Digital systems and basics of electronics

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Semiconductors - diodes and transistors - Lecture 4

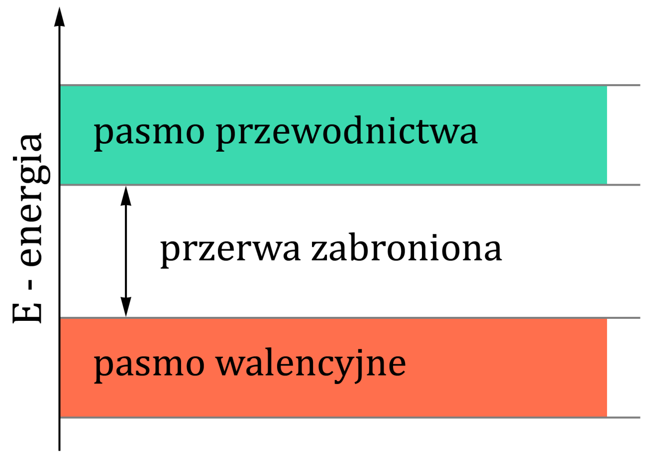
Semiconductor

- A *semiconductor* has electrical conductivity in between that of a *conductor* and that of an *insulator*,
- That conductivity can be controlled over a wide range,
- Semiconductors are tremendously important in technology.
- Silicon (Si) is used to create most semiconductors commercially, but dozens of other materials are used as well.

Semiconductor

- *Semiconductors* are very similar to insulators. *Insulators have larger band gaps* — energies that electrons must acquire to be free to move from atom to atom.
- In semiconductors at room temperature, just as in insulators, very few electrons gain enough thermal energy to leap the band gap from the valence band to the conduction band, which is necessary for electrons to be available for electric current conduction.

Semiconductor band structure - valence band



The *valence band* is the highest range of electron energies where electrons are normally present at absolute zero. In semiconductors and insulators, there is a bandgap above the valence band, followed by a conduction band above that. In metals, the conduction band has no energy gap separating it from the valence band.

Electron Holes

An *electron hole* is the concept describes the lack of an electron (different from the positron). The electron hole was introduced into calculations:

- If an electron is excited into higher state it leaves a hole in its old state.
- Used to attach the sign onto the electrical charge.

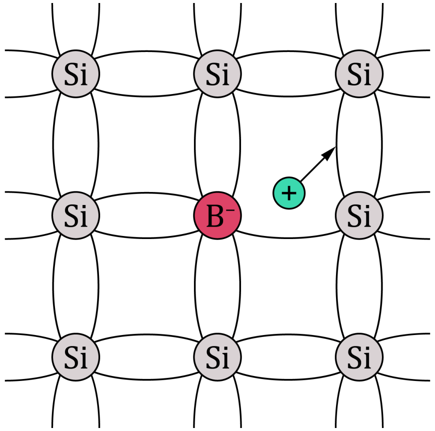
Intrinsic semiconductor i-type

- An *intrinsic semiconductor*, also called an *undoped* semiconductor or *i-type semiconductor*, is a pure semiconductor without any significant dopant species present. The number of charge carriers is therefore determined by the properties of the material itself instead of the amount of impurities. In intrinsic semiconductors the number of electrons and the number of holes are equal. $n = p$.
- The conductivity of intrinsic semiconductors can be due to crystal defects or to thermal excitation. In an intrinsic semiconductor the number of electrons in the conduction band is equal to the number of holes in the valence band.

Dopants

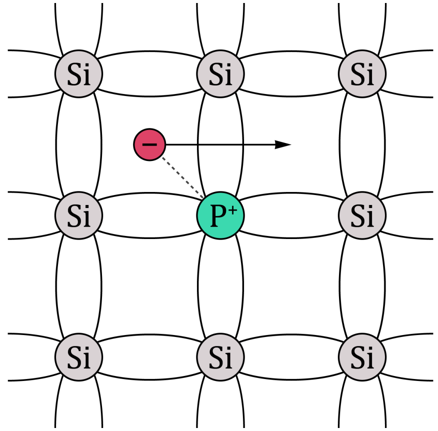
- Dopants that produce the desired controlled changes are classified as either electron acceptors or donors.
- *Donor* atom that activates valence electrons, creating excess negative charge carriers. Electrons at these states can be easily excited to conduction band, becoming free electrons. Semiconductors doped with donor impurities are called *n-type*.
- *Acceptor* produces a hole. Those doped with acceptor impurities are known as *p-type*.

Acceptors *p-type* semiconduct



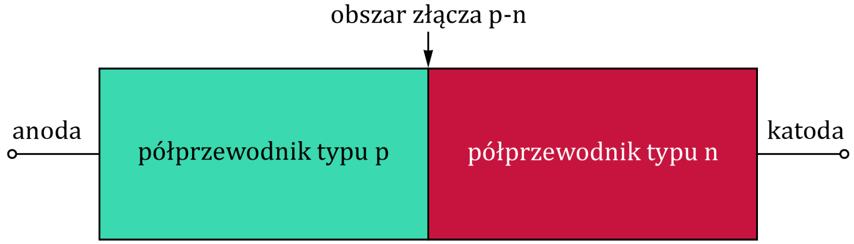
- When the silicon atoms (Si) (having four valence electrons) is doped with elements having three valence electrons (eg. Boron (B) or aluminum (Al) are of group III) there is a deficiency of electrons.
- Holes behave as a quantity of positive charge.
- The initially so doped semiconductor becomes positively charged.

Donors *n-type* **semiconductor**



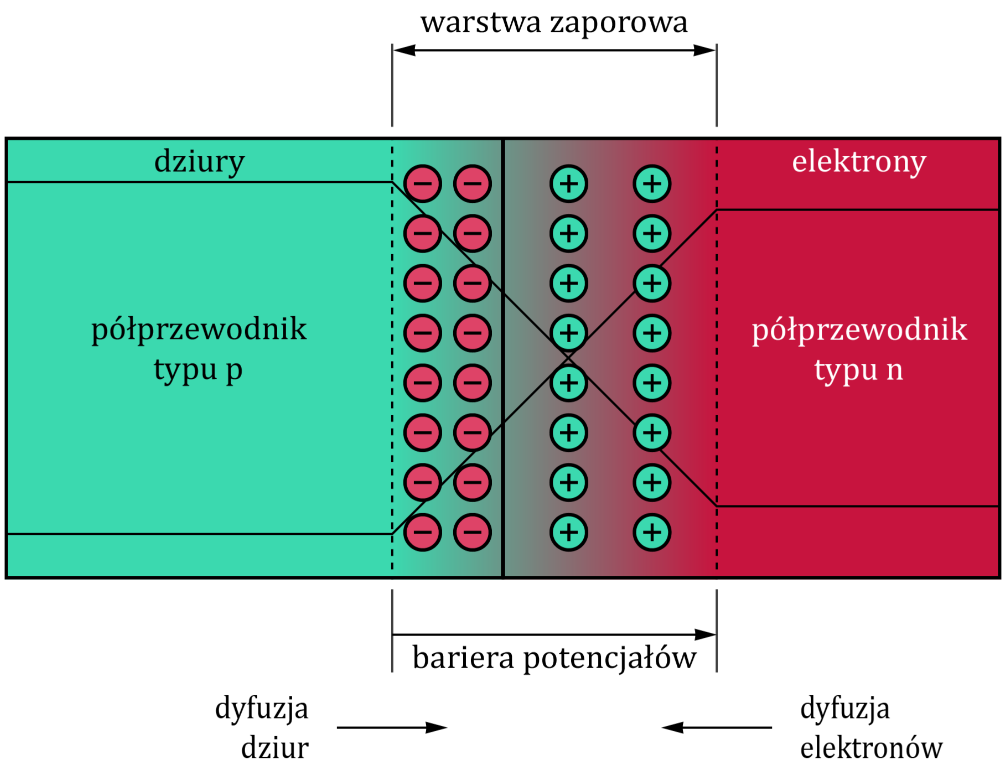
- When silicon atoms (Si) (having four valence electrons) is doped with elements having five valence electrons (eq. Phosphorus (P) or Arsenic (As) are group of V) there is the redundancy of electrons.
- additional electrons cause the semiconductor is negatively charged,
- The initially neutral donor becomes negatively charged.

p-n junction



- A p-n junction is formed by combining P-type and N-type semiconductors together in very close contact.
- The term *junction* refers to the region where the two types of semiconductor meet (border region between the P-type and N-type).
- P-doped and N-doped semiconductors are relatively conductive, but the junction between them is a nonconductor.
- In nonconducting layer electrons and holes attract and eliminate each other in a process called *recombination*.

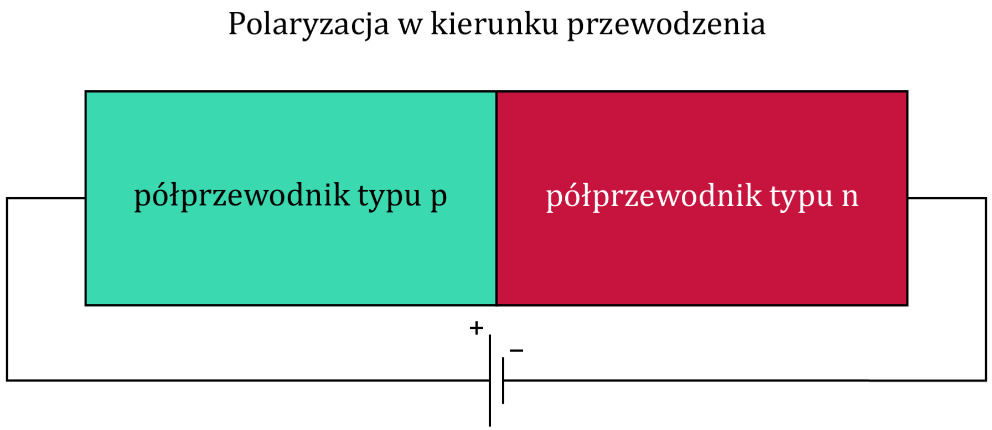
Charges in *p-n junction* region



- In a *p-n junction*, without an external applied voltage, an equilibrium condition is reached in which a potential difference is formed across the junction. This potential difference is called built-in potential V_{bi}.

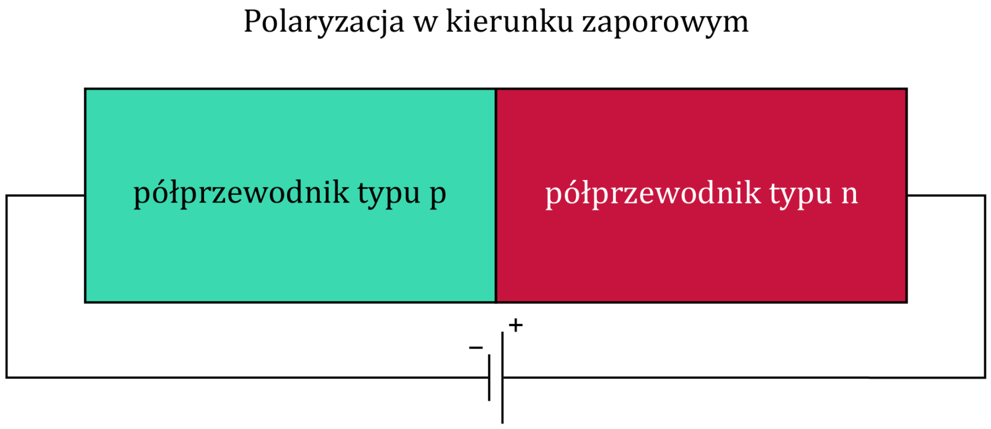
- In *p-n junction*, electrons near the junction diffuse into the p region. As electrons diffuse, they leave positively charged ions (donors) on the n region. Similarly holes near the p-n junction diffuse in the n-type region.
- The regions of *p-n junction* lose their neutrality and become charged, forming the space charge region or depletion layer.

Forward-bias



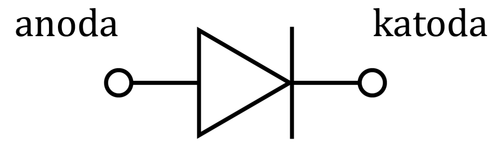
- Forward-bias occurs when the P-type block is connected to the positive terminal of a battery and the N-type block is connected to the negative terminal.
- As electrons and holes are pushed towards the junction, the distance between them decreases. This lowers the barrier in potential.

Reverse-bias



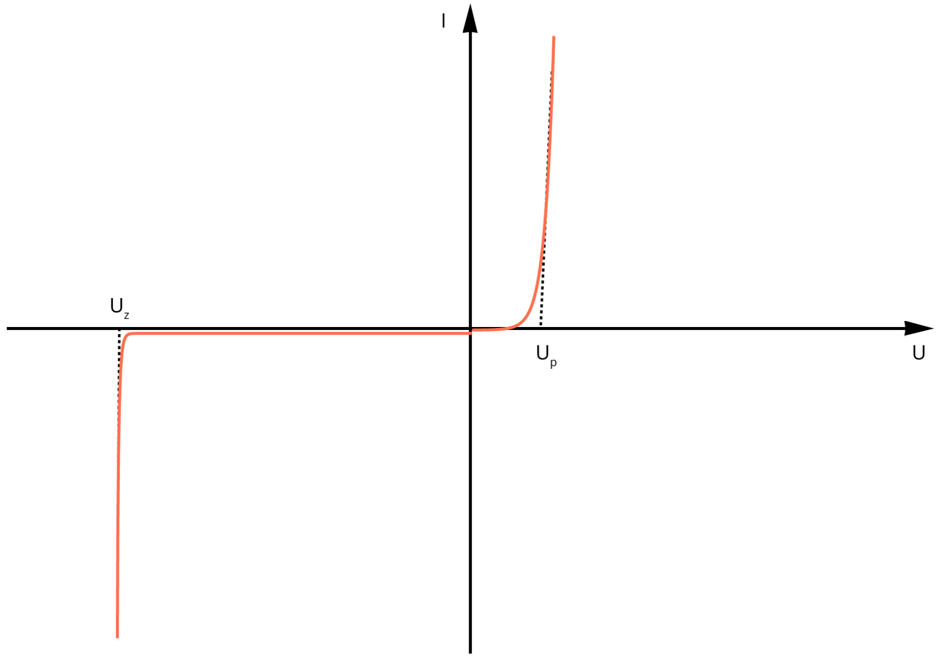
- Connecting the P-type region to the negative terminal of the battery and the N-type region to the positive terminal, produces the reverse-bias effect.
- This effectively increases the potential barrier and greatly increases the electrical resistance against the flow of charge carriers.

Diode



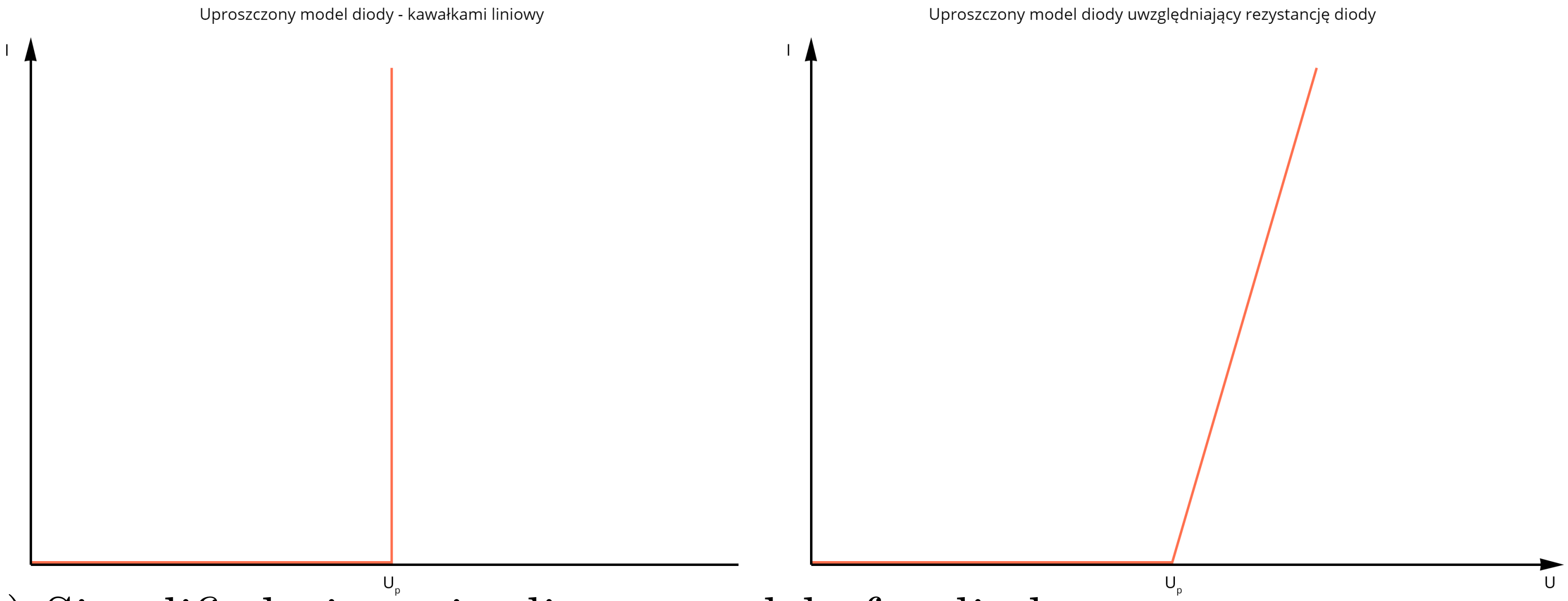
- *p-n junctions* are commonly used as *diodes* - electrical switches that allow a flow of electricity in one direction but not in the other (opposite) direction.
- This property is explained in terms of the forward-bias and reverse-bias effects, where the term bias refers to an application of electric voltage to the p-n junction.

Diode characteristic



- Diode is to allow an electric current to flow in one direction (forward biased) and to block it in the opposite direction (reverse biased).
- Real diodes do not display such a perfect on-off directionality but have a more complex non-linear electrical characteristic.

Simplified diode characteristics

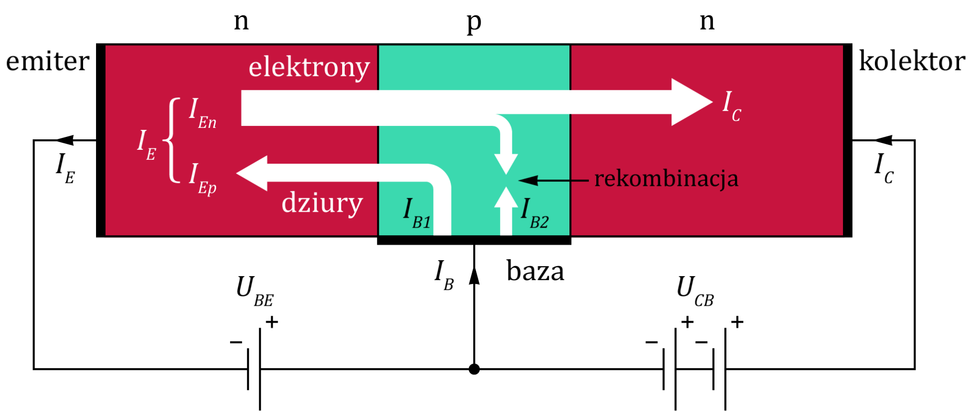


(a) Simplified piecewise linear model of a diode

(b) improved piecewise linear model of a diode.

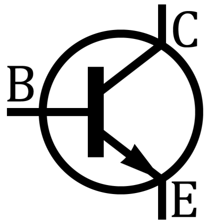
The diode cut-in voltage V_{D0} is defined as the voltage V_D at a very small current I_D typically at about $1nA$. For silicon diodes this voltage is typically $V_{D0} = 0.6V$.

Bipolar Junction Transistor



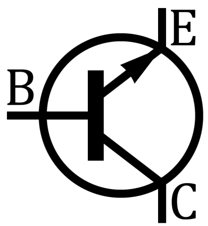
- It is a three-terminal device constructed of doped semiconductor material and may be used in amplifying or switching applications.
- Bipolar transistors involves both electrons and holes.

NPN bipolar transistor



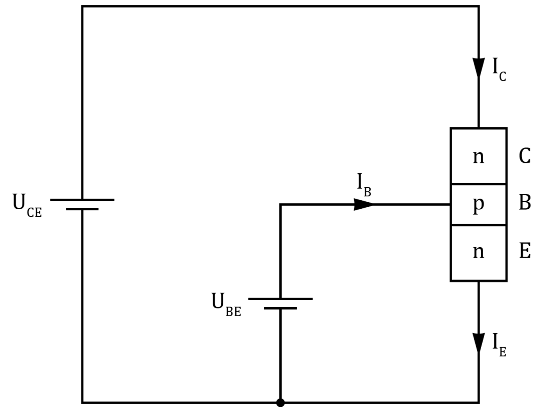
- Most bipolar transistors used today are NPN, because electron mobility is higher than hole mobility in semiconductors.
- NPN transistors consist of a layer of P-doped semiconductor (the "base") between two N-doped layers.
- The arrow in the NPN transistor symbol is on the emitter leg and points in the direction of the conventional current flow when the device is in forward active mode.

PNP bipolar transistor



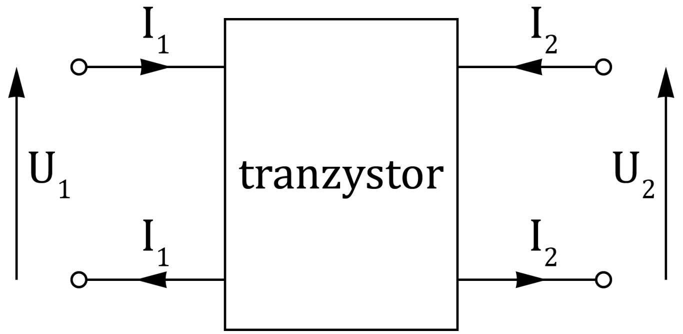
- Few transistors used today are PNP.
- The symbol of a PNP transistors consist of a layer of N-doped semiconductor between two layers of P-doped material.
- The arrow in the PNP transistor symbol is on the emitter leg and points in the direction of the conventional current flow when the device is in forward active mode.

Transistors in circuits



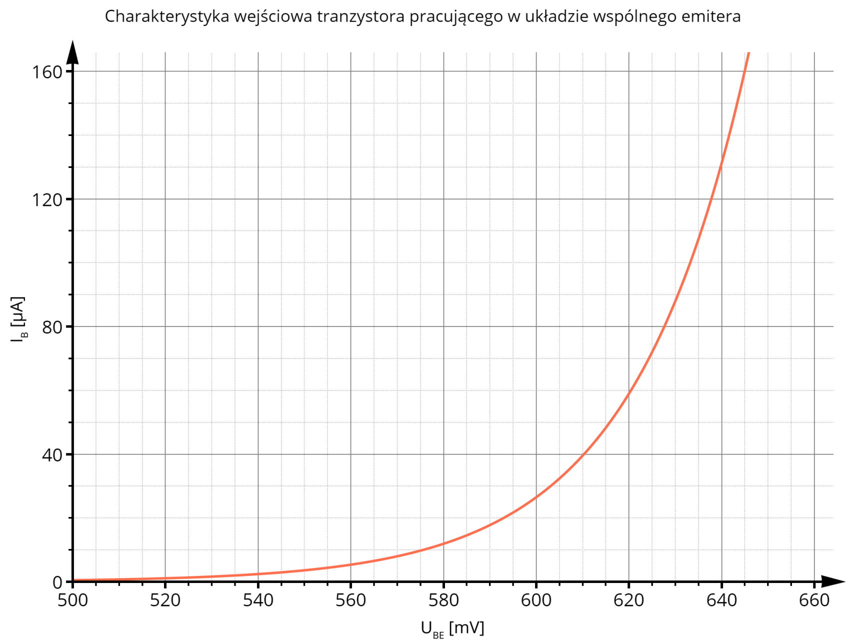
- To make the transistor conduct current from C to E must be above a minimum value (about $1mA$) then base-emitter voltage V_{BE} reaches *cut-in voltage* (usually about $600mV$).
- *Cut-in voltage* allowing a flow of electrons from the emitter into the base. The electric field between base and collector attracts these electrons cross the base-collector junction (current I_C).
- The ratio of the collector current to the base current is called the *DC current gain*. This gain is usually quite large and is often 100 or more

Transistor characteristics



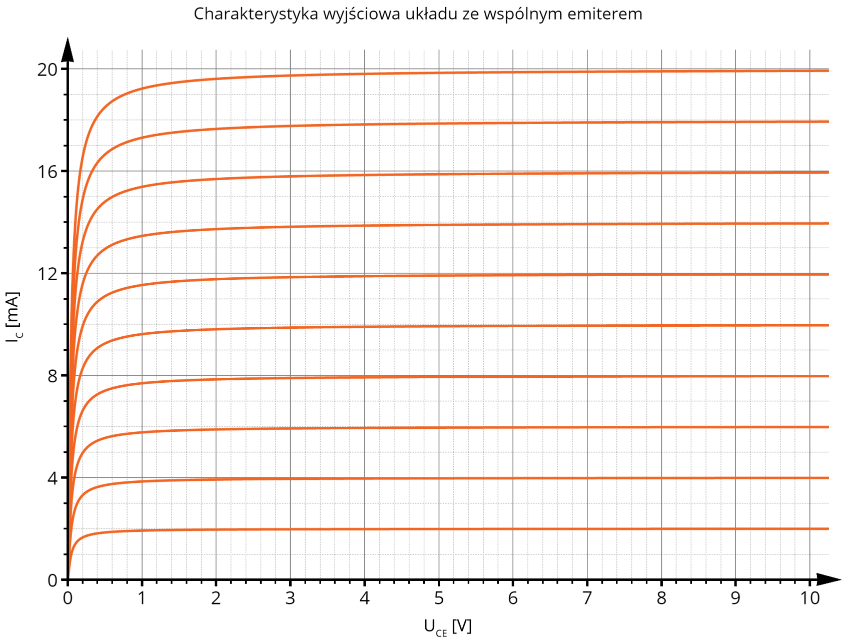
- input characteristic (input variables dependencies)
- output characteristic (output variables dependencies)
- transfer characteristics (input-output variables dependencies)

Common emitter input characteristic



- base-emiter junction in forward biased
- $J_B = f(U_{BE})$ - Base current as function of base-emiter voltage

Set of common emitter output characteristics



- $J_C = f(U_{CE})$ - Collector current as function of collector-emiter voltage

Transfer characteristic

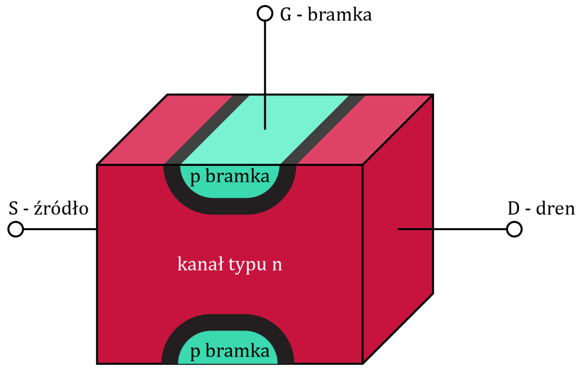
- $J_C = f(J_B)$ describes linear dependency.
- $\beta = \frac{J_c}{J_b}$ - amplification current gain

Operating (working) point

DC analysis

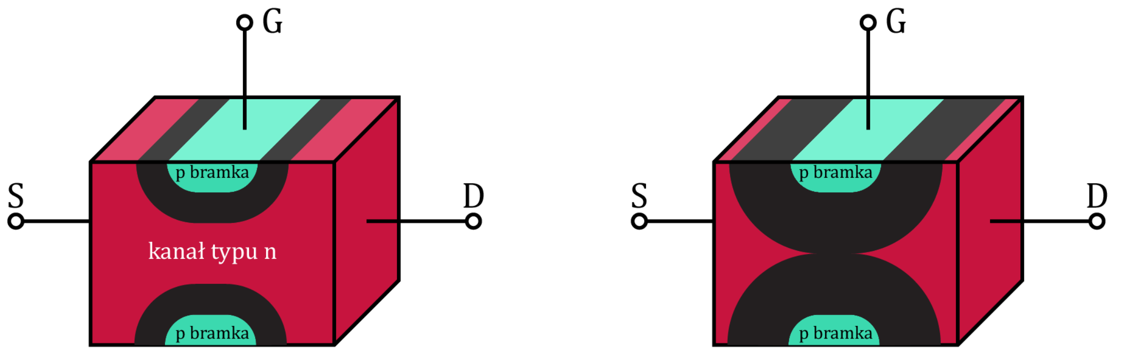
- Base current J_B and voltage base-emitter U_{BE} on input characteristic
- Collector current J_C and emitter-collector voltage U_{CE} on output characteristic

Junction Gate Field-Effect Transistor



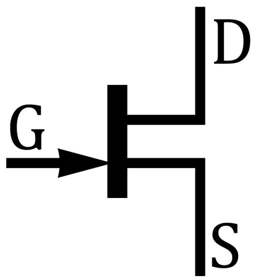
- Junction Gate Field-Effect Transistor (JFET) is the simplest type of field effect transistor.
- It is also used as a voltage-controlled resistance. An electric current flows from one connection, called the source, to a second connection, called the drain.
- A third connection, the gate, determines how much current flows. By changing gate voltage the current flow from source to drain can be controlled by pinching the channel (channel resistance).

Width channel control

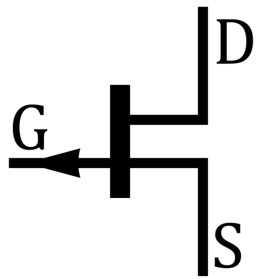


- In this JFET an conducting channel (n-type) exists between drain and source. The gate is a p-type region that surrounds the n-type channel. The *gate-channel p-n junction* is normally kept reverse-biased.
- As the reverse bias voltage between gate and channel increases, the depletion region width increases.
- As the gate voltage increases, the channel gets further constricted, and the current flow gets smaller. Finally when the depletion regions meet in the middle of the channel and current stop flowing.

Schematic symbols

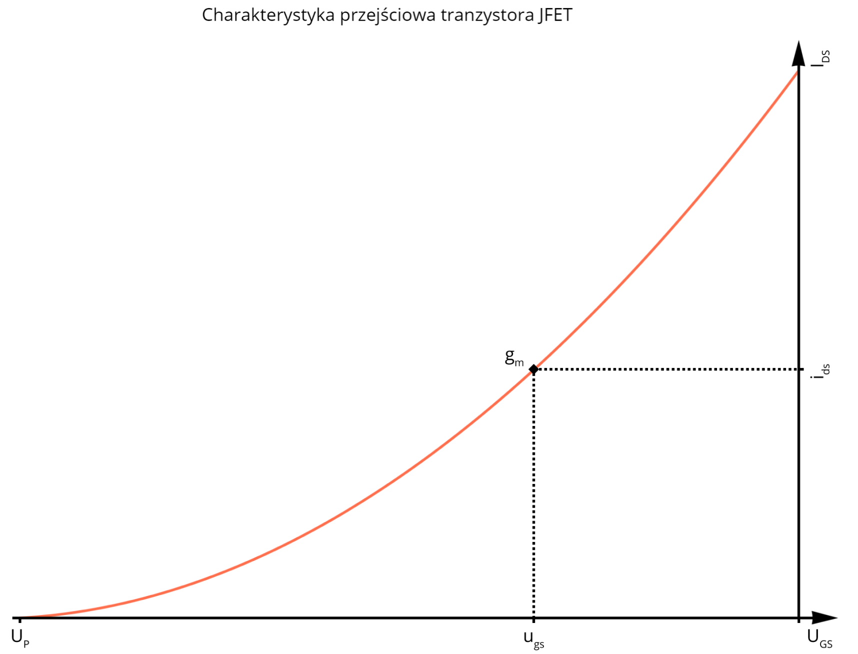


Kanał typu n



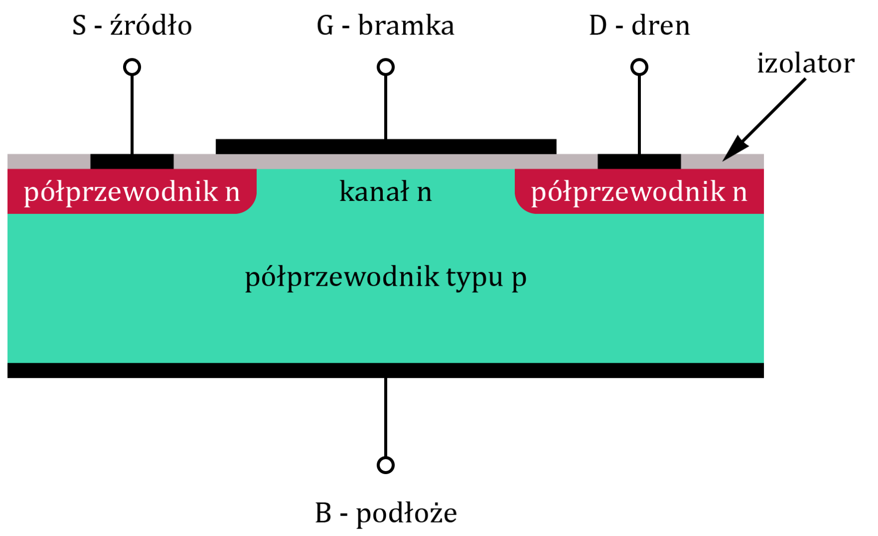
Kanał typu p

Transfer characteristic, trans-conductance.



- INPUT: gate voltage V_{GS}
- OUTPUT: dren current I_{DS}
- TRANSCONDUCTANCE: $g_m = \frac{OUTPU}{INPUT} = \frac{dI_{DS}}{dV_{GS}}$

Metal Oxide Semiconductor Field Effect Transistor - MOSFET



- MOSFET (Metal-Oxide Semiconductor Field-Effect Transistor) – field-effect transistors with insulated gate
- Most systems today are made with this technology - particularly in digital systems.
- There are transistors with channel n or channel p.