Advanced MOSFETs and Novel Devices

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2. Tutorial & Exercise

Band Diagrams

Exercise #2

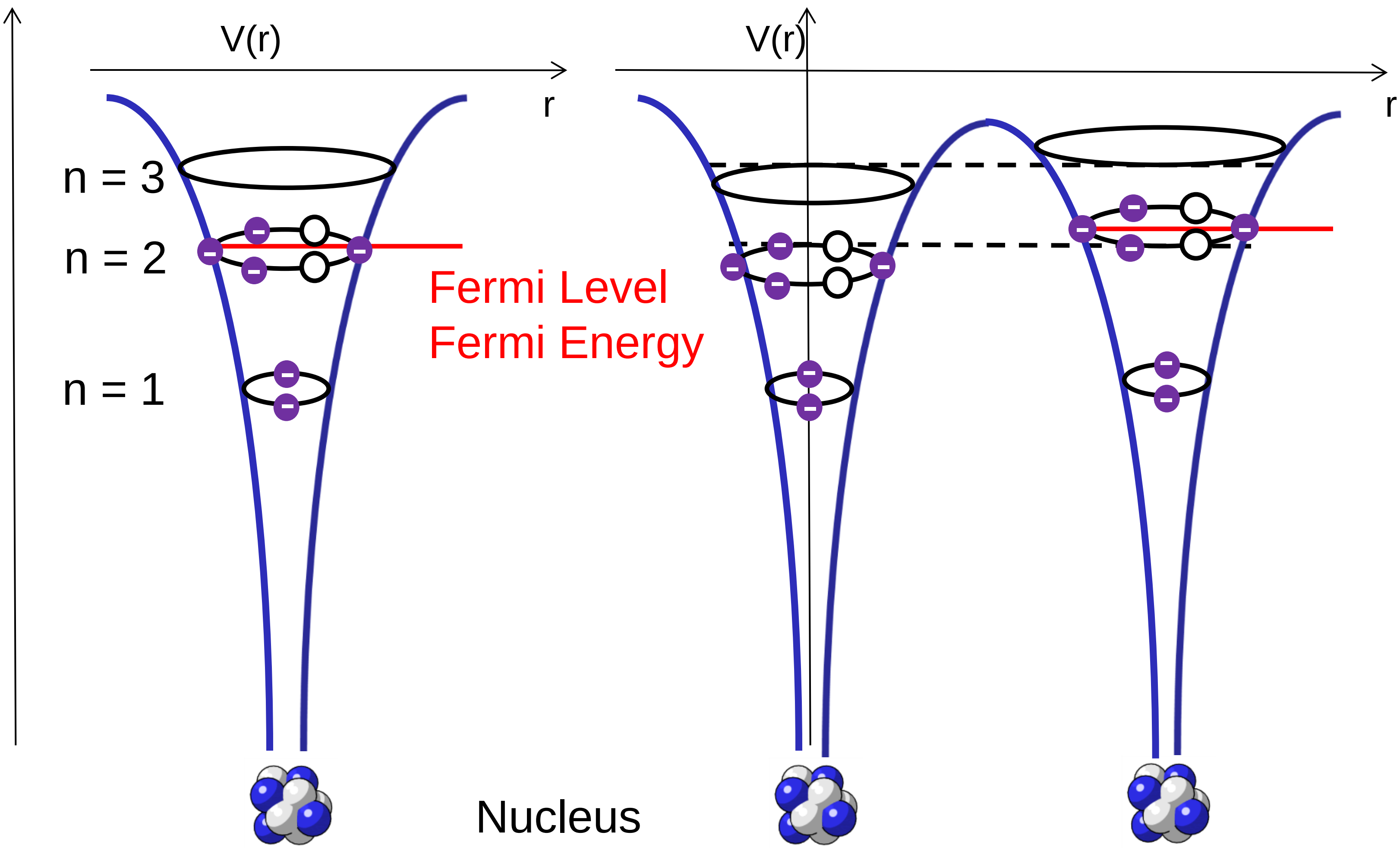
1 Tutorial: Band Diagrams

2 Band structure: n – MOSFET

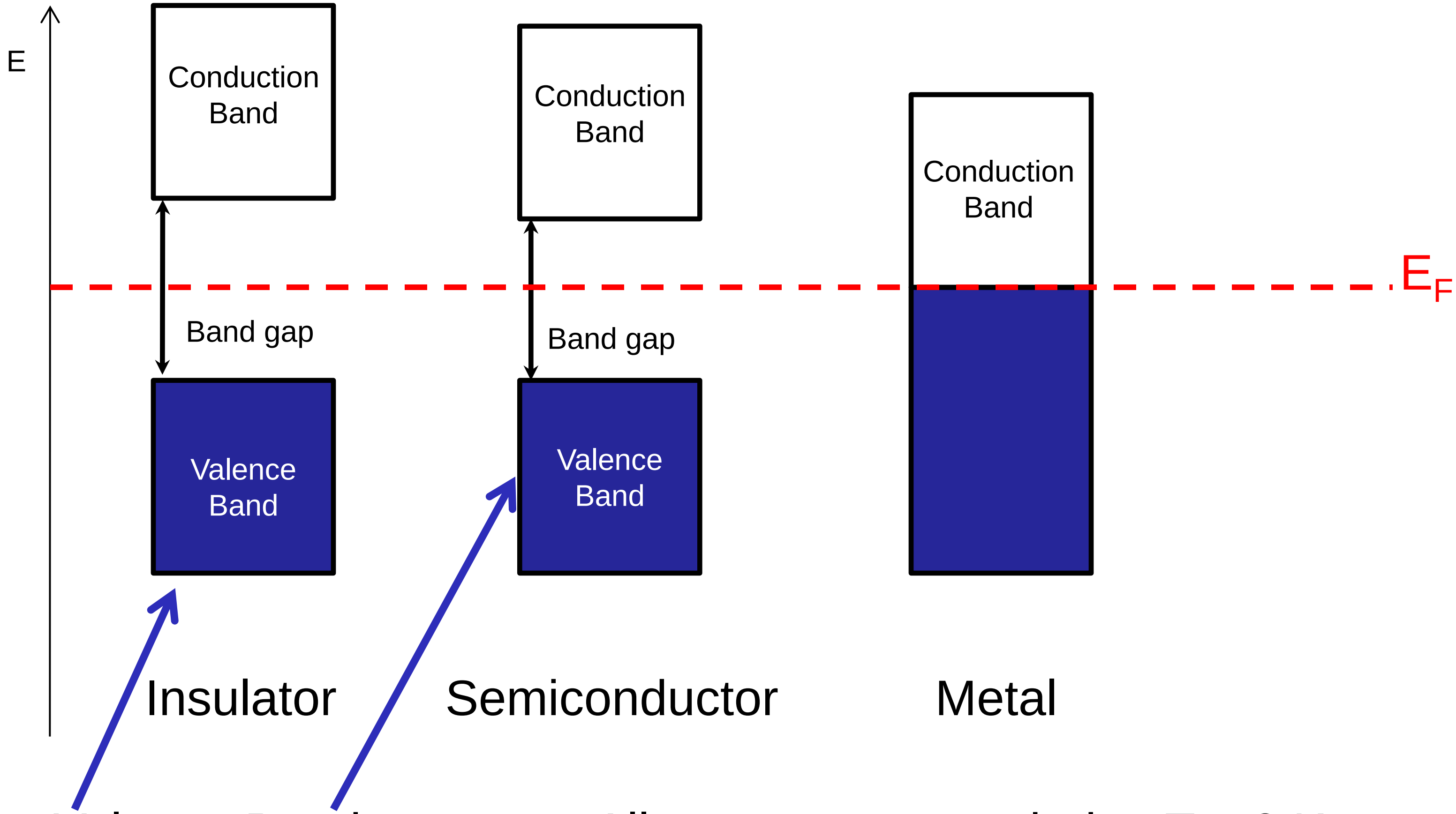
1 Tutorial: Band Diagrams

2 Band structure: n – MOSFET

Electron Energy Levels

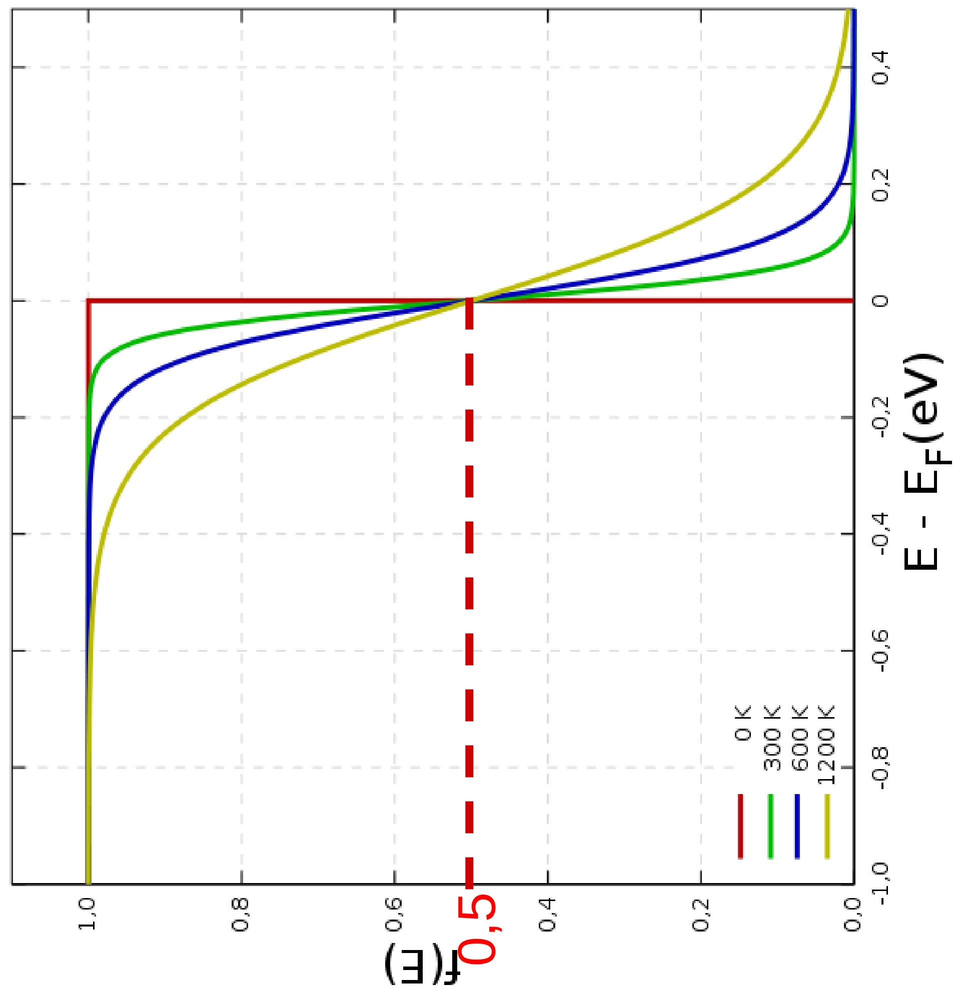


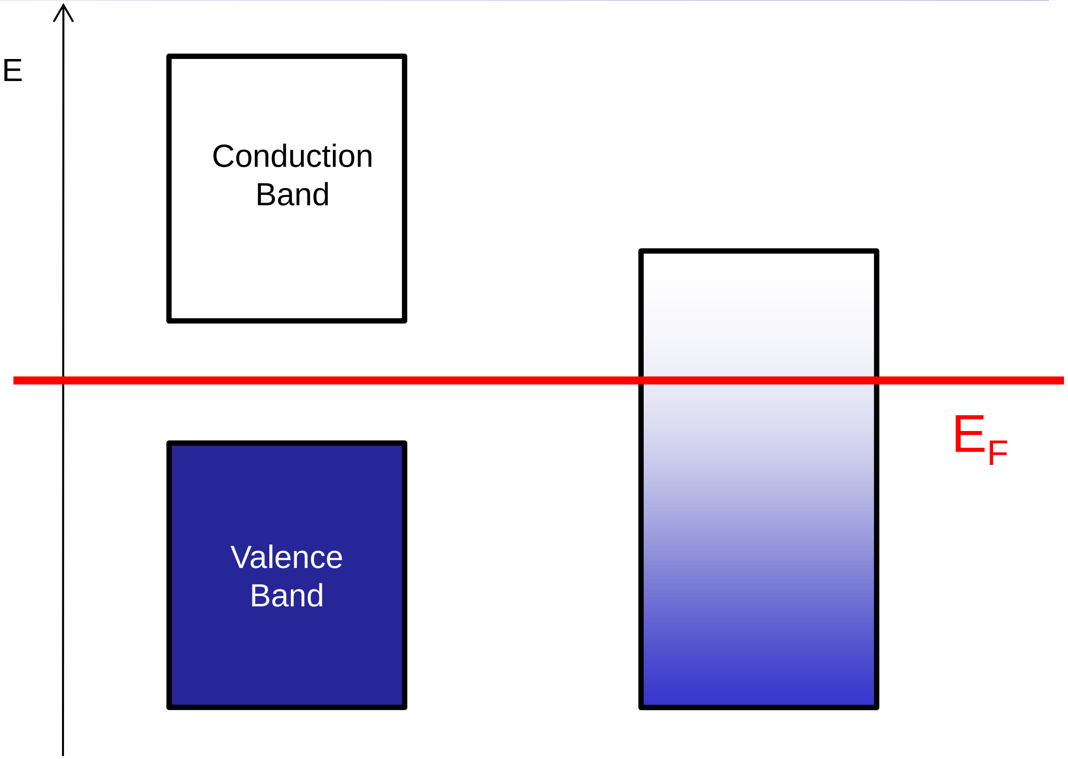
Band Diagrams - Introduction



Valence Band: All states are occupied at T = 0 K.
Conduction Band: At T = 0 K empty or partially filled.

T = 0 K means that there is no thermal excitation energy.

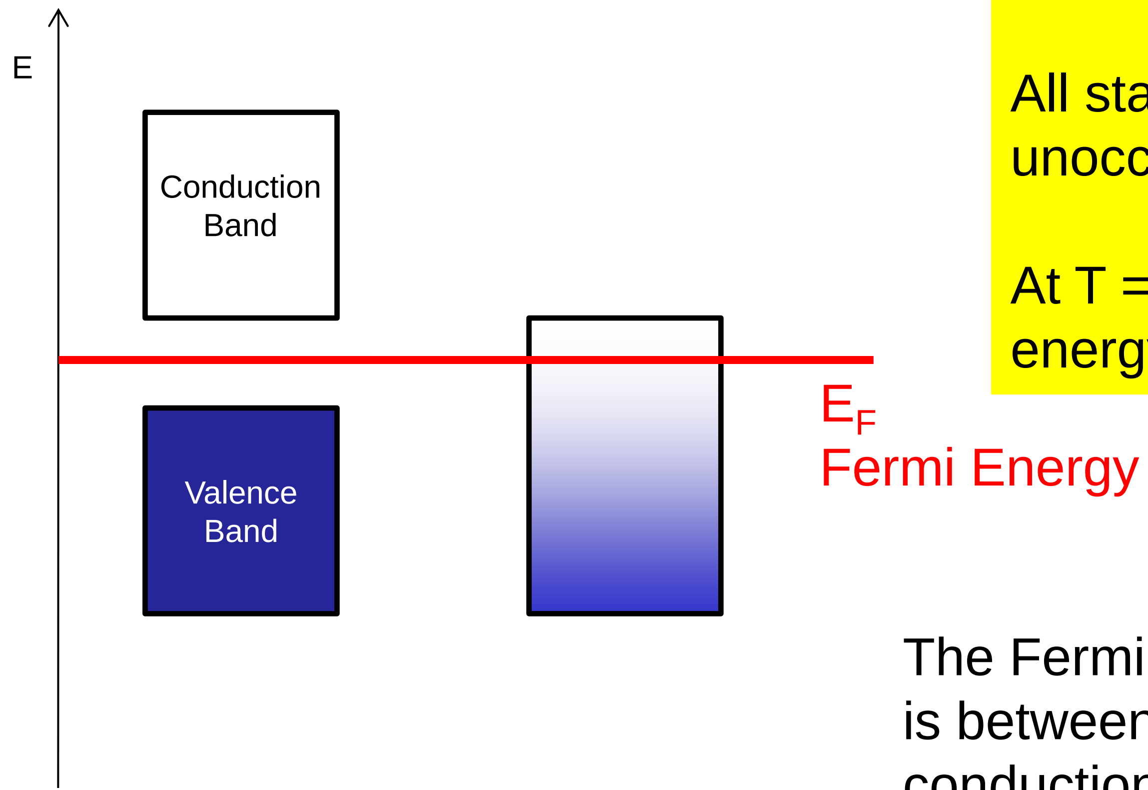




The Fermi – Dirac distribution shows how many fermions have a specified amount of energy, depending on the temperature.

$$f(E) = \frac{1}{exp\left(\frac{E - E_F}{k_B T}\right) + 1}$$

Band Diagrams - Introduction



Fermi Energy is the energy of the highest occupied state at T = 0 K.

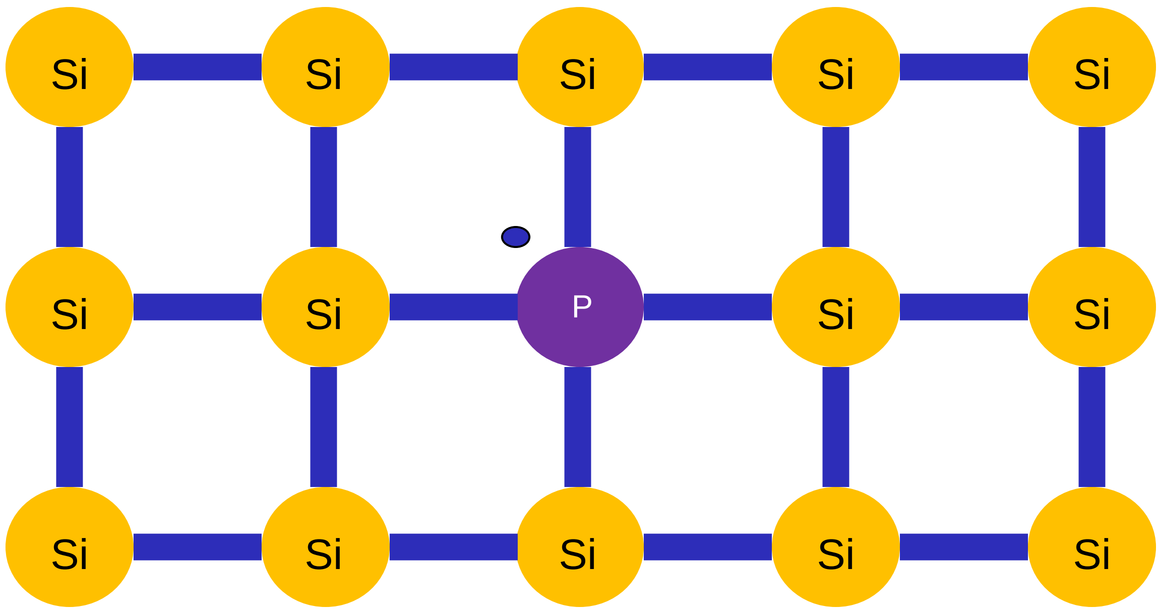
All states above the Fermi Energy are unoccupied at T = 0 K.

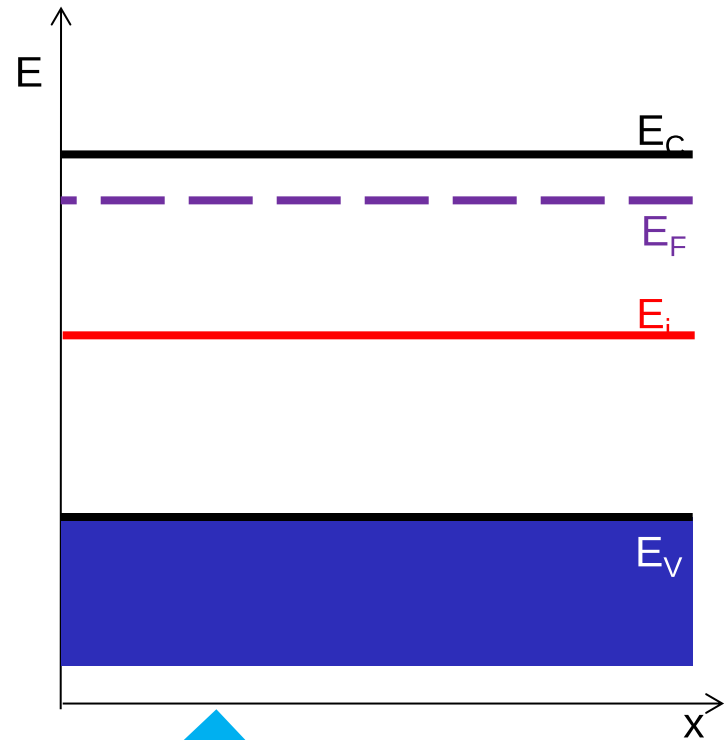
At T = 0 K there is no thermal excitation energy.

The Fermi level of an intrinsic semiconductor is between the valence band and the conduction band.

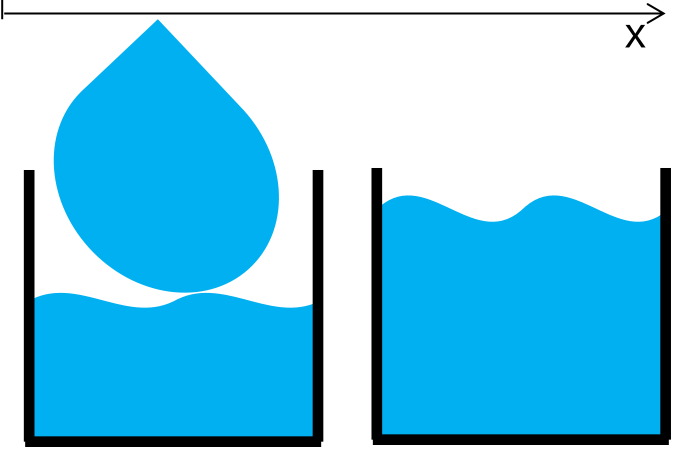
Band Diagrams - Introduction

n - Doping





$$E_F = E_i + k_B T\, ln\left(\frac{n}{n_i}\right)$$

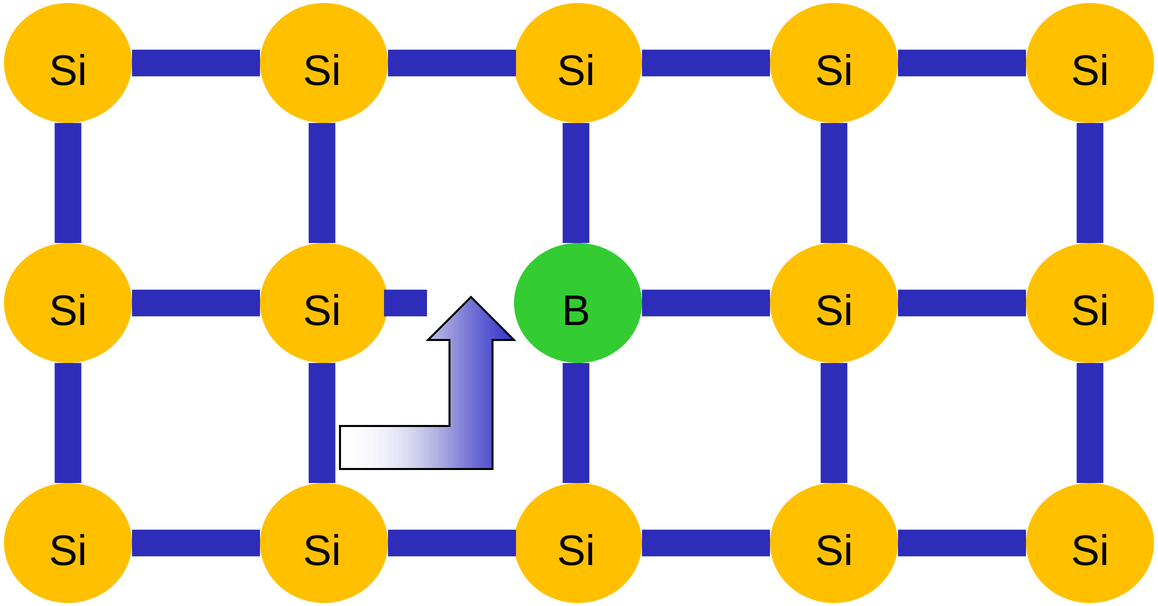


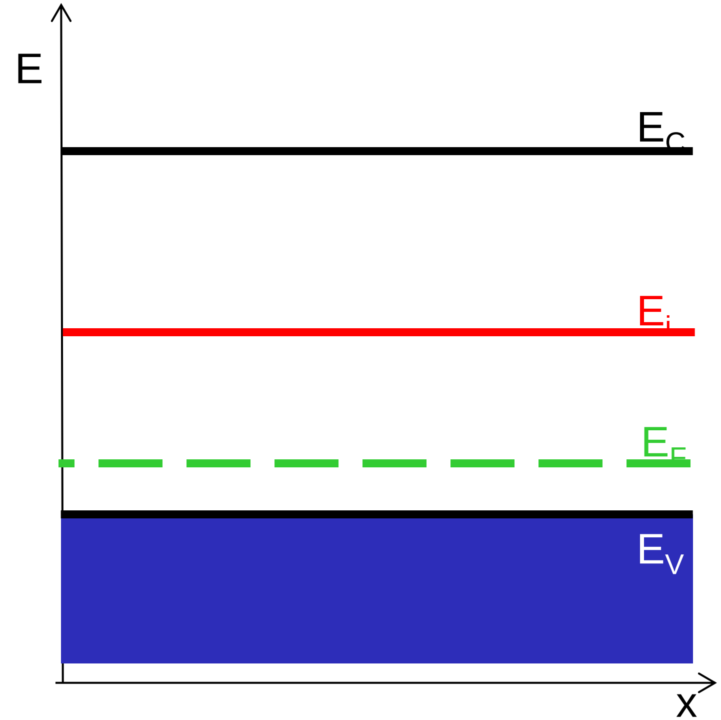
n: Concentration of free electrons.
Can move freely in crystal → fast.

n_i: Intrinsic carrier concentration.

E_i: Fermi energy in semiconductor without impurities.

p - Doping



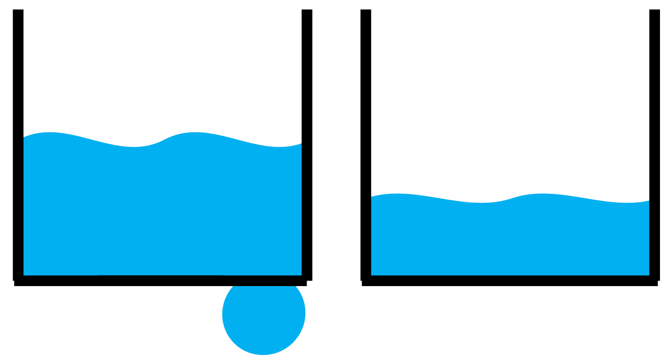


$$E_F = E_i - k_B T \ln\left(\frac{p}{n_i}\right)$$

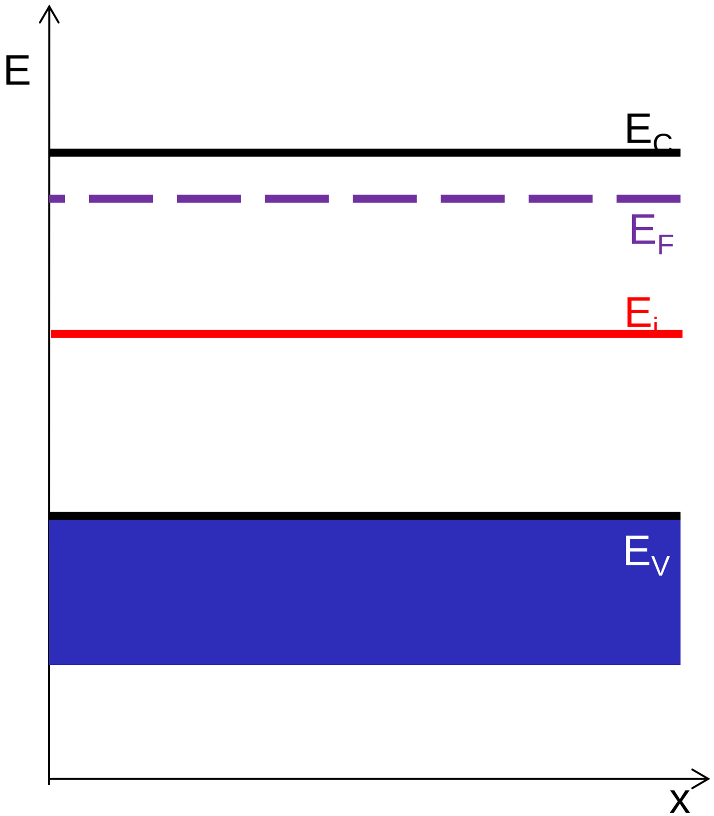
p: Concentration of free holes.
Holes move from bond to bond → slow.

n_i: Intrinsic carrier concentration.

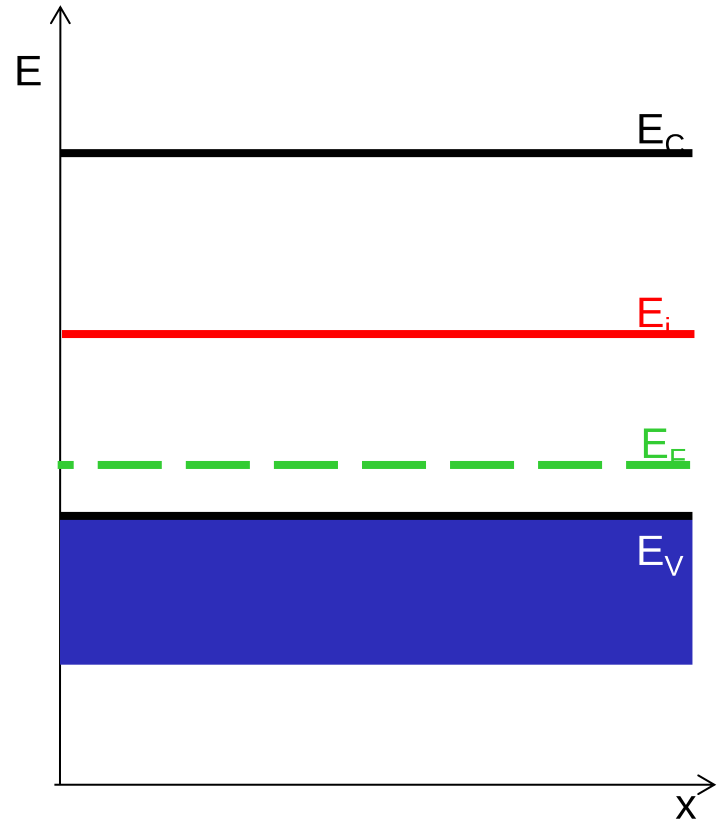
E_i: Fermi energy in semiconductor without impurities.



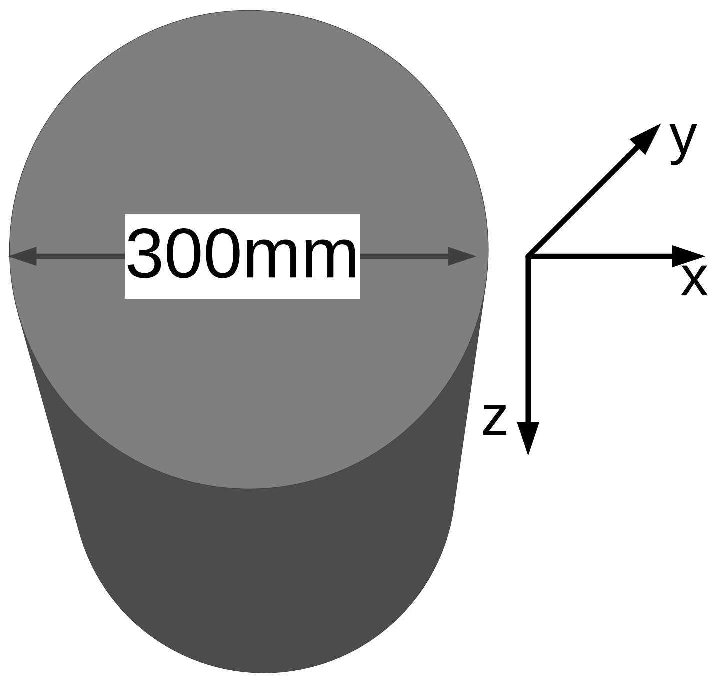
Electrons and Holes

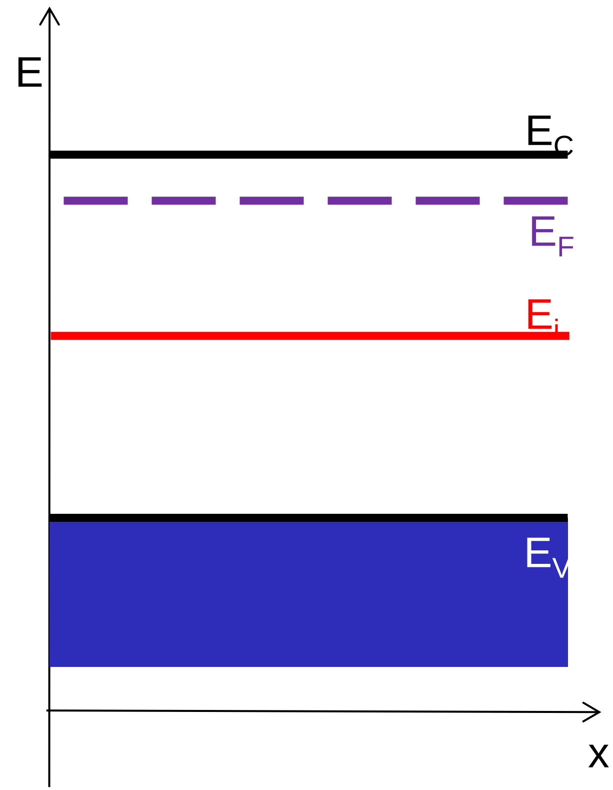


- Holes are quasiparticles for a missing electrons.
- Electrons move to lower unoccupied states.
- Holes move to higher occupied states.
- “Lowest” energy state for a hole is the valence band edge.
  $- E_e = E_h$
- Holes act in E – and B – fields like positive charged electrons.



Band Diagrams - Introduction





- N-doped wafer
- Band diagram exist for the whole wafer
- In this case x = 300 mm

1 Tutorial: Band Diagrams

2 Band structure: n – MOSFET

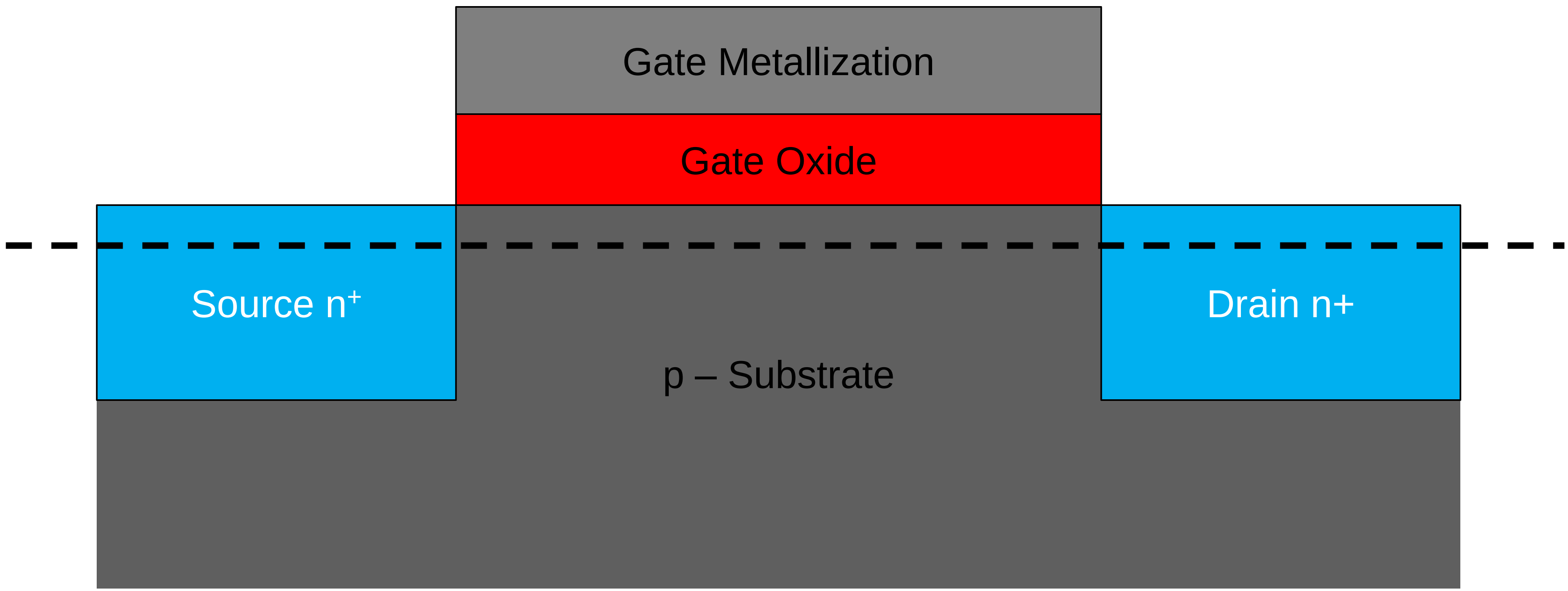
1. Create the 1 – D band structure of a n – MOSFET in thermal equilibrium from source to drain (see next slide).

2. How does the band structure change when a positive voltage is applied to the gate?

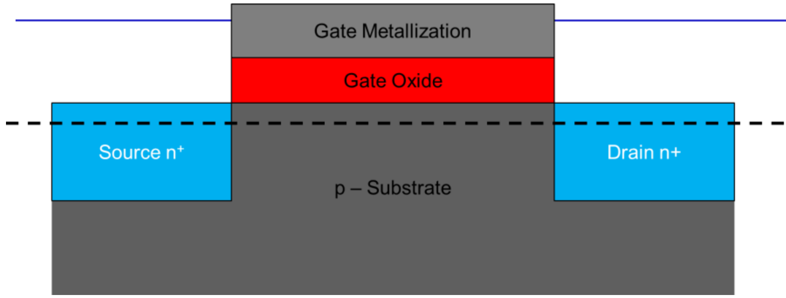
3. Which voltage has to be applied to the drain to turn the MOSFET on?

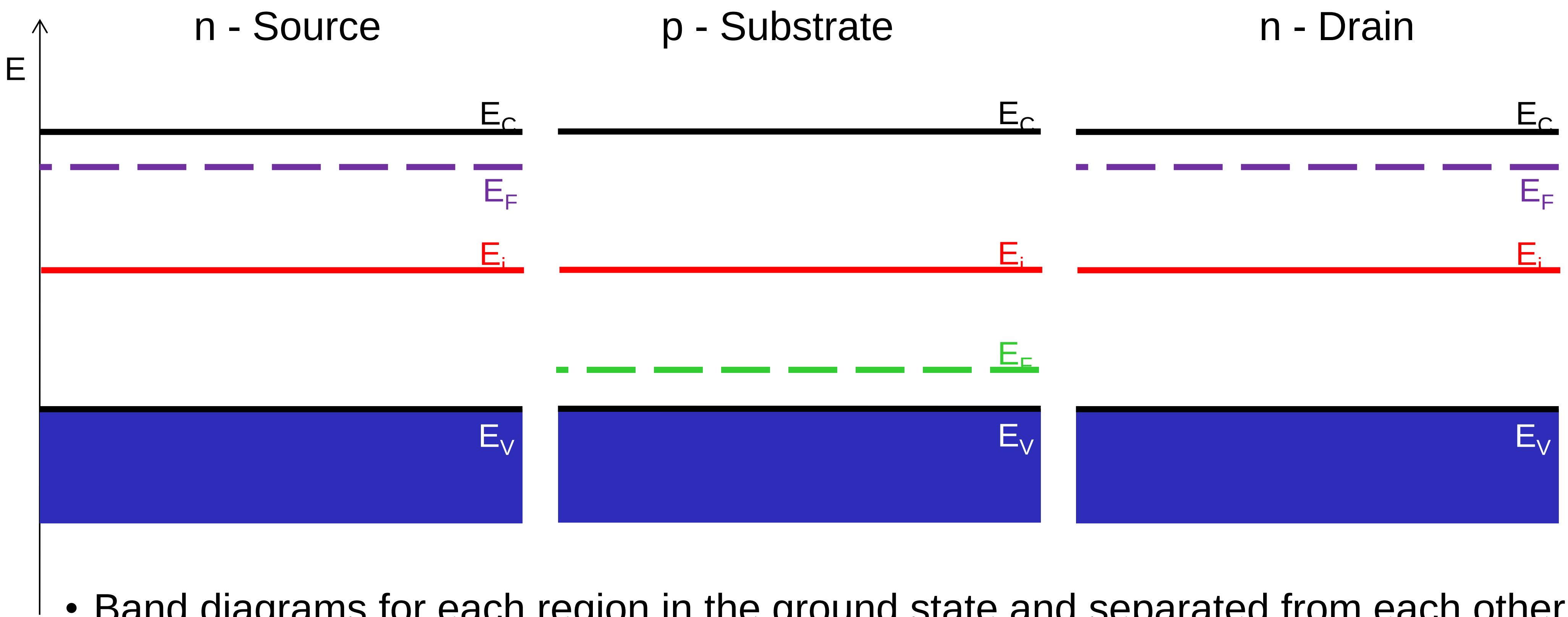
Band Diagrams – n - MOSFET

The picture shows the cross section of a n – MOSFET. Draw the band diagram along the black cutline.



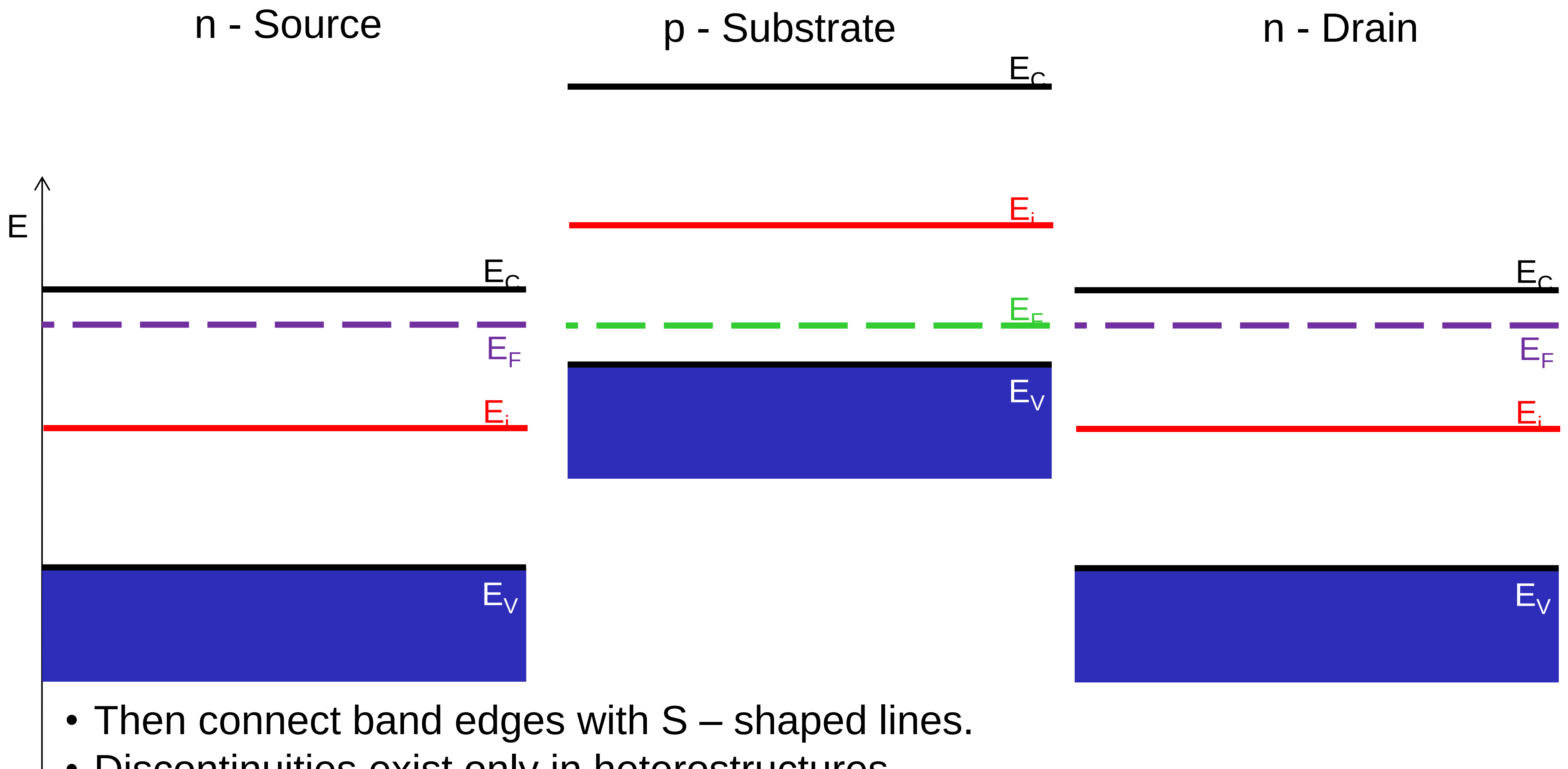
Band Diagrams – n - MOSFET



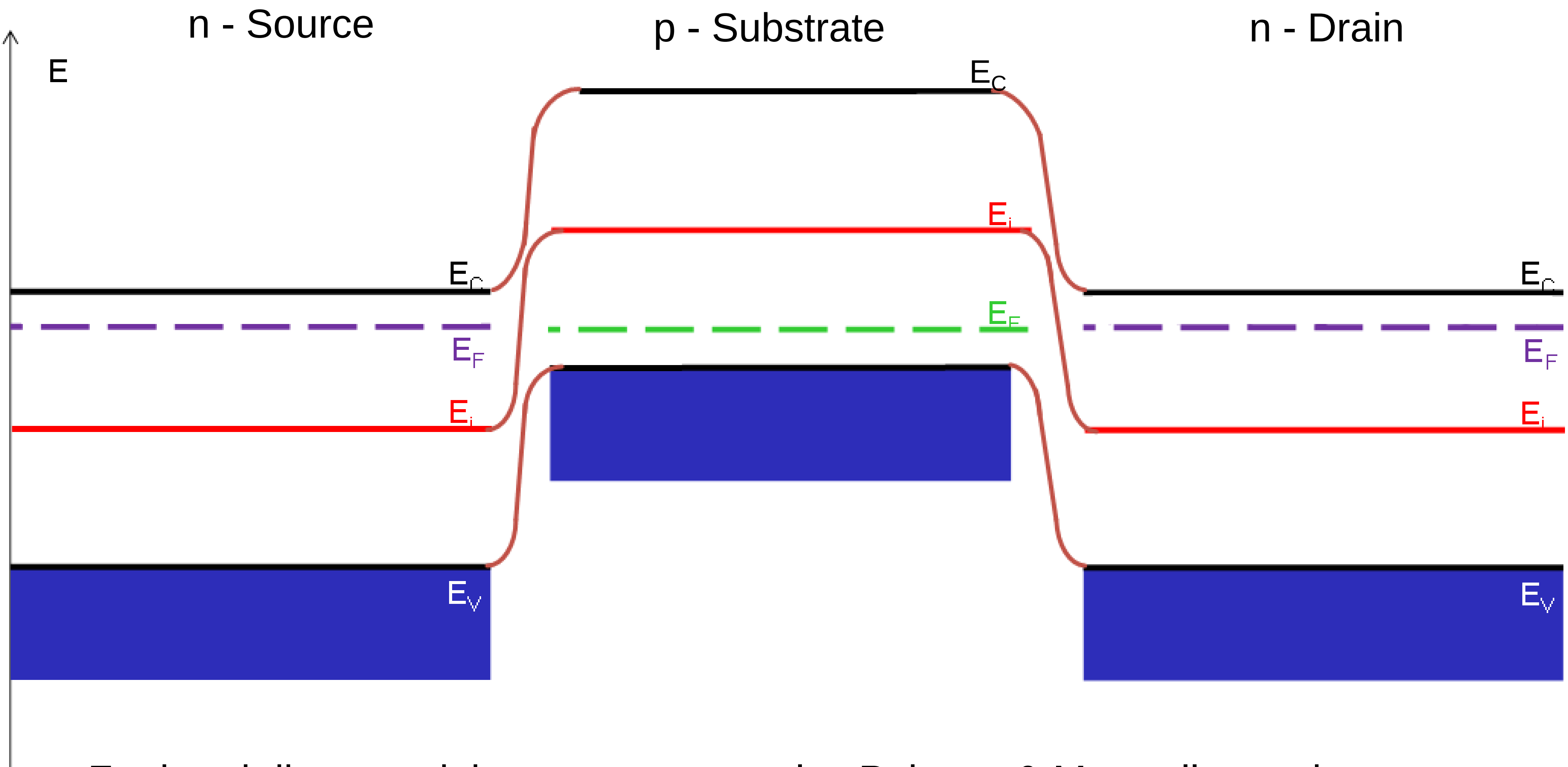


- Band diagrams for each region in the ground state and separated from each other.
- The next step is to get the regions in contact to each other and align Fermi levels.

Band Diagrams – n - MOSFET

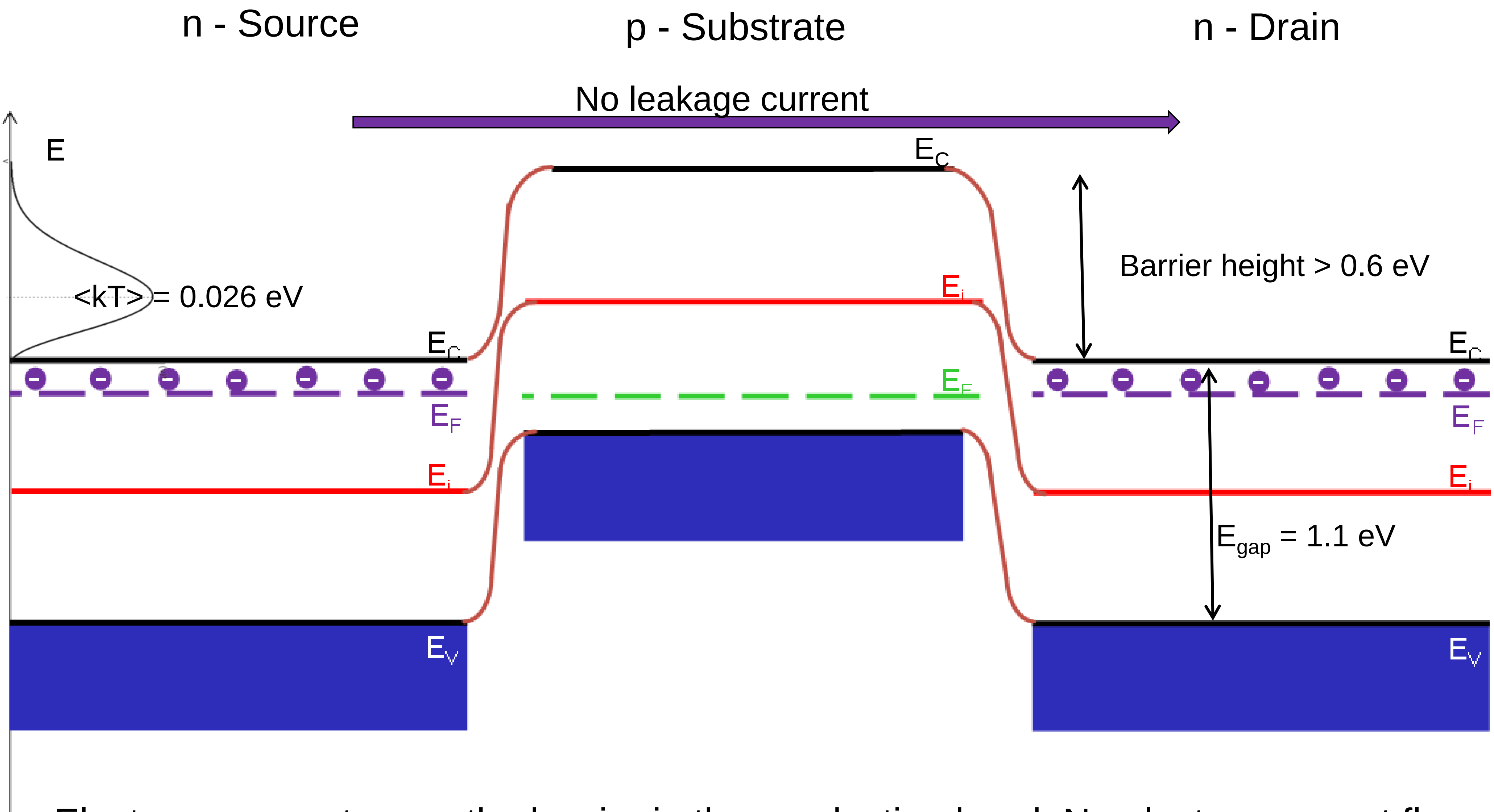


- Then connect band edges with S – shaped lines.
- Discontinuities exist only in heterostructures (semiconductor – oxide, III – V semiconductors).



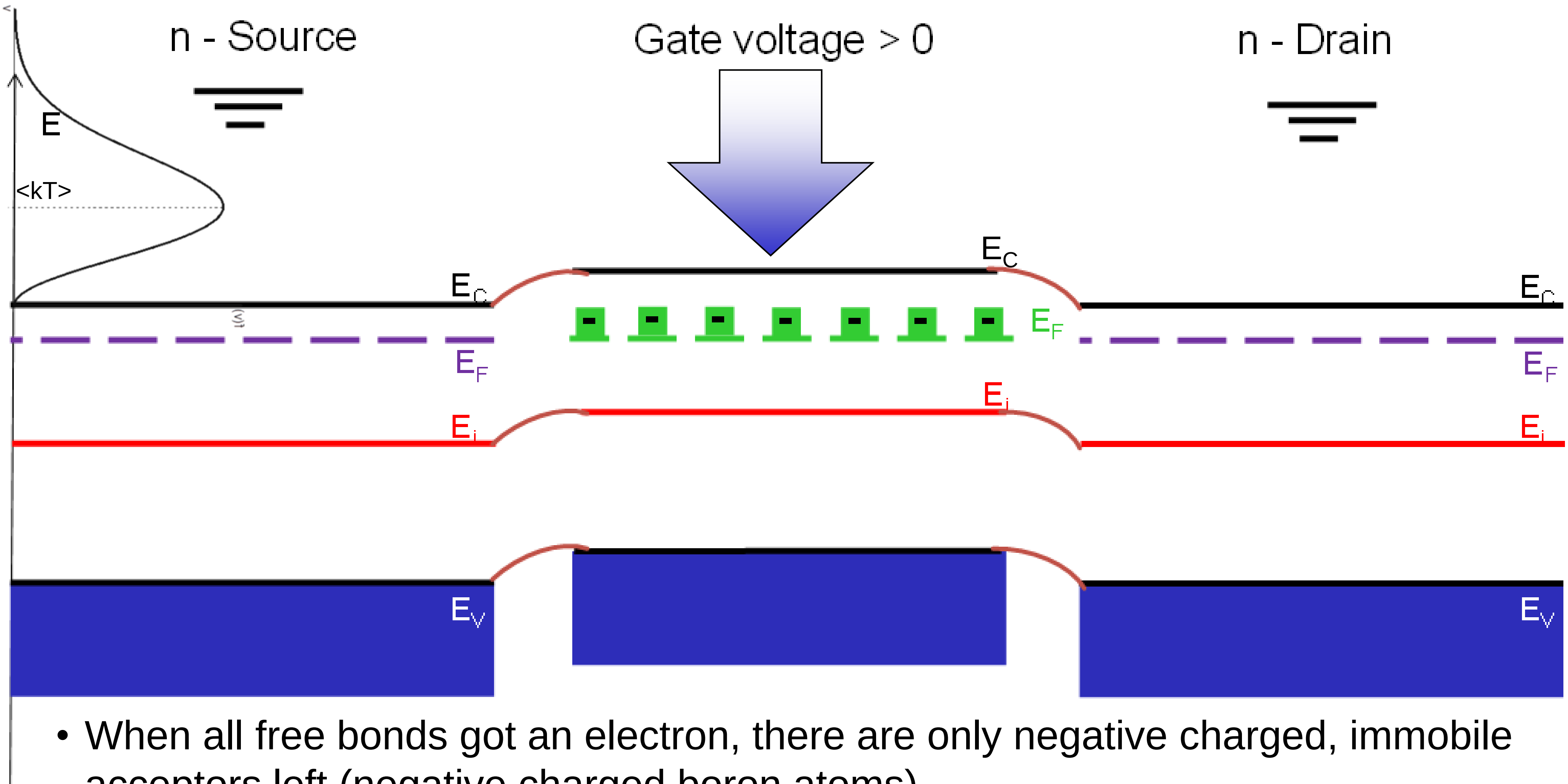
- For band diagrams it is necessary to solve Poisson & Maxwell equations.

Band Diagrams – n - MOSFET

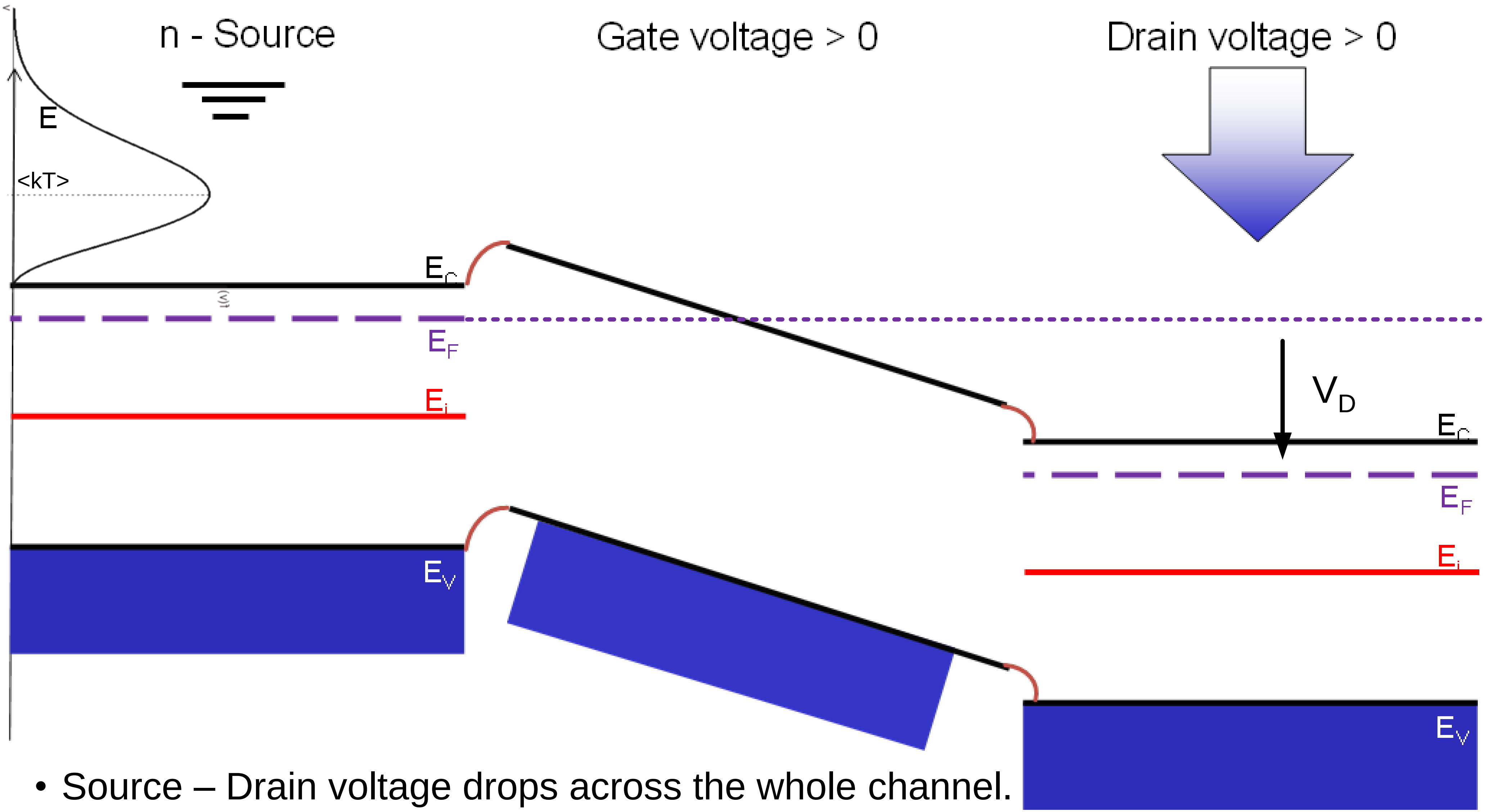


- Electrons can not cross the barrier in the conduction band. No electron current flows.

Band Diagrams – n - MOSFET



- When all free bonds got an electron, there are only negative charged, immobile acceptors left (negative charged boron atoms).
- Positive voltage lowers bands, negative voltage rises bands.
- When barrier is low enough, electrons can get over the barrier by thermal energy.



- Source – Drain voltage drops across the whole channel.
- Electrons can move from source to drain.