Recap of semiconductor fundamentals

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Device physics recap

Not intended to be a complete description of semiconductor physics.

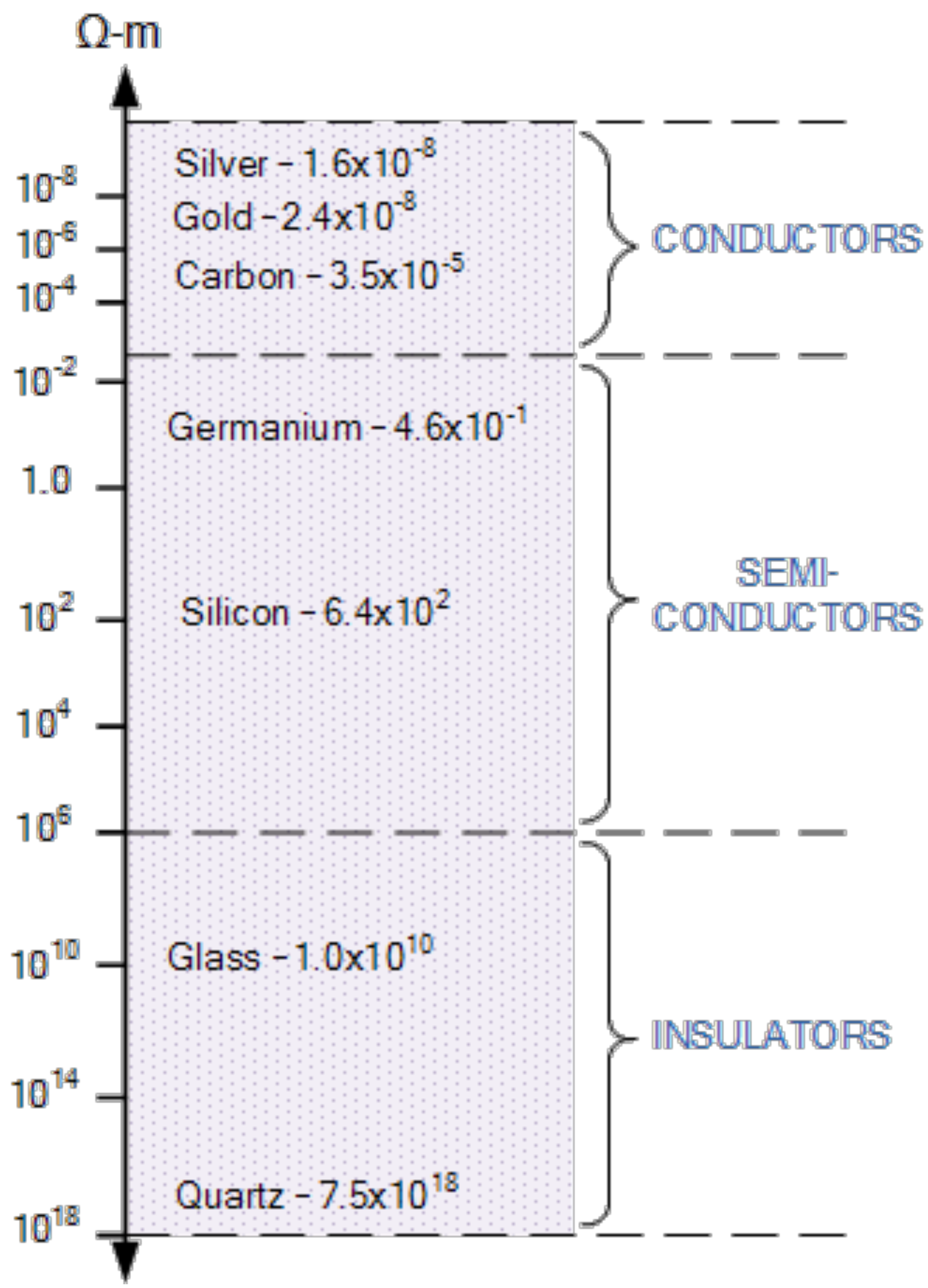
Just a broad overview.

Sufficient to understand the physical meaning of transistor parameters in this course.

Classification of materials

Insulator **Metal** **Semiconductor**

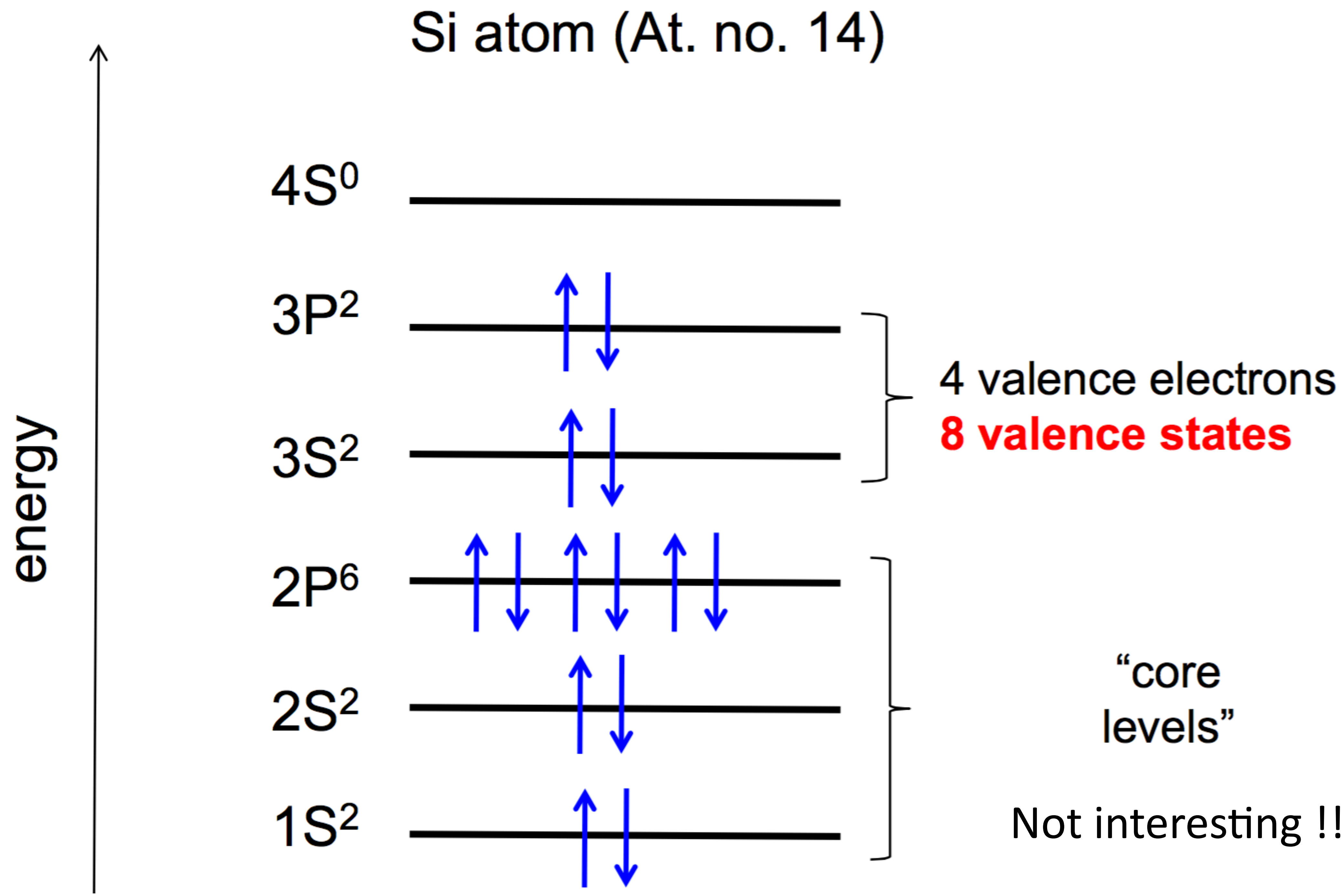
Question: What distinguishes these three classes of materials?



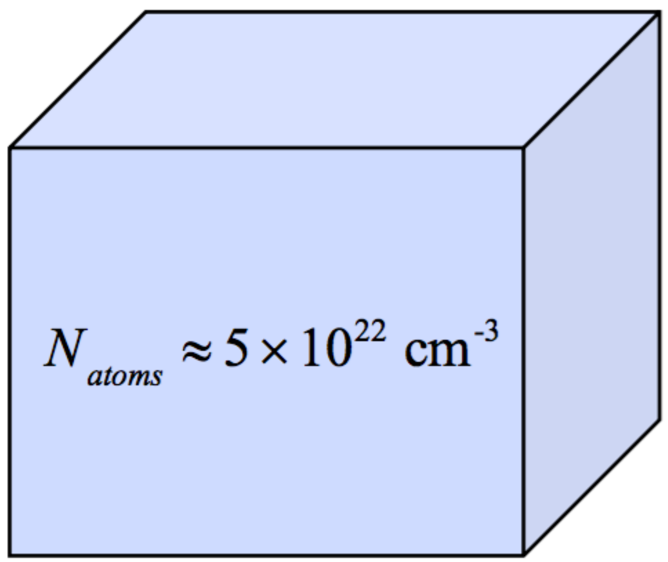
Answer: Resistivity

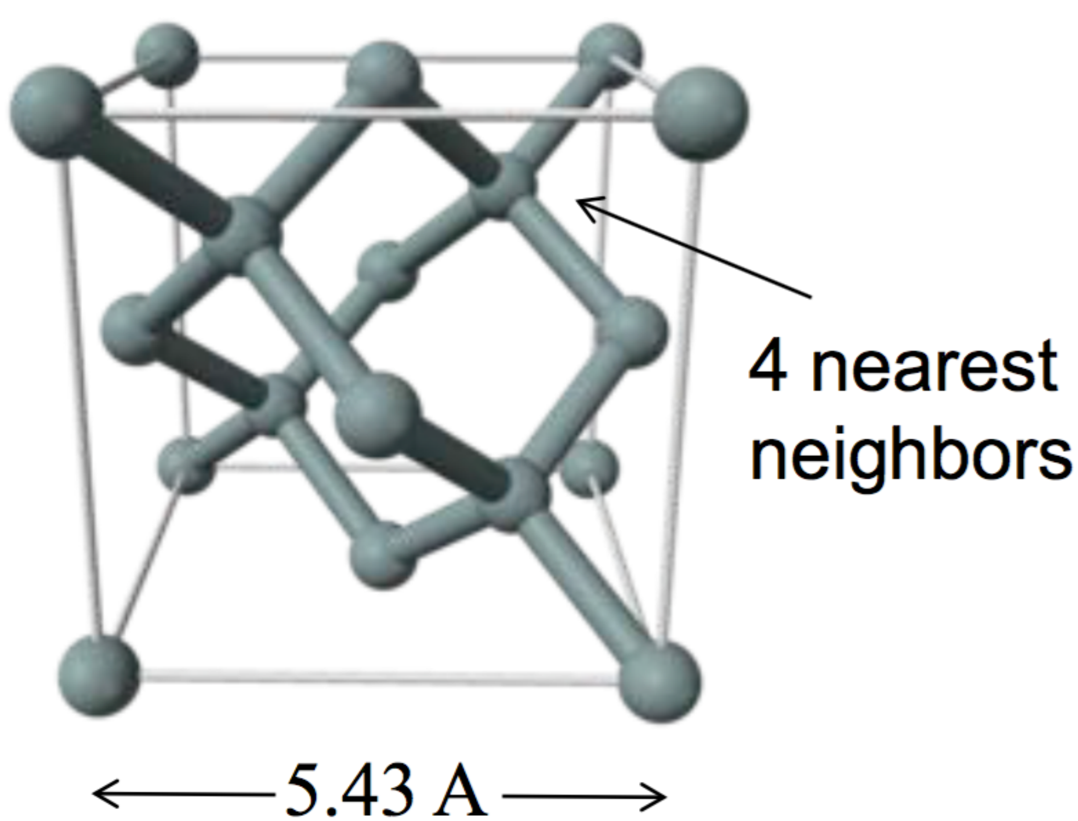
Also: resistivity of metals increases with temperature, while resistivity of semiconductors decreases with temperature.

Silicon energy levels



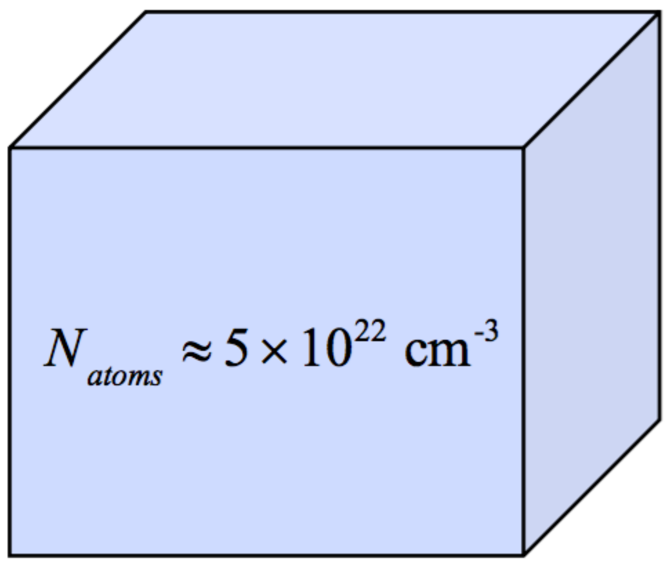
Silicon energy levels/energy bands

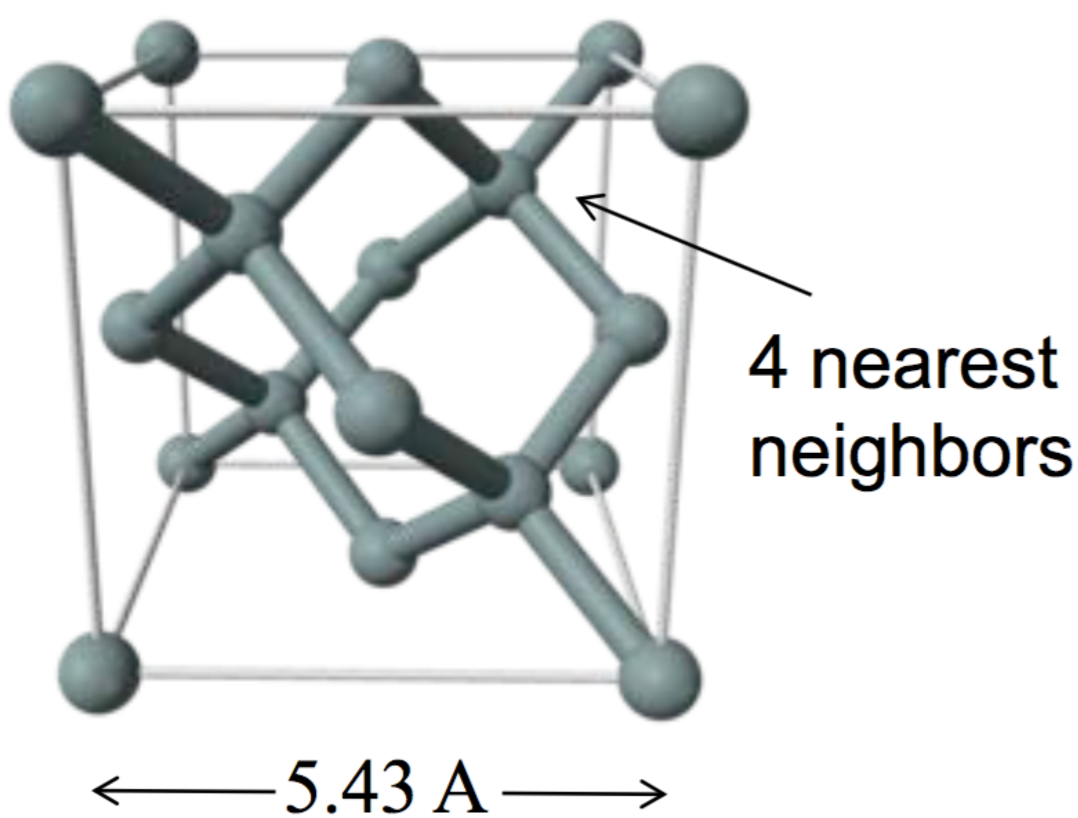




- Silicon crystal consists of approximately 5×10^{22} cm^{-3} atoms.
- When atoms are brought closer, then their energy levels are altered due to the electron wave function overlaps.

Silicon energy levels/energy bands

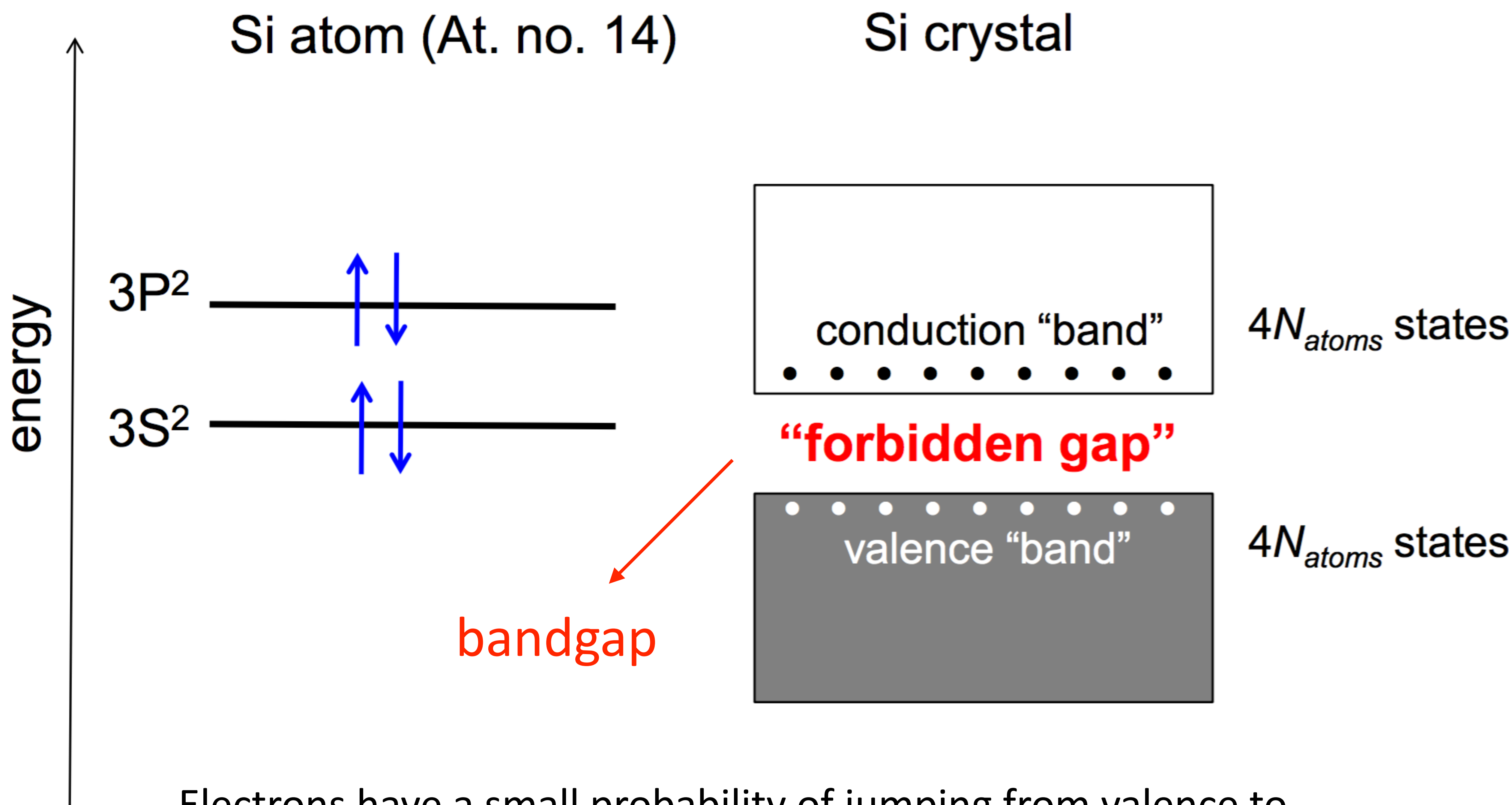




- Only the valence states are of interest to us.
- The 8 valence states give rise to $8N_{atoms}$ states per cm^3 in the solid.
- The interaction of atoms creates two separate bands.

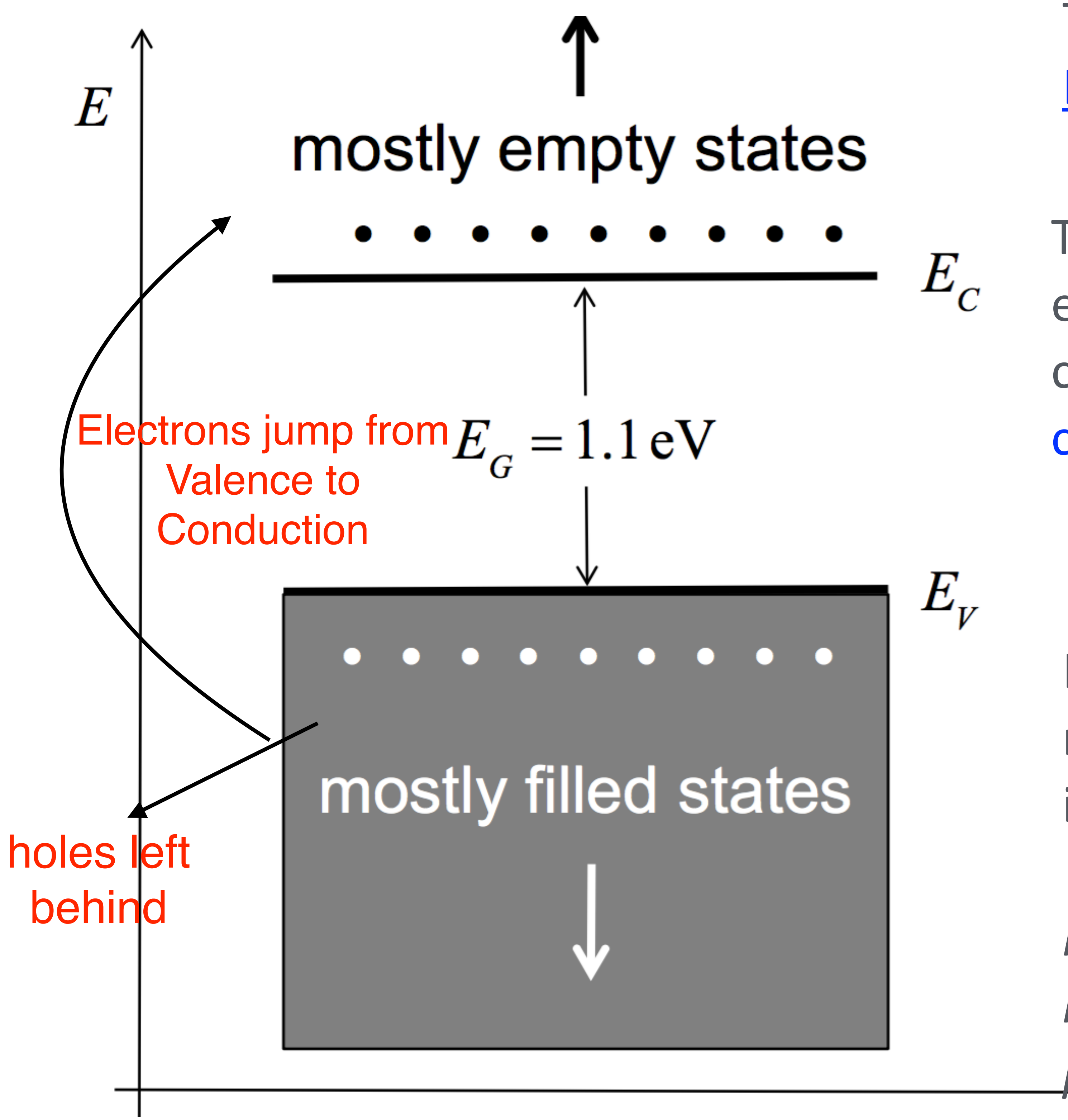
Valence band   Conduction band

Silicon energy levels —> energy bands



Electrons have a small probability of jumping from valence to conduction band.

Silicon energy bands



This state of silicon crystal is called <u>INTRINSIC</u> silicon.

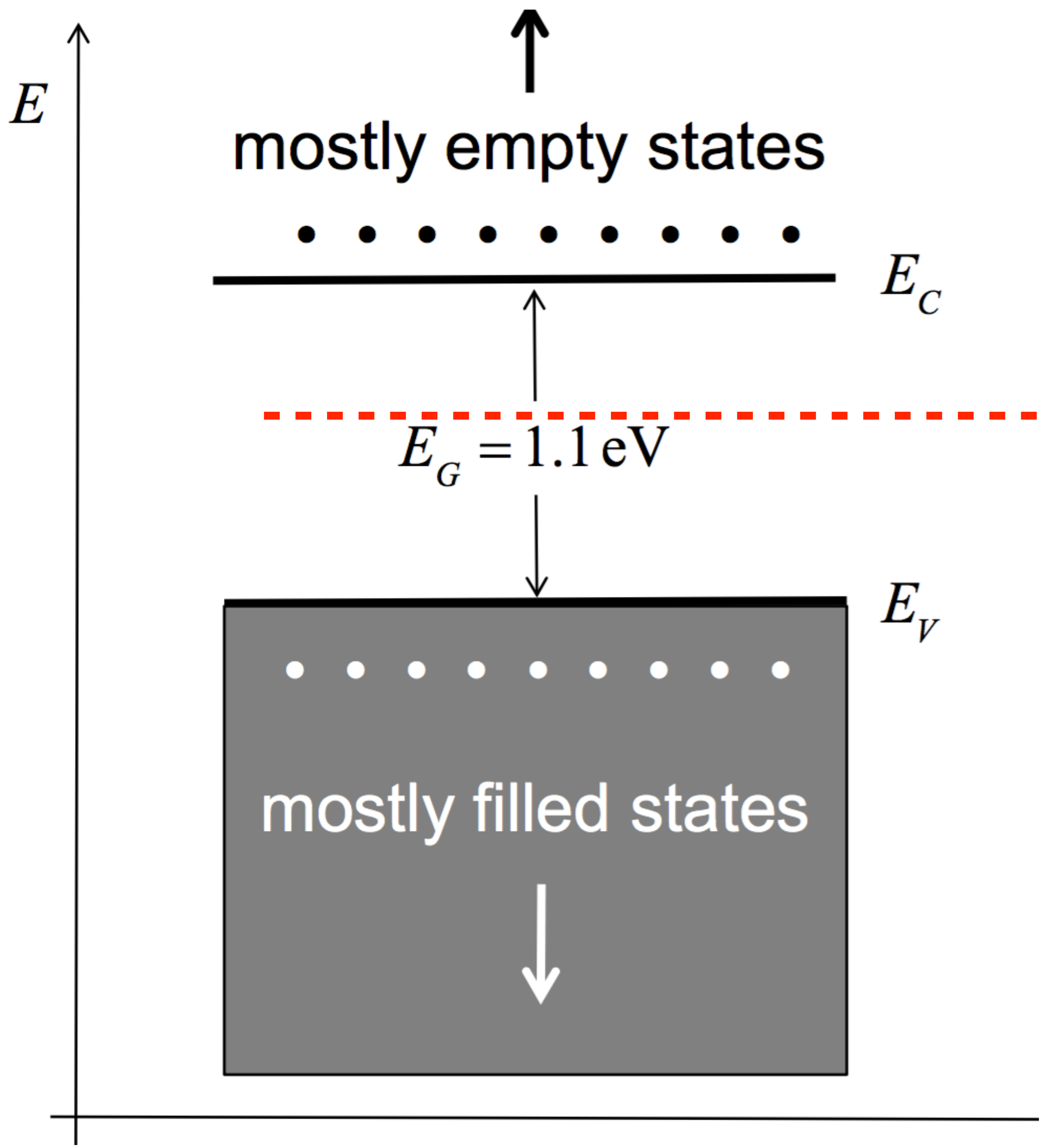
There is a finite probability of electrons jumping from valence to conduction band: Intrinsic carrier concentration.

$$\boxed{n_i = 1.5 \times 10^{10}\, cm^{-3}}$$

Intrinsic semiconductor has equal number of electrons as holes. That is,

$n = p = n_i$
n = electron conc.
p = hole conc.

Silicon energy bands



Fermi level
(*almost in the middle of the band-gap for intrinsic silicon*)

Concept of Fermi level

- Fermi level is denoted as μ or E_f.
- E_f does not correspond to an actual energy level.
- It always lies in the band gap for an insulator.
- E_f is related to the thermodynamic work required to add an electron to the material.

More reading:
R.F. Pierret, Semiconductor Device Fundamentals, 2nd Ed. Addison Wesley.

Semiconductor doping

"Doping" is what makes semiconductors special.

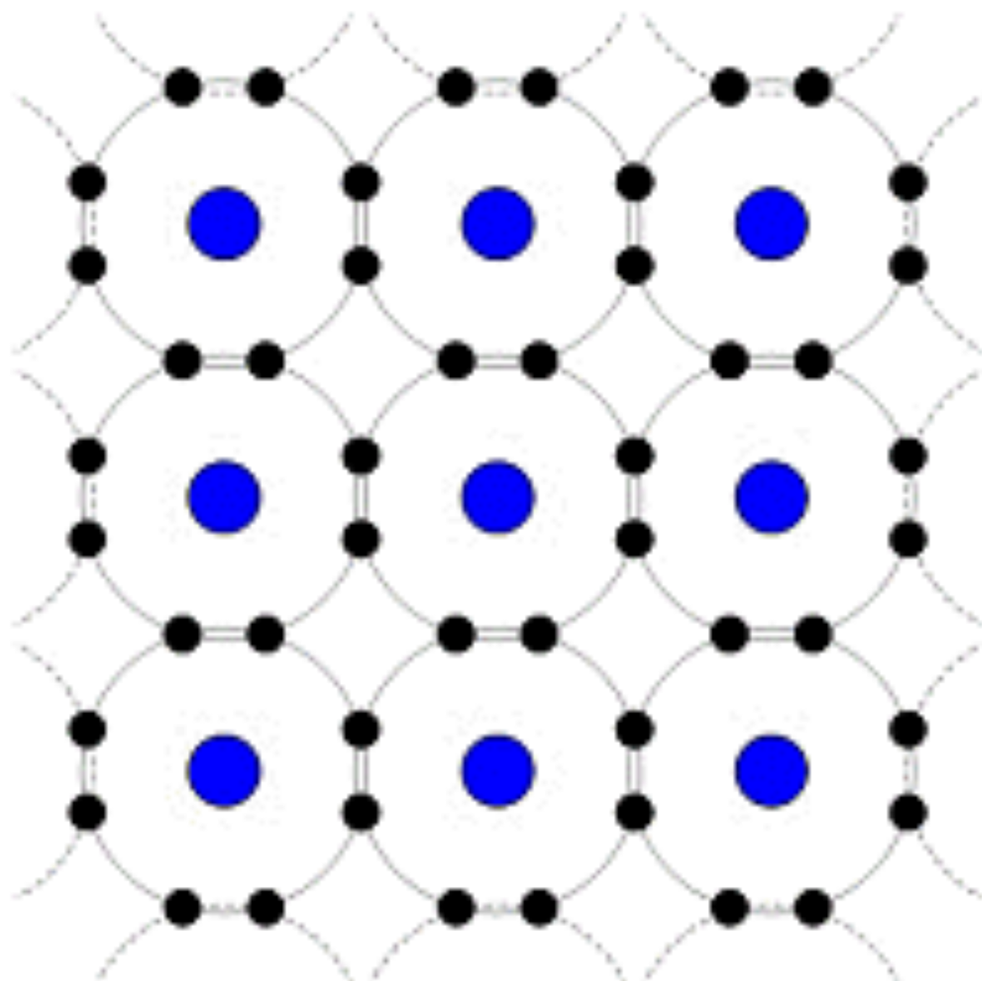
By doping, we control the location of the Fermi level (carrier densities).

Semiconductor doping

Intrinsic or pure silicon

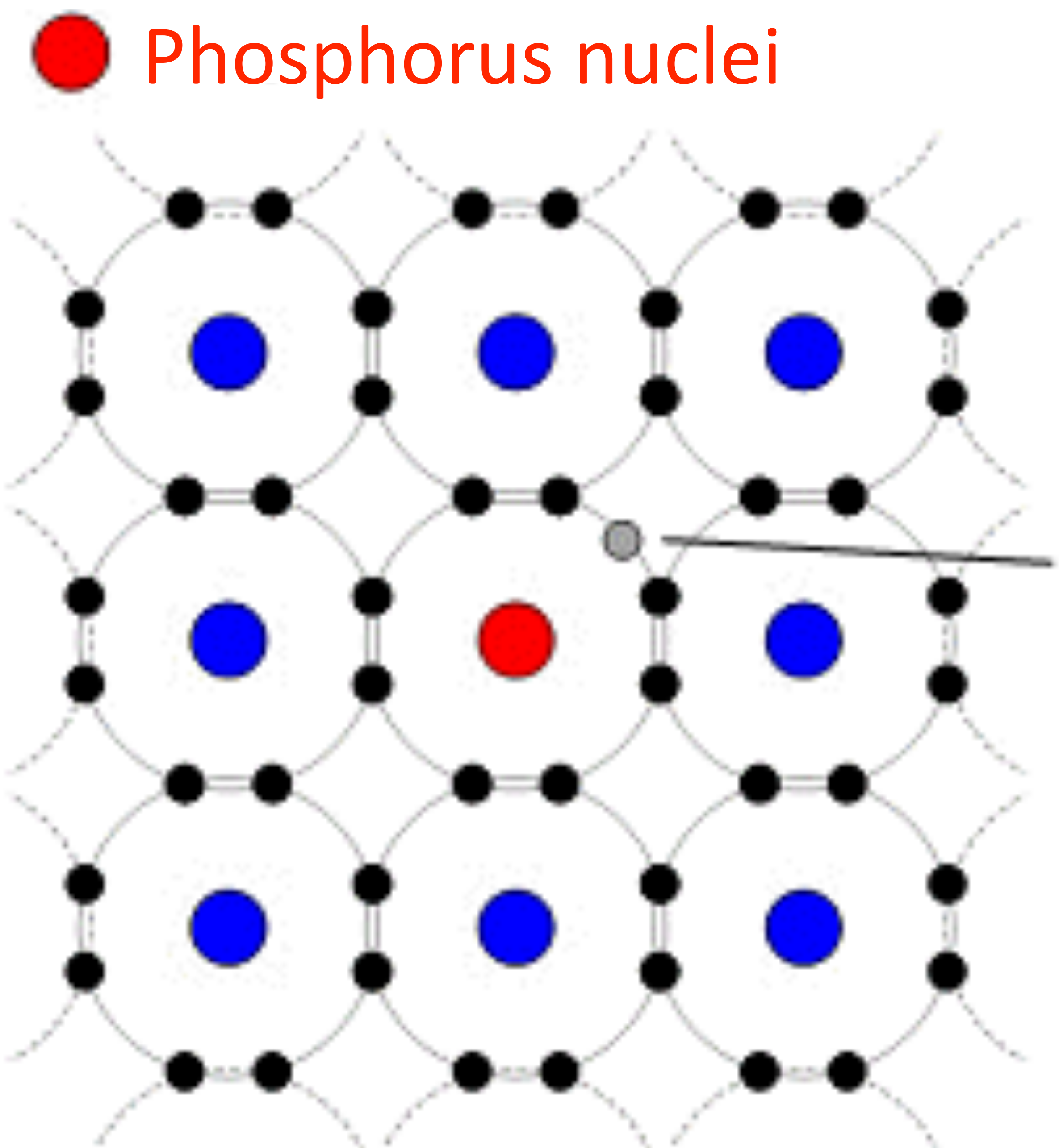
Pure silicon

Silicon nuclei



Semiconductor doping- N type (donor)

n-type silicon



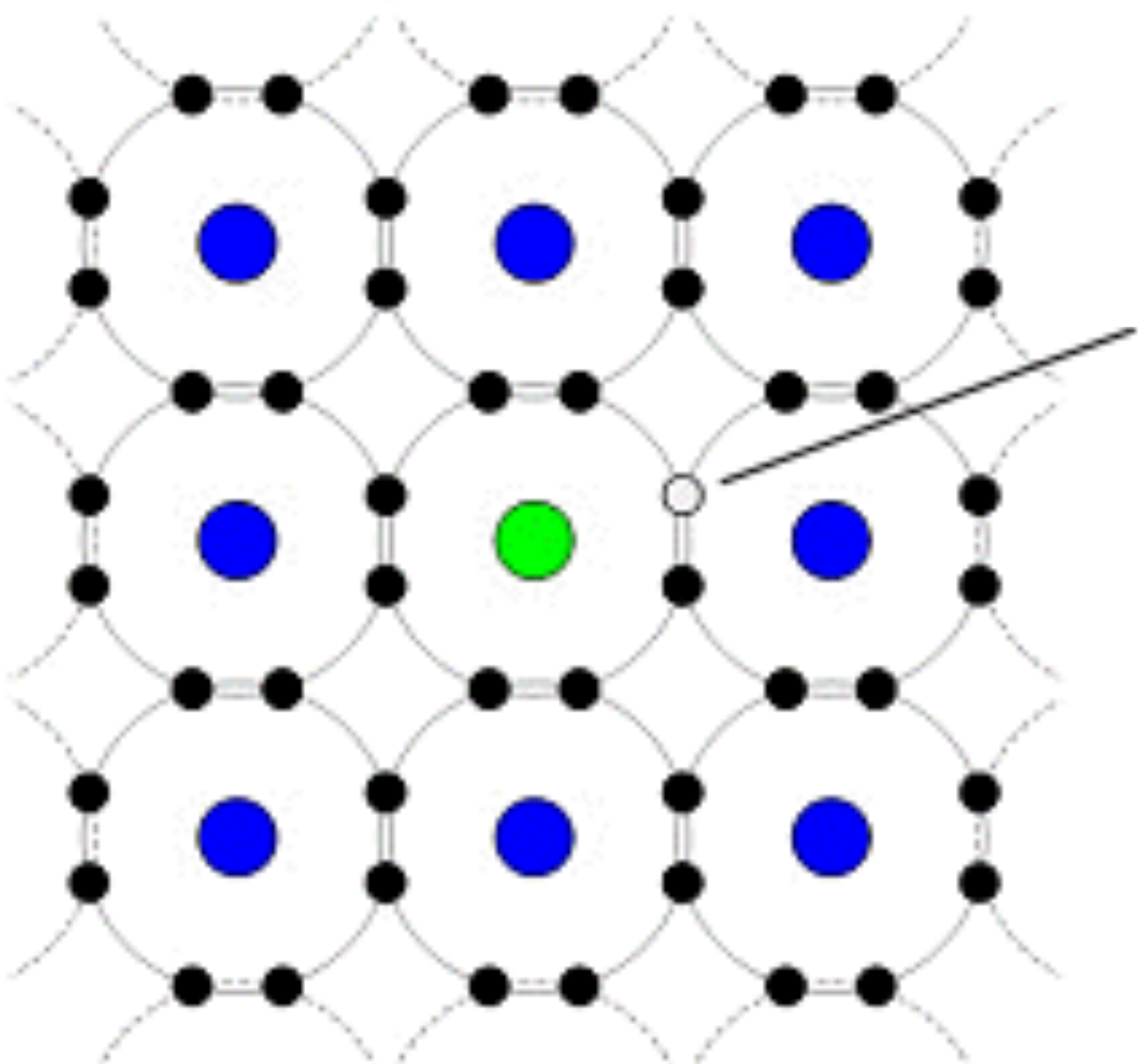
Phosphorus atom contributes an extra electron. It is called donor type impurity.

Other donor-type impurity: As, Sb, Bi

Semiconductor doping- P-type (acceptor)

p-type silicon

Boron nuclei

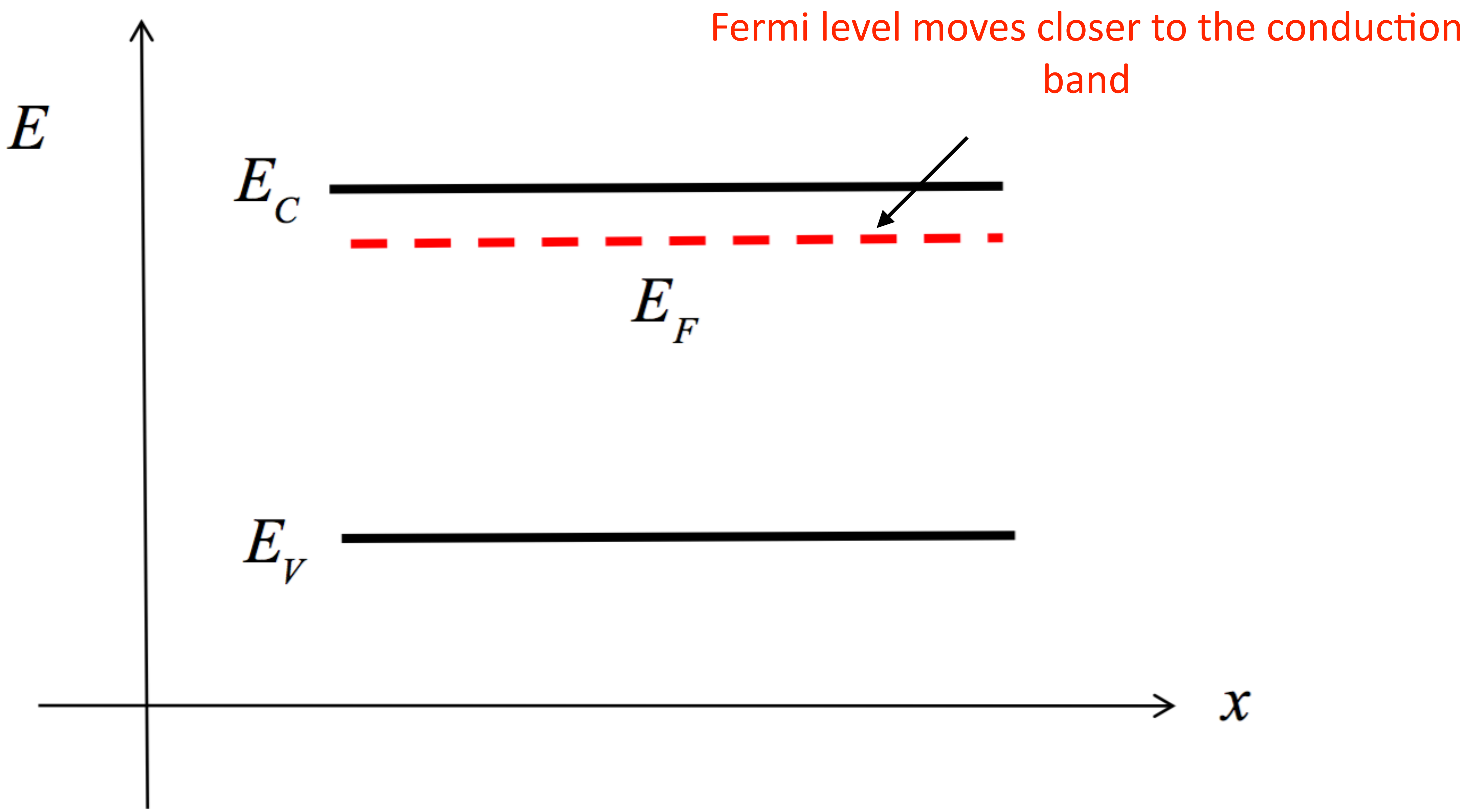


Boron atom takes away an electron and creates a hole. It is called acceptor type impurity.

Acceptor-type impurity atoms: Al, In, Ga

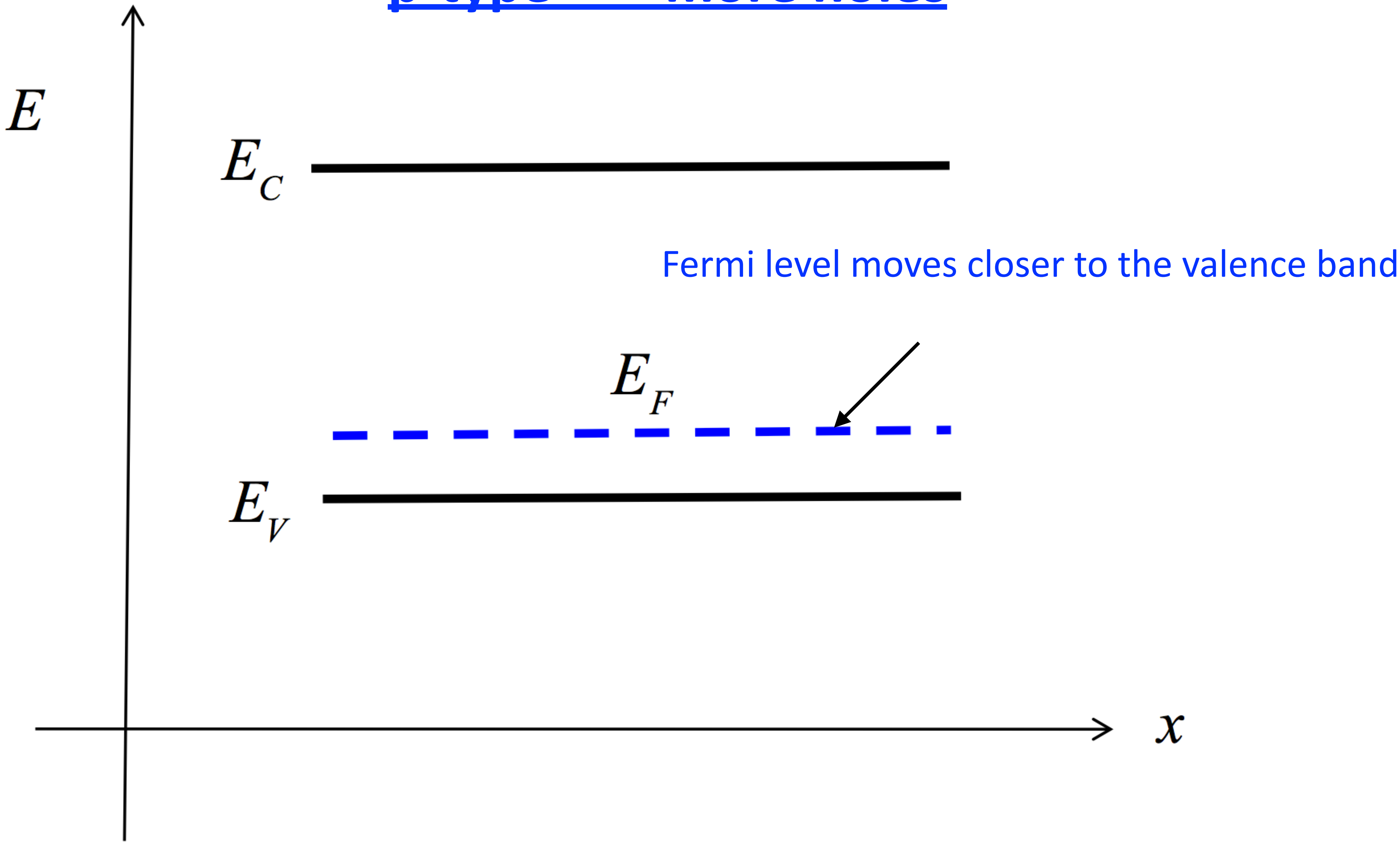
Semiconductor doping- Impact on Fermi level

n-type —> more electrons



Semiconductor doping- Impact on Fermi level

p-type —> more holes



Summary of semiconductor doping

"Doping" is what makes semiconductors special.

By doping, we control the location of the Fermi level (carrier densities).

N-type doping

Creates more electrons than holes in silicon.

Requires donor type impurity atoms like phosphorus, arsenic, antimony, bismuth.

P-type doping

Creates more holes than electrons in silicon.

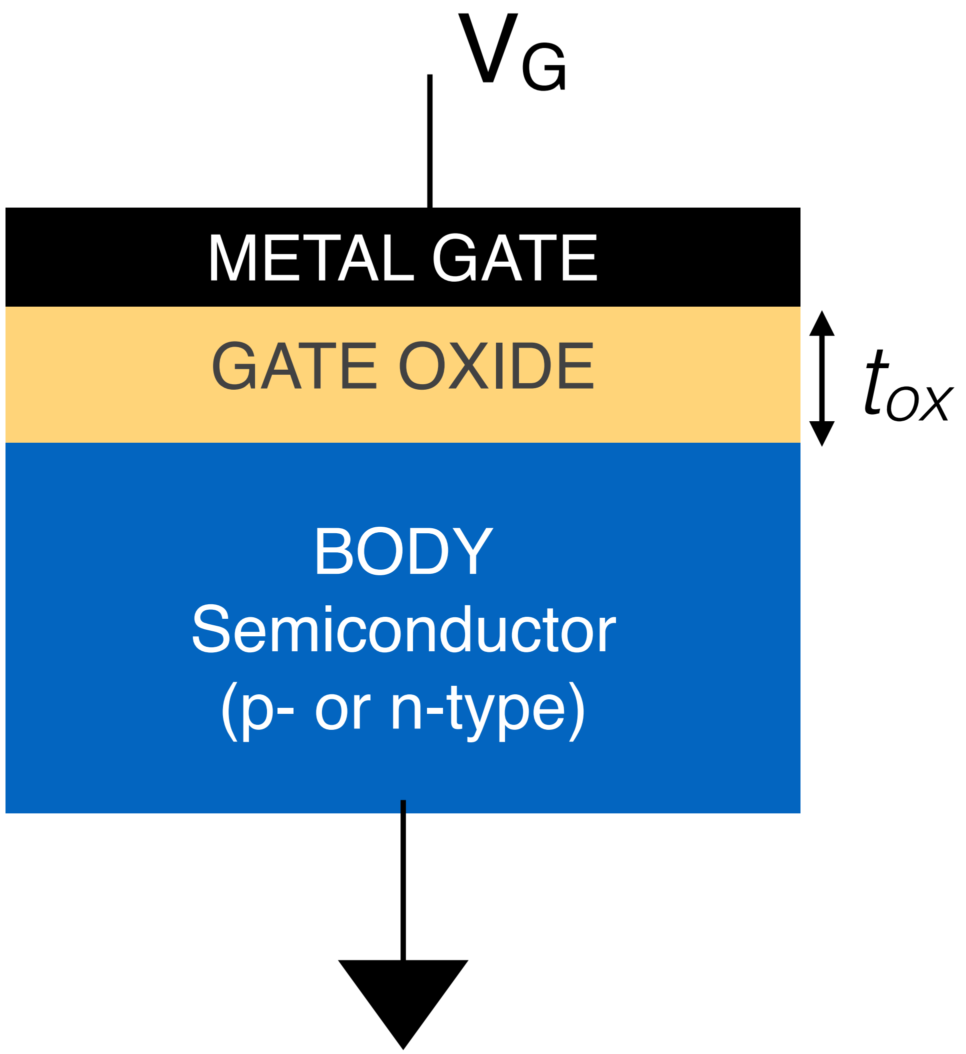
Requires acceptor type impurity atoms like boron, aluminum, indium, gallium.

For more info:
http://hyperphysics.phy-astr.gsu.edu/hbase/solids/dope.html

Metal-oxide-semiconductor physics

To understanding silicon MOSFET transistors, we must first understand metal-oxide-semiconductor capacitors.

Metal-oxide-semiconductor physics



$$\boxed{C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}}$$

oxide permittivity

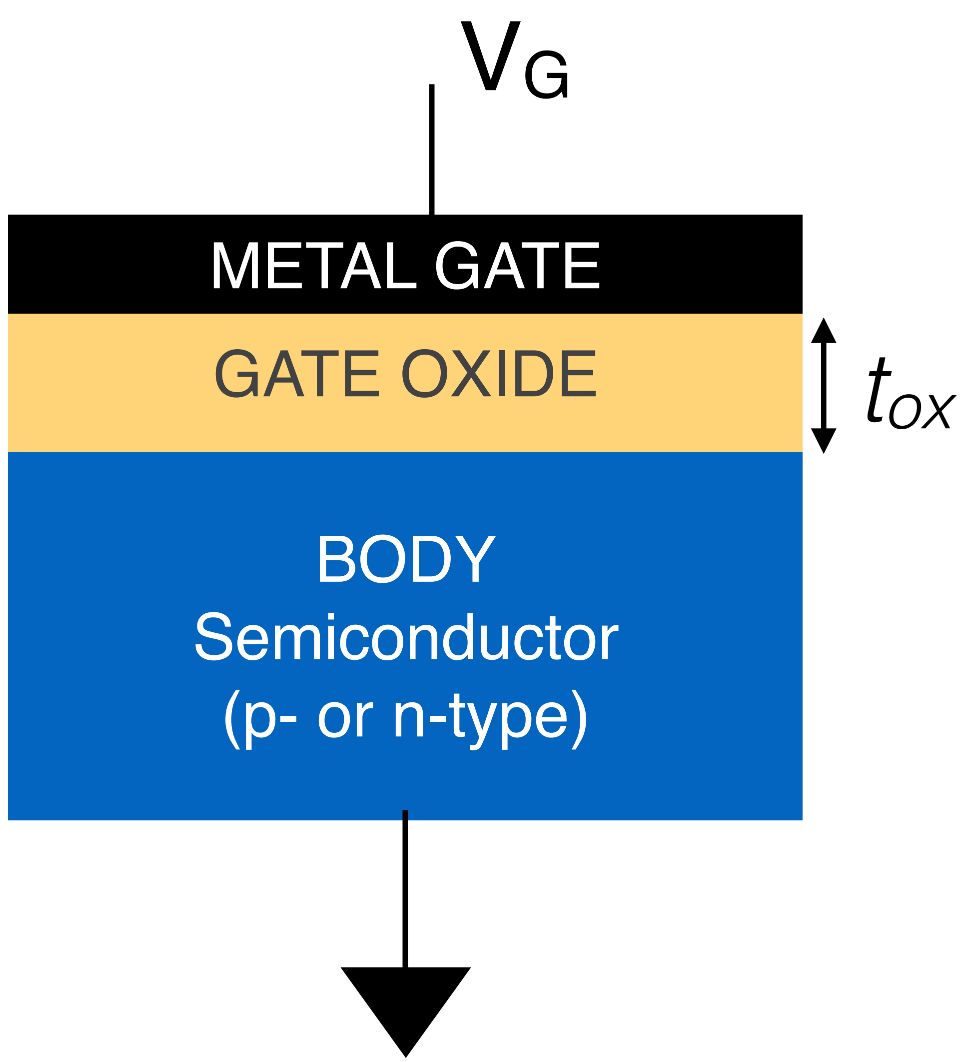
oxide thickness

No current flows through the oxide.
It separates the body from the metal gate.

Gate does not necessarily have to be made of metal. It can be made of poly silicon too.
Poly-Si is the less pure crystal form of silicon. It has grain boundaries.

Kirchoff's voltage law (KVL) dictates that the gate voltage V_G must drop across gate oxide and surface potential at the interface between the oxide and the body.

Threshold voltage, V_T or V_t or V_{th}



The body of the MOS capacitor is either p- or n-type.

Threshold voltage is that amount of gate voltage required that would change the polarity of the charge at surface of the body-oxide from its original value.

That is, if the body is p-type to begin with then when VG > VT, the surface will be n-type and vice versa.

KCL: $$\boxed{V_G = \underbrace{V_{ox}}_{\text{Oxide voltage drop}} + \underbrace{\psi_s}_{\text{Semiconductor-oxide surface voltage drop}}}$$

Threshold voltage, V_T or V_t or V_{th}

KCL: $$\boxed{V_G = V_{ox} + \psi_s}$$

Oxide voltage drop

Surface potential

To find V_T, we substitute V_{ox} and ψ_s in the above equation with their values when the surface of the semiconductor is inverted.

$$V_T = V_{ox,inv} + \psi_{s,inv}$$

$$V_{ox,inv} = -\frac{Q_{B,inv}}{C_{ox}}$$

Body charge @ inversion

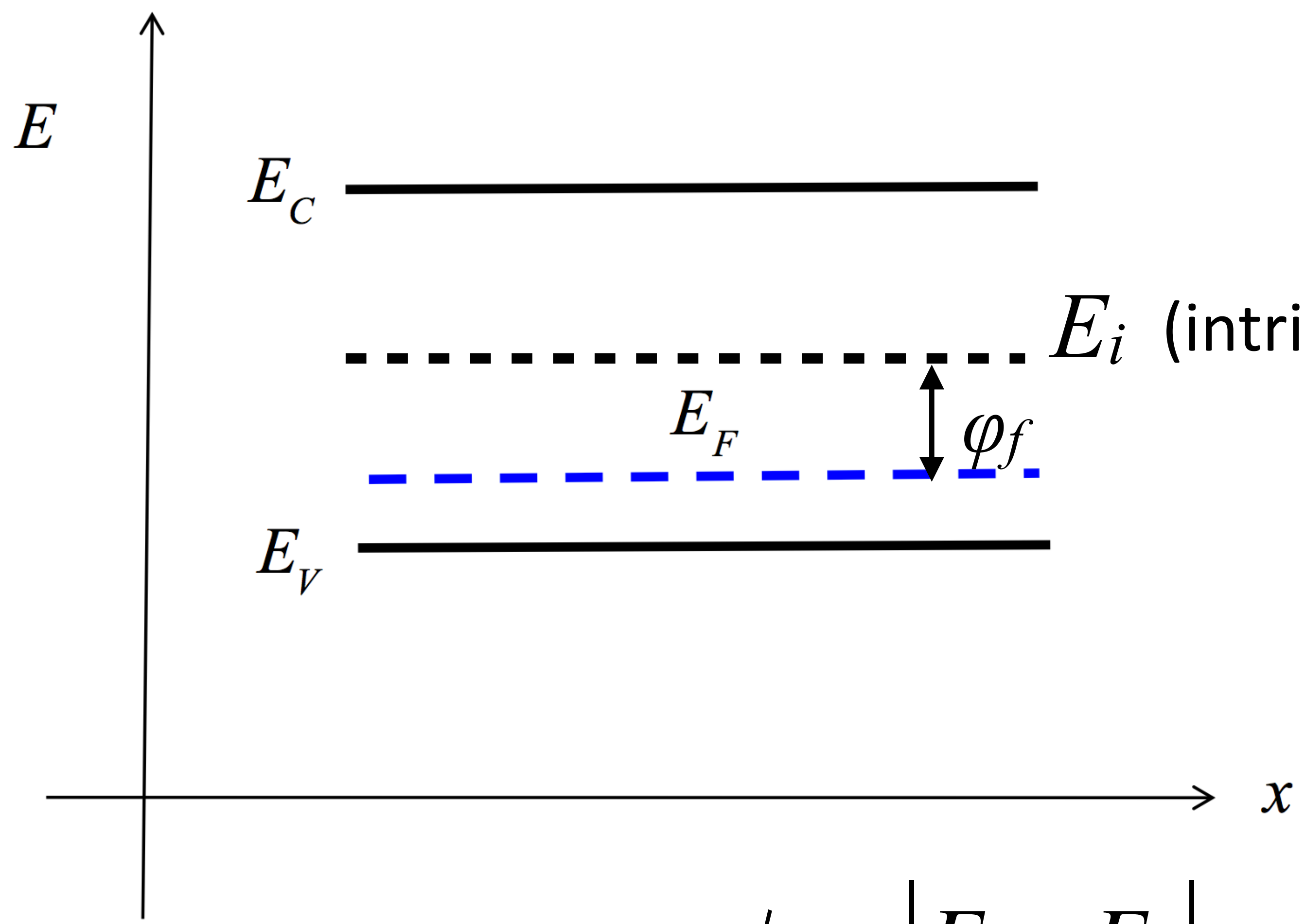
$$\psi_{s,inv} = 2\phi_f$$

Surface potential @ inversion

Twice the bulk Fermi level

How can we compute surface potential at inversion?

Lets say the body is p-type to begin with,
when no voltage is applied.



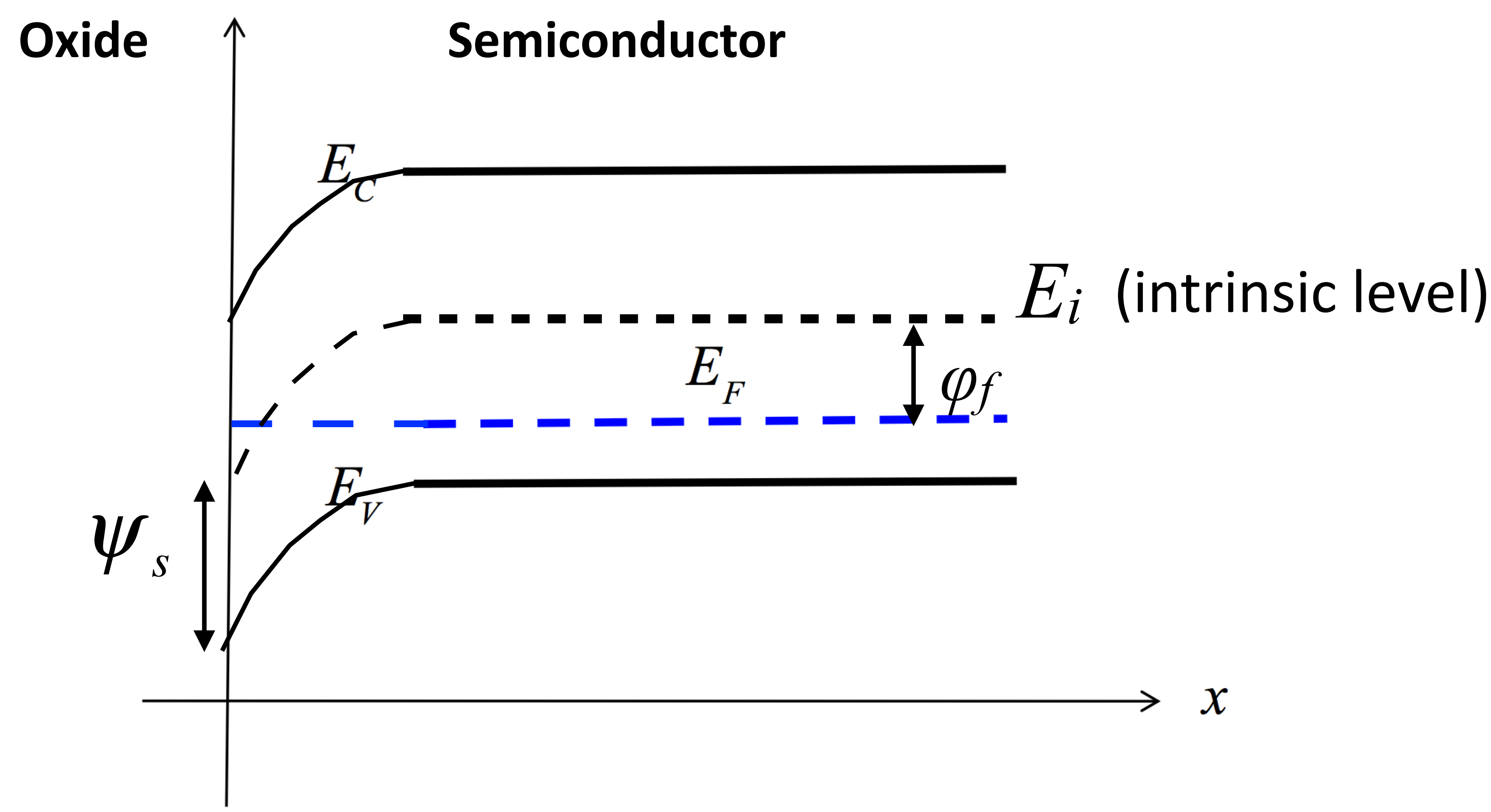
Bulk Fermi level

$$\phi_f = \left| E_i - E_f \right|$$

$$\phi_f = \frac{k_B T}{q} \ln\left(\frac{N_A}{n_i} \right)$$

How can we compute surface potential at inversion?

Band diagram when a large positive voltage is applied



Band bending happens at the interface.
When ψ_s becomes $2\phi_f$, we see the surface is inverted.

How can we compute surface potential at inversion?

When Vg is not zero, band bending happens at the interface.
When ψ_s becomes $2\phi_f$, we see the surface is inverted.

$$\phi_f = \left| E_i - E_f \right|$$

$$\phi_f = \frac{k_B T}{q} \ln\left(\frac{N_A}{n_i}\right)$$

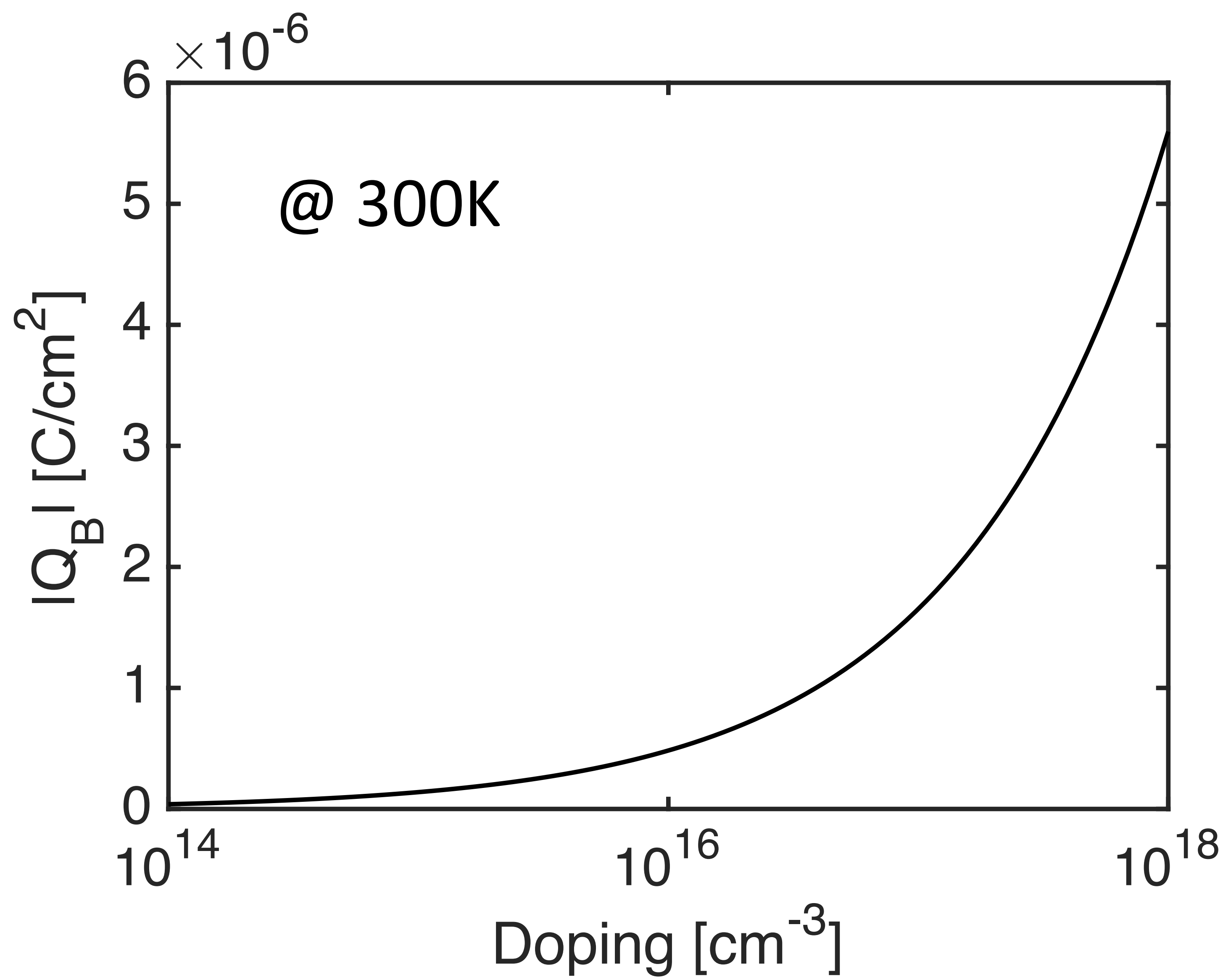
Thermal voltage
@ 300K, $k_B T/q$ = 26 mV

k_B: Boltzmann constant
T: Temperature in K
q: Elementary charge [C]
N_A: doping concentration
n_i: Intrinsic carrier concentration

Calculate N_A for ϕ_f = 0.4 V at 300 K

Body charge at inversion

$$\boxed{Q_{B,inv} = -\sqrt{2q\varepsilon_{si}N_A\left(2\phi_f\right)}}$$



Threshold voltage, V_T or V_t or V_{th}

$$V_T = V_{ox,inv} + \psi_{s,inv}$$

$$V_{ox,inv} = -\frac{Q_{B,inv}}{C_{ox}}$$

$$\Longrightarrow \quad V_T = \frac{\sqrt{2q\varepsilon_{si}N_A\left(2\phi_f\right)}}{C_{ox}} + 2\phi_f$$

$$\psi_{s,inv} = 2\phi_f$$

So far, we have ignored two effects:

(i) metal-semiconductor work-function difference, ϕ_{ms}

(ii) charges in the oxide, Q_{ox}

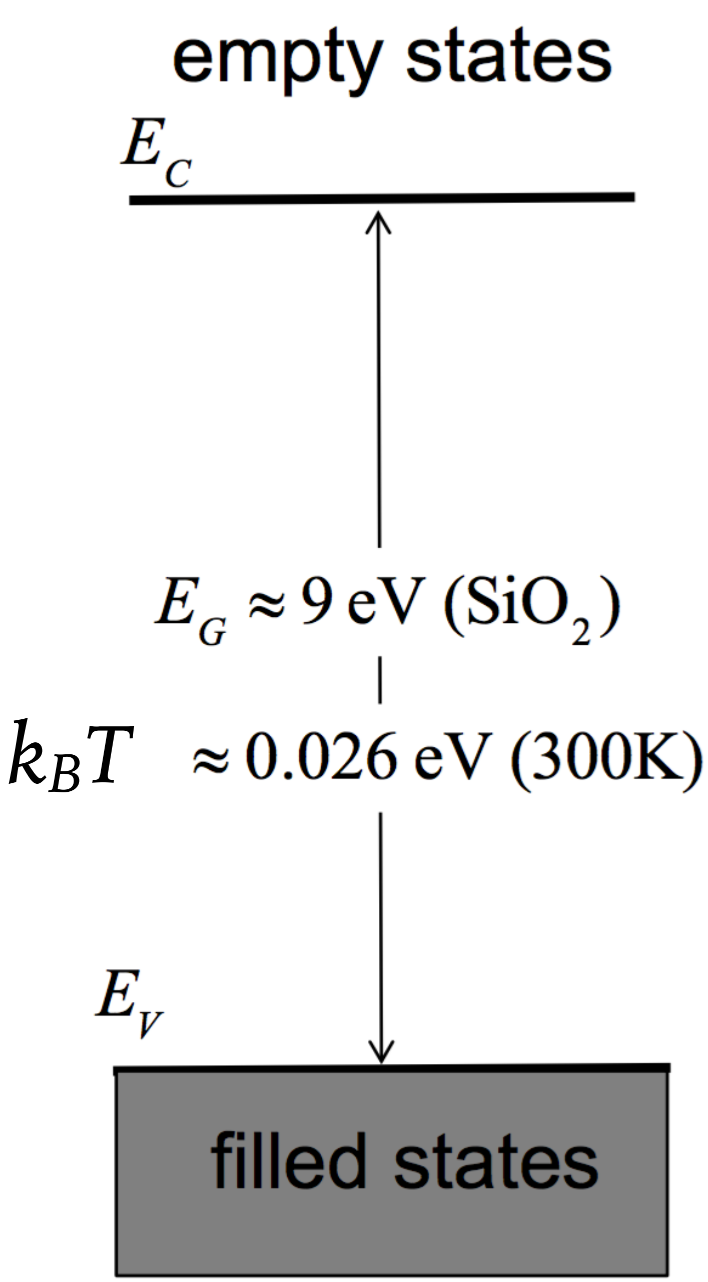
Put together in Flat-band voltage, $\mathbf{V_{fb}}$

Final model

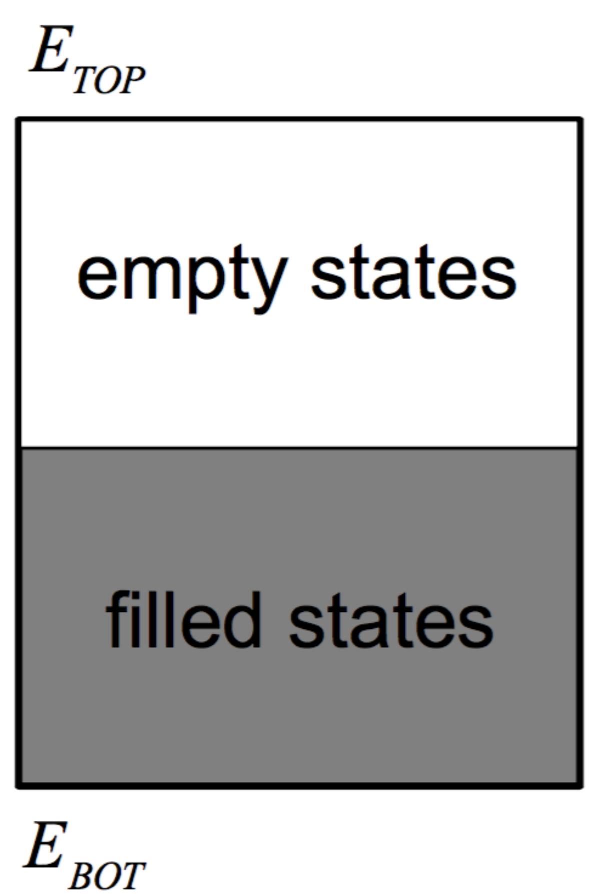
$$\boxed{V_T = \frac{\sqrt{2q\varepsilon_{si}N_A\left(2\phi_f\right)}}{C_{ox}} + 2\phi_f + V_{fb}}$$

Classification of materials

Insulator



Metal



Semiconductor