p$ – time of life of excess carriers

increase of conductivity:

$$\Delta\sigma = q(\Delta p)(\mu_n + \mu_p)$$

**photoconductivity**

Materials:
CdS – cadmium sulfide
CdSe – cadmium selenide
CdTe – cadmium telluride
PbS, PbSe, CdHgTe, InSb, PbSnTe ,and others

# PHOTORESISTOR

## *Parameters:*

- **spectral sensitivity**
- **dark resistance** - no light
- **resistance at a certain light** (np. 10lx, 100lx)
- **max. sensitivity for a wavelength**
- **permissible power loss**
- **response time** (at switching),

## *Applications:*

- simple light meters
- automatic switching of lighting
- cosmic ray detectors

# PIEZORESISTOR

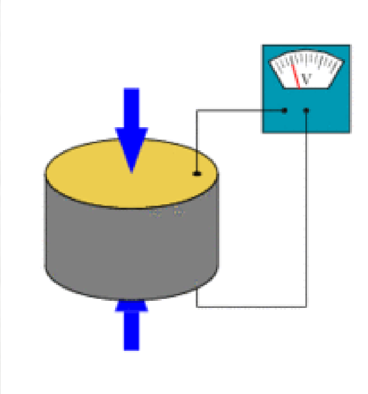
Semiconductor nonlinear resistor
with **resistance** dependent on **stress** or
mechanical **deformation**

**piezoresistivity** [gr.], **piezoelectric phenomena,** formation of electrical charge on the walls of some crystals under stress or stretching along one of the crystallographic axis; discovered in 1880 by Pierre and Paul Curie; used in measuring instruments, microphones, energy harvesters.

**tensometer**

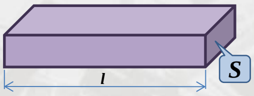
**mechanic and electrical sensors**

# PIEZORESISTOR



# PIEZORESISTOR

## Resistive tensometer



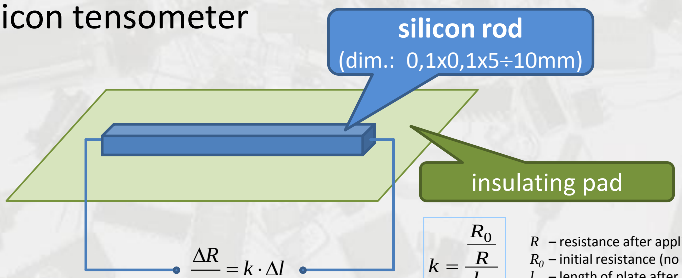
$$R = \rho \frac{l}{S}$$

**deformation:** $\Delta l \Rightarrow \Delta R$

**low sensitivity**

**k = 1,6÷3,5**

## Silicon tensometer



$$\frac{\Delta R}{R_0} = k \cdot \Delta l$$

**k = 40÷300**

$$k = \frac{\frac{R_0}{R}}{\frac{l_0}{l}}$$

$R$ – resistance after applied stress,
$R_0$ – initial resistance (no stress)
$l$ – length of plate after applied stress,
$l_0$ – initial length of plate (no stress)

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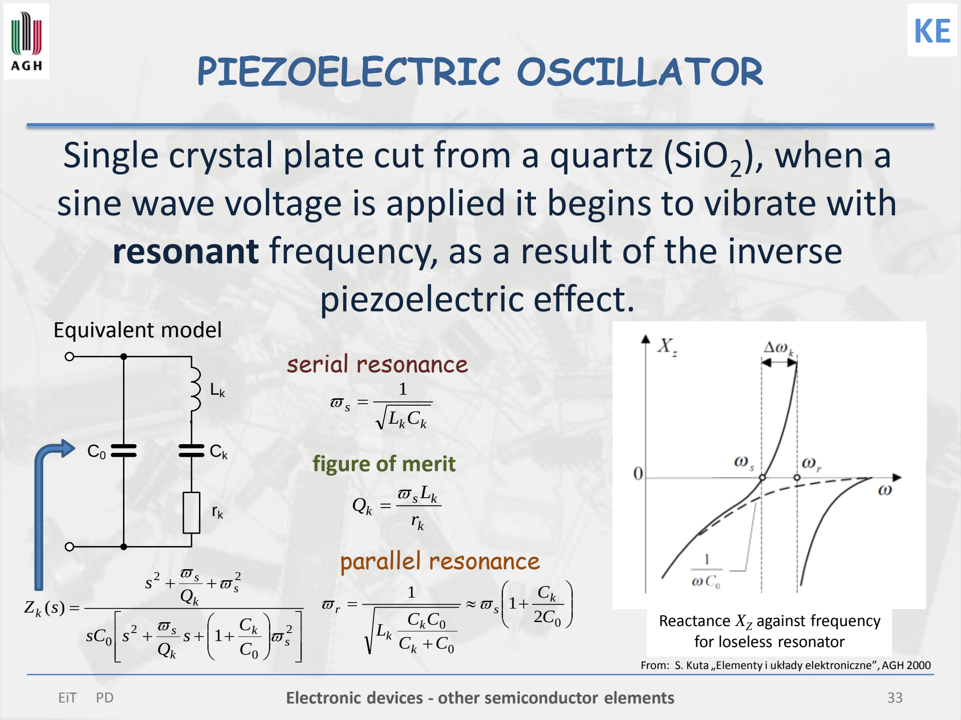
# PIEZORESISTOR - TENSOMETER

## *Parameters:*

- **sensitivity**
- **resistance**
- **dimensions**

## *Applications:*

- Semiconductor tensometers
- piezoresistive pressure sensors (in integrated circuits)
- piezoelectric acceleration sensor
- piezoelectric motor (micromotor)



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# PIEZOELECTRIC OSCILLATOR

Single crystal plate cut from a quartz ($SiO_2$), when a sine wave voltage is applied it begins to vibrate with **resonant** frequency, as a result of the inverse piezoelectric effect.

Equivalent model

$$Z_k(s) = \frac{s^2 + \frac{\varpi_s}{Q_k} + \varpi_s^2}{sC_0\left[s^2 + \frac{\varpi_s}{Q_k}s + \left(1 + \frac{C_k}{C_0}\right)\varpi_s^2\right]}$$

serial resonance

$$\varpi_s = \frac{1}{\sqrt{L_k C_k}}$$

figure of merit

$$Q_k = \frac{\varpi_s L_k}{r_k}$$

parallel resonance

$$\varpi_r = \frac{1}{\sqrt{L_k \frac{C_k C_0}{C_k + C_0}}} \approx \varpi_s\left(1 + \frac{C_k}{2C_0}\right)$$

Reactance $X_Z$ against frequency for loseless resonator

From: S. Kuta „Elementy i układy elektroniczne”, AGH 2000

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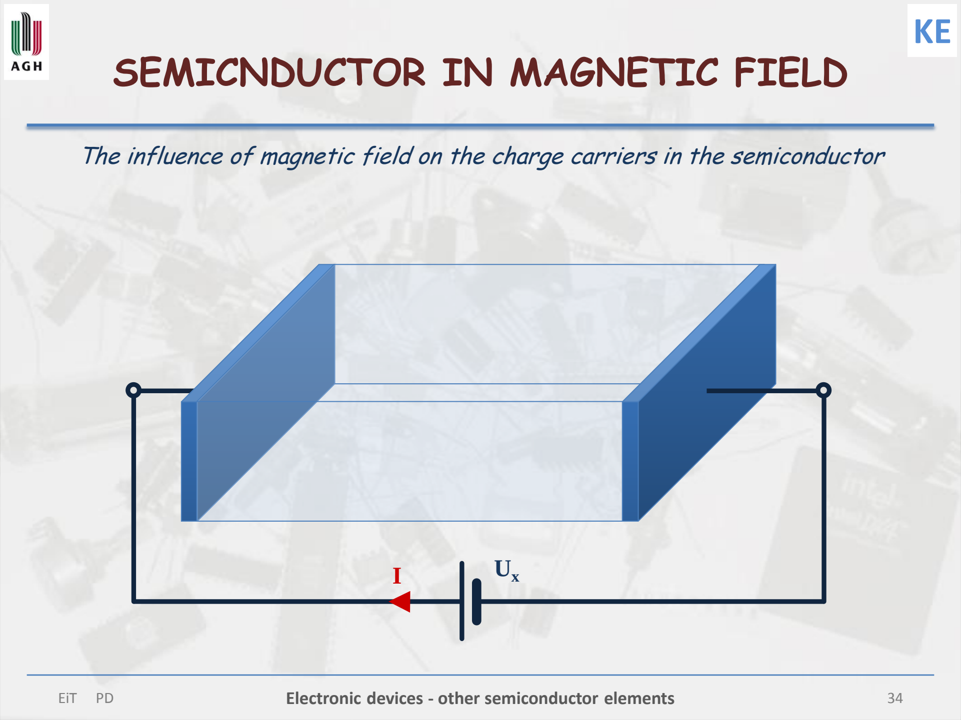

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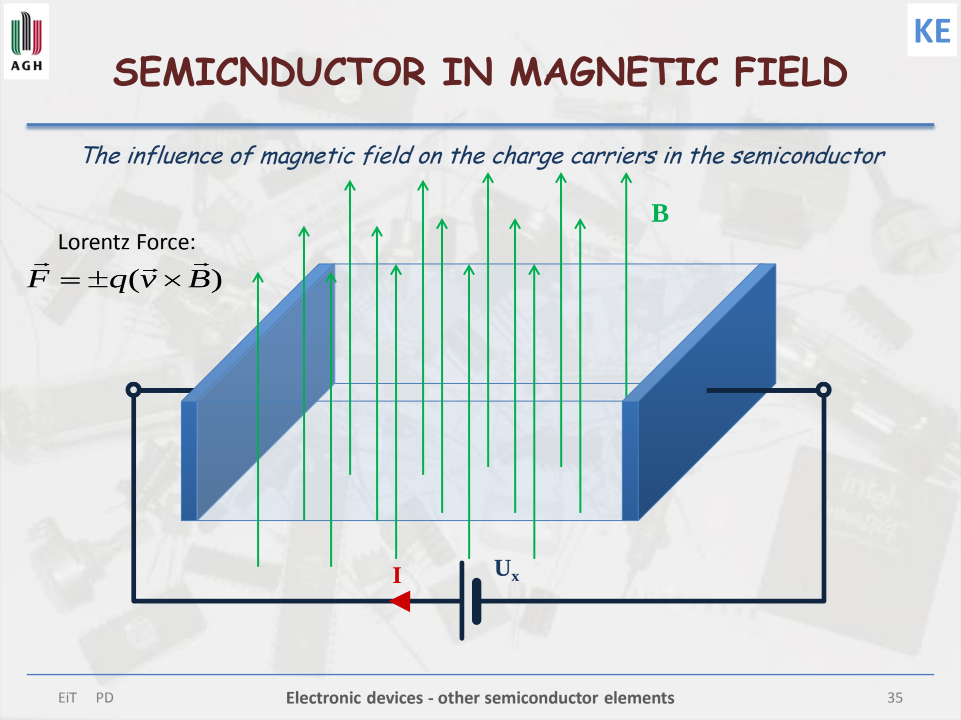
# SEMICNDUCTOR IN MAGNETIC FIELD

*The influence of magnetic field on the charge carriers in the semiconductor*

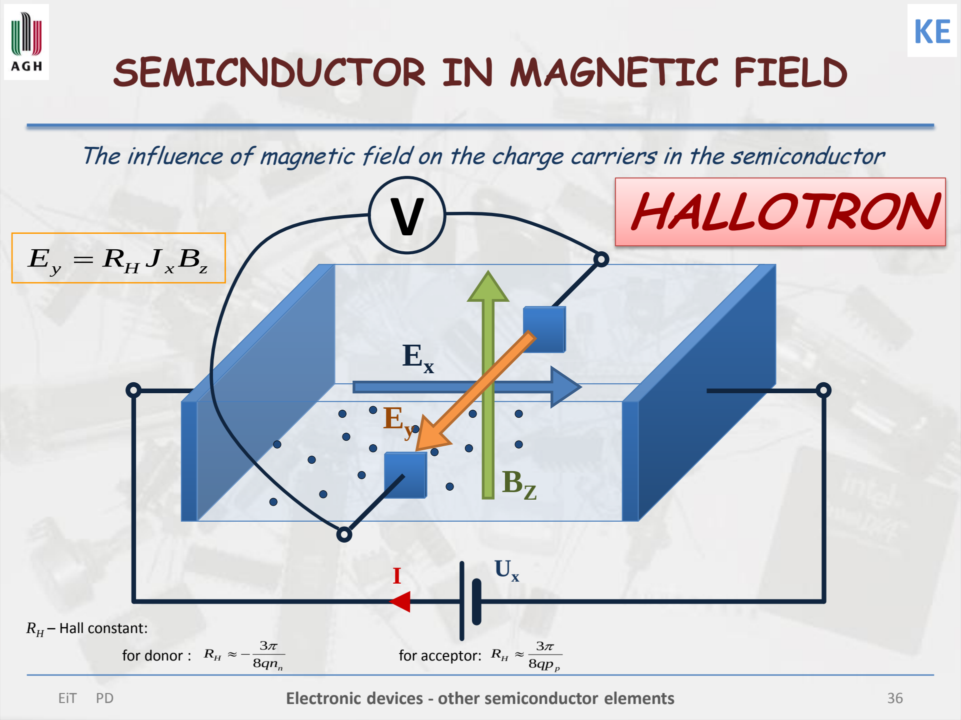


# SEMICNDUCTOR IN MAGNETIC FIELD

*The influence of magnetic field on the charge carriers in the semiconductor*

Lorentz Force:

$$\vec{F} = \pm q(\vec{v} \times \vec{B})$$



# SEMICNDUCTOR IN MAGNETIC FIELD

*The influence of magnetic field on the charge carriers in the semiconductor*

**HALLOTRON**

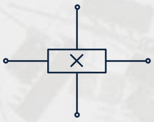
$$E_y = R_H J_x B_z$$

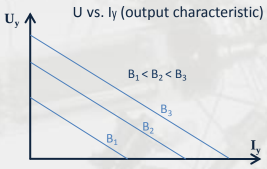
$R_H$ – Hall constant:

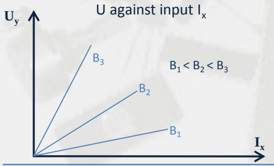
for donor : $R_H \approx -\frac{3\pi}{8qn_n}$ for acceptor: $R_H \approx \frac{3\pi}{8qp_p}$

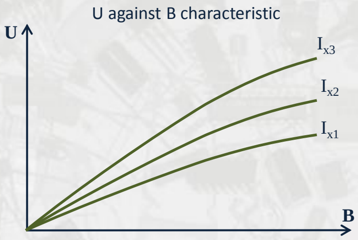
# HALLOTRON

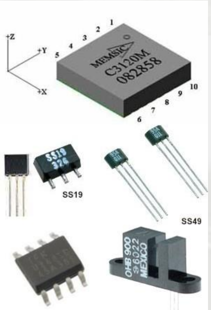
A semiconductor device,
based on the Hall effect











http://www.cyfronika.com.pl

$$U_y = U_y(0) - R_y I_y$$

$$U_y(0) = \frac{R_H}{c} I_x B_z$$

$R_y$ – resistance of the working area
$R_H$ – Hall constant
c – thickness of the working area

# HALLOTRON

## *Parameters:*

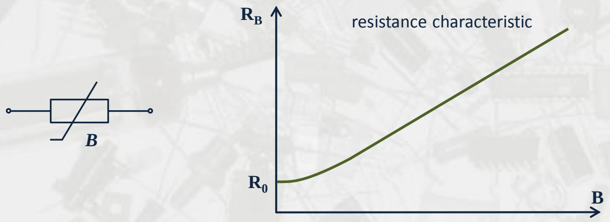
- **Sensitivity**
- **Input resistance $R_x$**
- **Temperature coefficient of resistance and Hall constant**
- Limiting parameters (max. current, voltage, temperature, etc.)

## *Applications:*

- Measurements of magnetic field intensity
- Sensors of motion
- Indirect measurements of high currents
- Measurements of non-electrical quantities
  (angle of rotation, displacement, vibrations, etc.)

# MAGNETORESISTOR - GAUSSOTRON

Semiconductor nonlinear resistor
with **resistance** dependent on **magnetic field**



$$\frac{\Delta R}{R_0} = \frac{R_B - R_0}{R_0} \approx SB^2$$

$R_0$ – initial resistance
S – square coefficient of magnetoresistance
B – intensity of magnetic field

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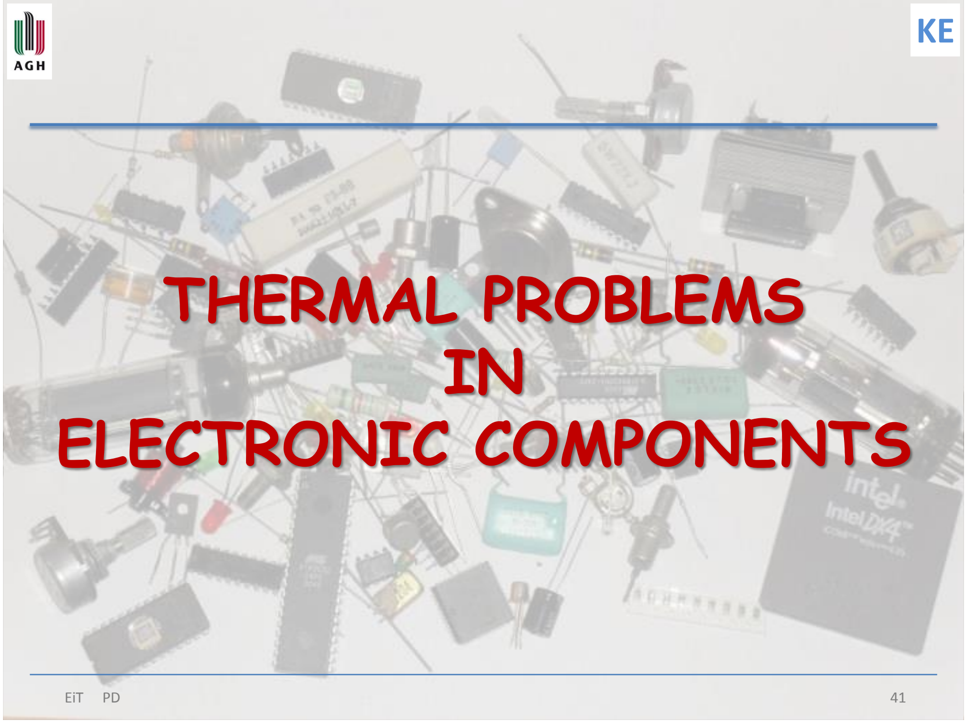
# GAUSSOTRON

## *Parameters:*

- **initial resistance**
- **coefficient of magnetoresistance**

## *Applications:*

- Similar to Hallotron



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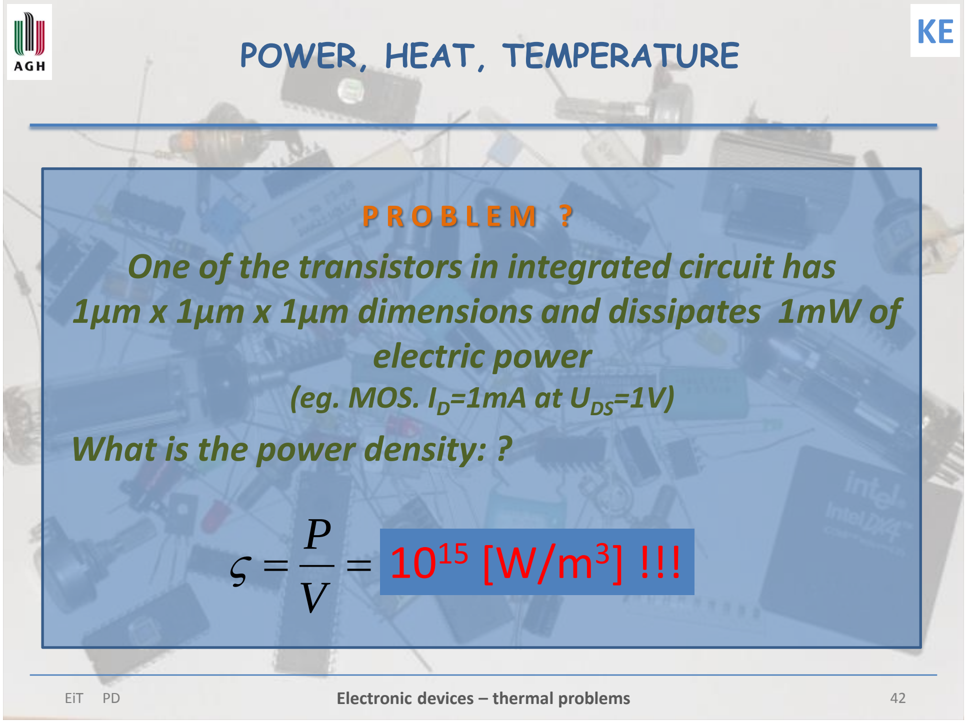
# THERMAL PROBLEMS
# IN
# ELECTRONIC COMPONENTS



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## POWER, HEAT, TEMPERATURE

**PROBLEM ?**

*One of the transistors in integrated circuit has 1µm x 1µm x 1µm dimensions and dissipates 1mW of electric power*

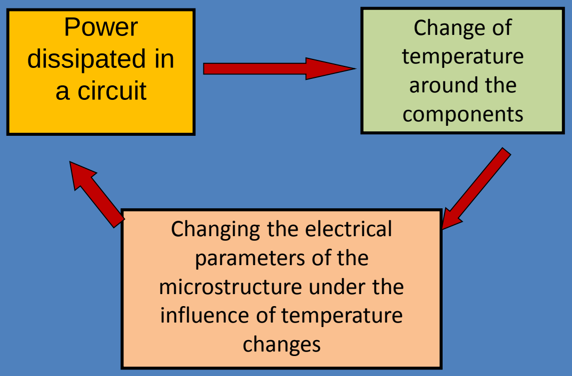
*(eg. MOS. $I_D$=1mA at $U_{DS}$=1V)*

*What is the power density: ?*

$$\varsigma = \frac{P}{V} = 10^{15}\ [\mathrm{W/m^3}]\ !!!$$

# POWER, HEAT, TEMPERATURE

## ELECTROTHERMAL FEEDBACK



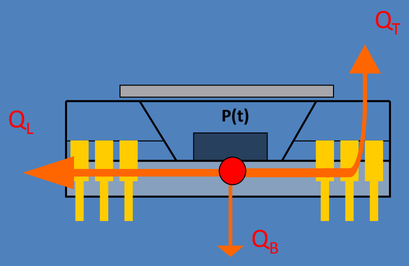
Power dissipated in a circuit

Change of temperature around the components

Changing the electrical parameters of the microstructure under the influence of temperature changes

# POWER, HEAT, TEMPERATURE

## WAYS AND PATHS FOR DISSIPATION OF HEAT



**P(t)** – *power dissipated in a circuit*

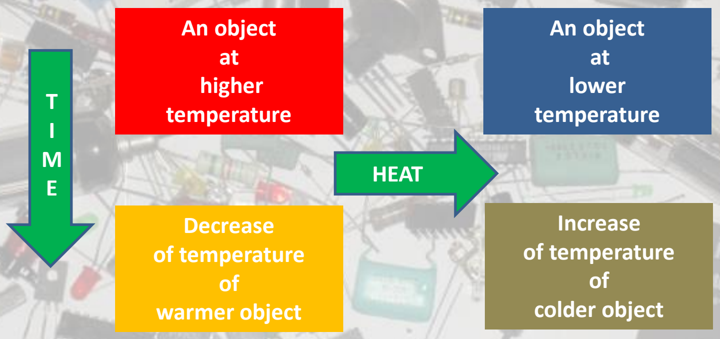
**$Q_B$** – *the heat dissipated by the lower surface of the IC*

**$Q_T$** – *the heat dissipated by the upper surface of the IC*

**$Q_L$** – *heat dissipated by the IC terminals*

# METHODS OF HEAT TRANSFER

**CONDUCTION**



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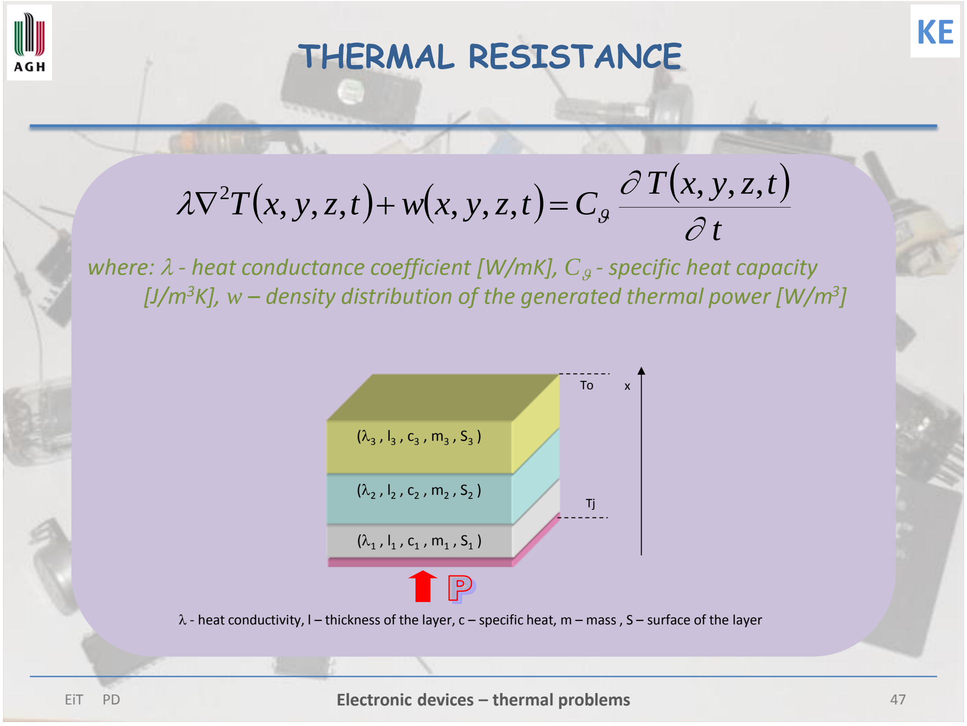
# SPOSOBY PRZEKAZYWANIA CIEPŁA

**KONWEKCJA**

Convection is the process of transferring heat from the object into the surrounding fluid (gas or liquid). Heat transfer thus occurs not only through heat conduction, but also by the movement of the free molecules. Natural convection is caused by the difference of the local density of the medium. Thin liquid rises to the top in the presence of a gravitational field.

**RADIACJA**

The process of radiation does not involve any medium. Heat is transmitted to the environment via electromagnetic waves (the most effective in vacuum). Heat dissipation depends only on the temperature and emissivity of the surface of the material of which it is made. Radiation process is governed by the Stefan-Boltzmann law, according to which the energy of the radiation is proportional to the fourth power of the temperature.



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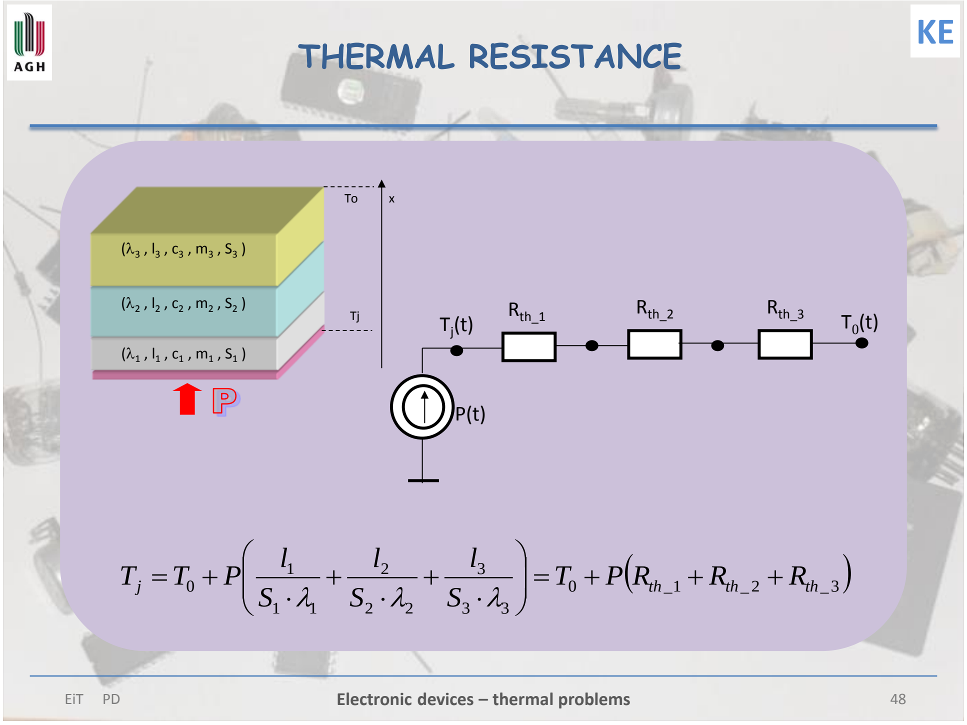
# THERMAL RESISTANCE

$$\lambda \nabla^2 T(x,y,z,t) + w(x,y,z,t) = C_\vartheta \frac{\partial T(x,y,z,t)}{\partial t}$$

*where: $\lambda$ - heat conductance coefficient [W/mK], $C_\vartheta$ - specific heat capacity [J/m$^3$K], w – density distribution of the generated thermal power [W/m$^3$]*

λ - heat conductivity, l – thickness of the layer, c – specific heat, m – mass , S – surface of the layer

EiT PD Electronic devices – thermal problems 47



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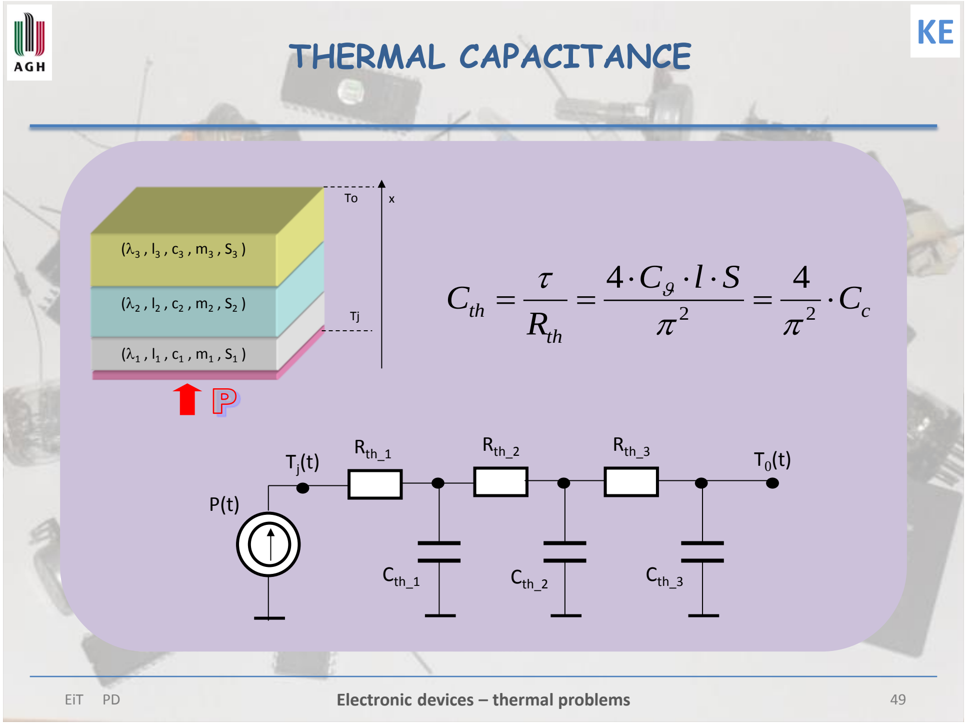
# THERMAL RESISTANCE

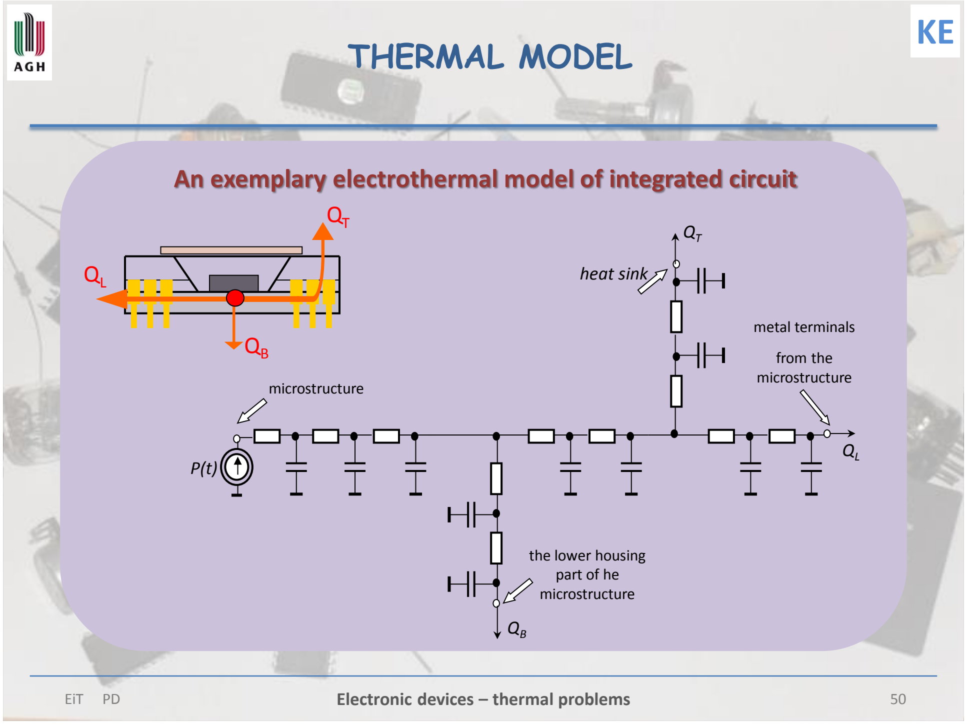
$$T_j = T_0 + P\left(\frac{l_1}{S_1 \cdot \lambda_1} + \frac{l_2}{S_2 \cdot \lambda_2} + \frac{l_3}{S_3 \cdot \lambda_3}\right) = T_0 + P\left(R_{th\_1} + R_{th\_2} + R_{th\_3}\right)$$

EiT PD Electronic devices – thermal problems 48



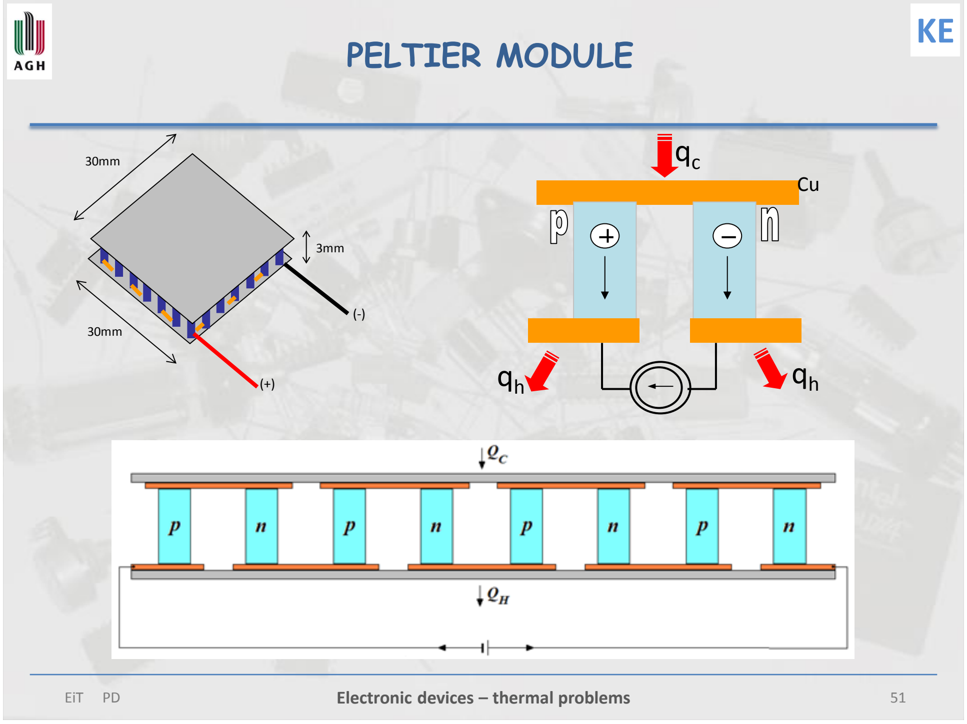
# THERMAL CAPACITANCE

$$C_{th} = \frac{\tau}{R_{th}} = \frac{4 \cdot C_g \cdot l \cdot S}{\pi^2} = \frac{4}{\pi^2} \cdot C_c$$



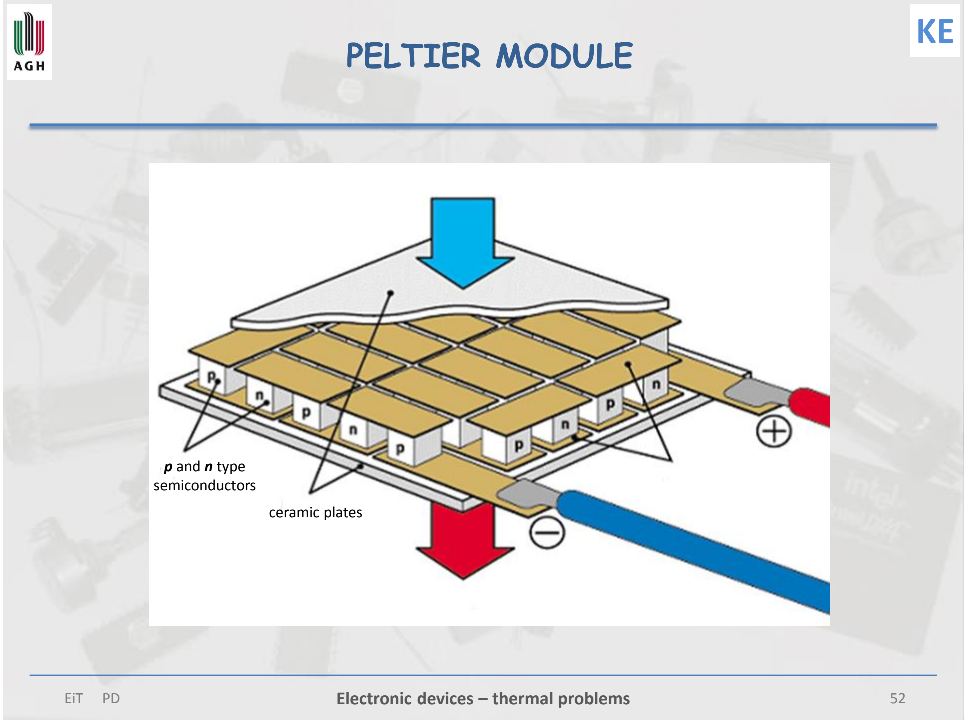
# THERMAL MODEL

An exemplary electrothermal model of integrated circuit



## PELTIER MODULE

EiT PD Electronic devices – thermal problems 51

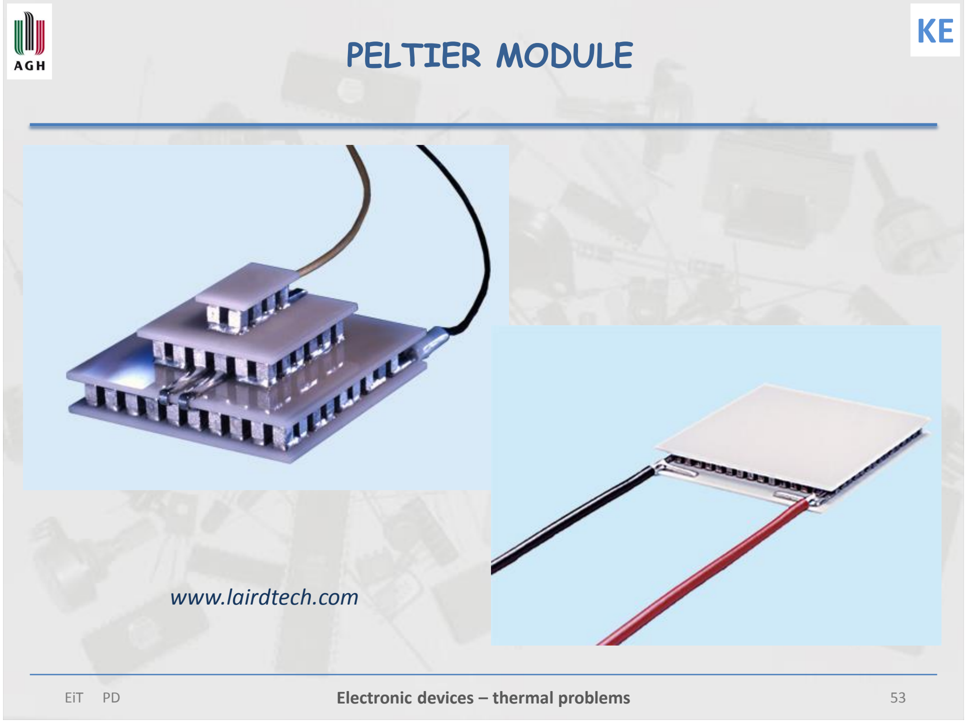


## PELTIER MODULE

***p*** and ***n*** type semiconductors

ceramic plates

EiT PD Electronic devices – thermal problems 52



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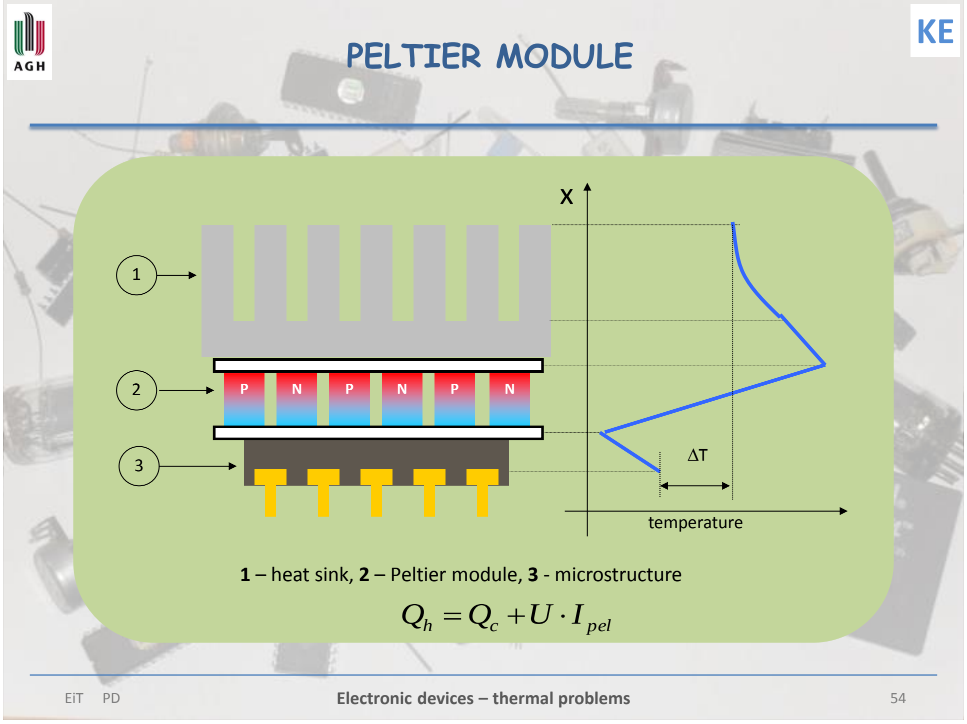
## PELTIER MODULE

*www.lairdtech.com*



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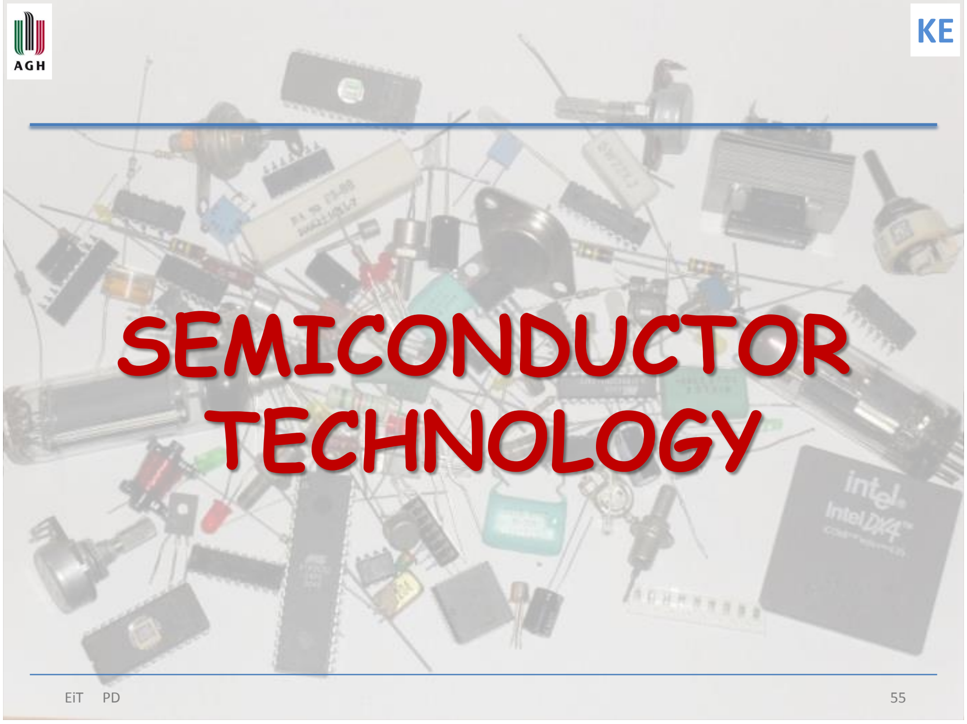
## PELTIER MODULE

**1** – heat sink, **2** – Peltier module, **3** - microstructure

$$Q_h = Q_c + U \cdot I_{pel}$$



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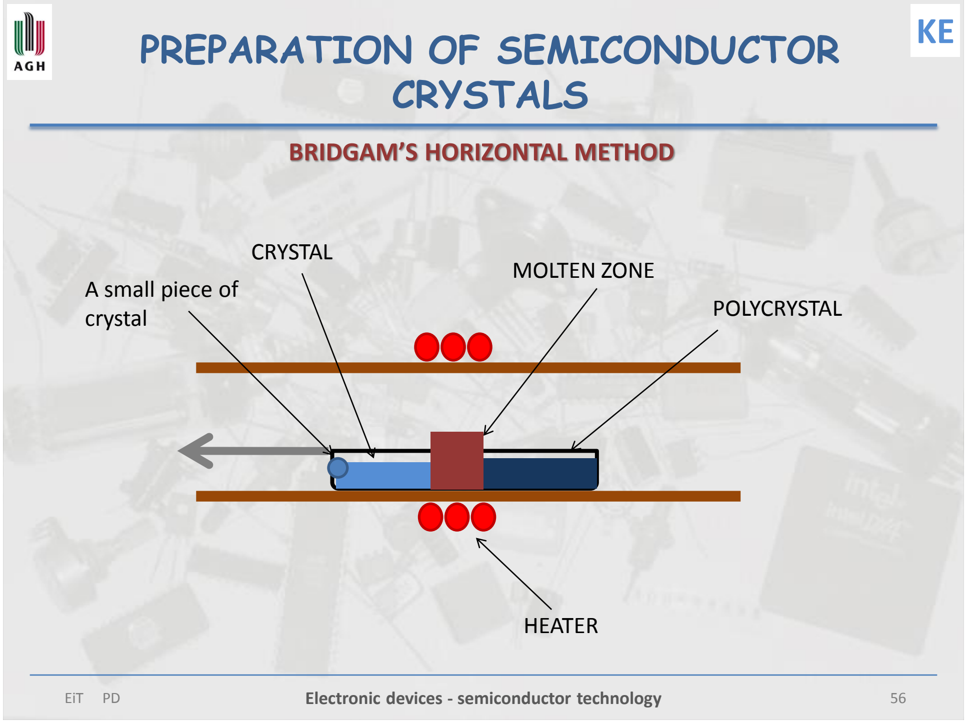
# SEMICONDUCTOR TECHNOLOGY



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## PREPARATION OF SEMICONDUCTOR CRYSTALS

### BRIDGAM'S HORIZONTAL METHOD

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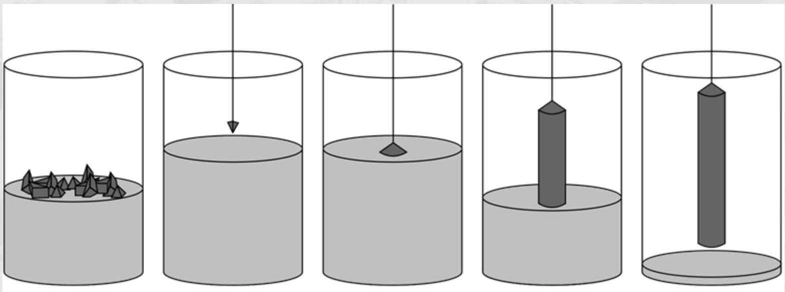
# PREPARATION OF SEMICONDUCTOR CRYSTALS

## CZOCHRALSKI's METHOD



| Melting of silicon polycrystals | Introducing a small piece of crystal | Start of crystal growth | Pulling the crystal from the liquid phase, rotation of the rod | A formed single crystal rod |
|---|---|---|---|---|

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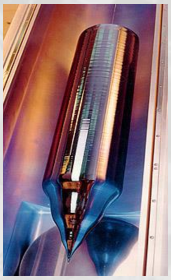
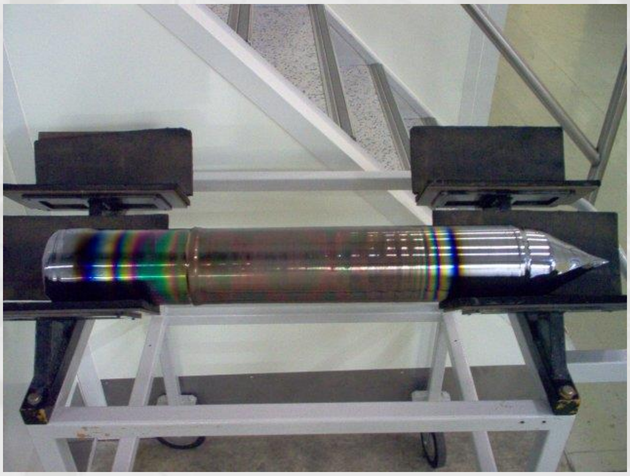
# PREPARATION OF SEMICONDUCTOR CRYSTALS

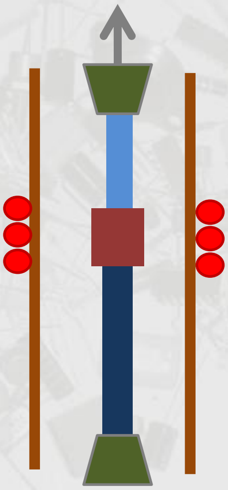
## CZOCHRALSKI's METHOD





# PREPARATION OF SEMICONDUCTOR CRYSTALS

## WITHOUT MELTING POT



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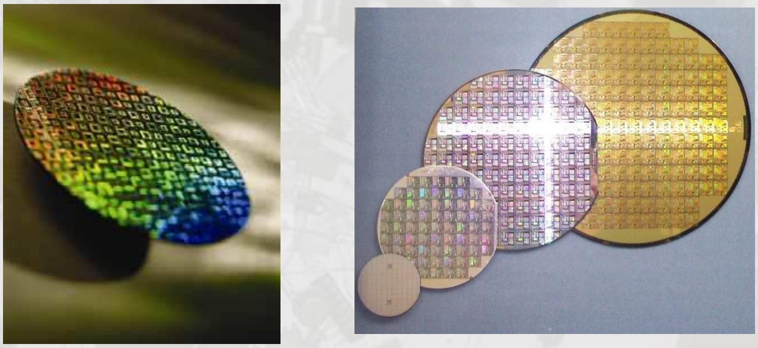
# PREPARATION OF SEMICONDUCTOR CRYSTALS



SEMICONDUCTOR WAFER

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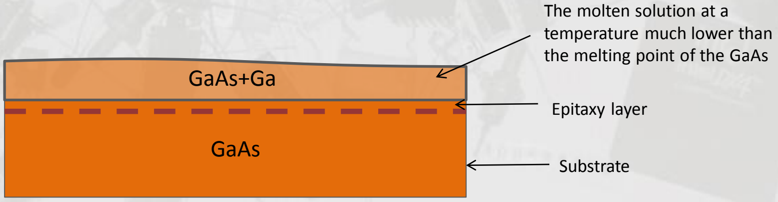
# PREPARATION OF SEMICONDUCTOR CRYSTALS

## EPITAXY

*A semiconductor crystal growth technique from the solutions and the gas phase on the existing crystalline substrate.*

*The most important application of this technique is the production of thin monocrystalline layers.*

*Its main advantage is the possibility of obtaining the semiconductor materials at temperatures much lower than the melting point.*



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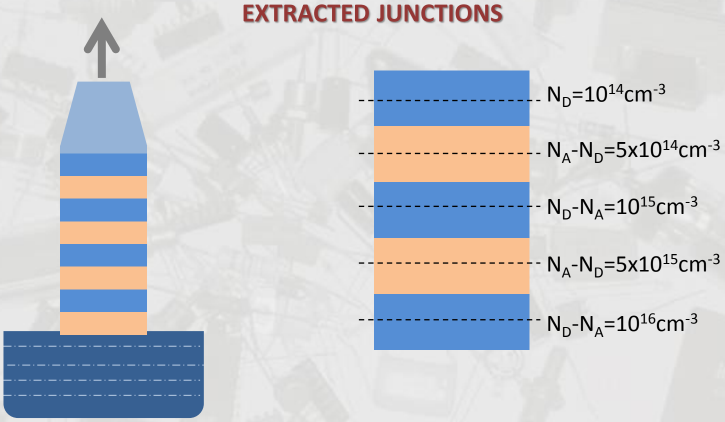
# FORMING P-N JUNCTIONS

## EXTRACTED JUNCTIONS



OVERCOMPENSATION - resultant change in the concentration of dopant

*Extraction method has been replaced by methods consisting in the introduction of dopants after receipt of the single crystal layer, or epitaxy methods of opposite conductivity type to the substrate.*

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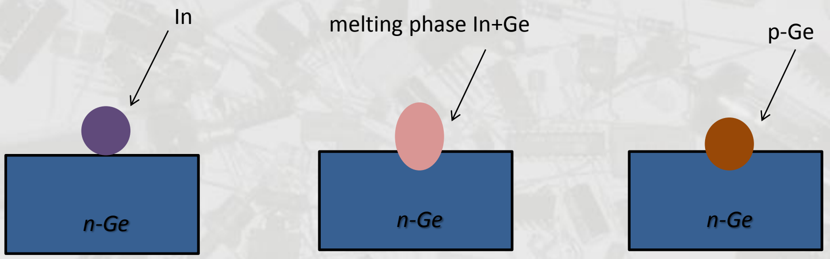
# FORMING P-N JUNCTIONS

## MELTING JUNCTIONS



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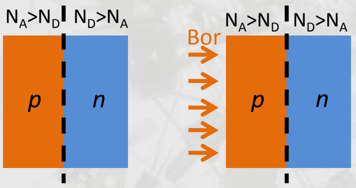
# FORMING P-N JUNCTIONS

## DIFFUSION JUNCTIONS

Diffusion method is currently used on a large scale. It is performed at high temperature.



Diffusion from a source with a finite capacity
Linear junction

Diffusion from a source with a constant performance
Abrupt junction

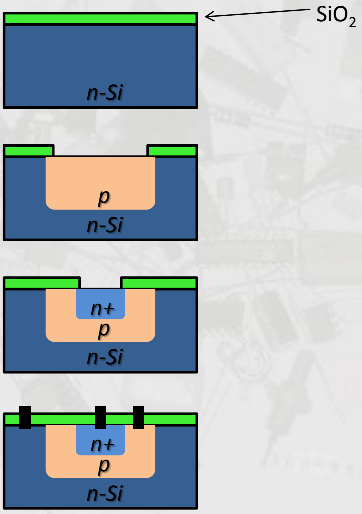
## IONS IMPLANTATION

Implantation is carried out at relatively low temperatures. Implantation can be performed through the oxide layer, but generally does not occur through the layer of metal.

Implantation is used for the preparation of very thin layers, for introducing dopants that can not be introduced by diffusion.

The implantation allows to obtain very precise geometry and quality of the doped areas.

# FORMING N-P-N TRANSISTORS



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# UKŁADY SCALONE

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## INTEGRATED CIRCUIT

**Integrated circuit** – an electronic circuit designed as disconnectable connection of electronic components in a single technological cycle inside, or on a common substrate.

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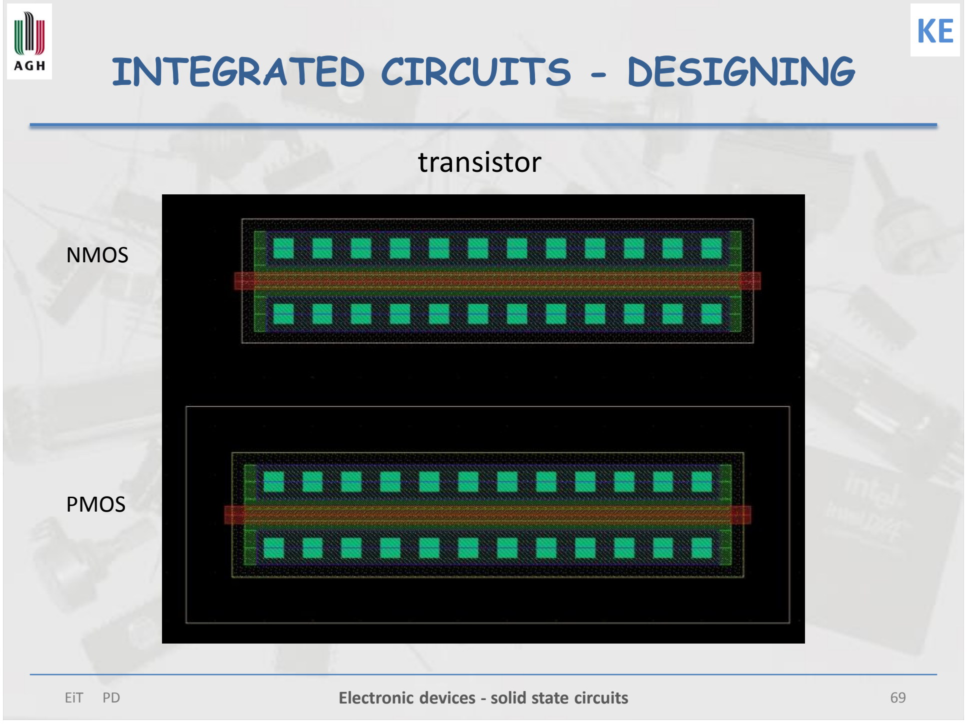
## INTEGRATED CIRCUITS

- Monolithic – made of the "block" of the semiconductor
  - bipolar
  - unipolar
- Hybrid – made on a common substrate
  - thin layer
  - thick layer

- Analogue – for analogue signal processing
- Digital – for digital signal processing



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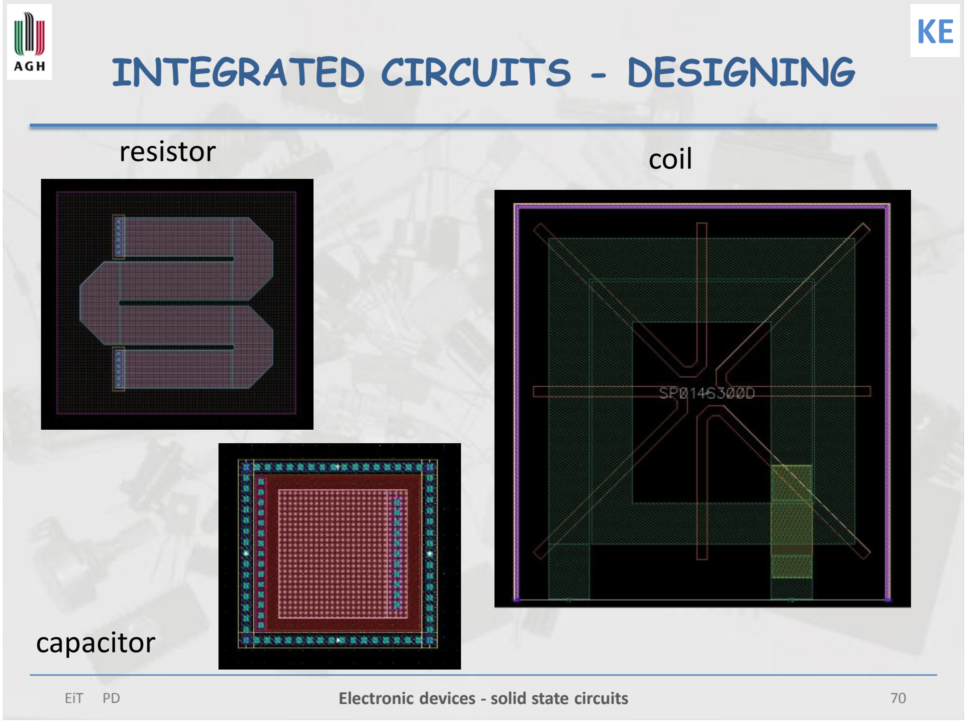
# INTEGRATED CIRCUITS - DESIGNING

transistor

NMOS

PMOS



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# INTEGRATED CIRCUITS - DESIGNING

resistor

coil

capacitor

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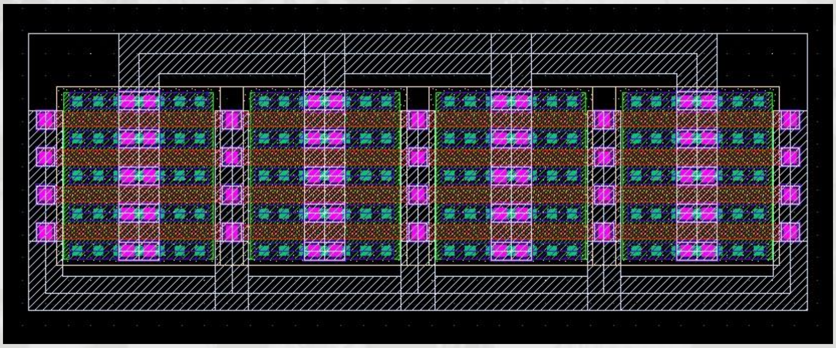
# INTEGRATED CIRCUITS - DESIGNING

varactor



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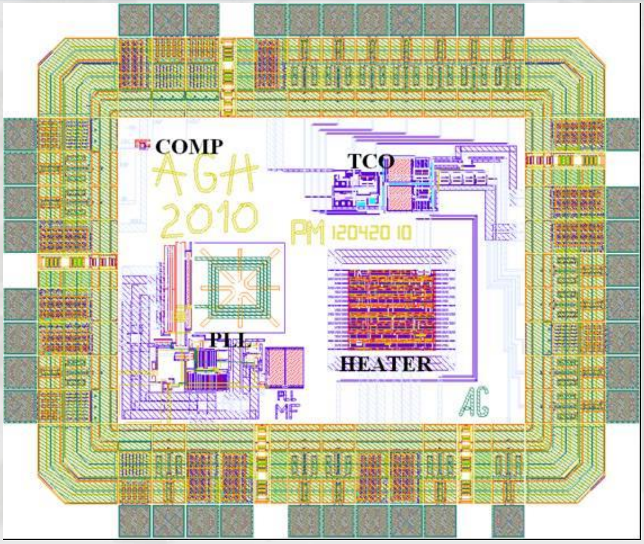
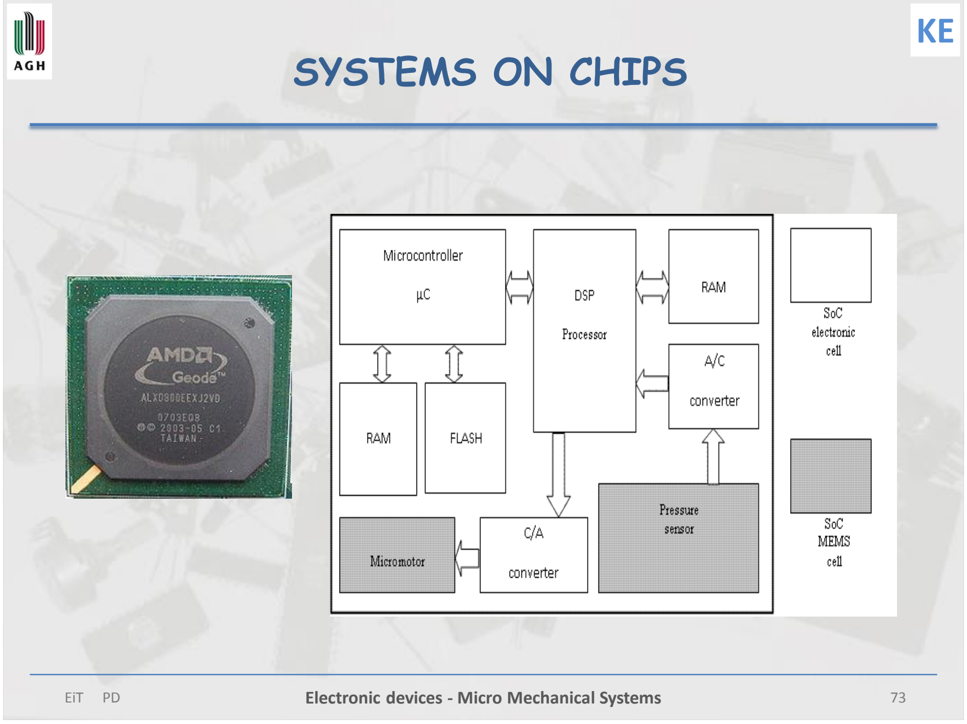
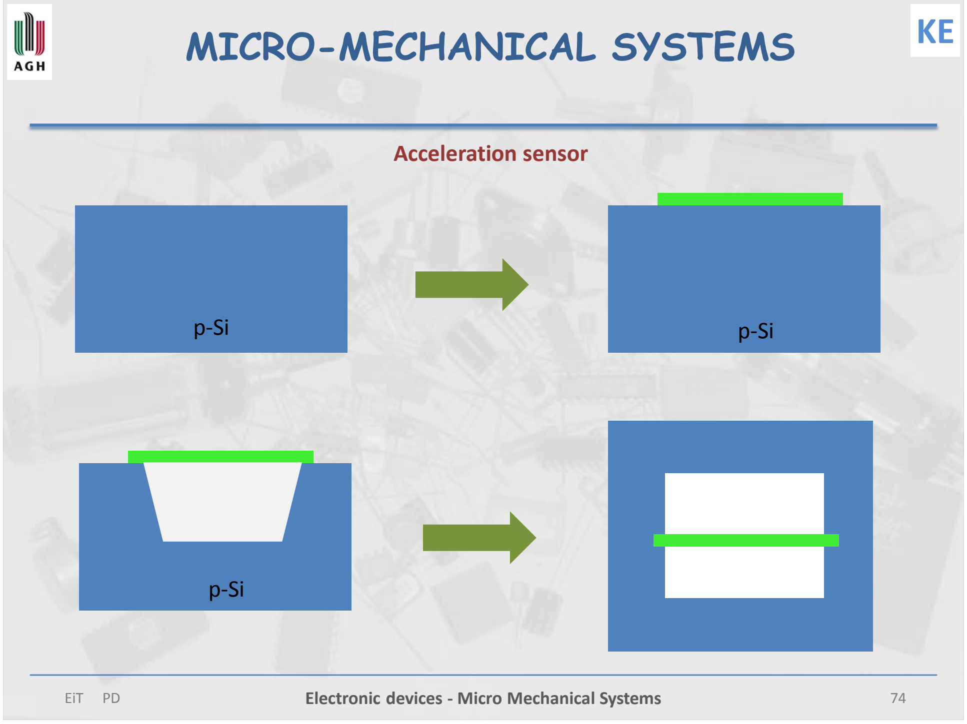
# INTEGRATED CIRCUITS - DESIGNING



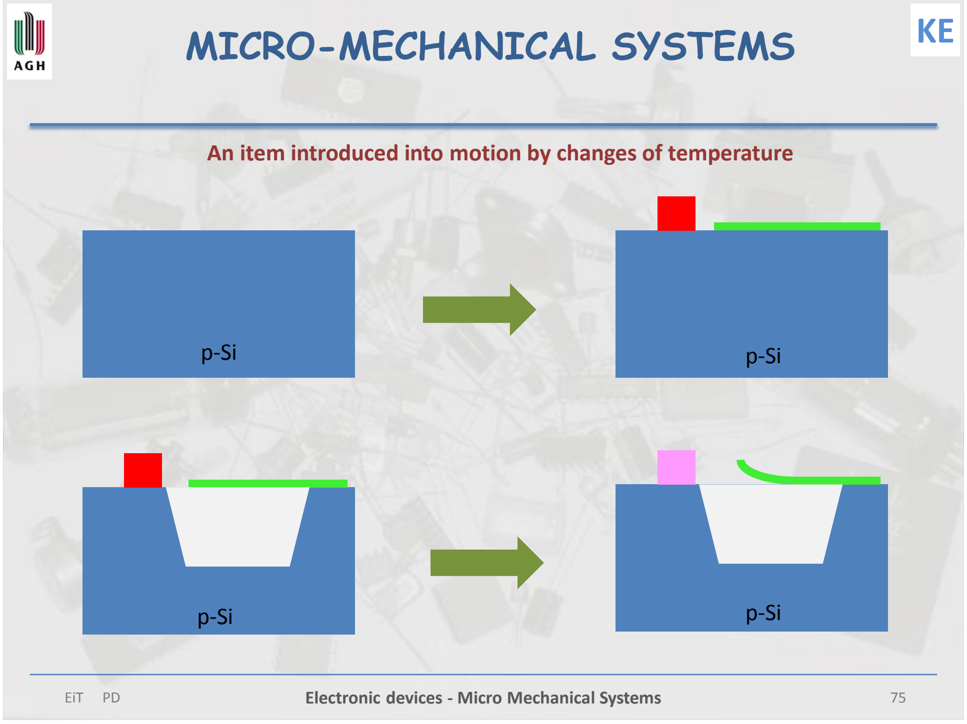


# SYSTEMS ON CHIPS



# MICRO-MECHANICAL SYSTEMS

**Acceleration sensor**



# MICRO-MECHANICAL SYSTEMS

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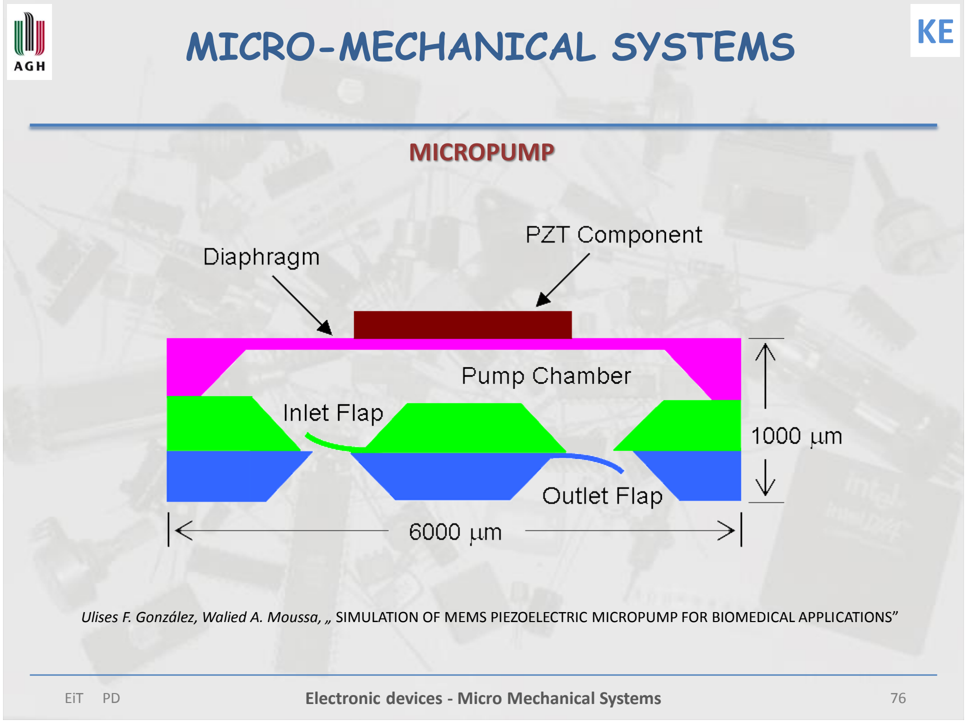
## An item introduced into motion by changes of temperature



# MICRO-MECHANICAL SYSTEMS

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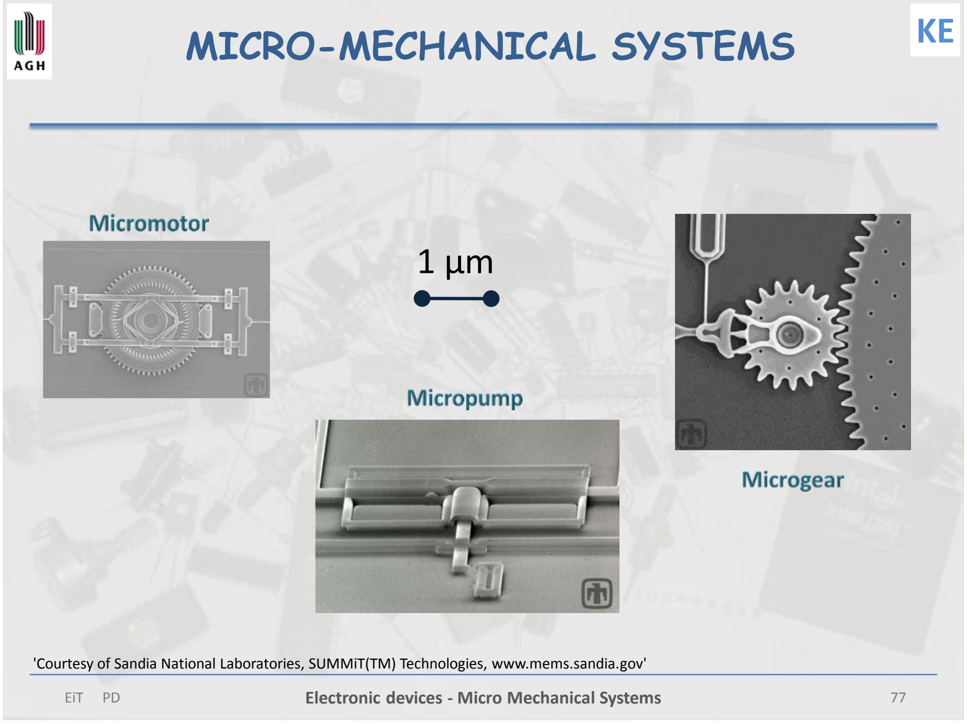
## MICROPUMP

*Ulises F. González, Walied A. Moussa*, „ SIMULATION OF MEMS PIEZOELECTRIC MICROPUMP FOR BIOMEDICAL APPLICATIONS"



# MICRO-MECHANICAL SYSTEMS

'Courtesy of Sandia National Laboratories, SUMMiT(TM) Technologies, www.mems.sandia.gov'