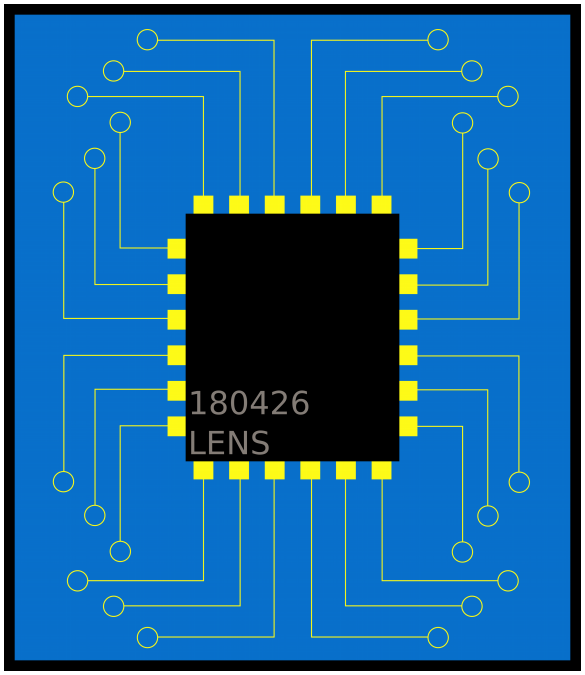
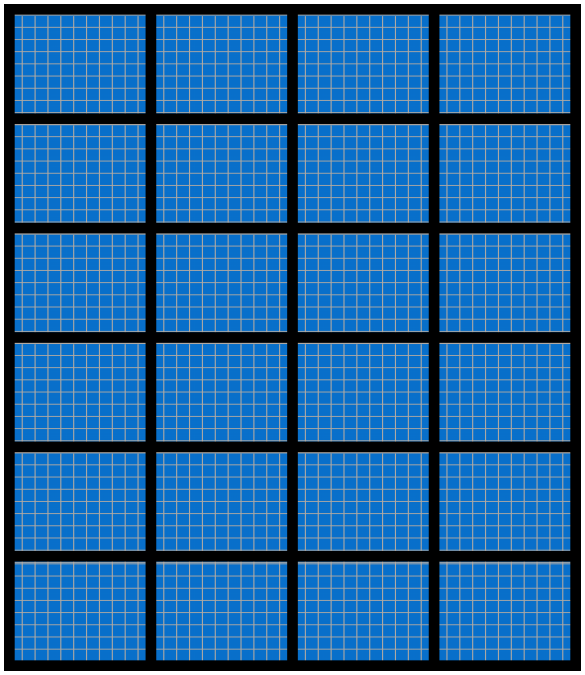
UiO : Centre for Materials Science and Nanotechnology
University of Oslo

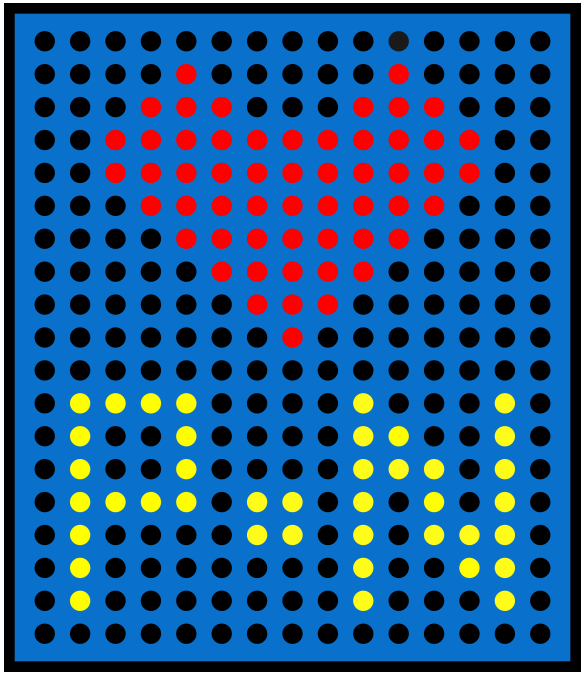
Fundamentals of *p*-*n* junctions

Christian Zimmermann

p-n junctions are fundamental







Kittel, C., *Introduction to solid state physics* (2005)
Hunklinger, S., *Festkörperphysik* (2014)

Let's start at the beginning...

Kittel, C., *Introduction to solid state physics* (2005)
Hunklinger, S., *Festkörperphysik* (2014)

...with semiconductors.

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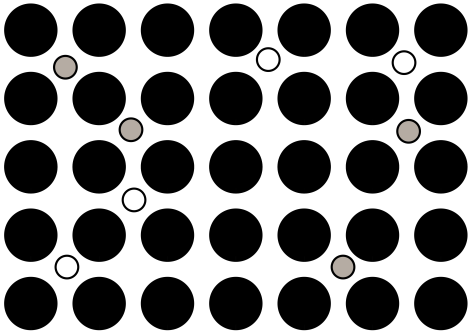

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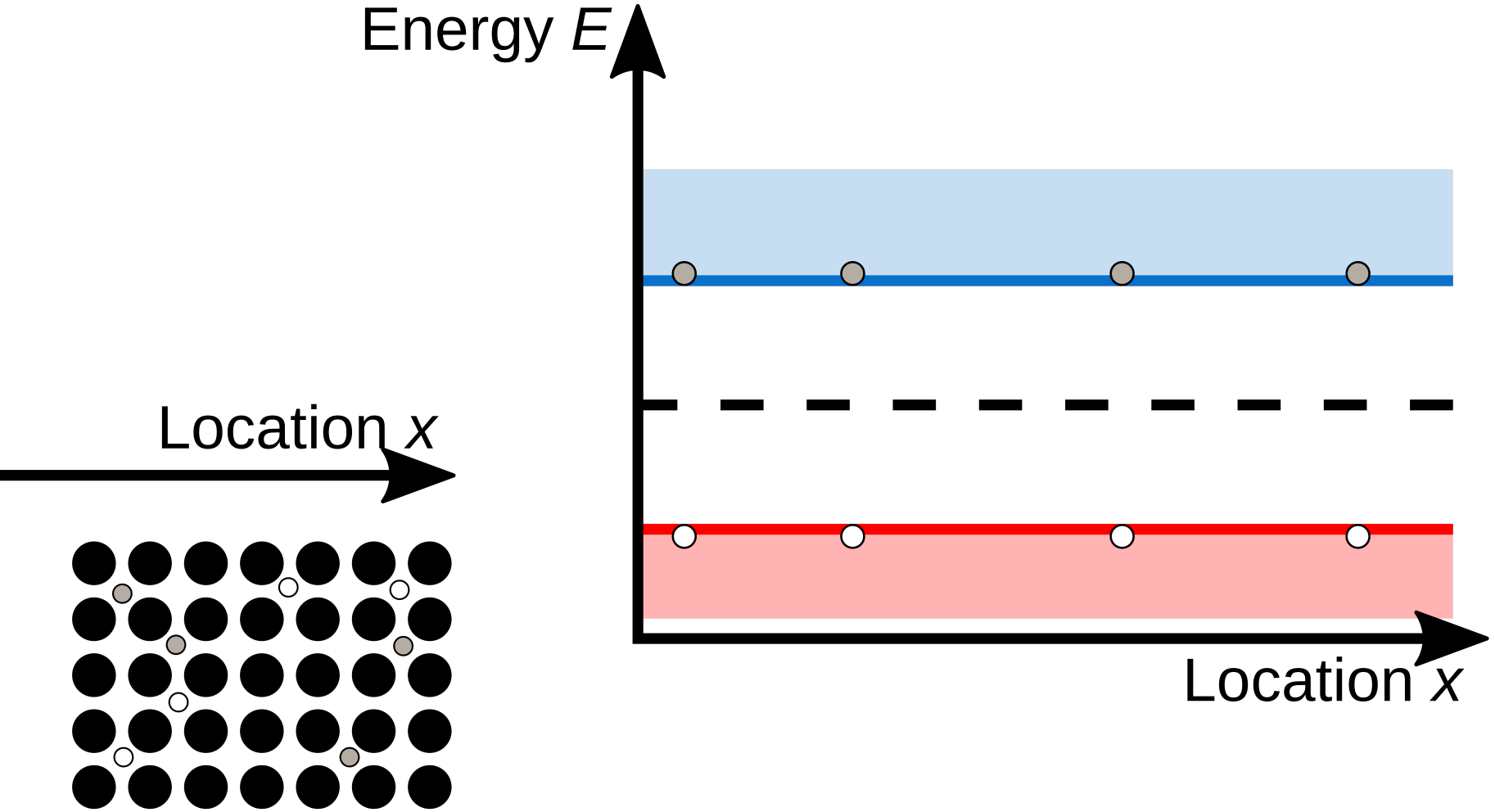

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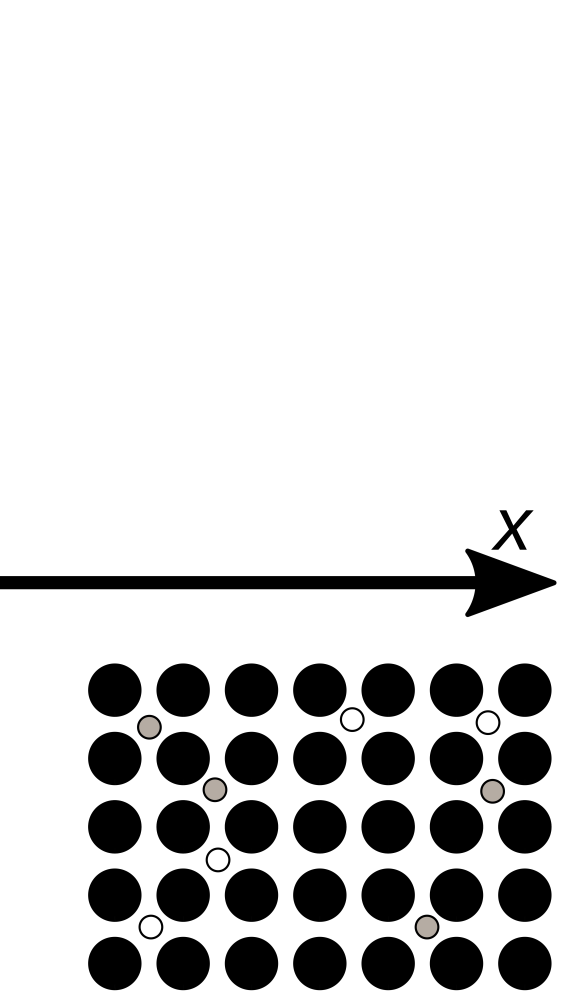
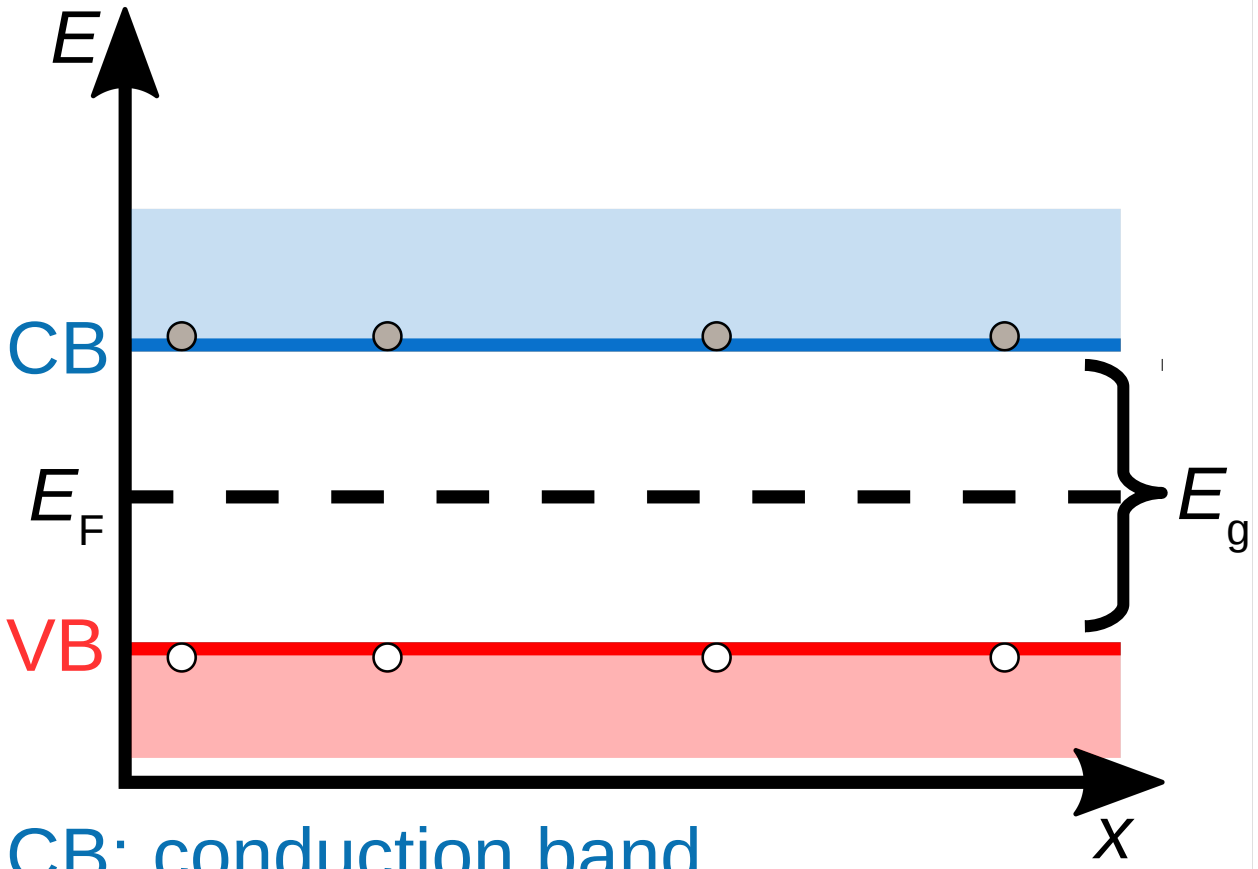
The band diagram





CB: conduction band

VB: valence band

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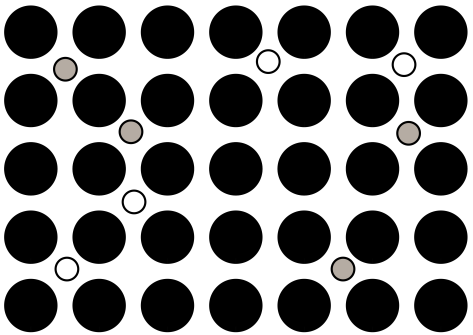
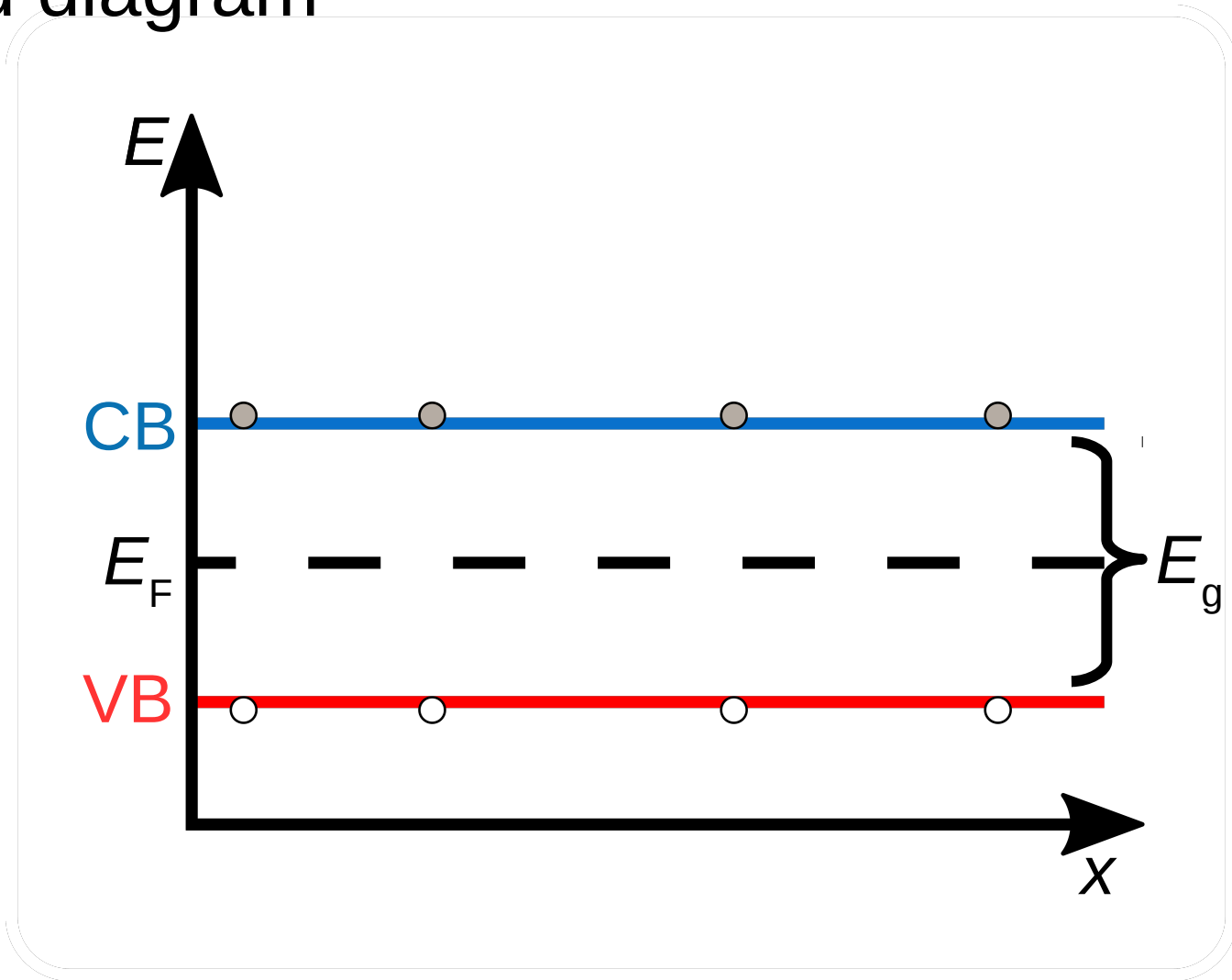
The band diagram





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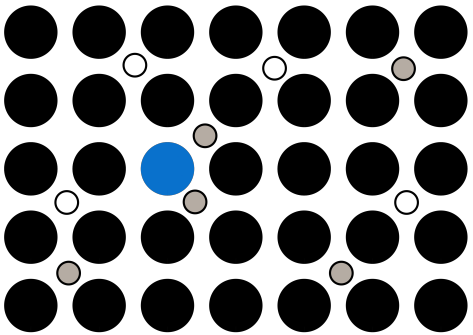
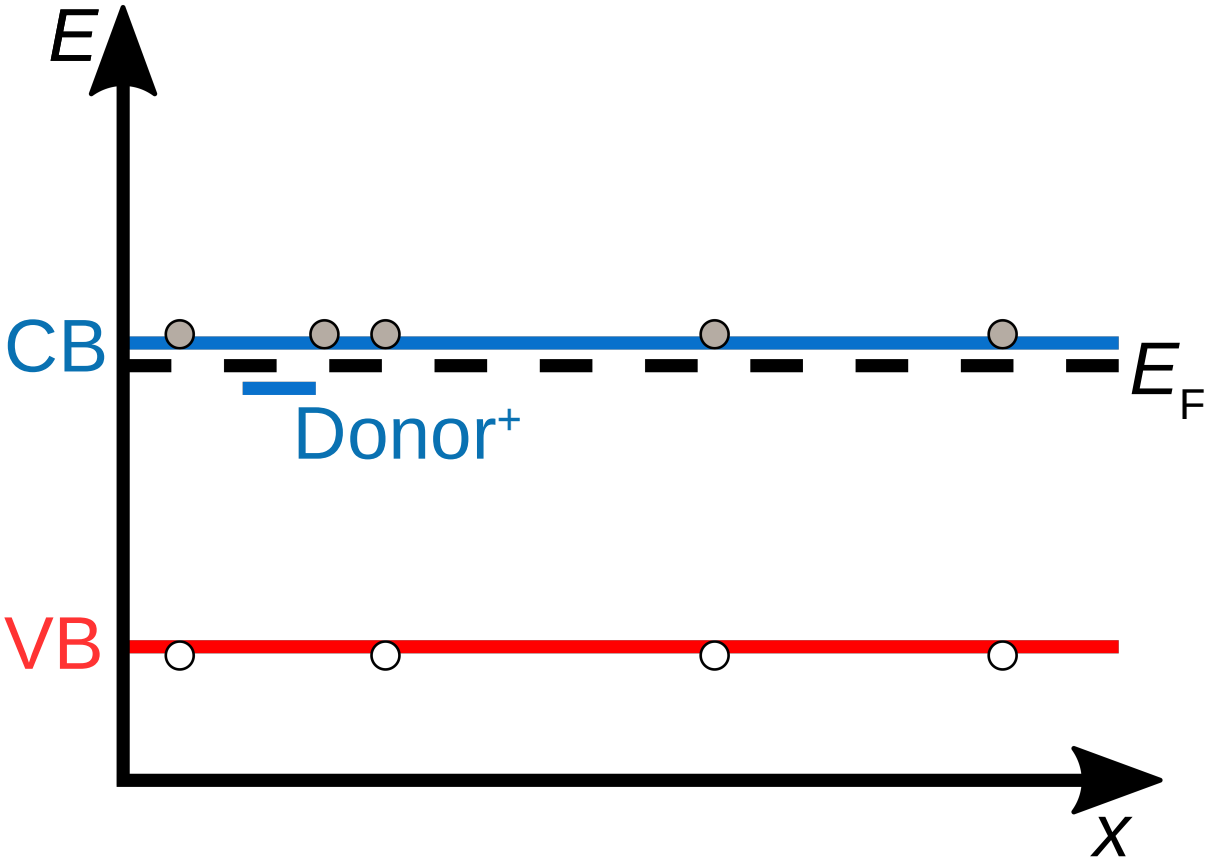
The band diagram: *n*-Doping





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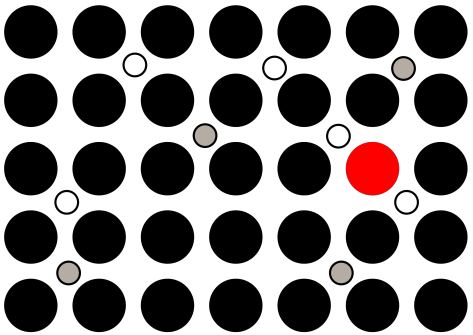
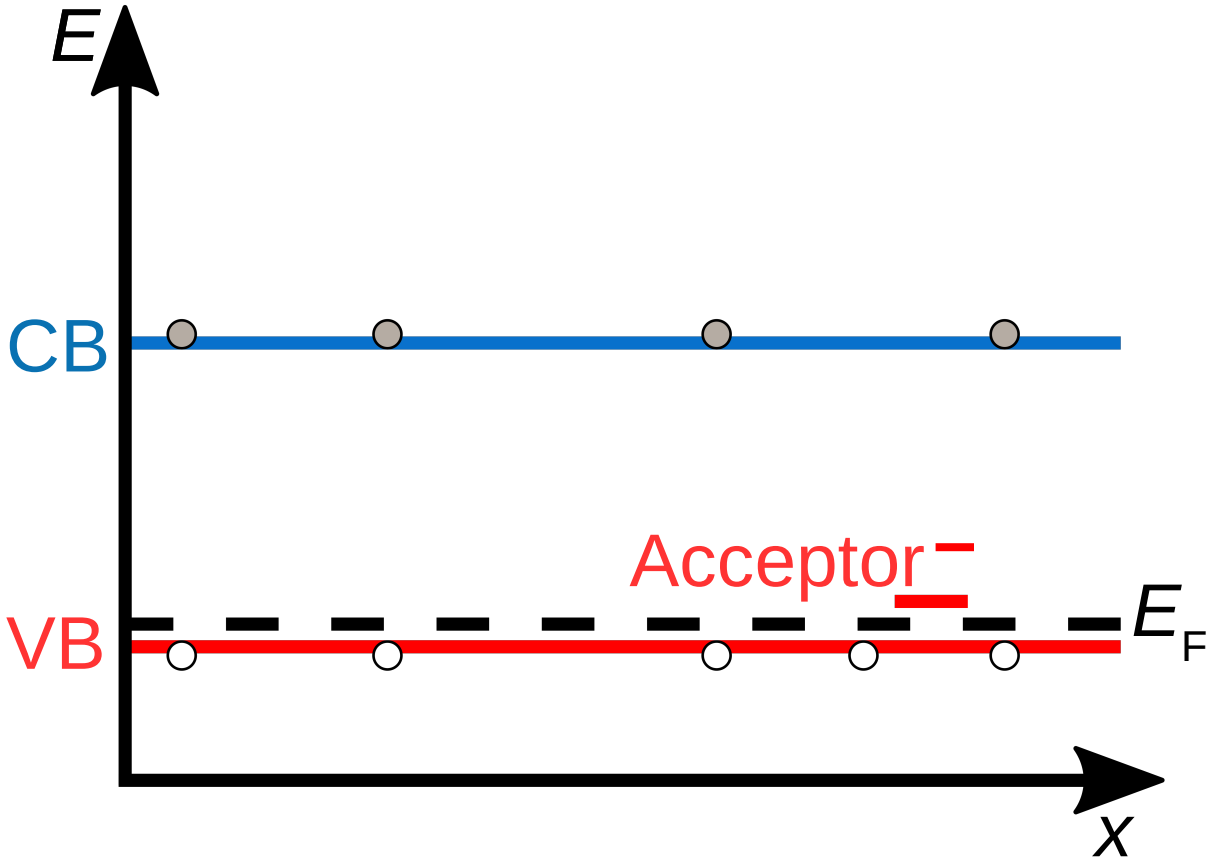
The Band diagram: *p*-Doping





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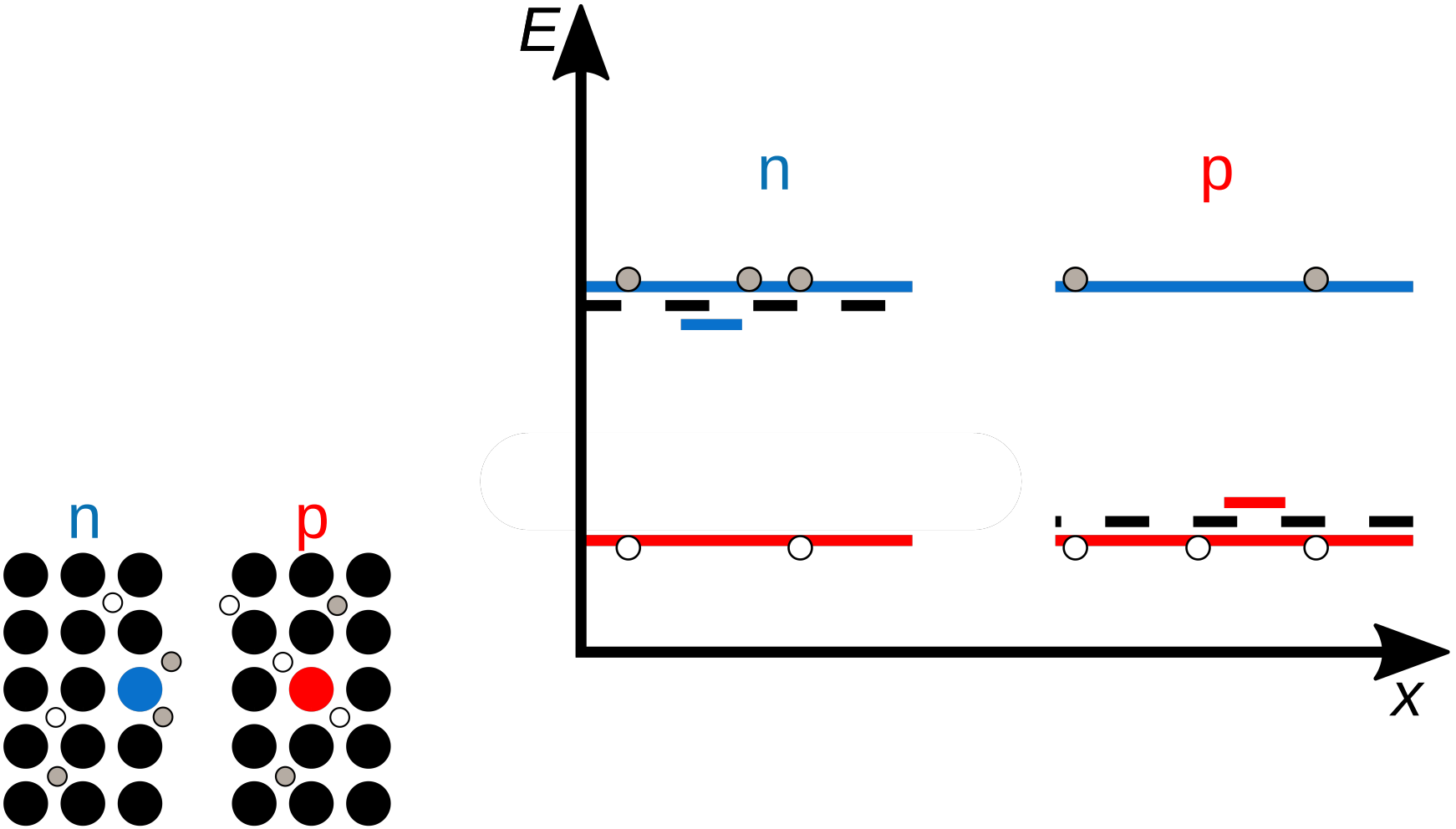
The band diagram of *p*-*n* junctions



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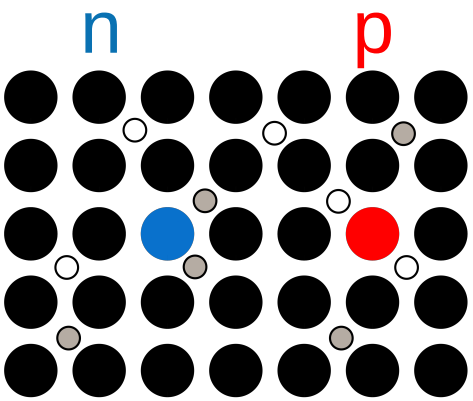

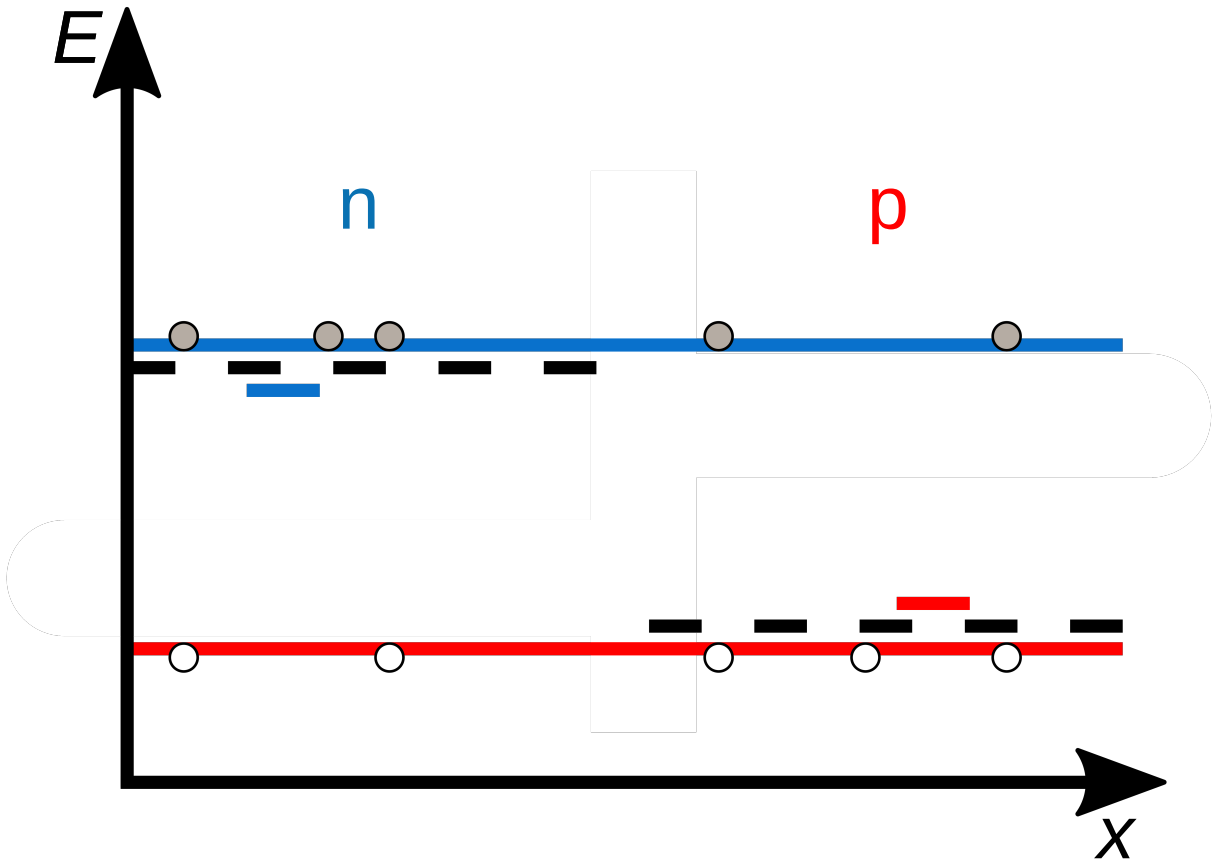

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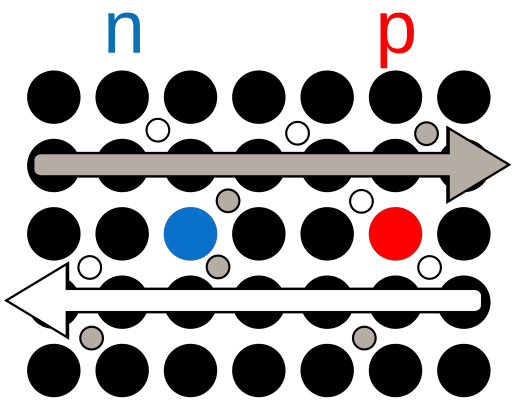

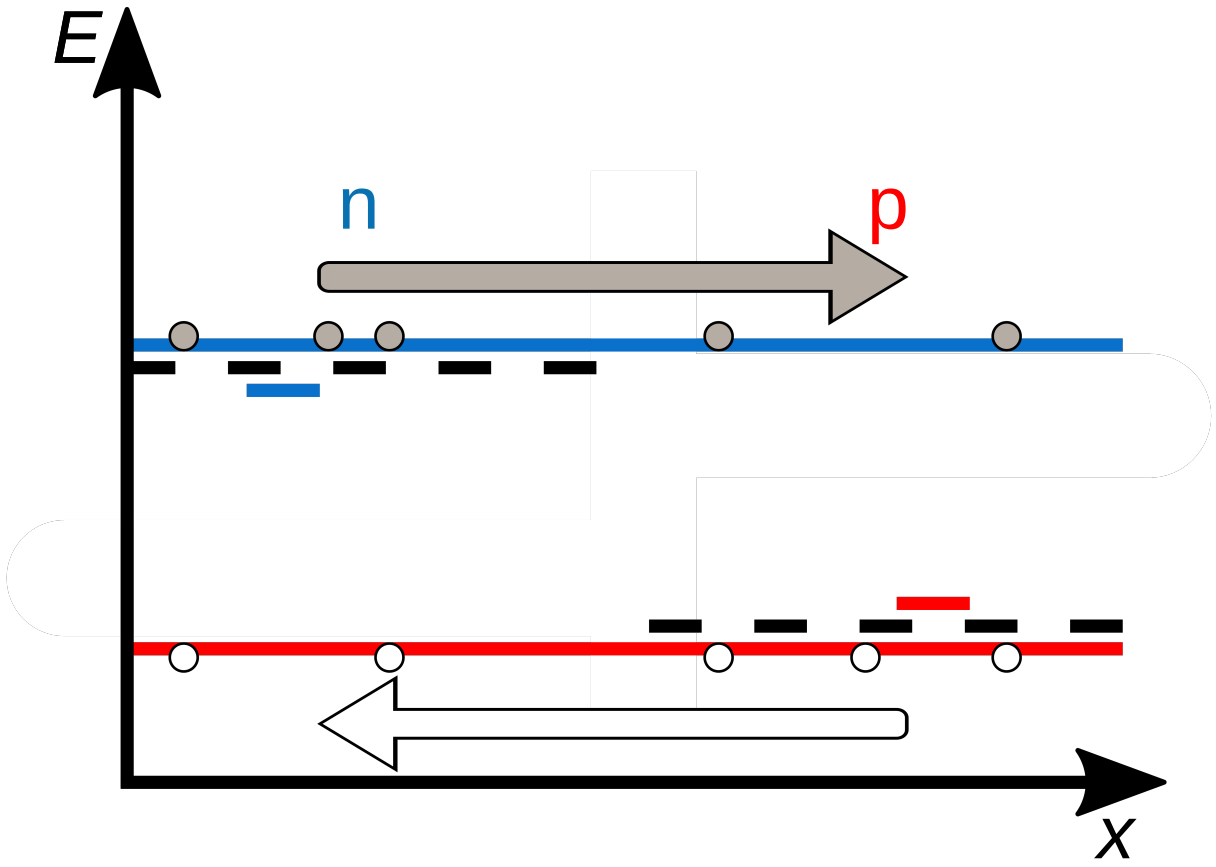

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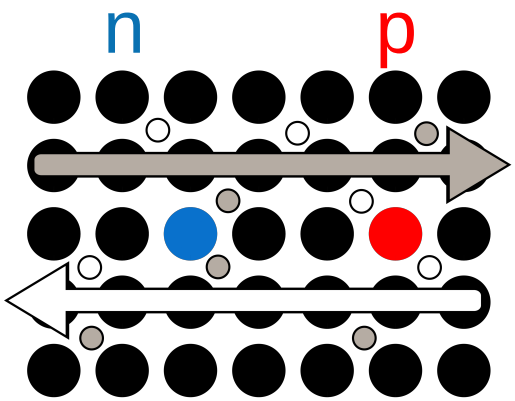
The band diagram of *p*-*n* junctions

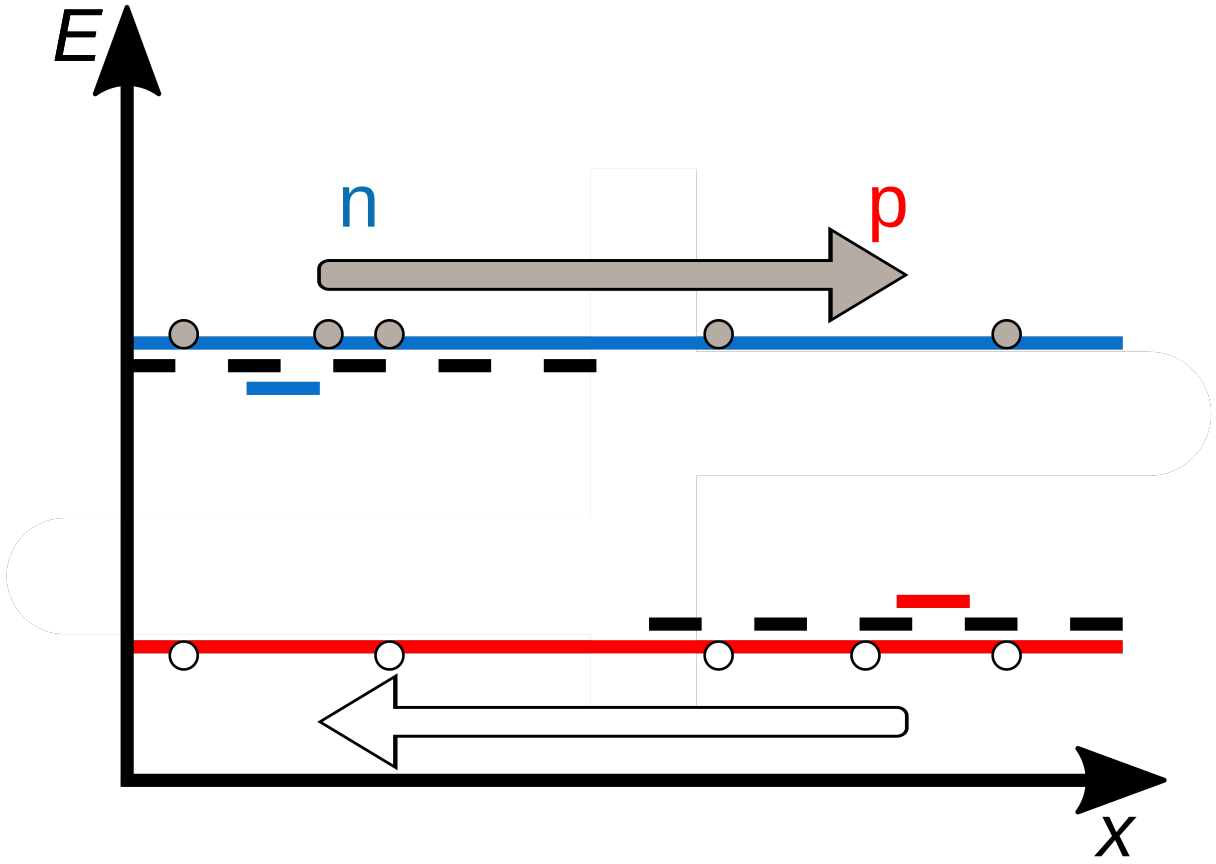
Steady-State with

Diffusion

=

Drift





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The band diagram of *p*-*n* junctions

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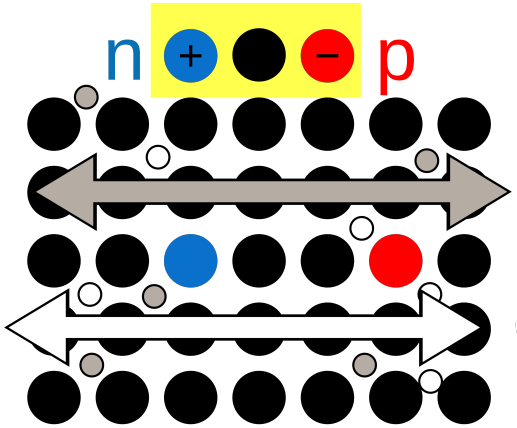

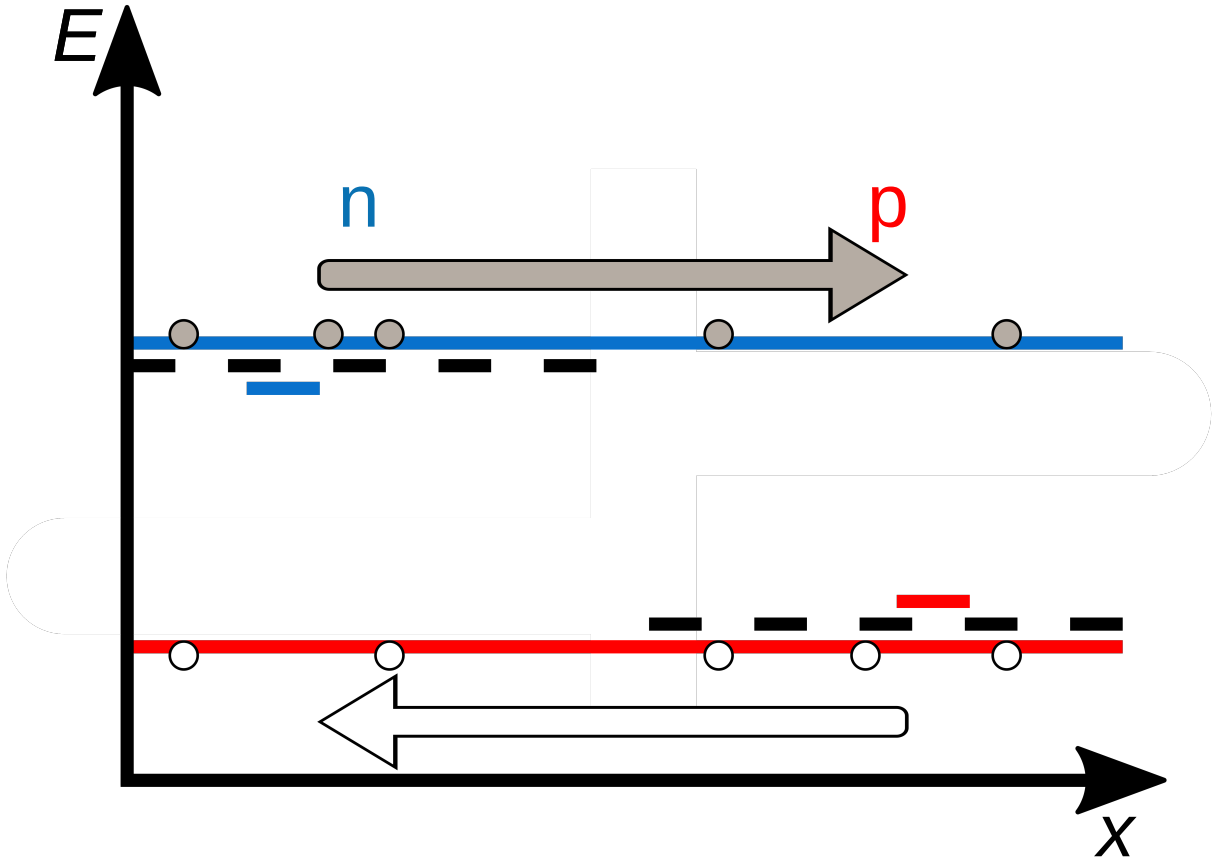

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The band diagram of *p-n* junctions

Steady-State with

Diffusion

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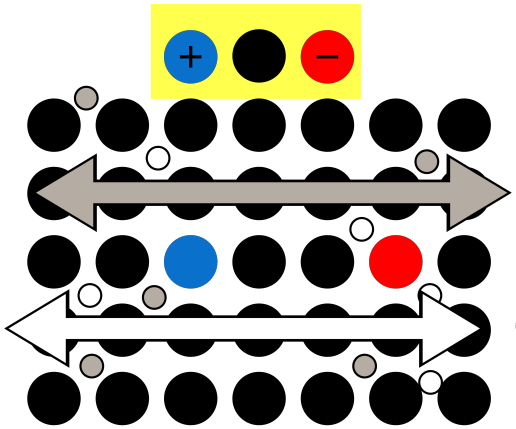
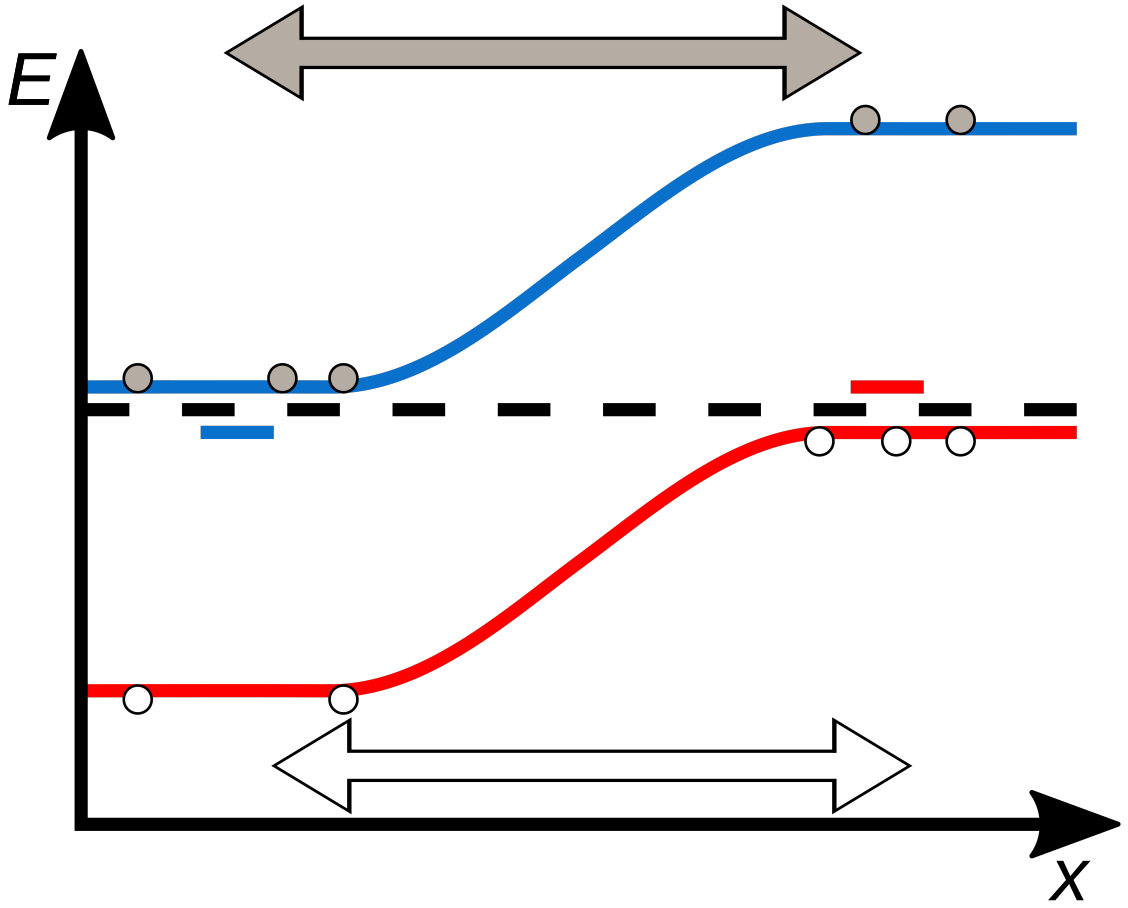
Drift





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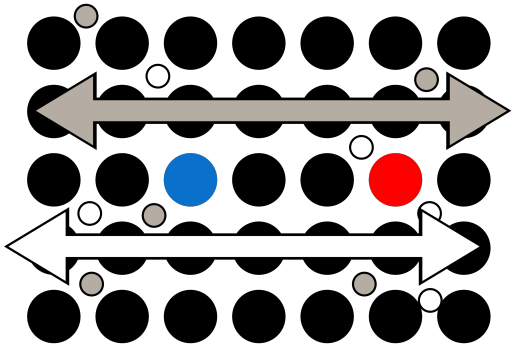
The band diagram of *p-n* junctions

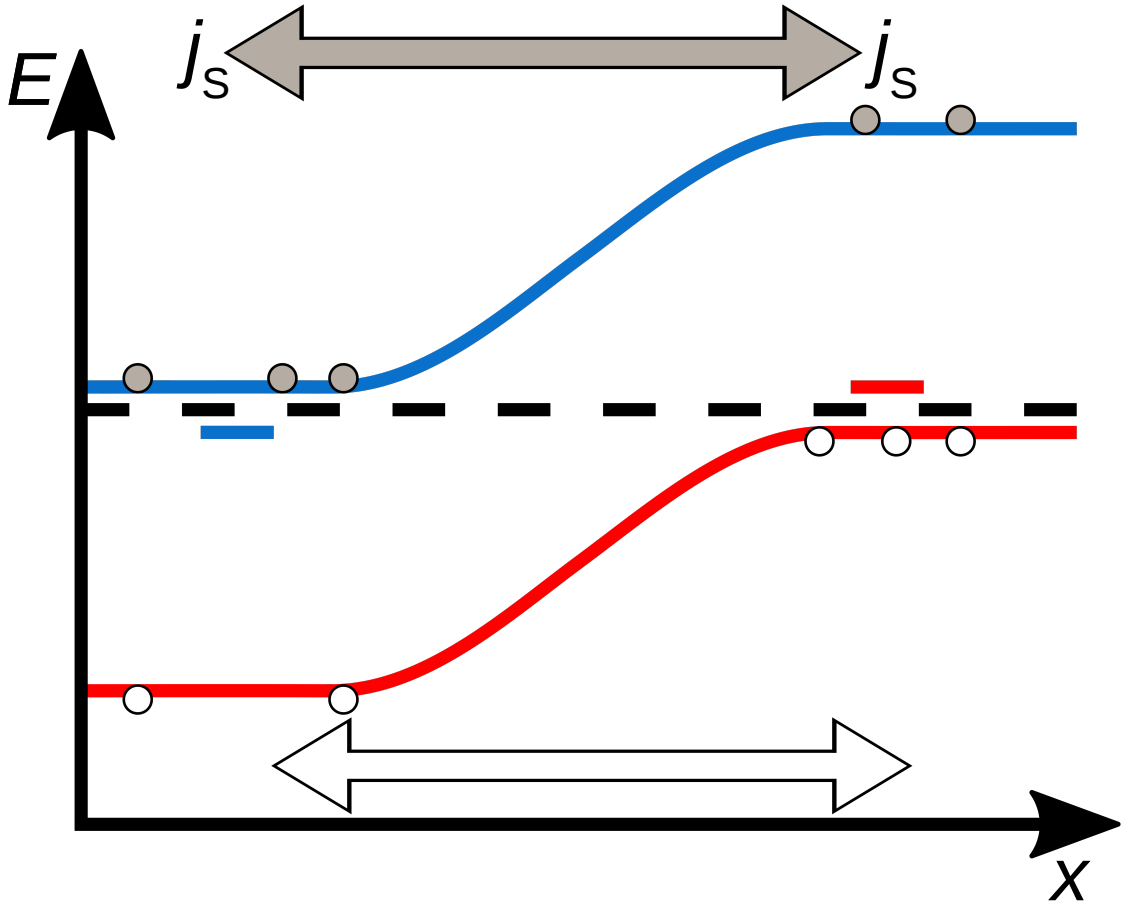
Steady-State with

Saturation Current

=

j_s





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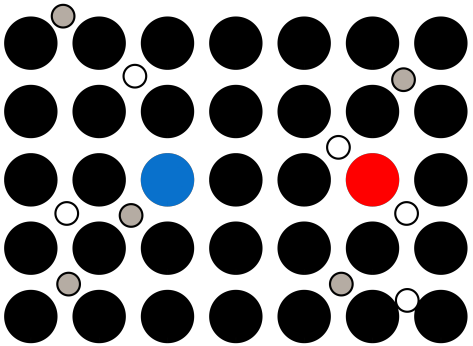
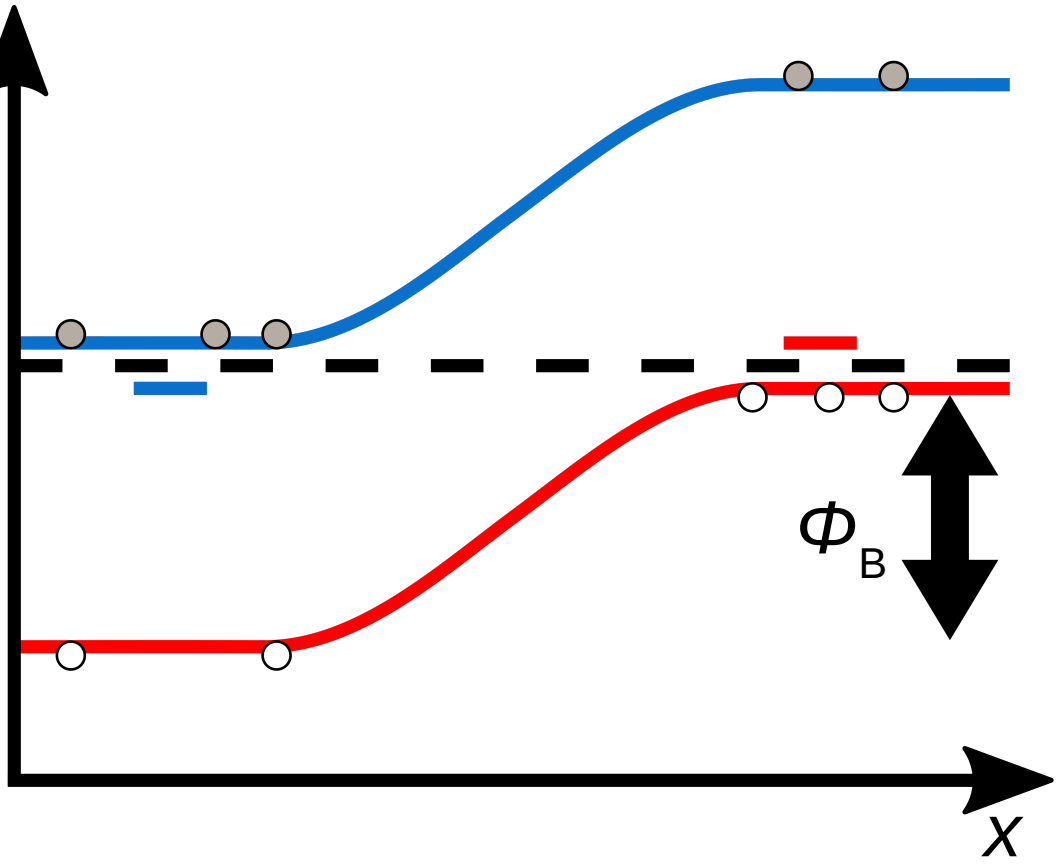
p-n junctions: Barrier height





Φ_B: barrier height/ built-in voltage

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Hunklinger, S., *Festkörperphysik* (2014)
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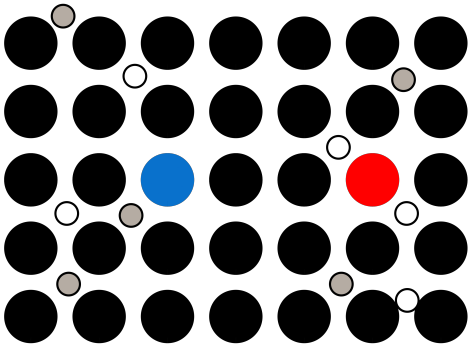
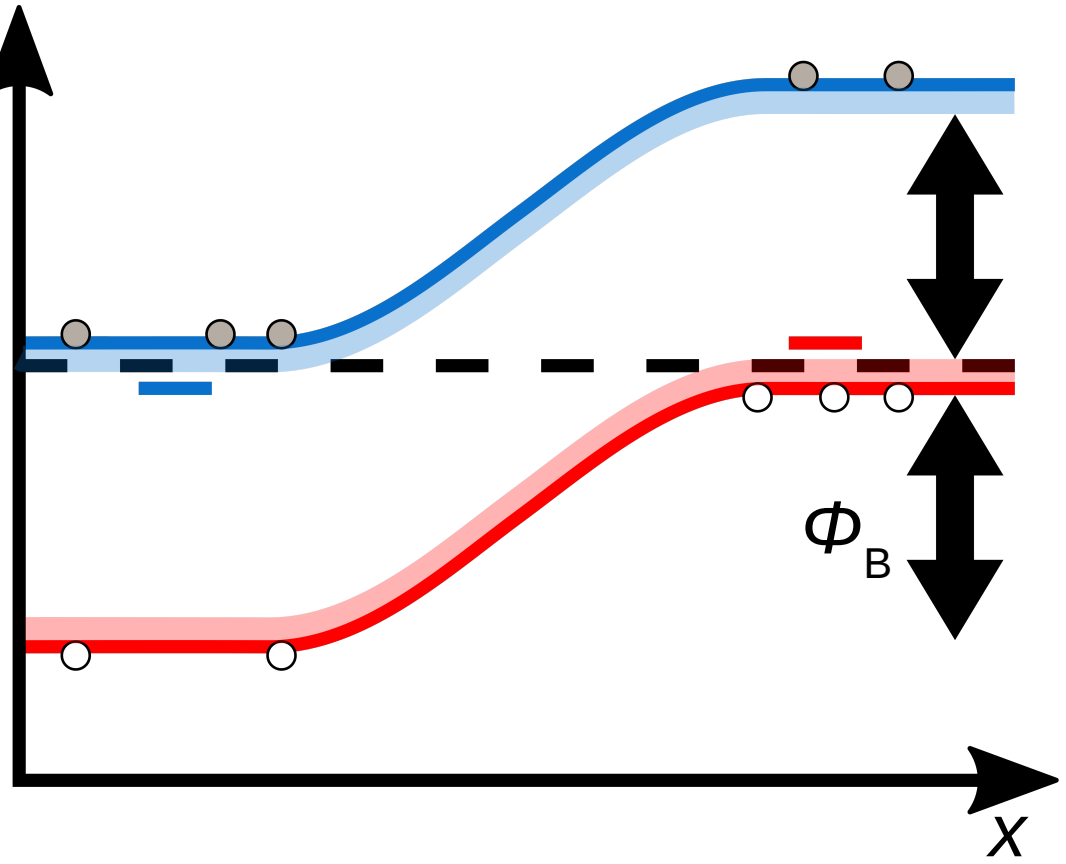
p-n junctions: Barrier height





Φ_B: barrier height/ built-in voltage

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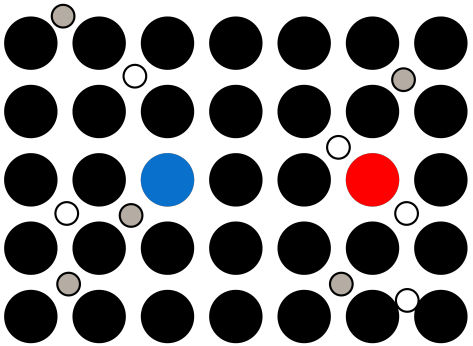
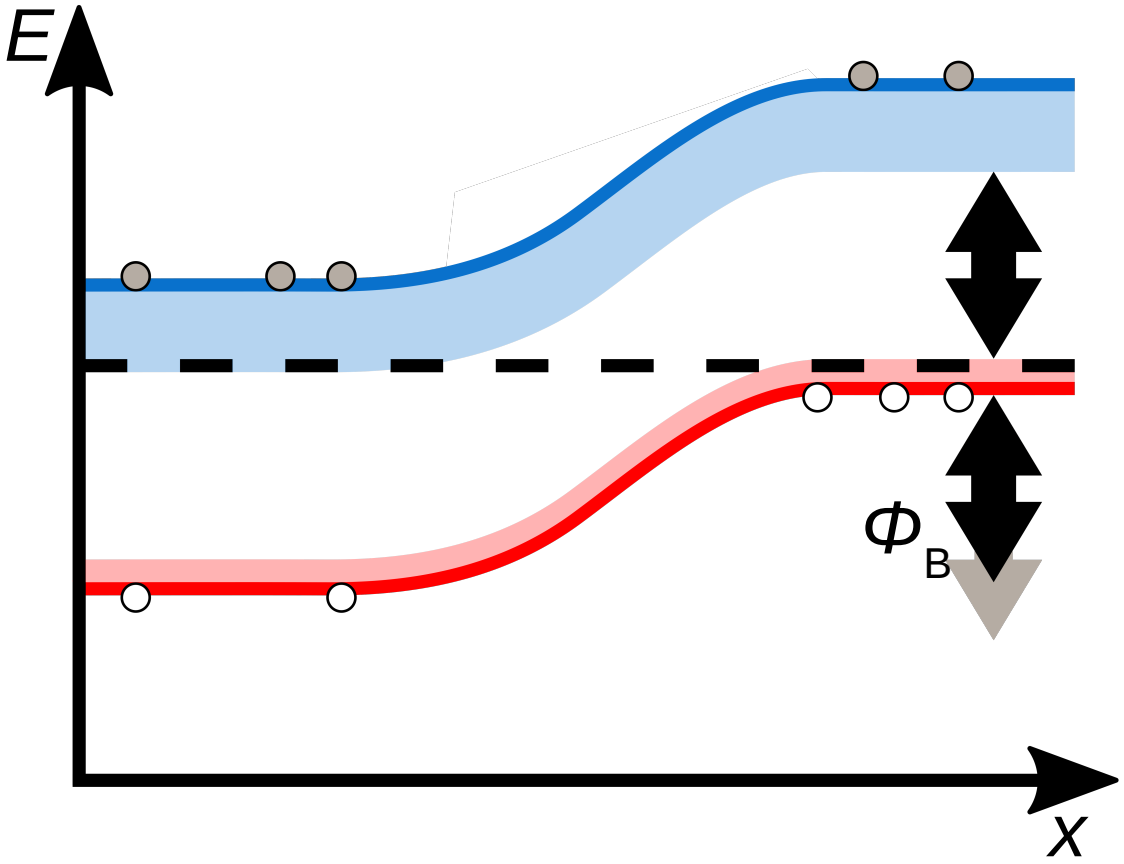
p-n junctions: Barrier height





Φ_B: barrier height/ built-in voltage

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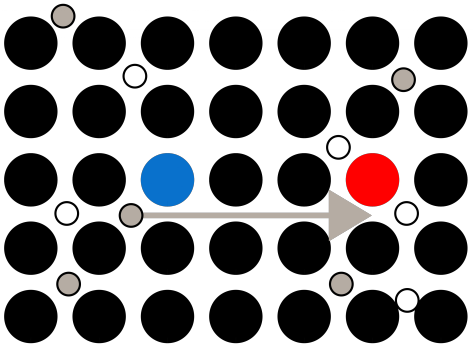
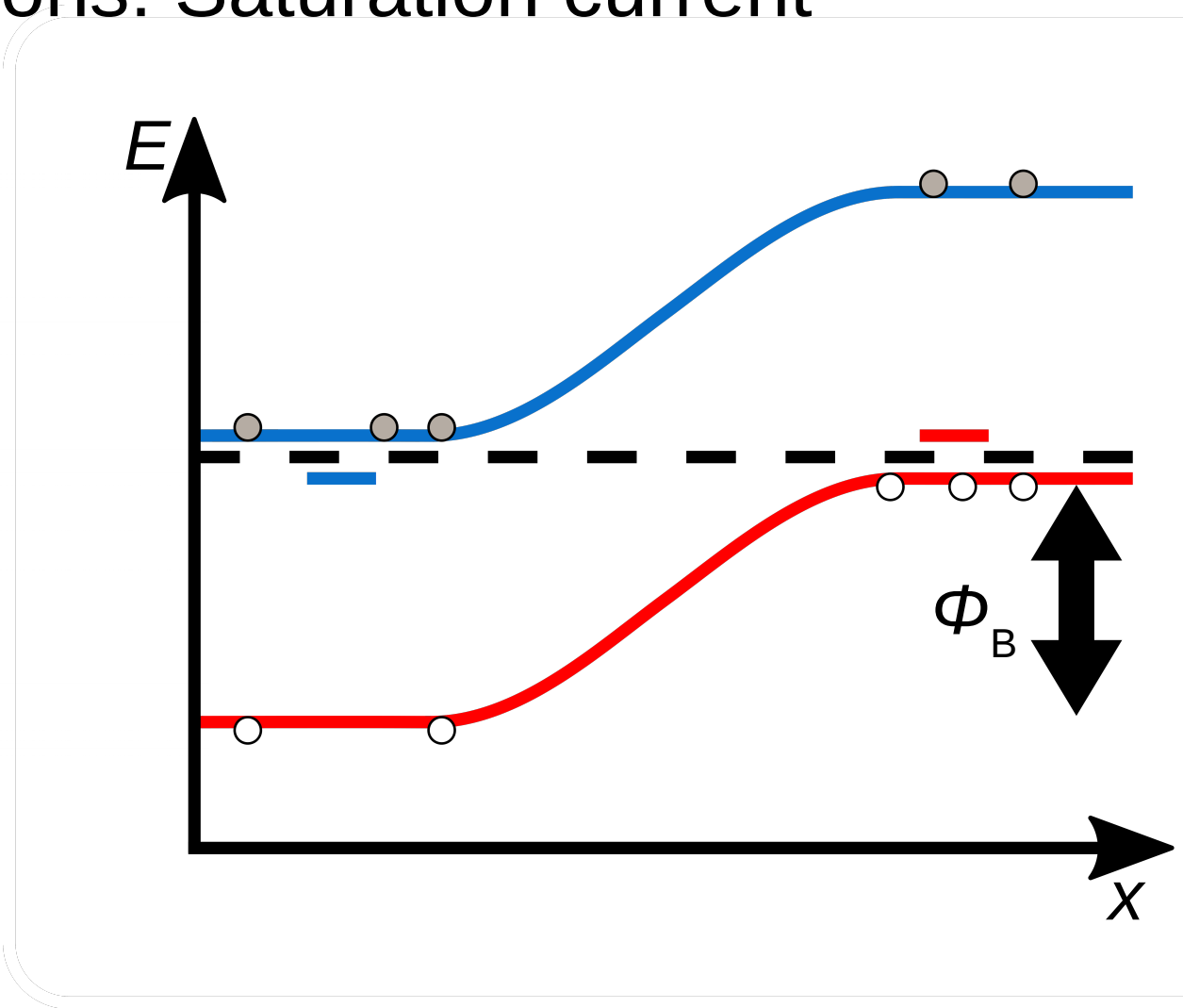
p-n junctions: Saturation current

$j_S =$





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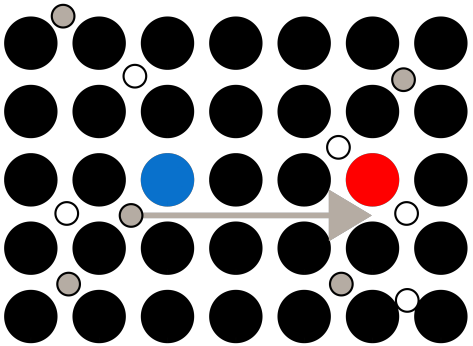
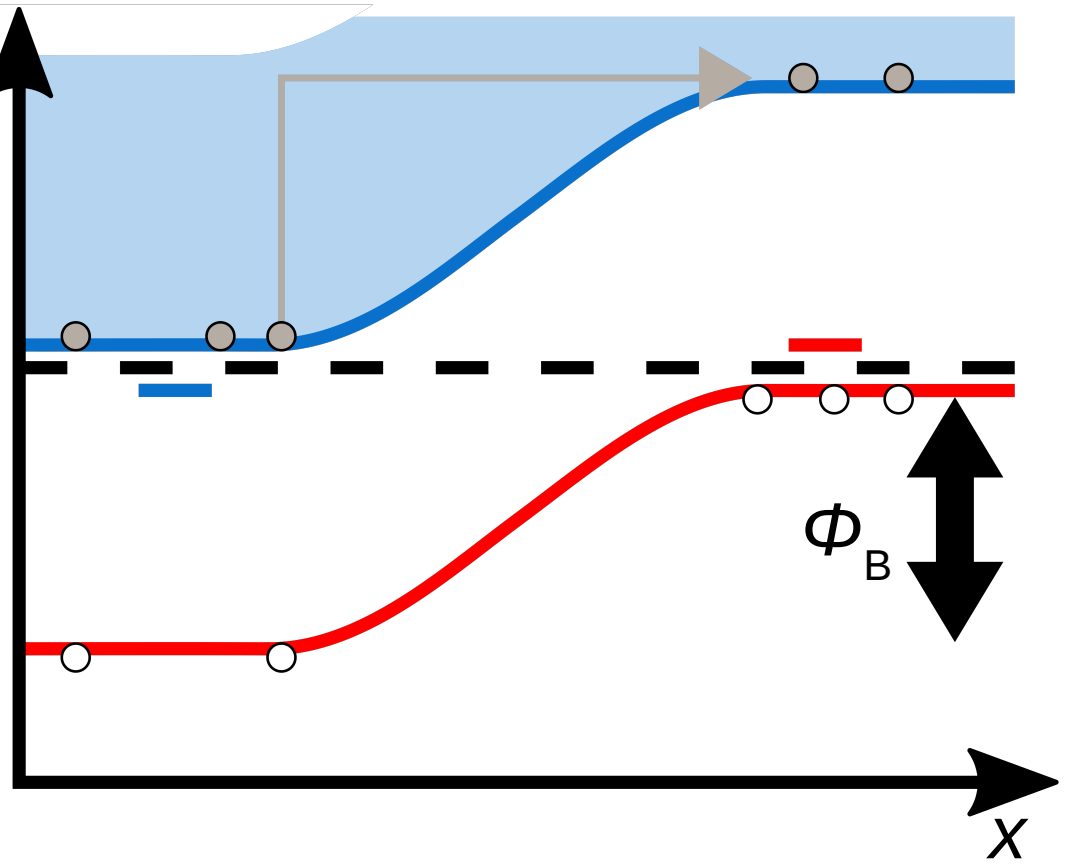
p-n junctions: Saturation current

Thermionic emission

$$j_S = AT^2 e^{\frac{-\Phi_B}{kT}}$$





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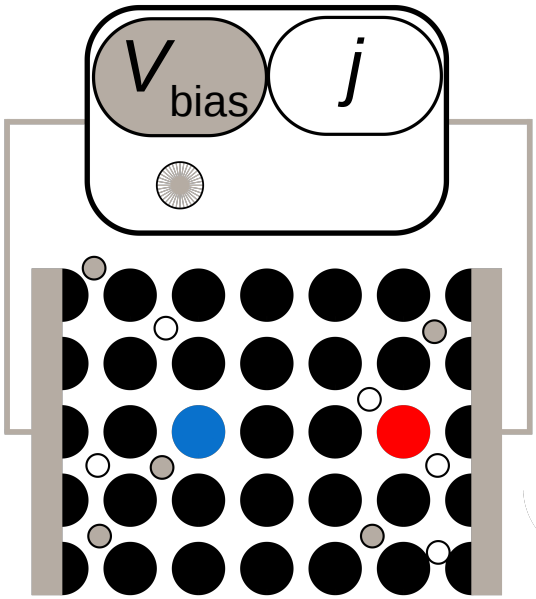
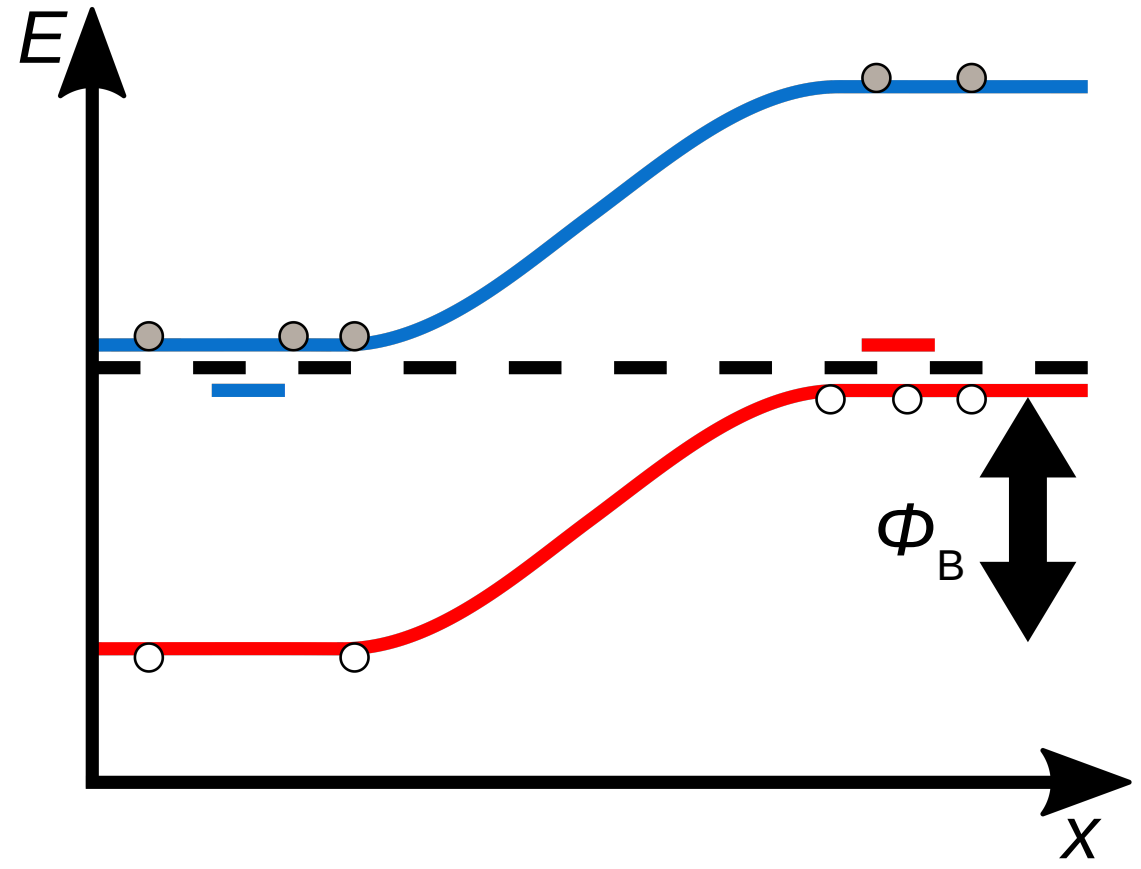
p-n junctions under applied voltage





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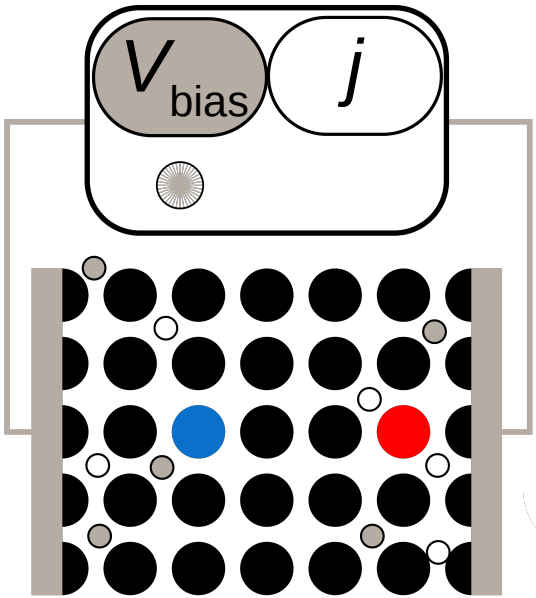
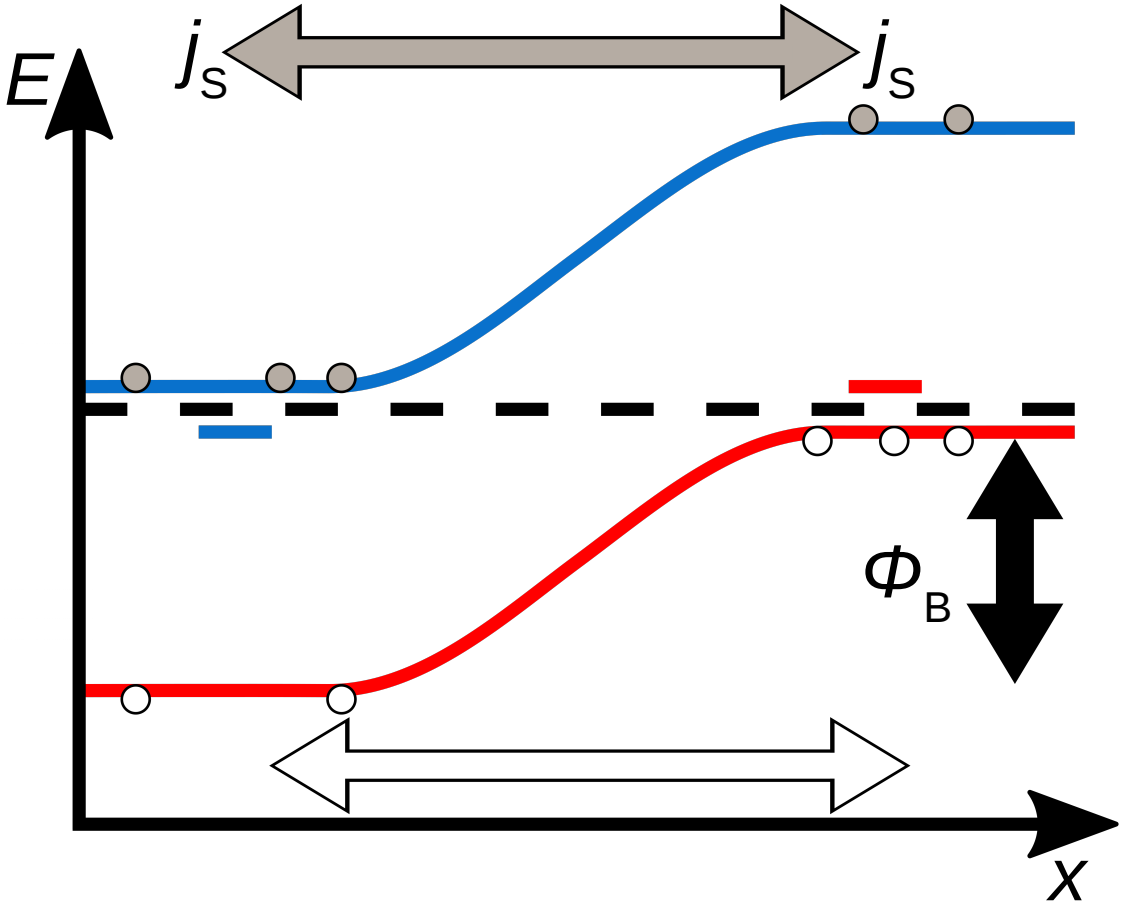
p-n junctions under applied voltage

$V_{bias} = 0$ V:

$j = j_S - j_S$





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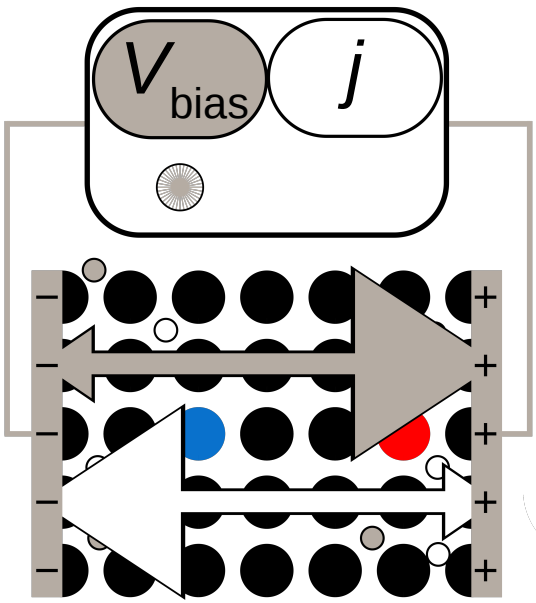
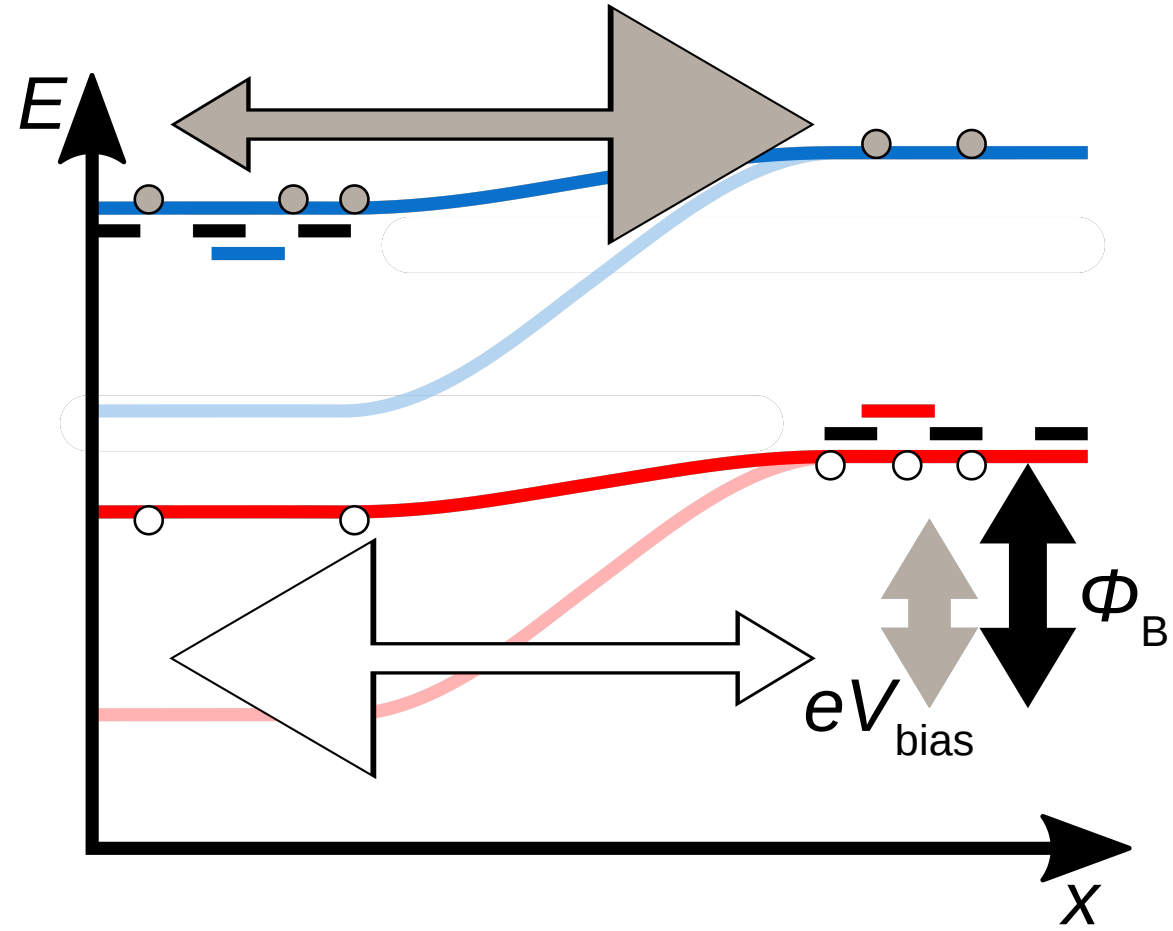
p-n junctions under forward bias

$V_{bias} > 0\,V$





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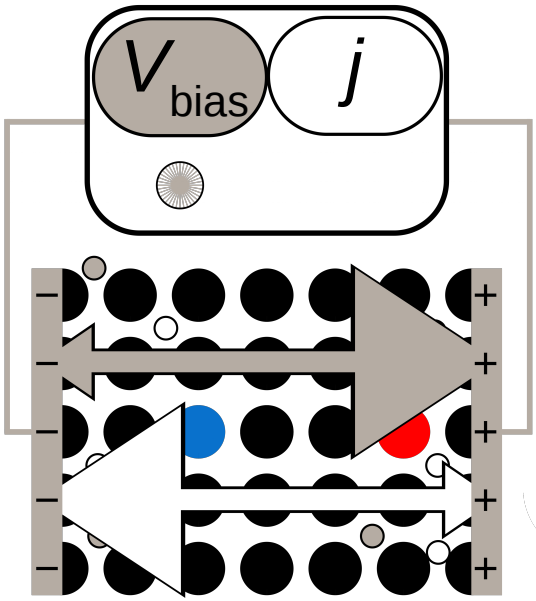
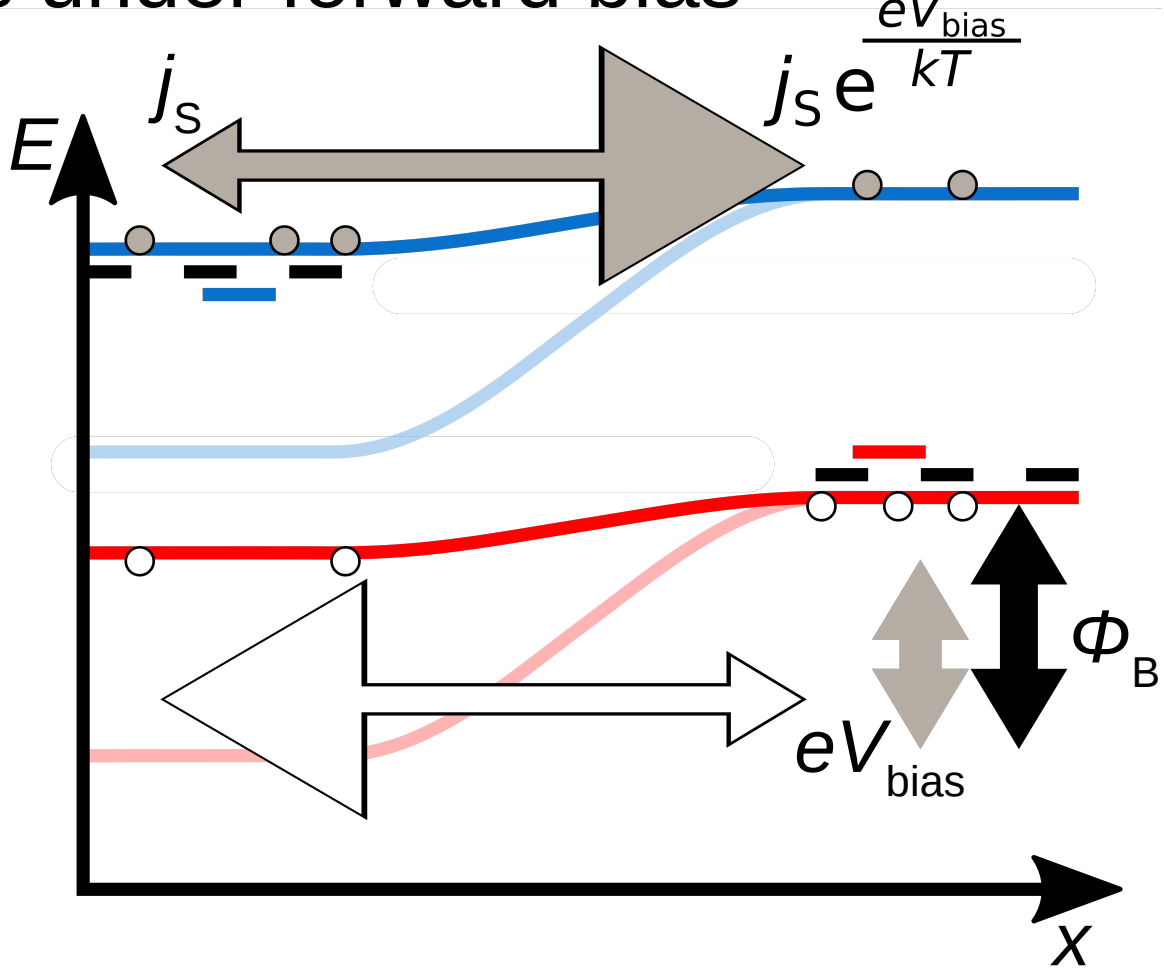
p-n junctions under forward bias

$V_{bias} > 0\,V$:

$$j = j_S e^{\frac{eV_{bias}}{kT}} - j_S$$





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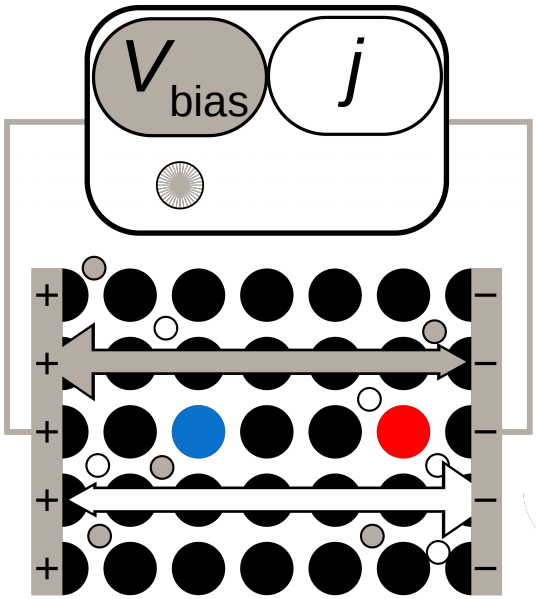
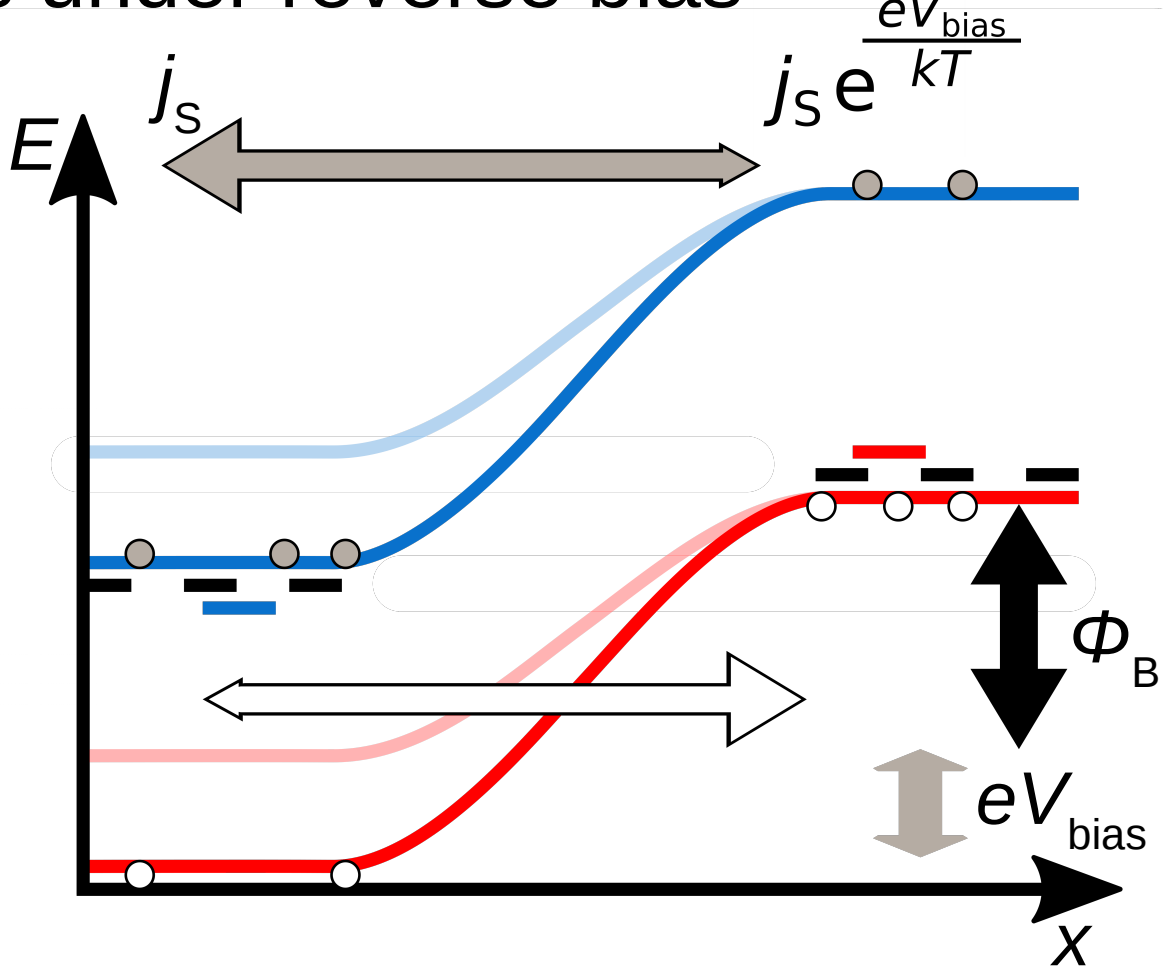
p-n junctions under reverse bias

$V_{bias} < 0$ V:

$$j = j_S e^{\frac{eV_{bias}}{kT}} - j_S$$





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Wuerfel, P, *Physics of Solar Cells* (2005)
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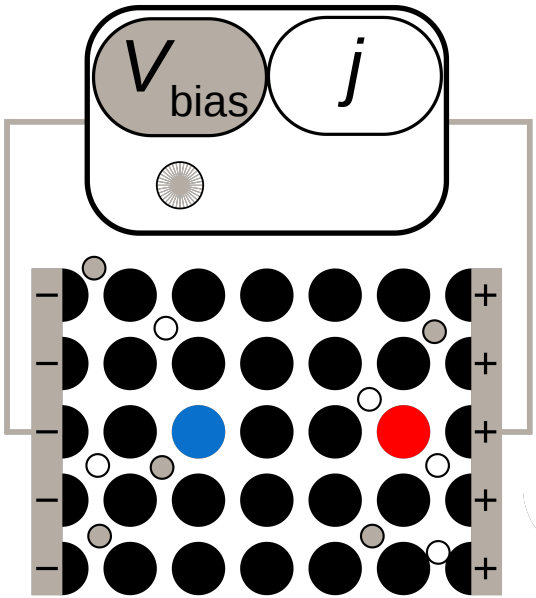
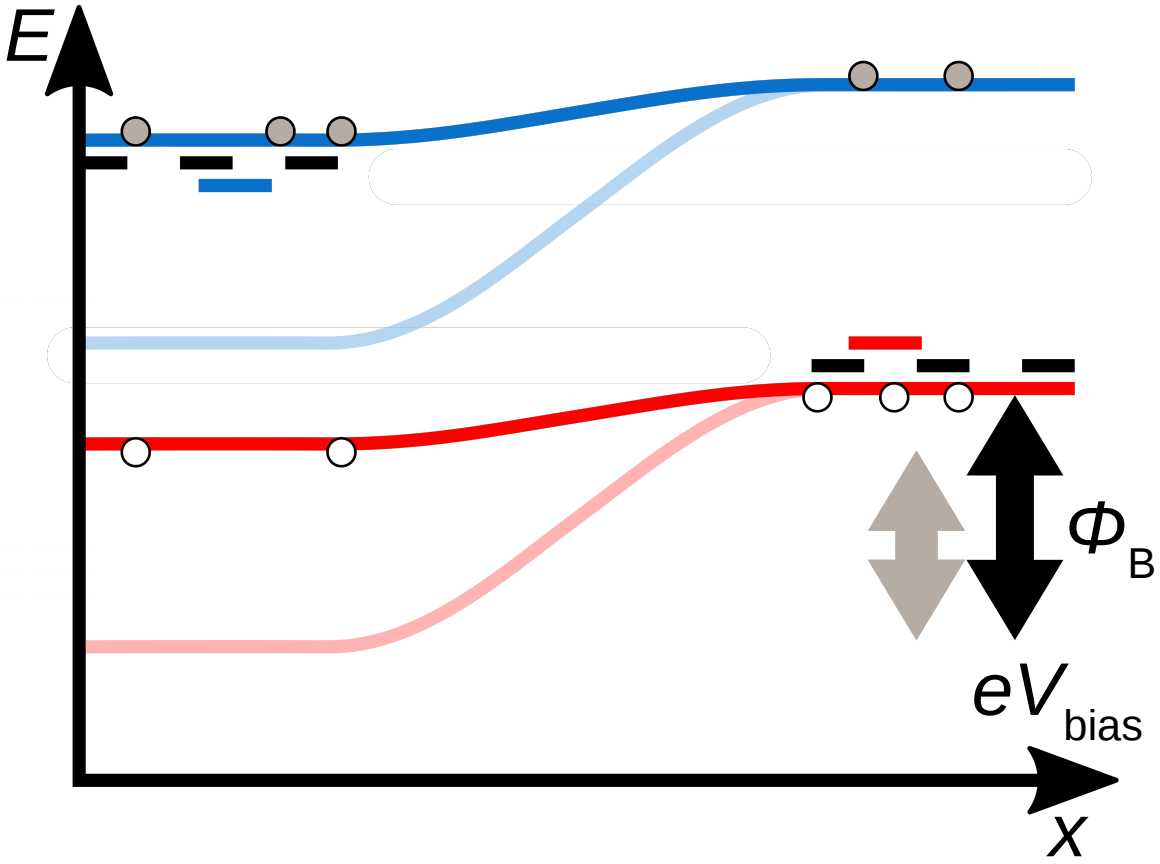
p-n junctions under forward bias

$$j = j_S(e^{\frac{eV_{bias}}{kT}} - 1)$$





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MacIntosh, K. R., *Proceedings of the 16th of the European Photovoltaic Solar Energy Conference* (2000)
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p-n junctions: Influence of defects

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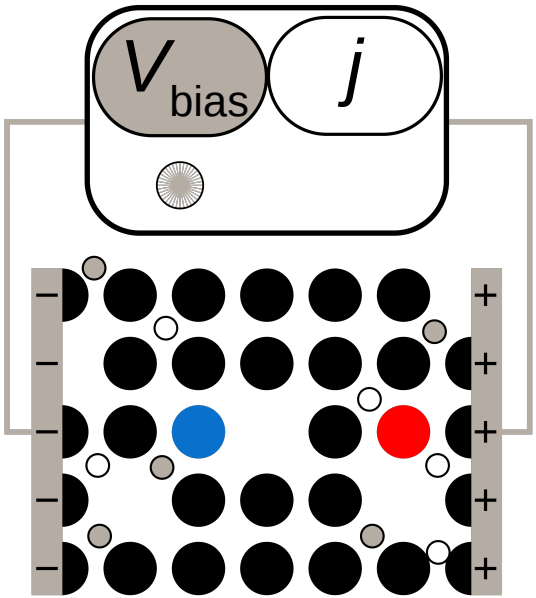

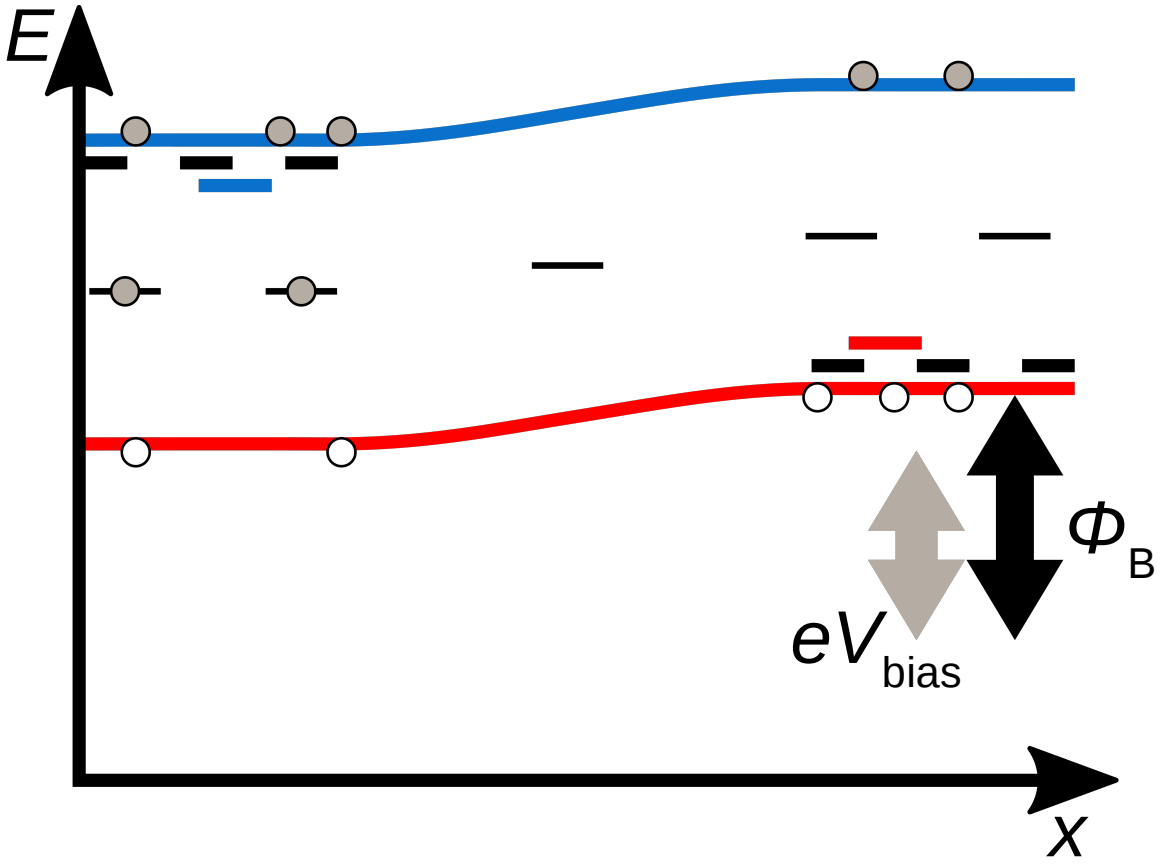

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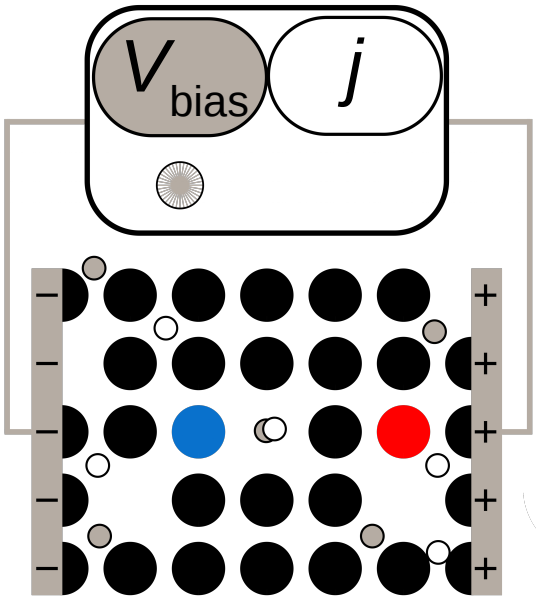

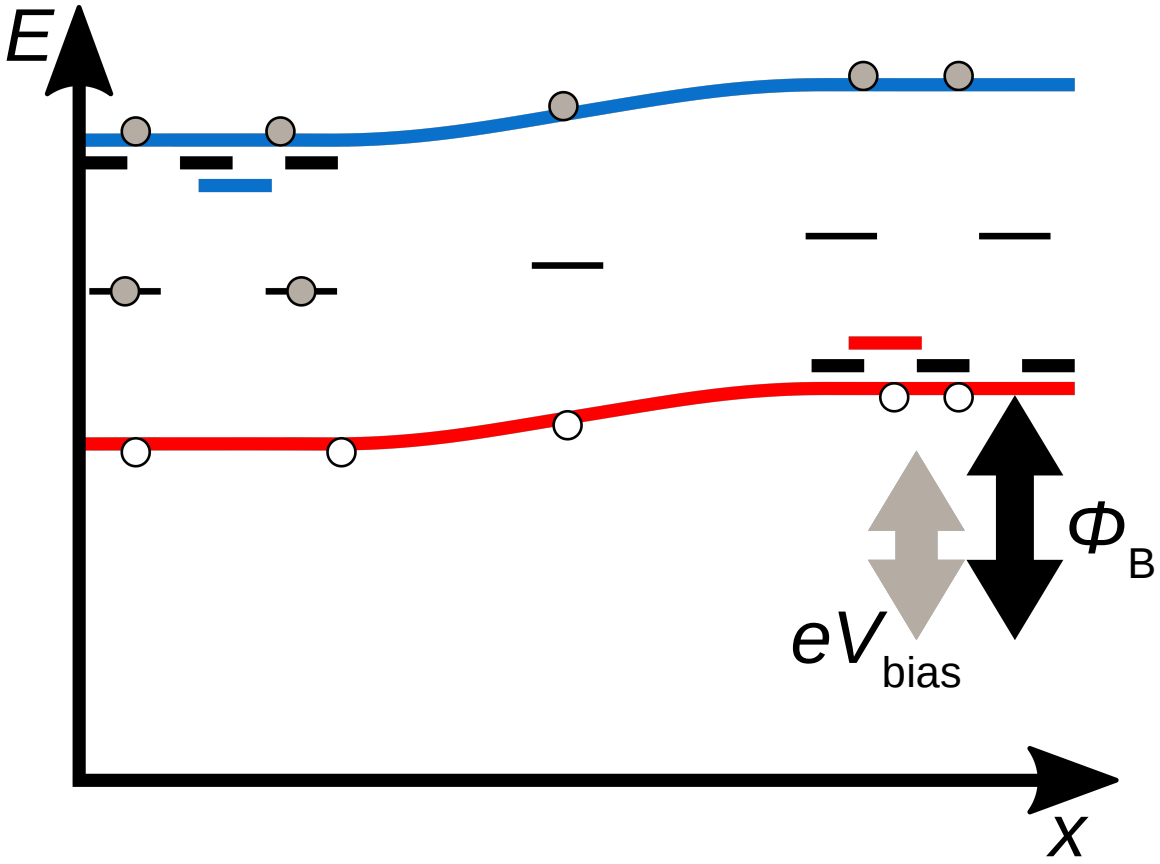

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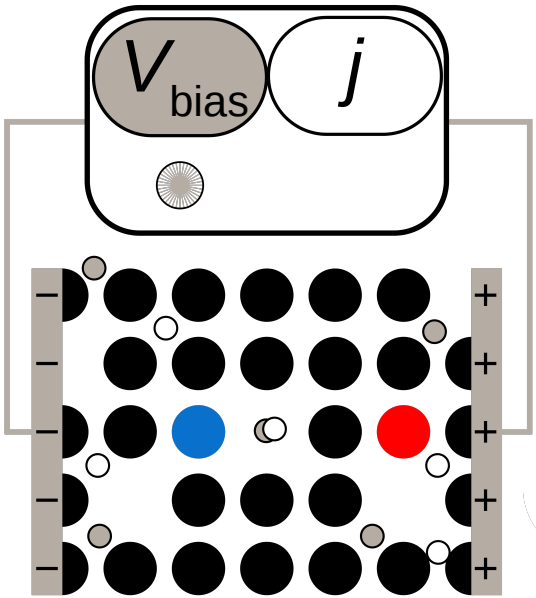

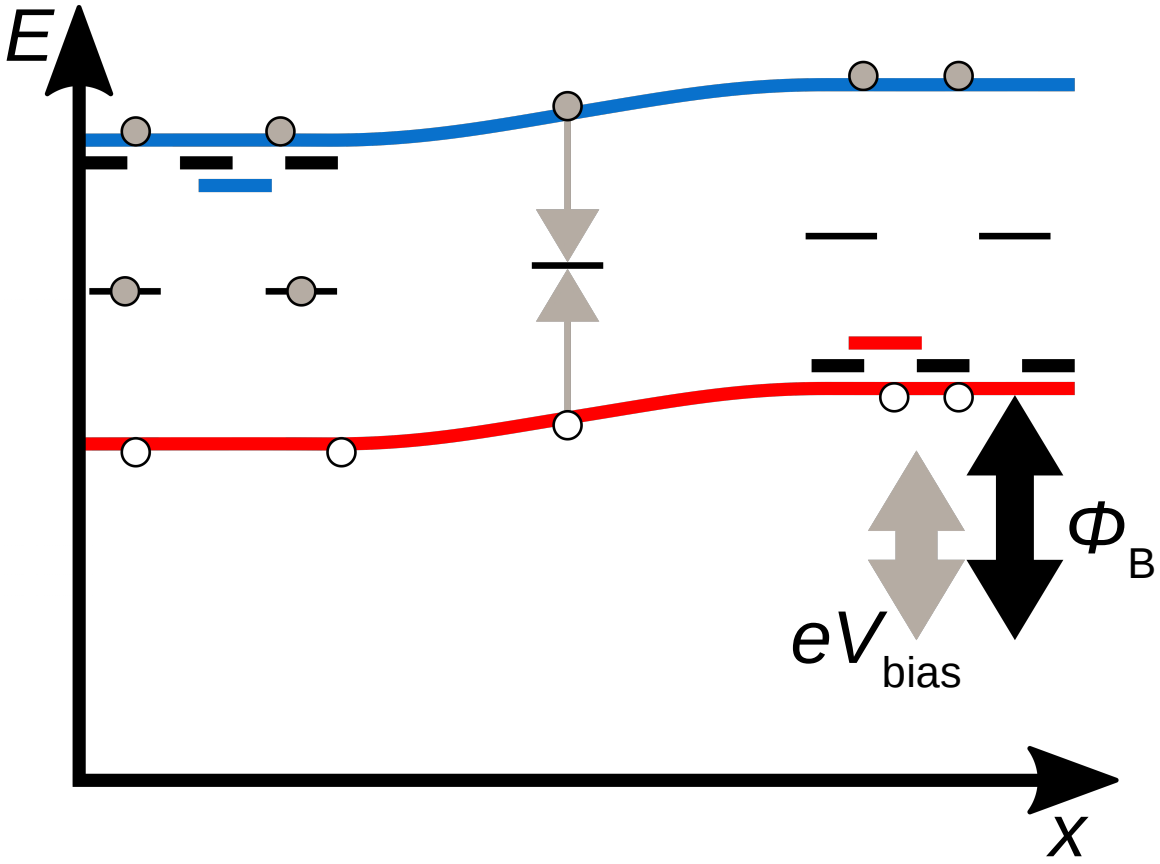

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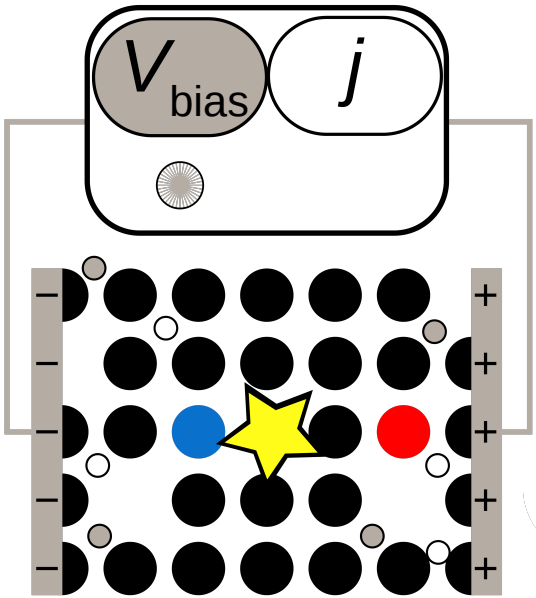

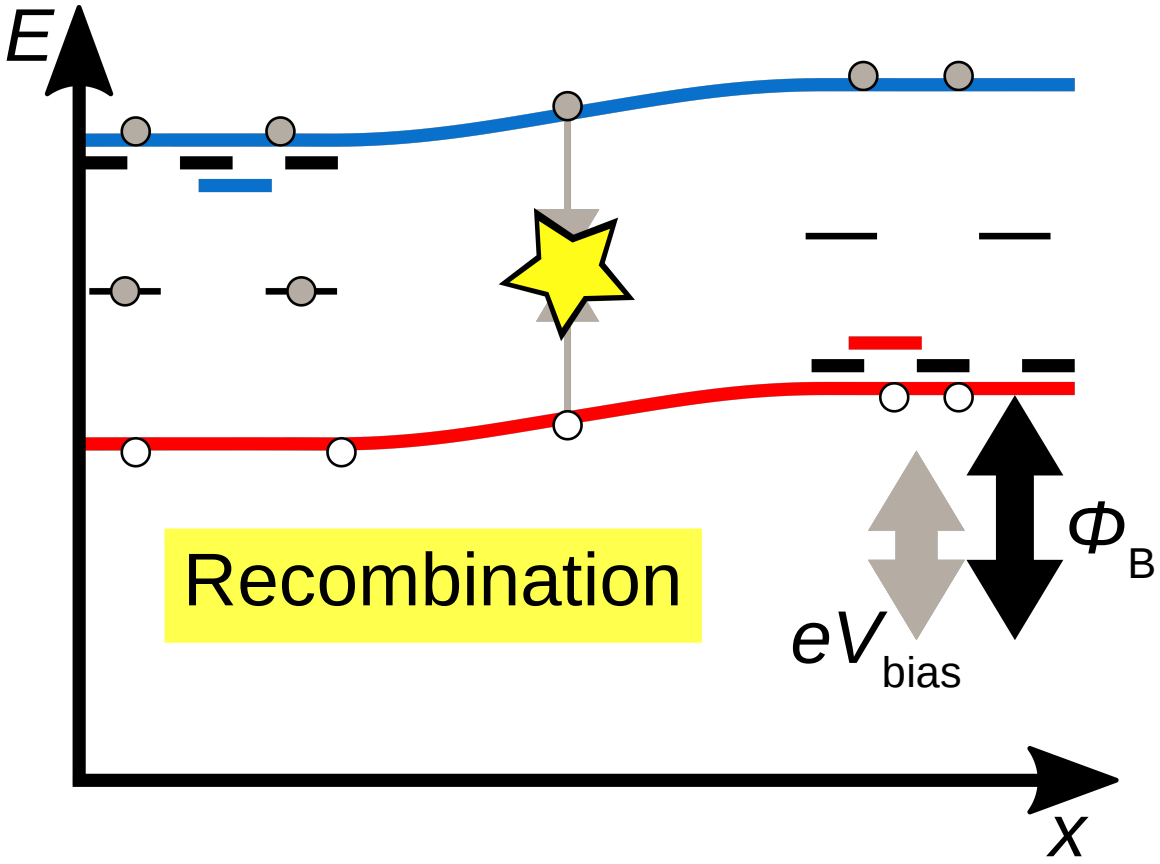

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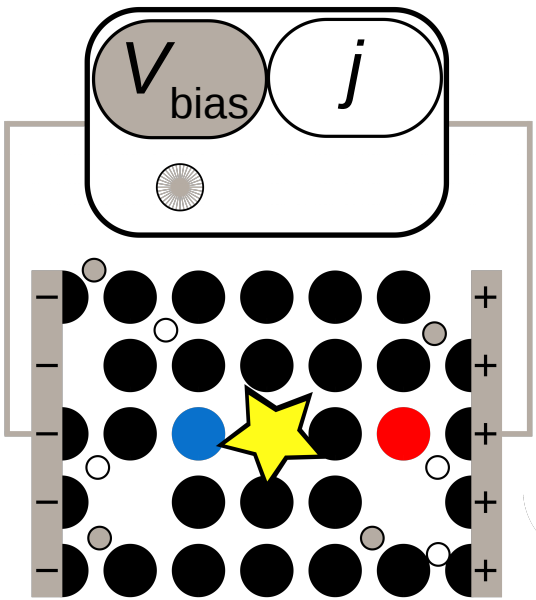
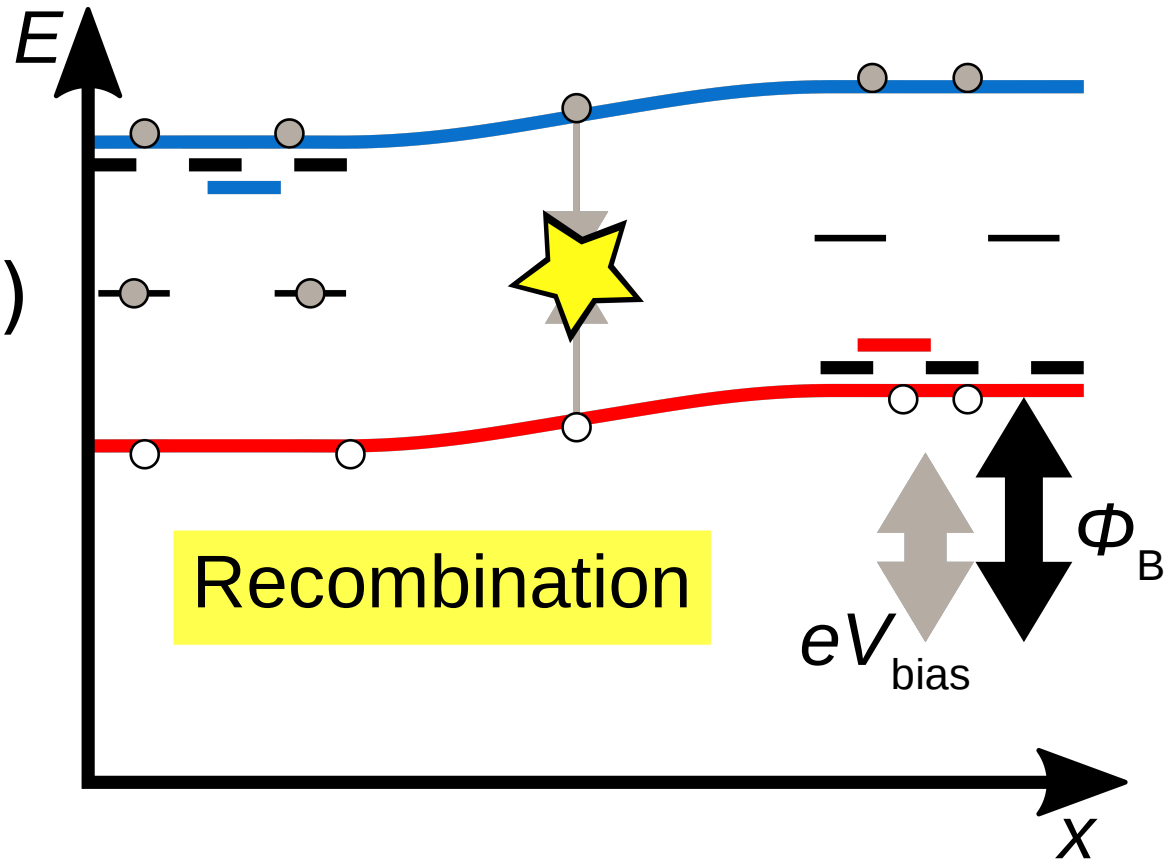
p-n junctions: Influence of defects

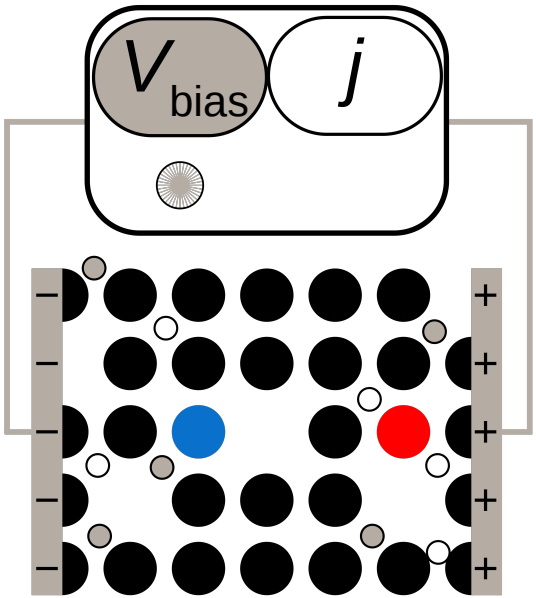
$$1 \leq n_{ideal} \leq 2$$

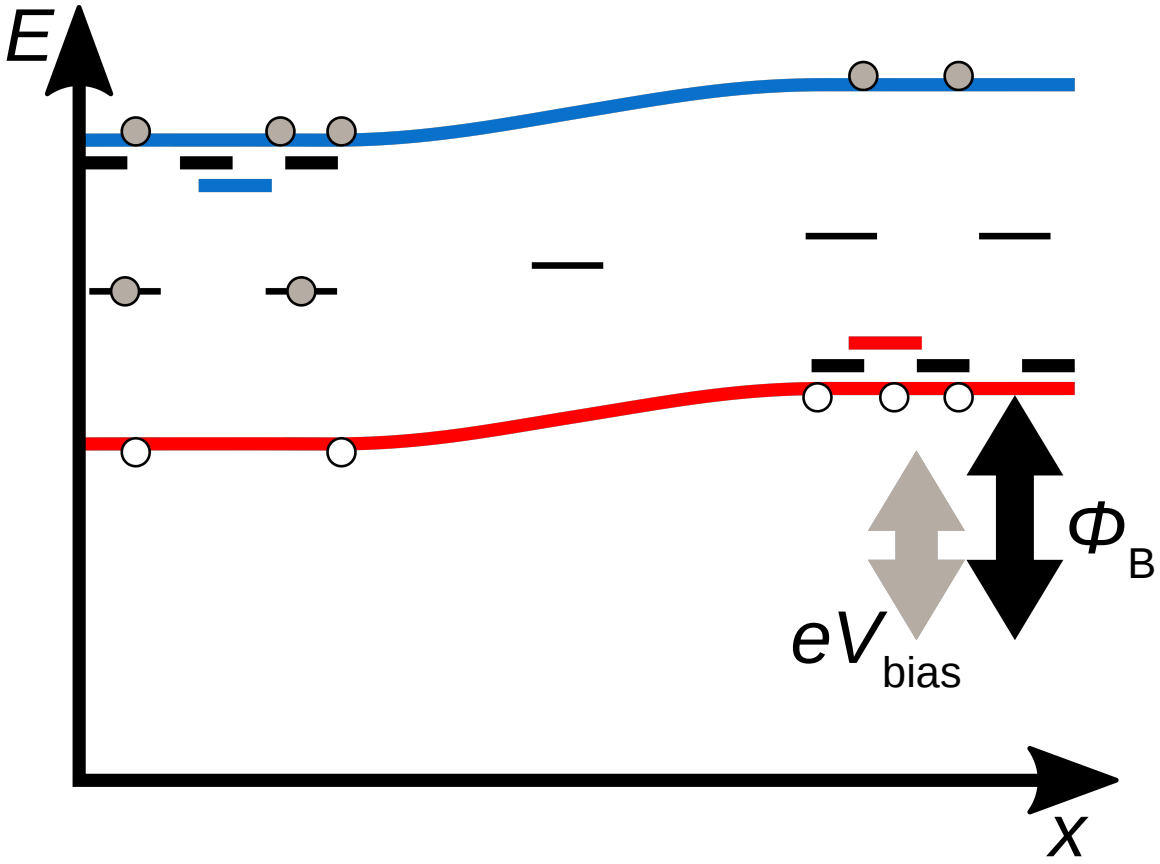
$$j = j_S(e^{\frac{eV_{bias}}{n_{ideal}kT}} - 1)$$





p-n junctions: Series resistance





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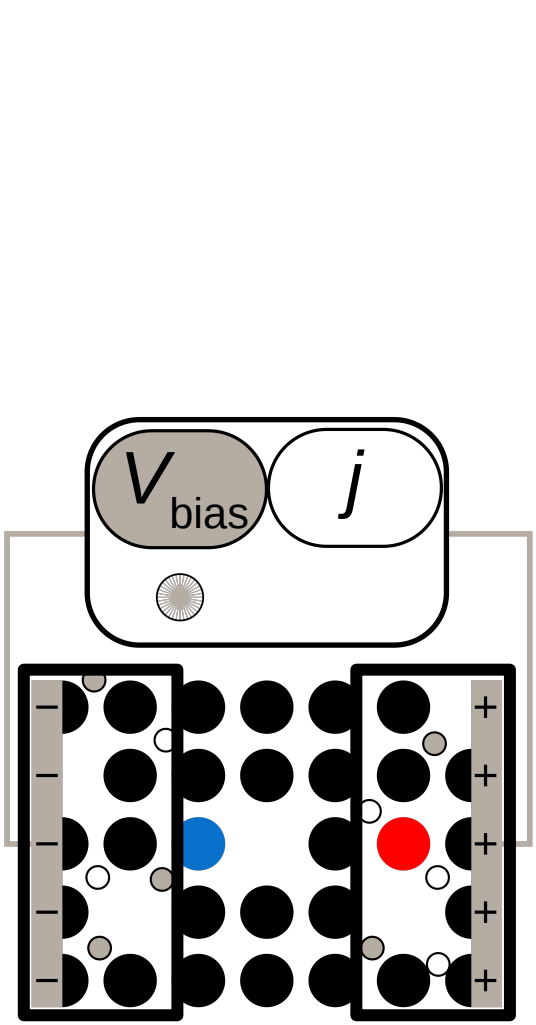

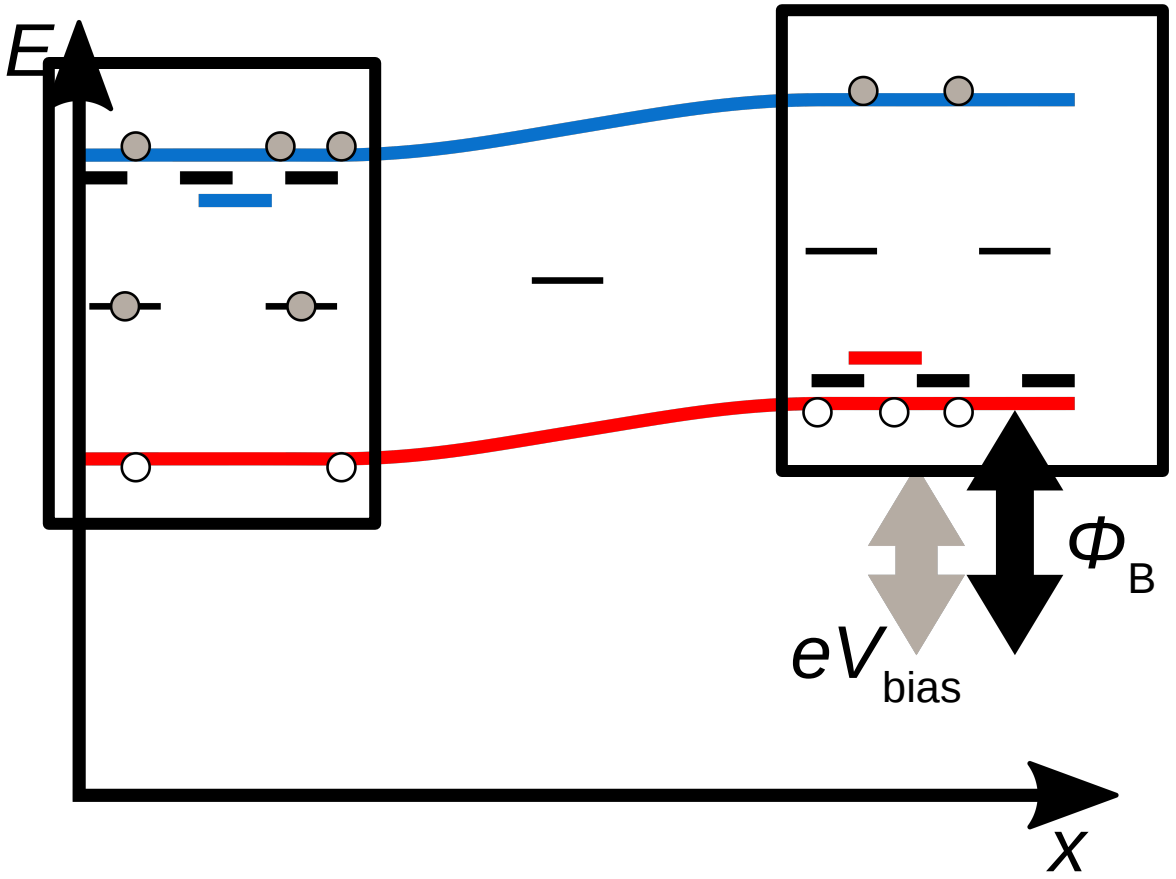

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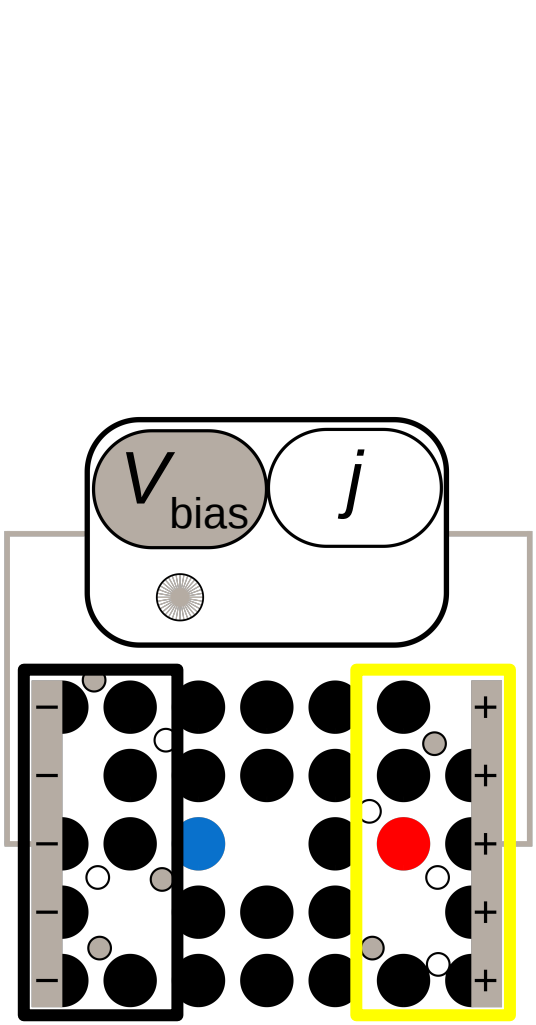

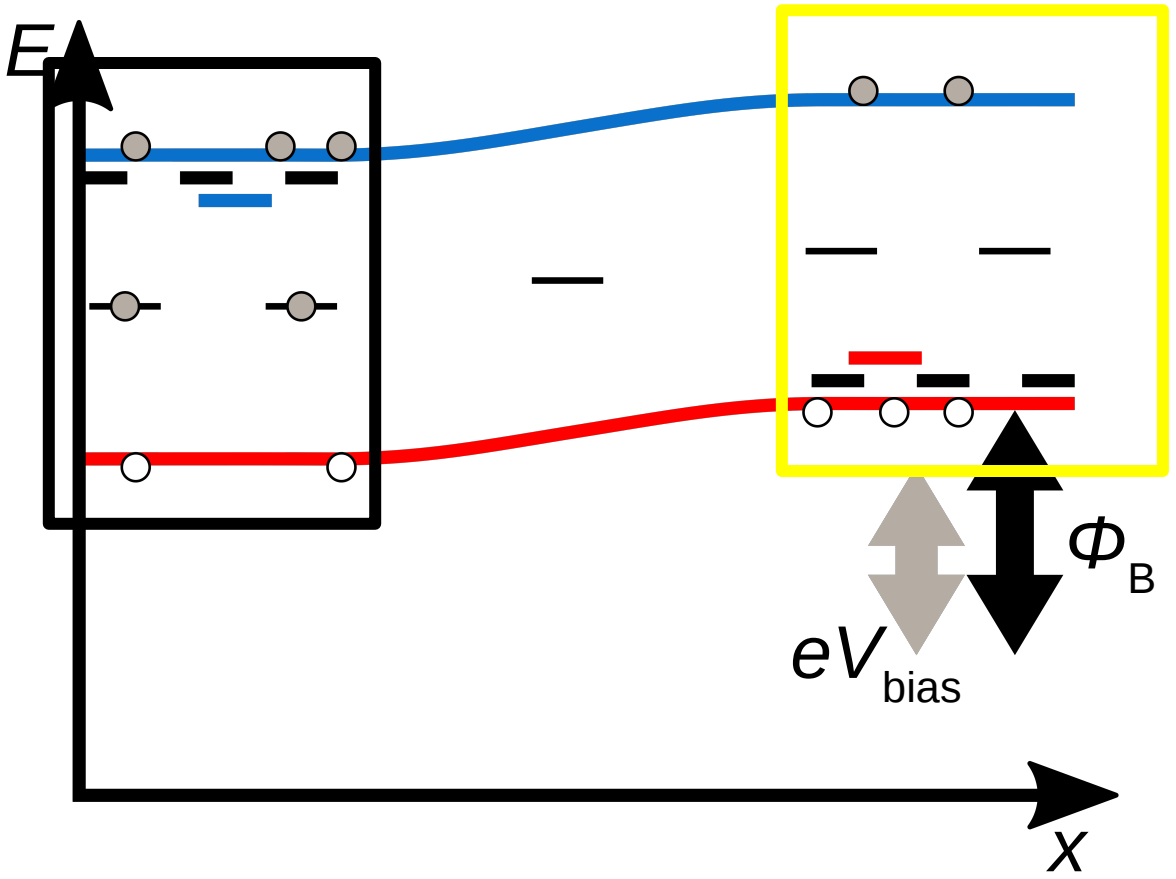

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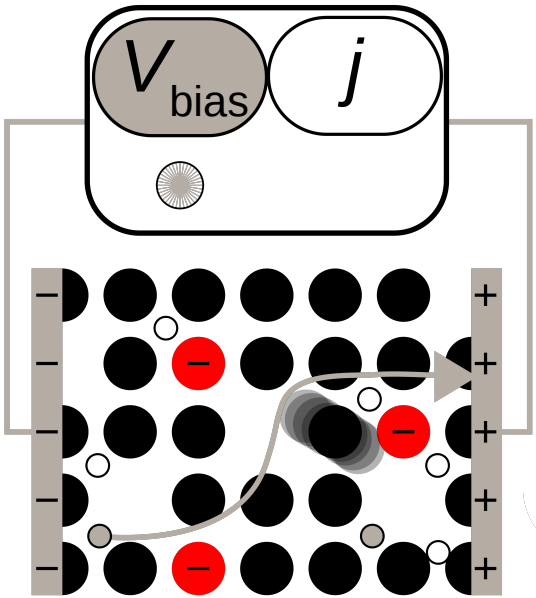

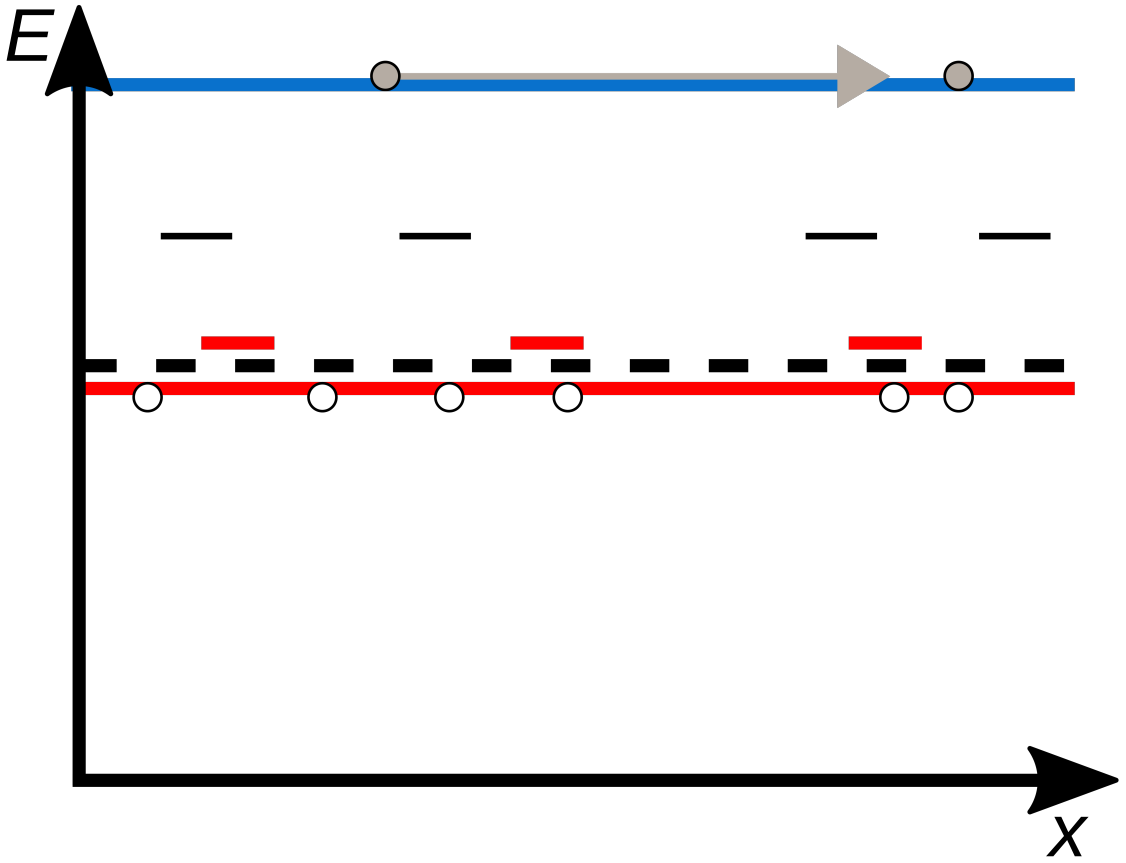

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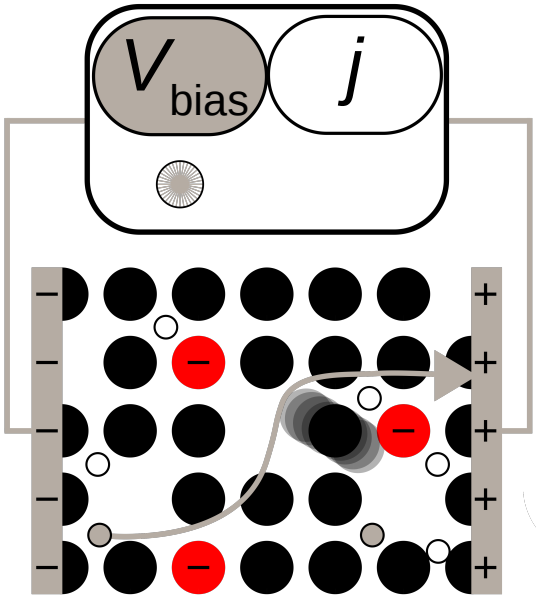
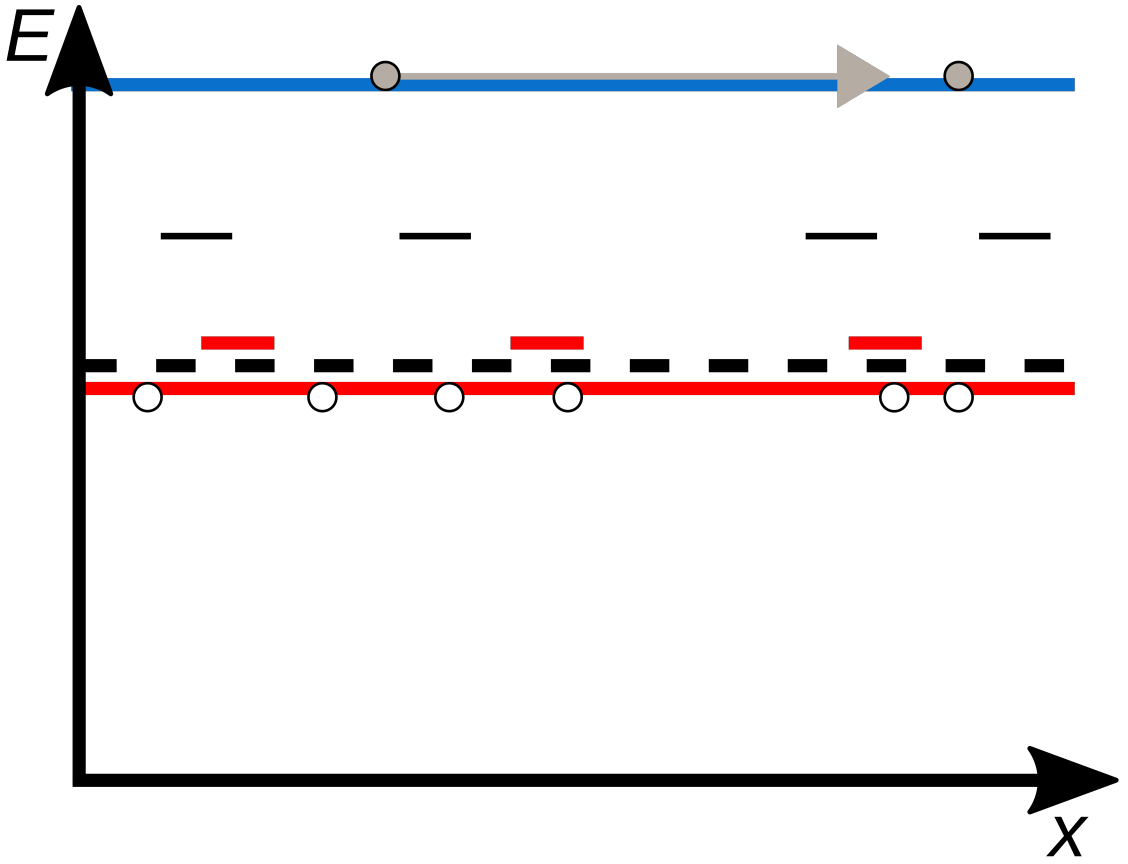
p-n junctions: Series resistance

Intrinsic Mobility





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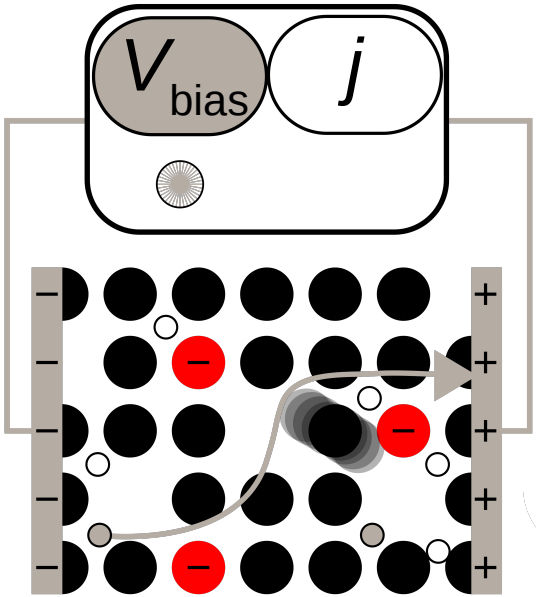
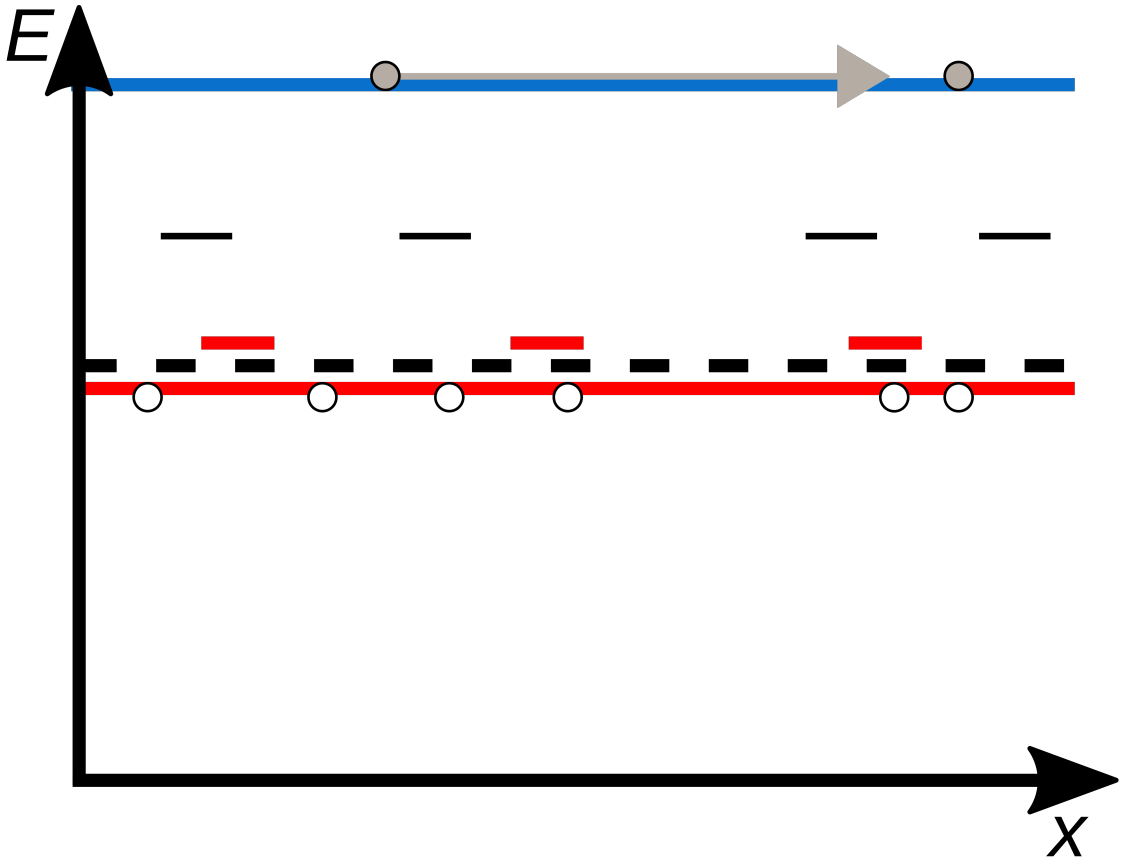
p-n junctions: Series resistance

Intrinsic Mobility Scattering





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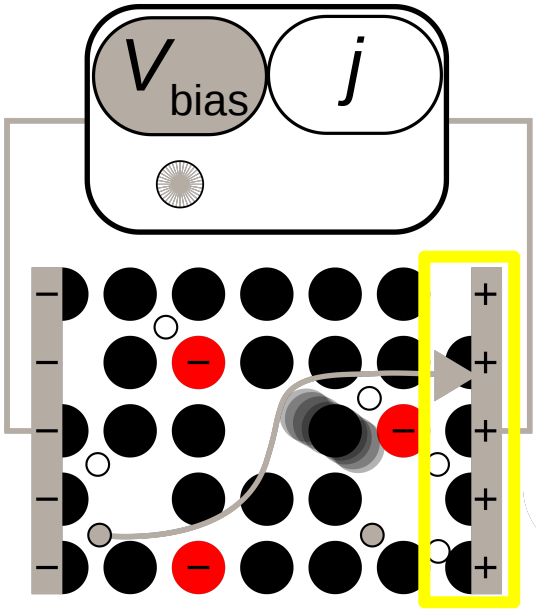

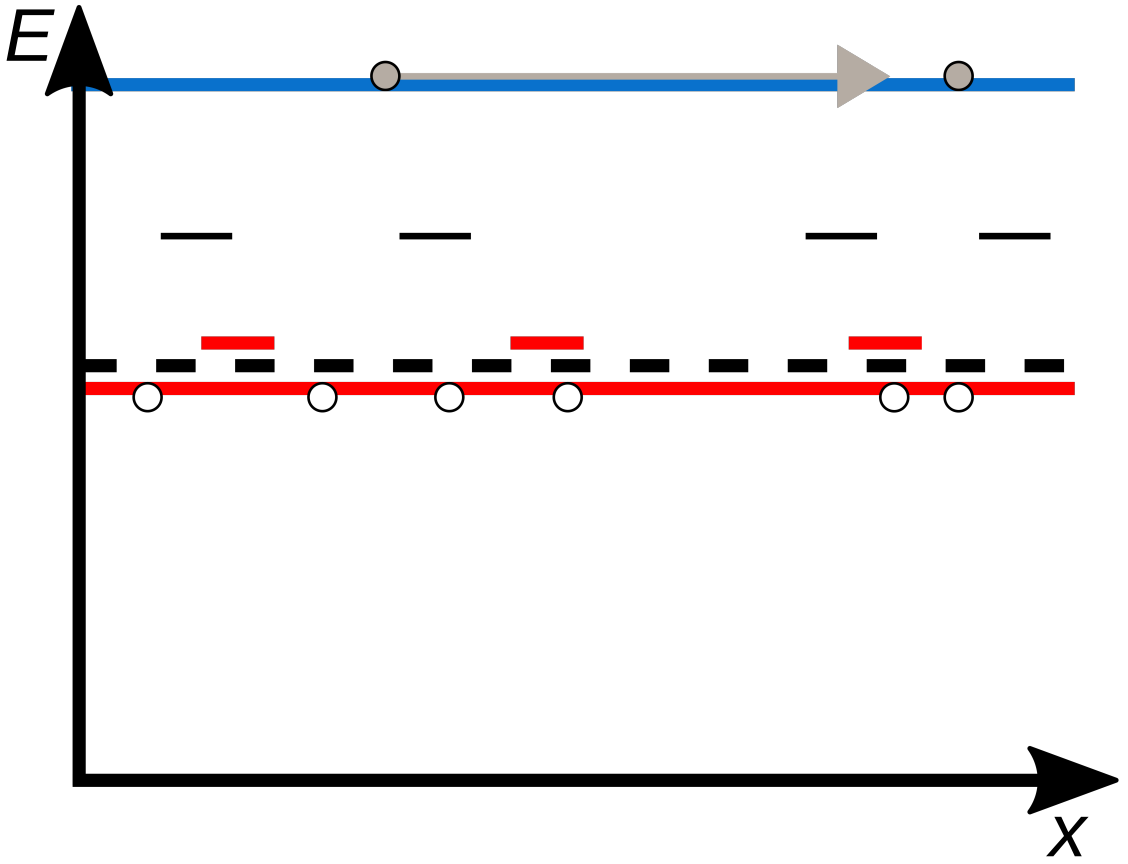

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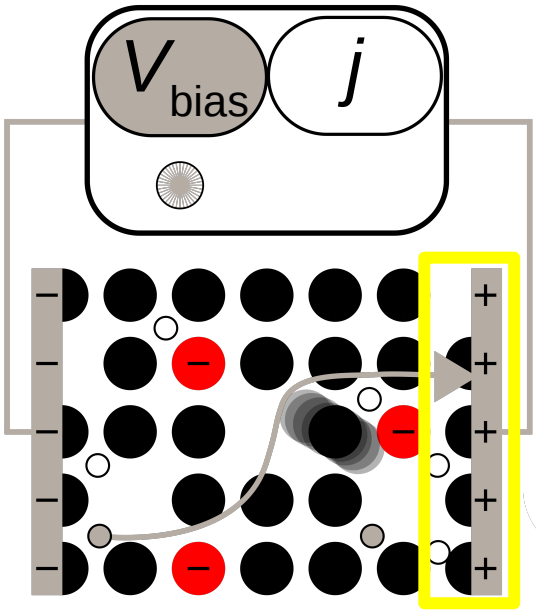
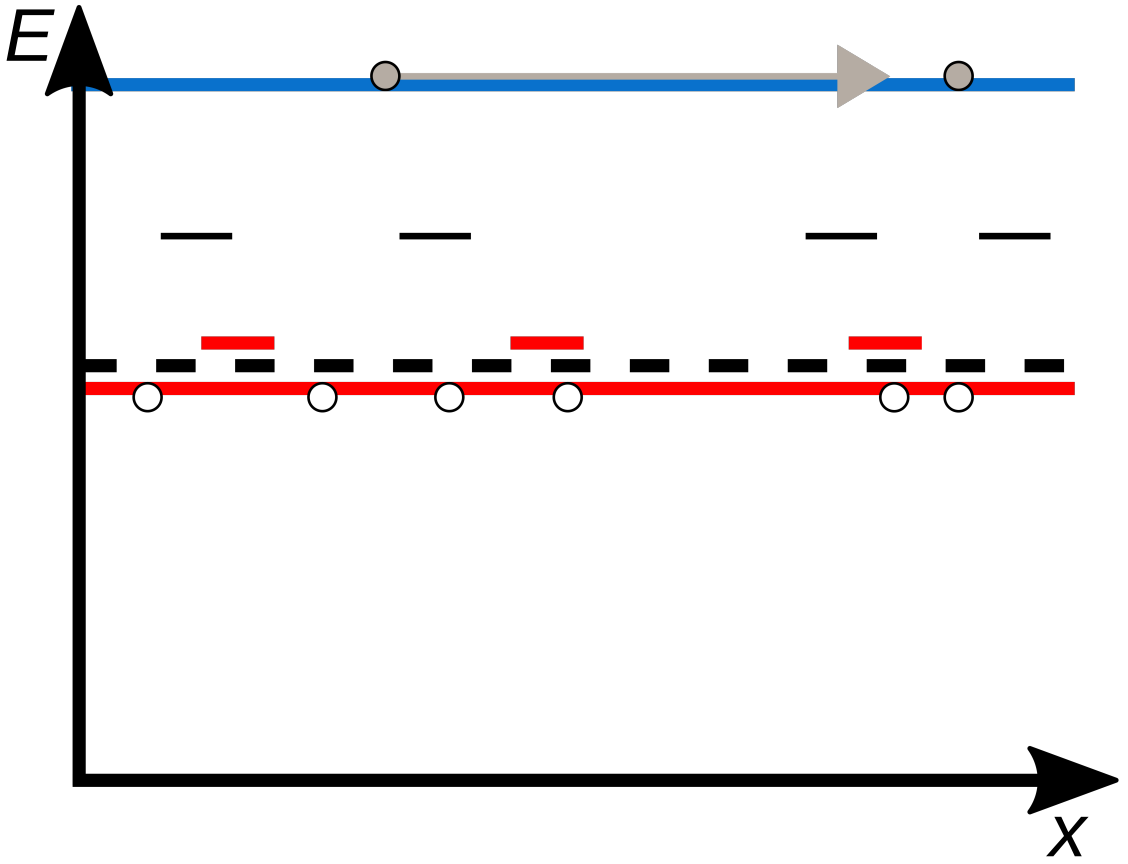
Intrinsic Mobility
Scattering
Contacts





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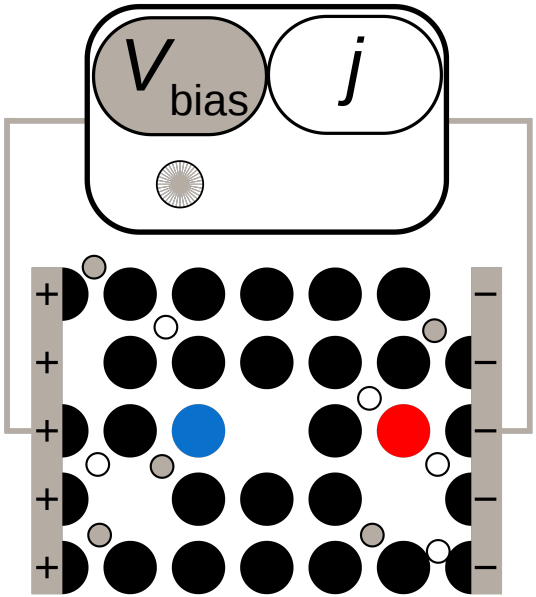
p-n junctions: Shunt resistance



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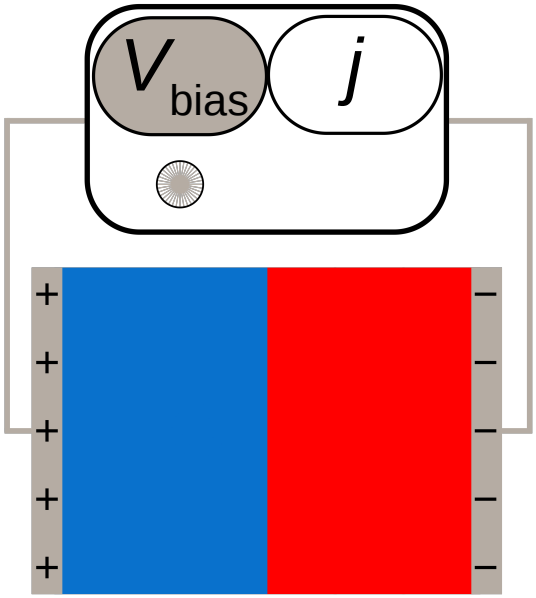

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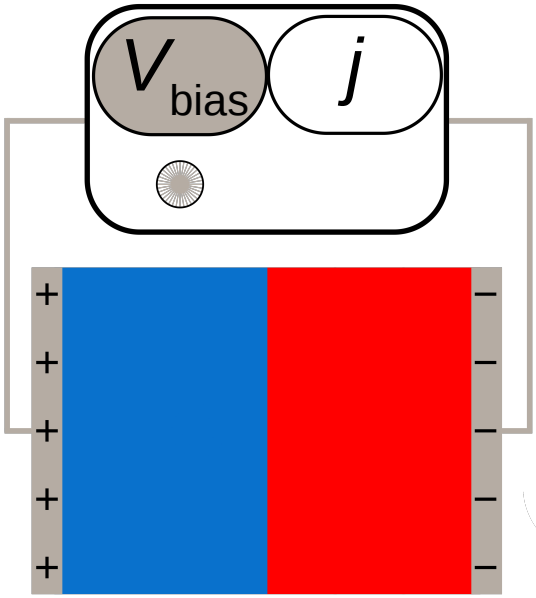

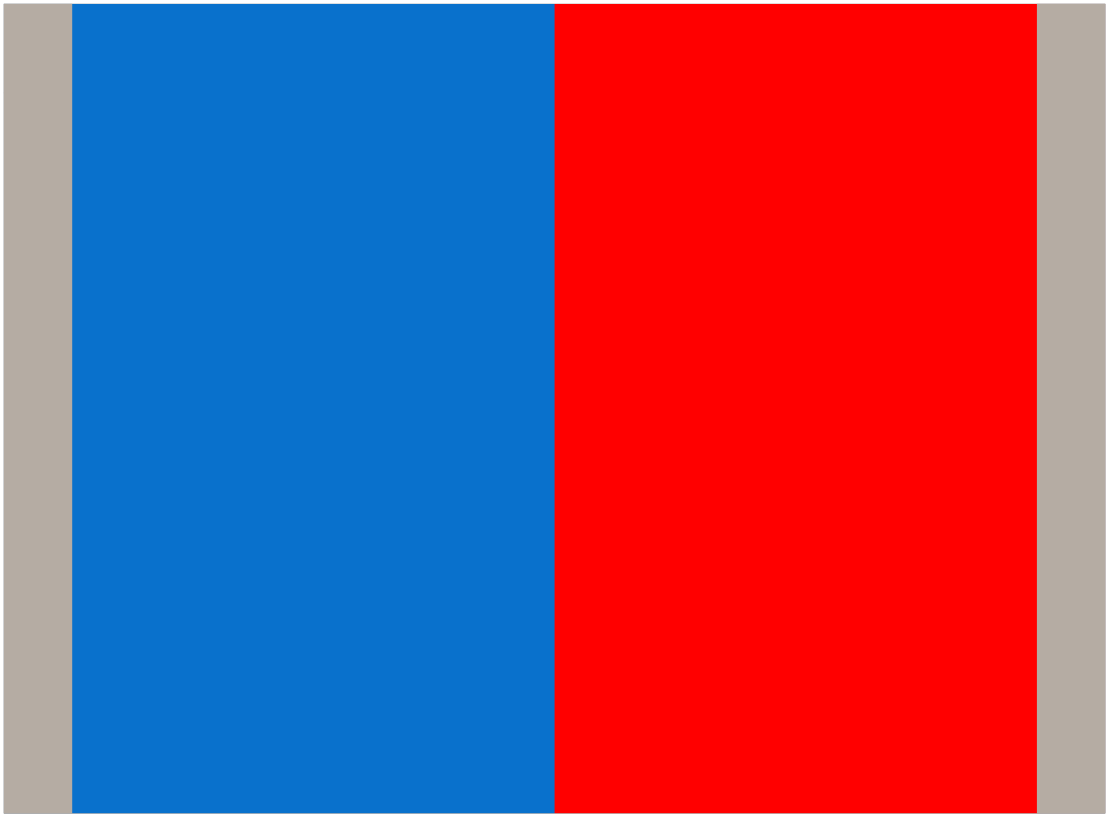

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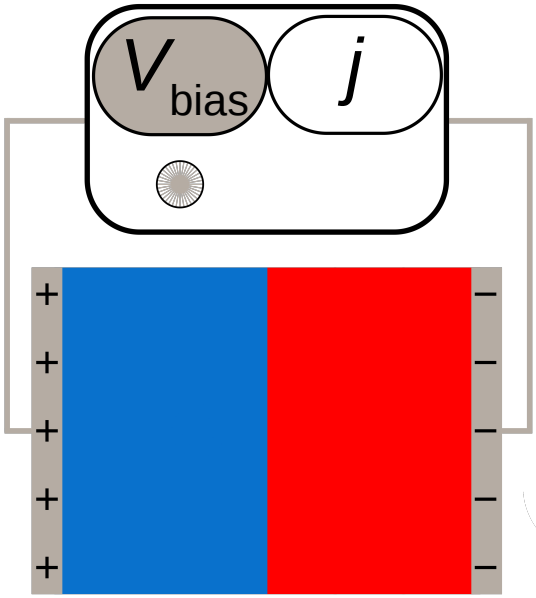

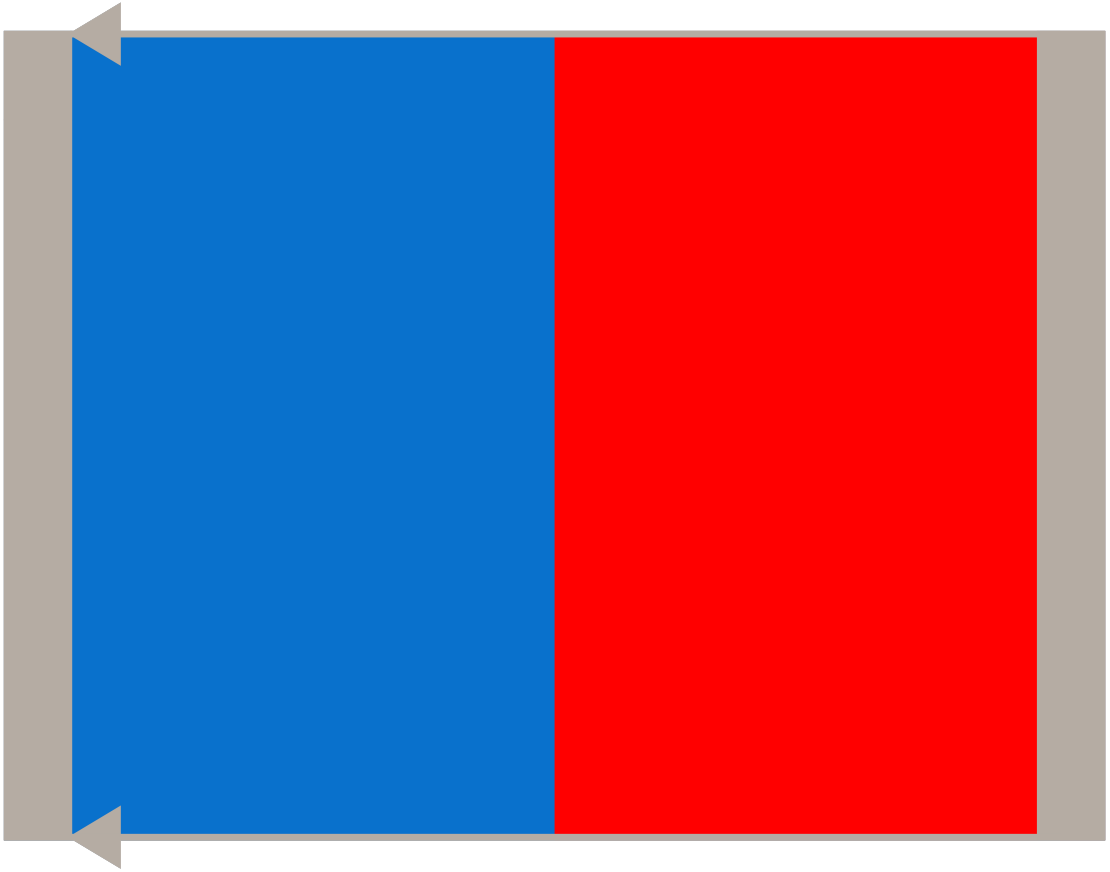

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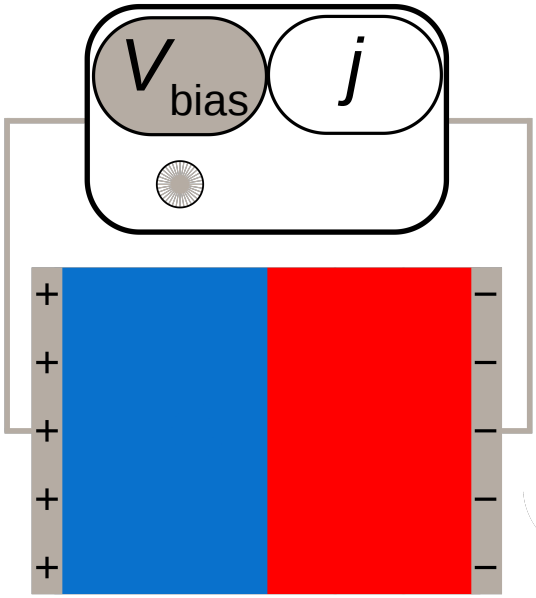
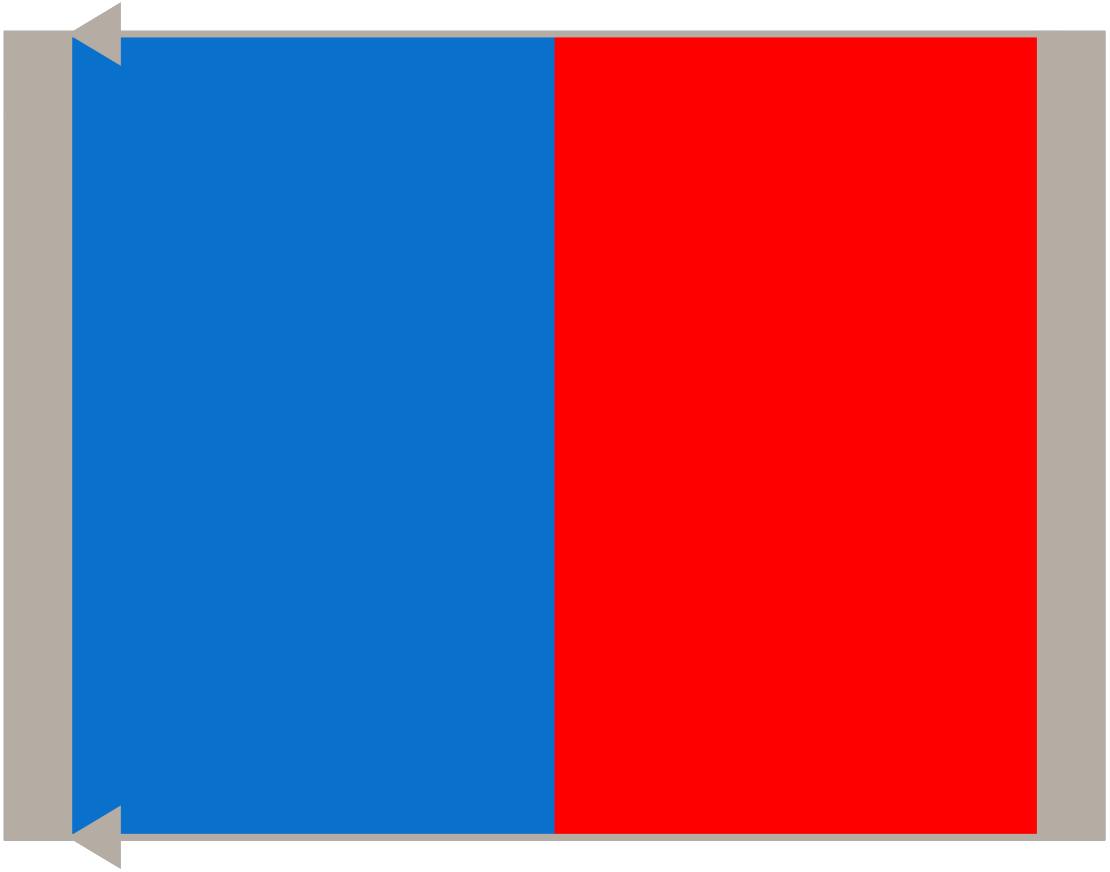
Edges





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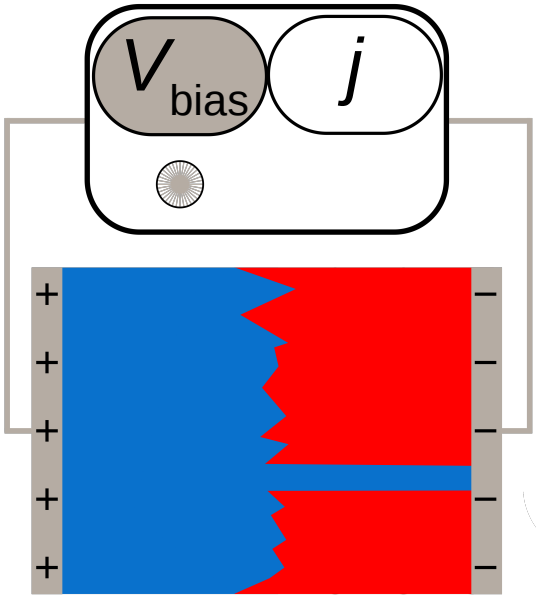

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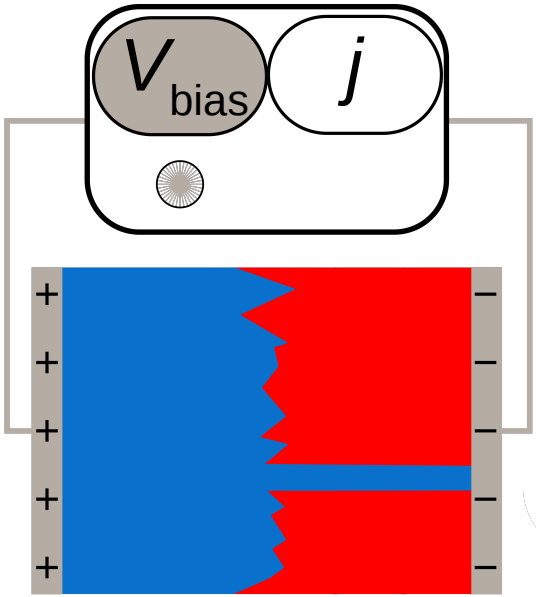

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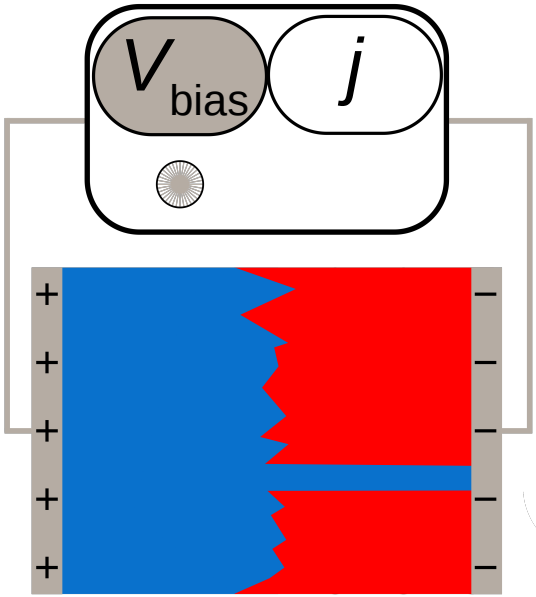
p-n junctions: Shunt resistance

Edges
Punch throughs



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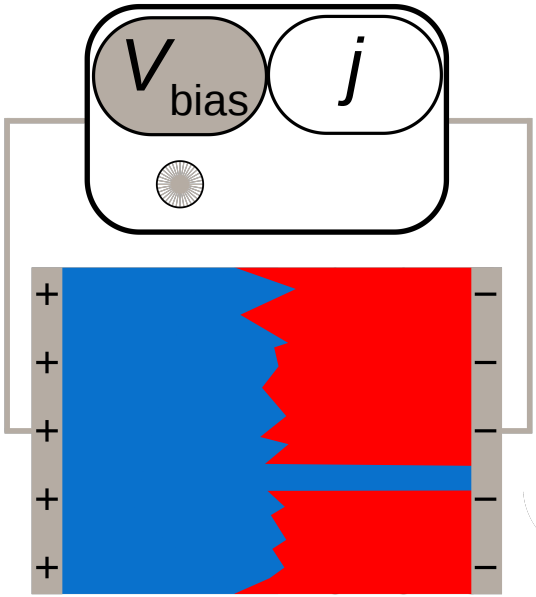

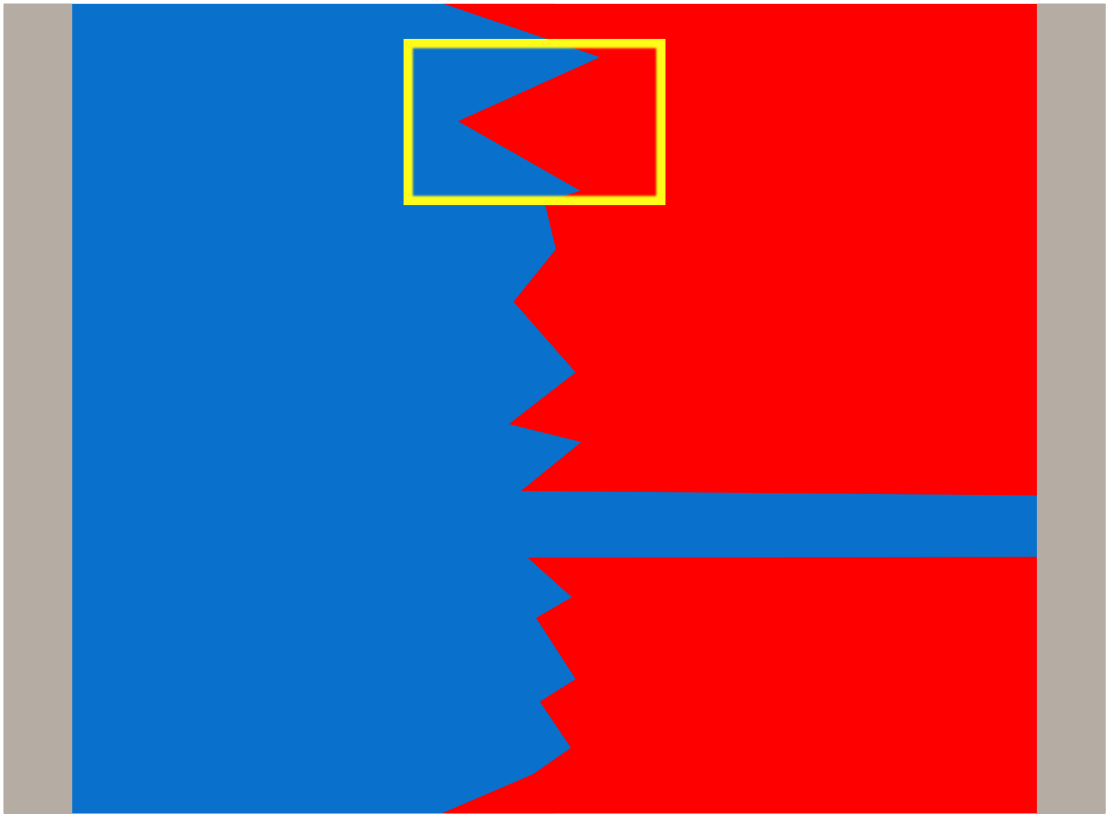

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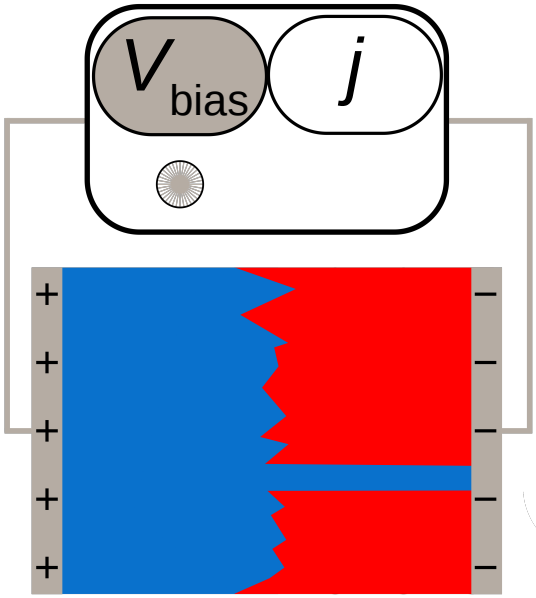
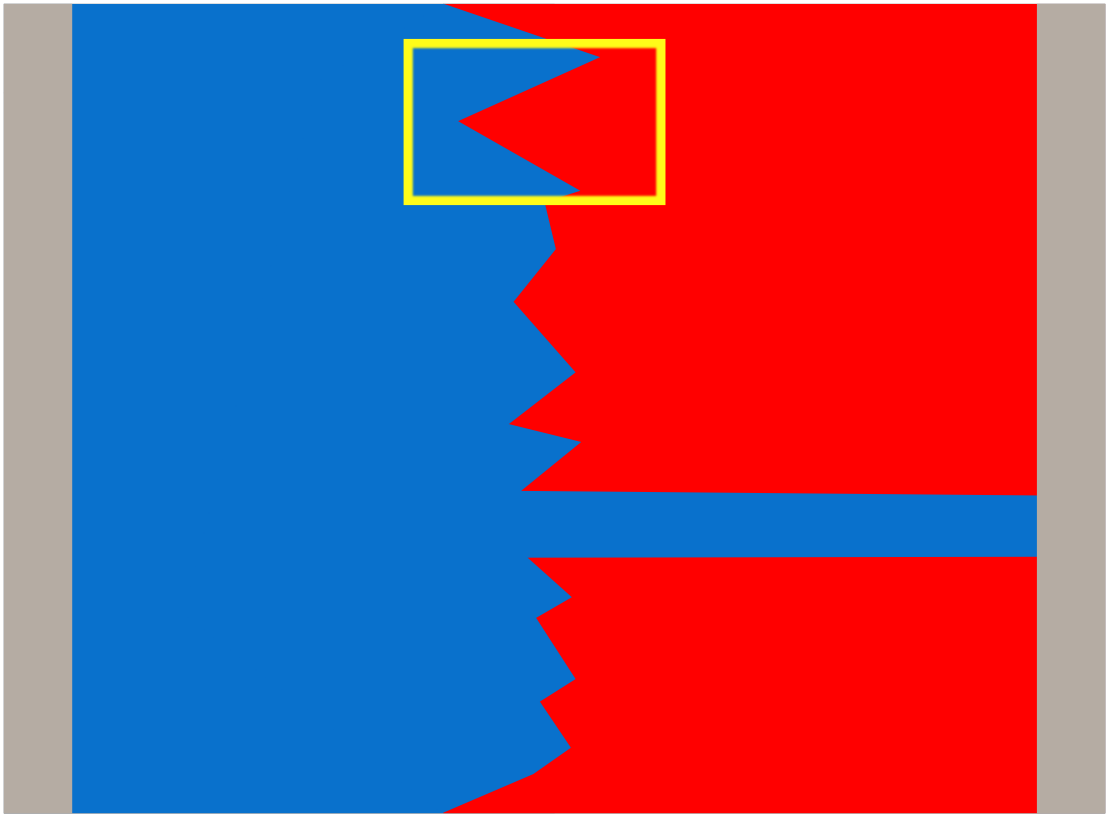
p-n junctions: Shunt resistance

Edges
Punch throughs
Tunneling





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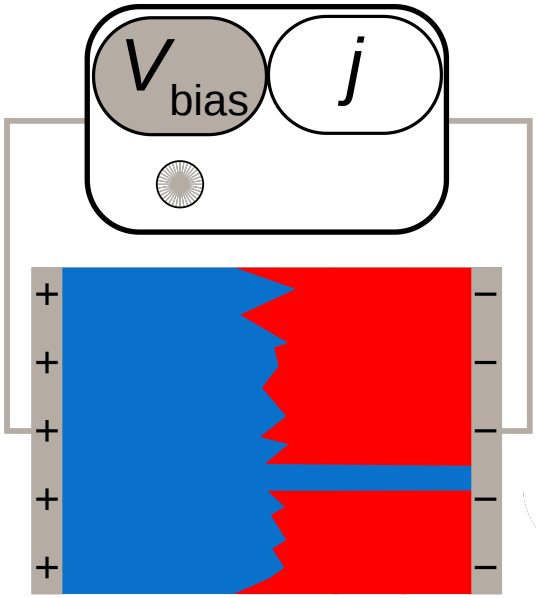

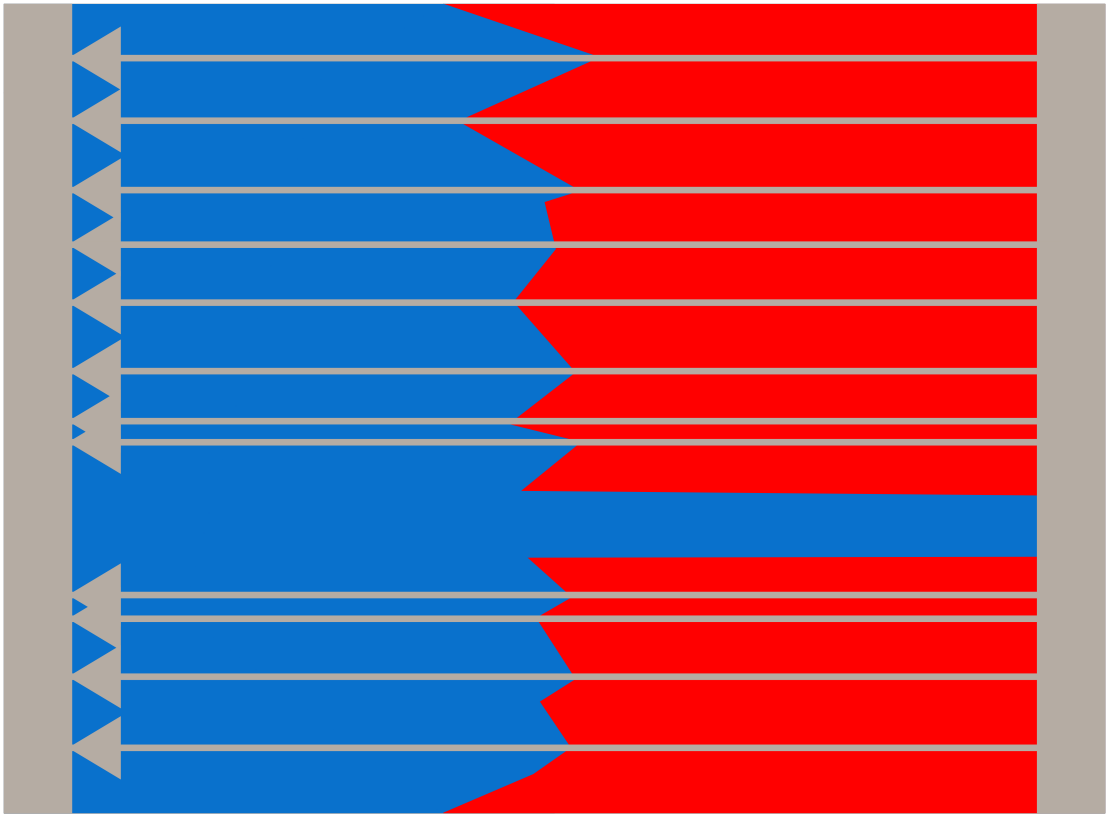

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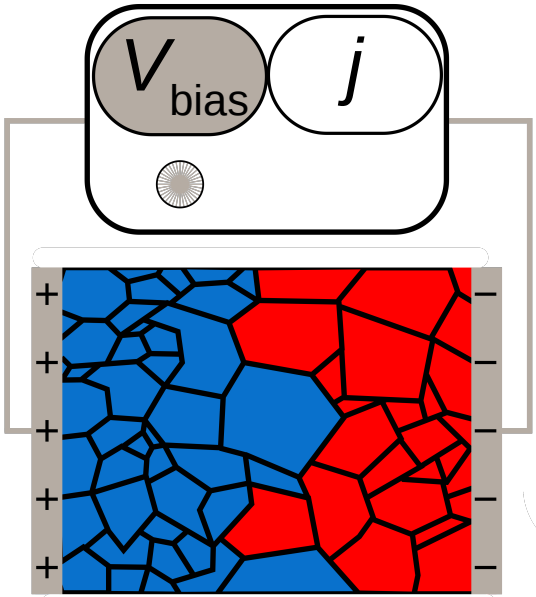

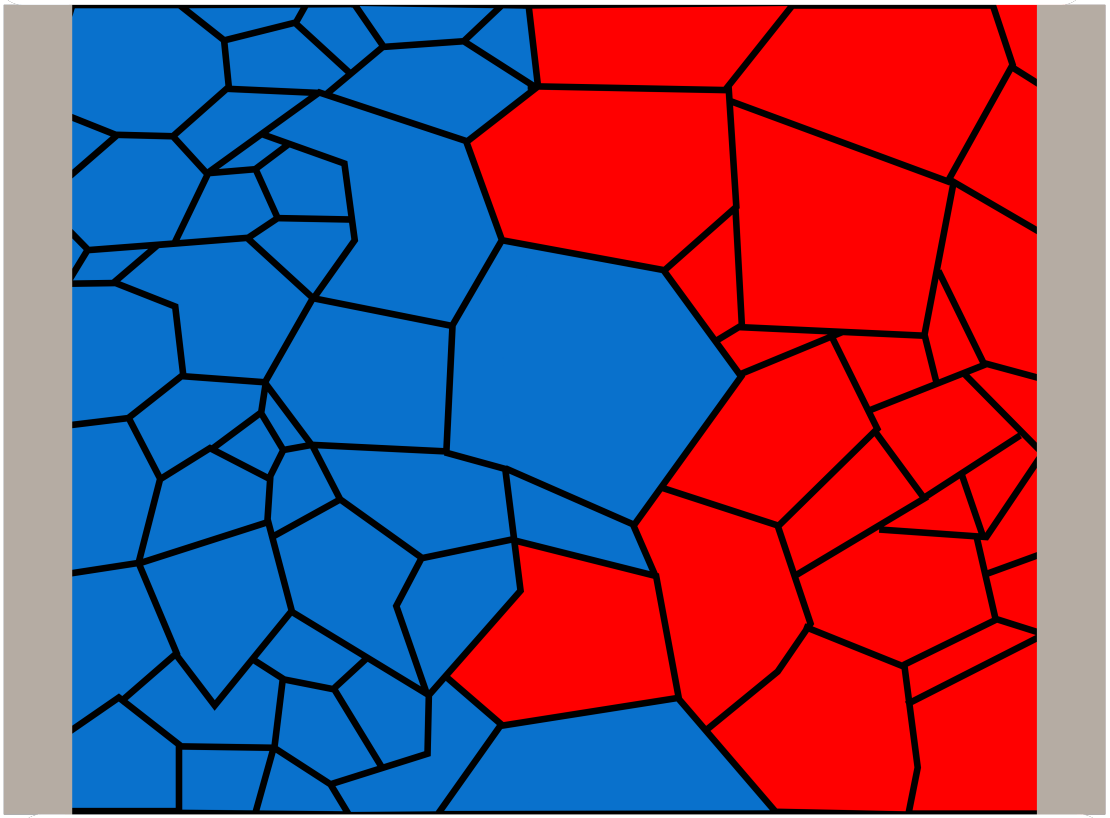

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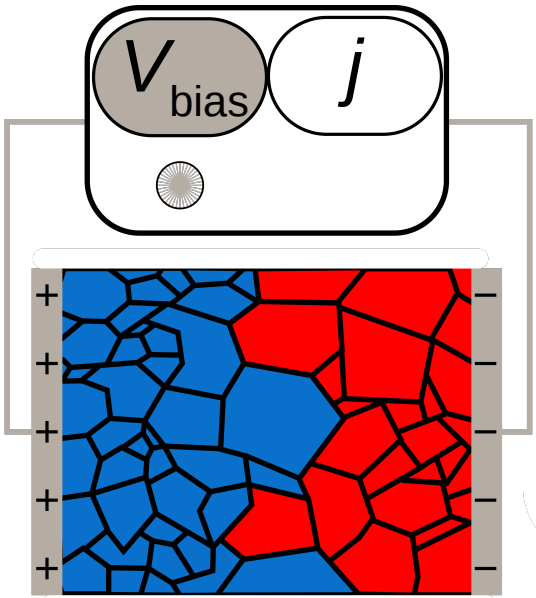
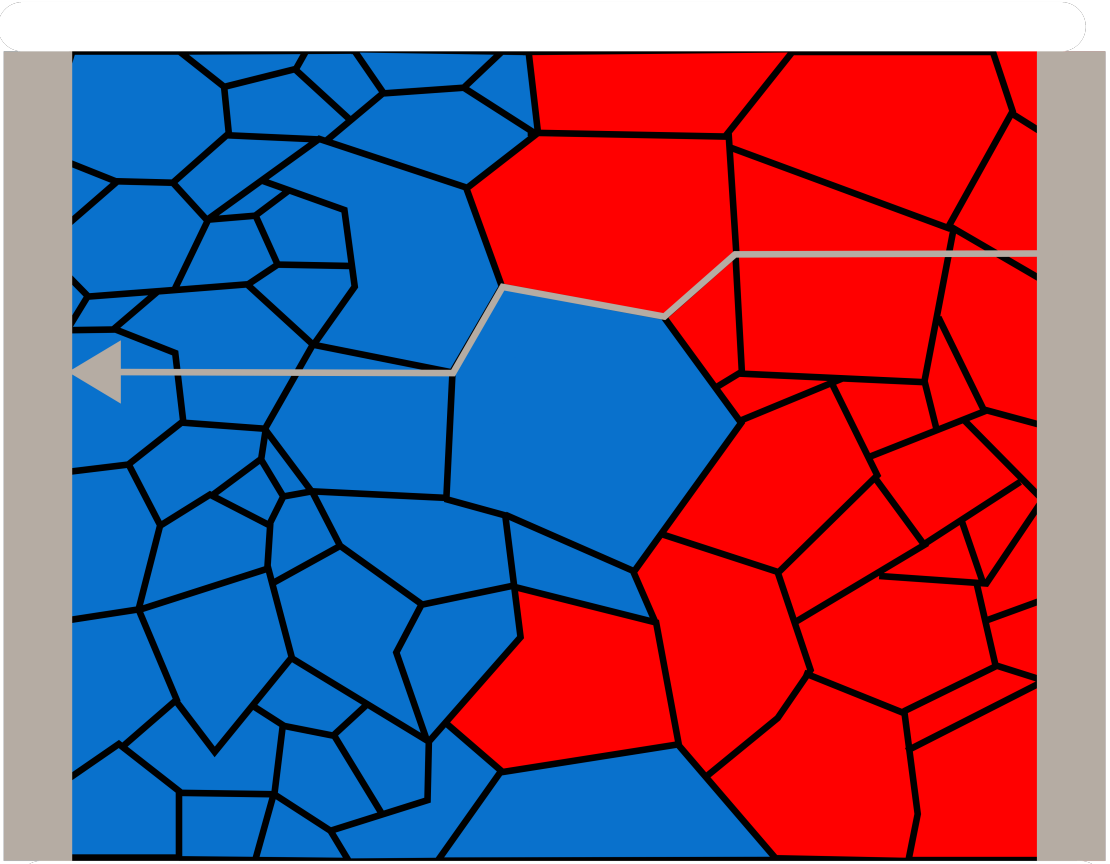
p-n junctions: Shunt resistance

Edges
Punch throughs
Tunneling





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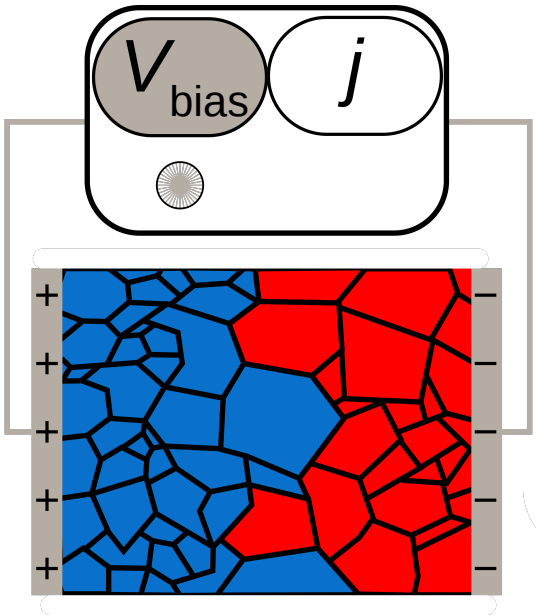
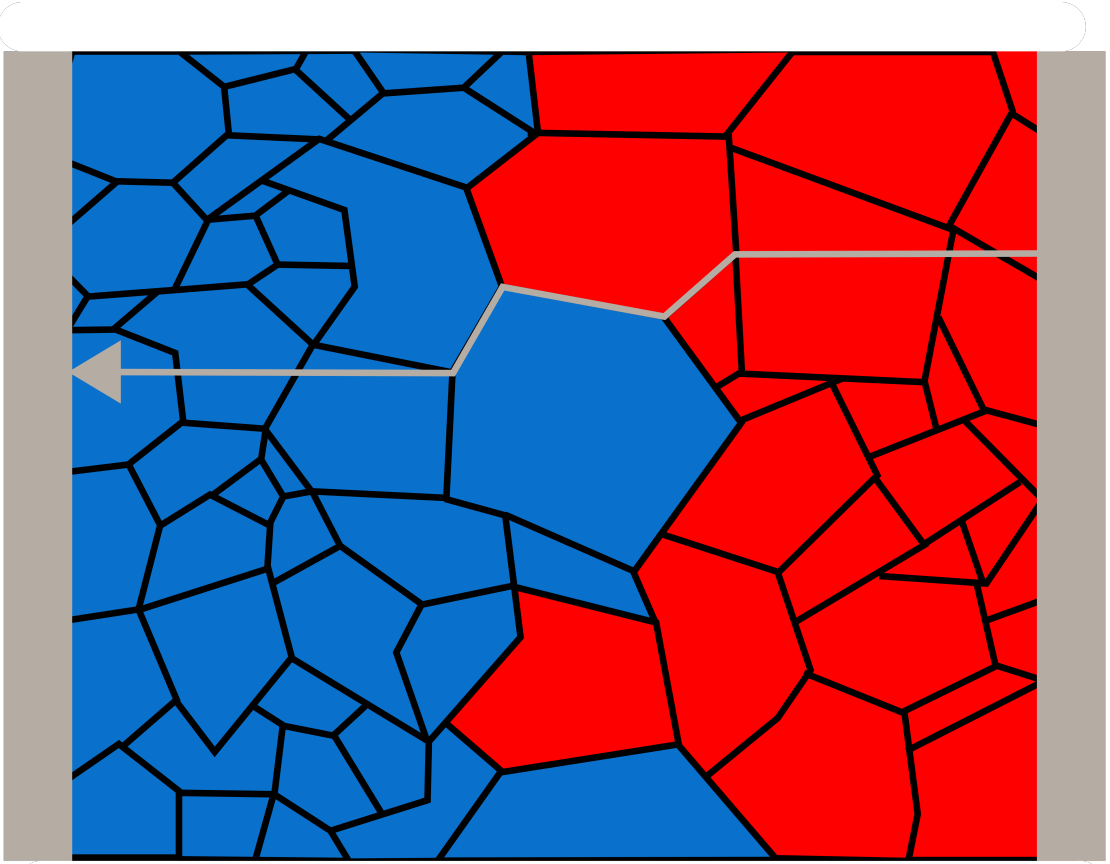
p-n junctions: Shunt resistance

Edges
Punch throughs
Tunneling
Grain boundaries





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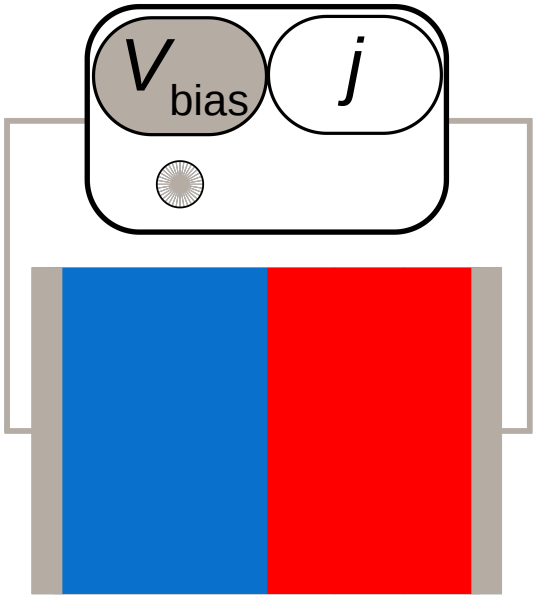
p-n junctions: Equivalent circuit



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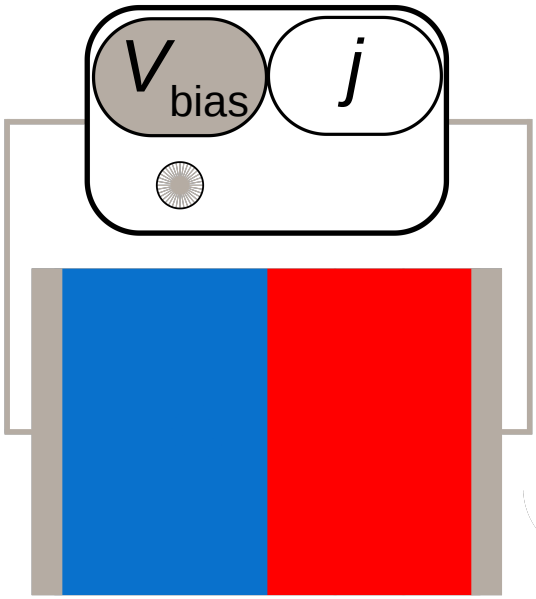

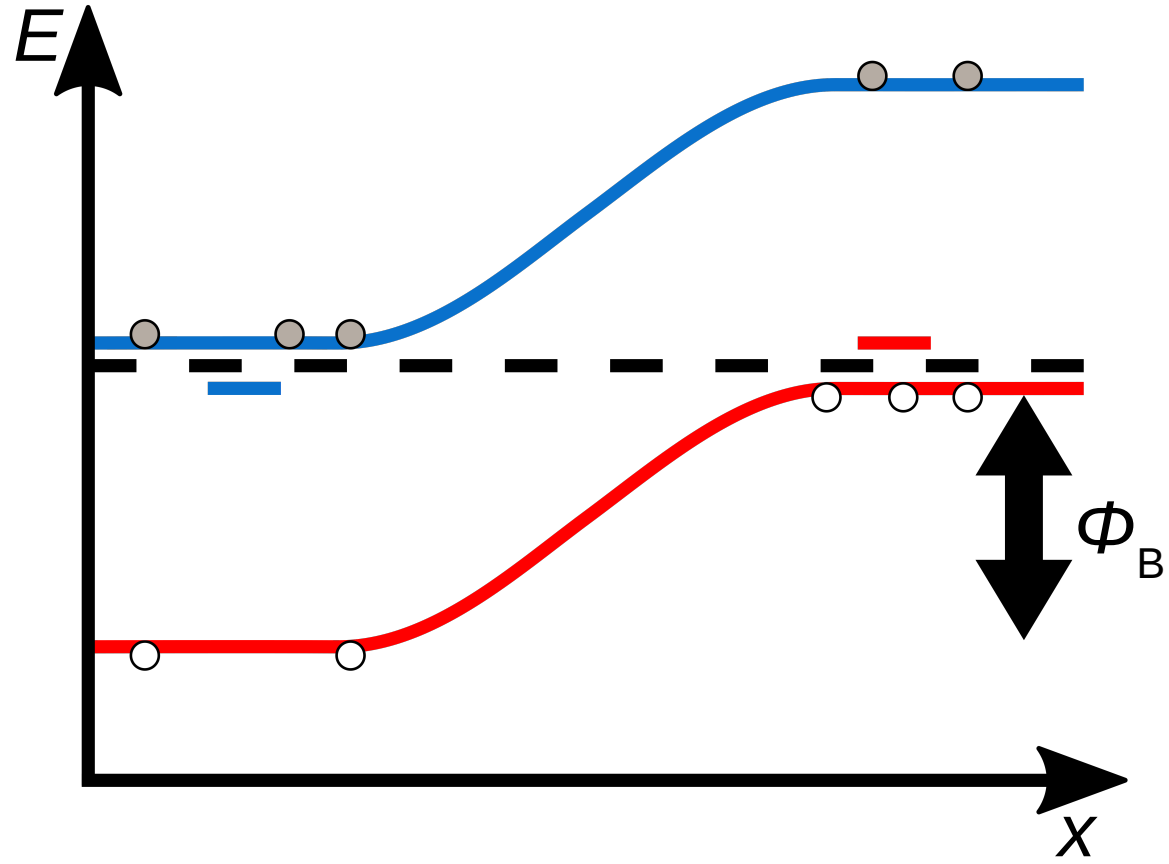

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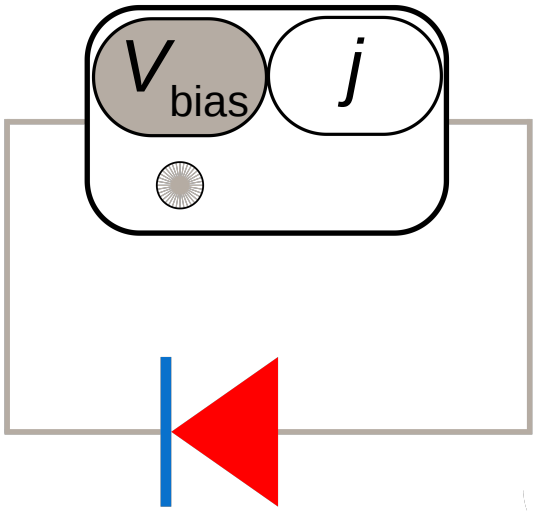
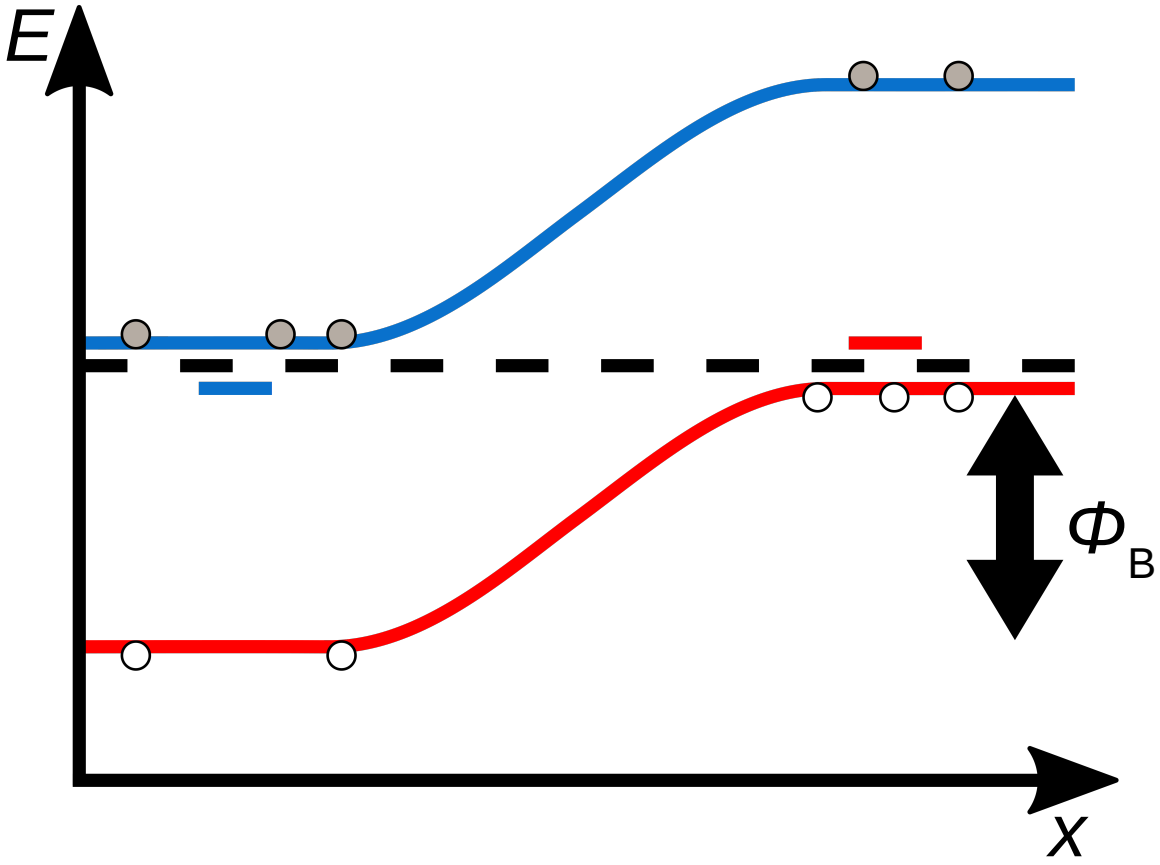
$$j = j_S(e^{\frac{eV_{bias}}{kT}} - 1)$$





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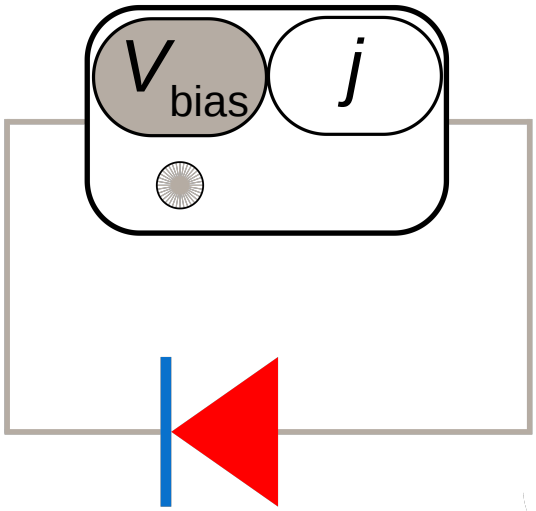
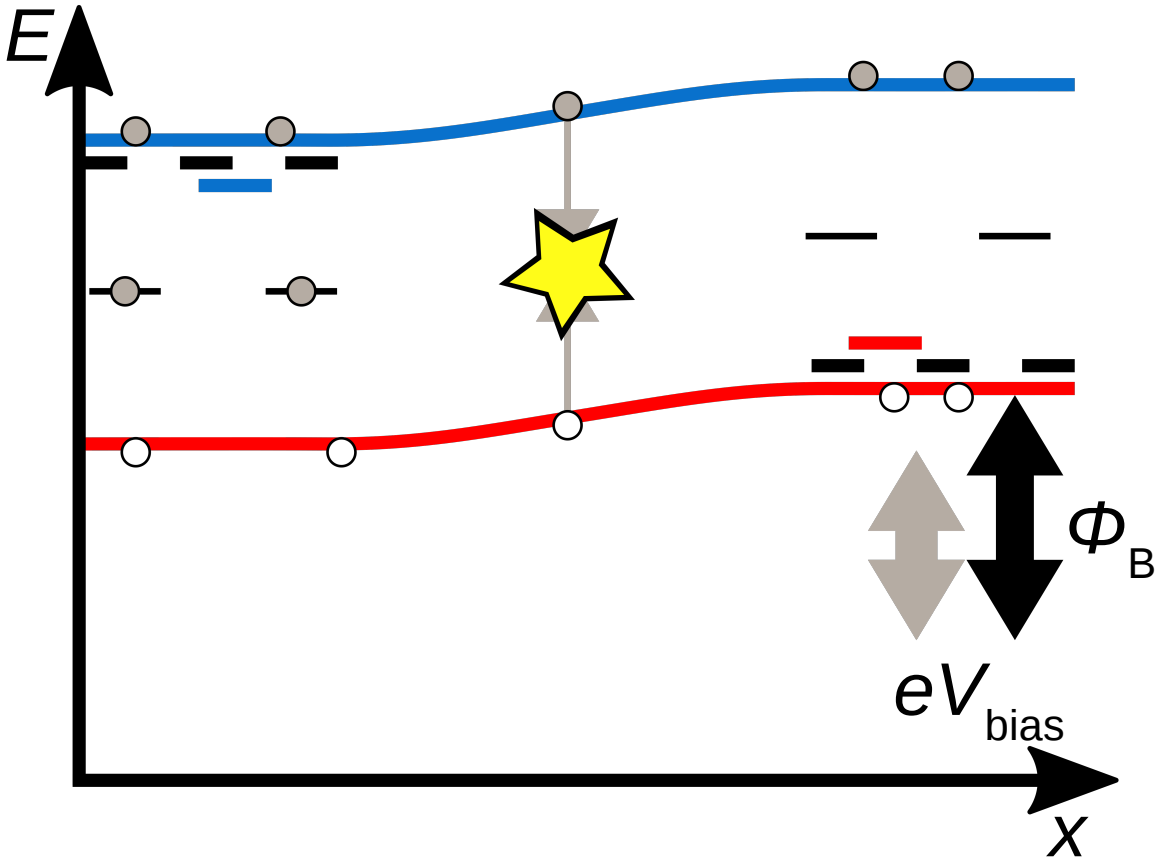
$$j = j_S(e^{\frac{eV_{bias}}{n_{ideal}kT}} - 1)$$





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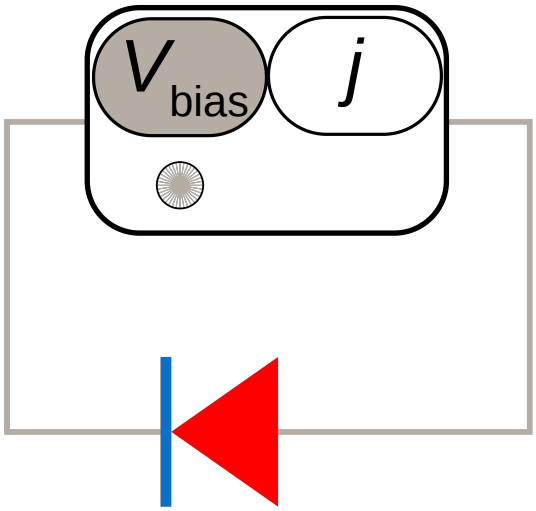

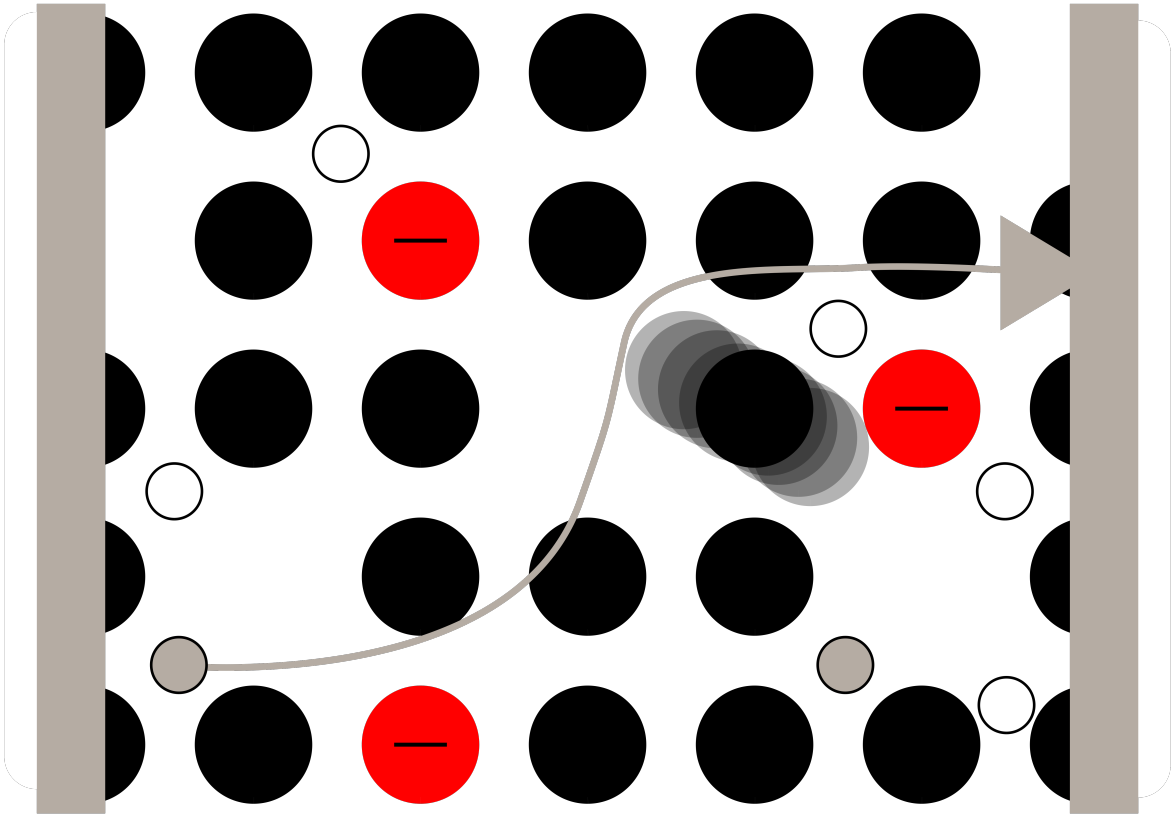

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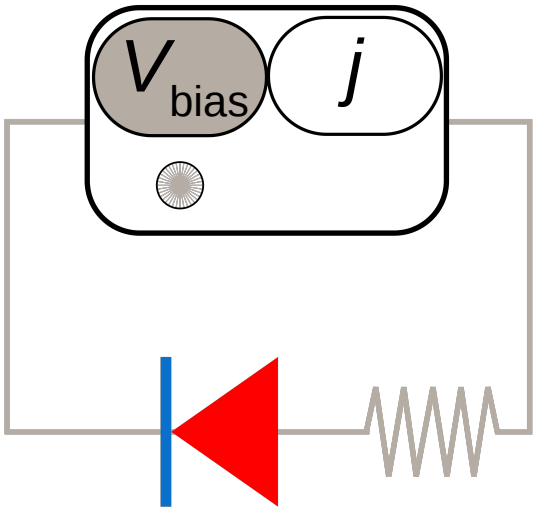
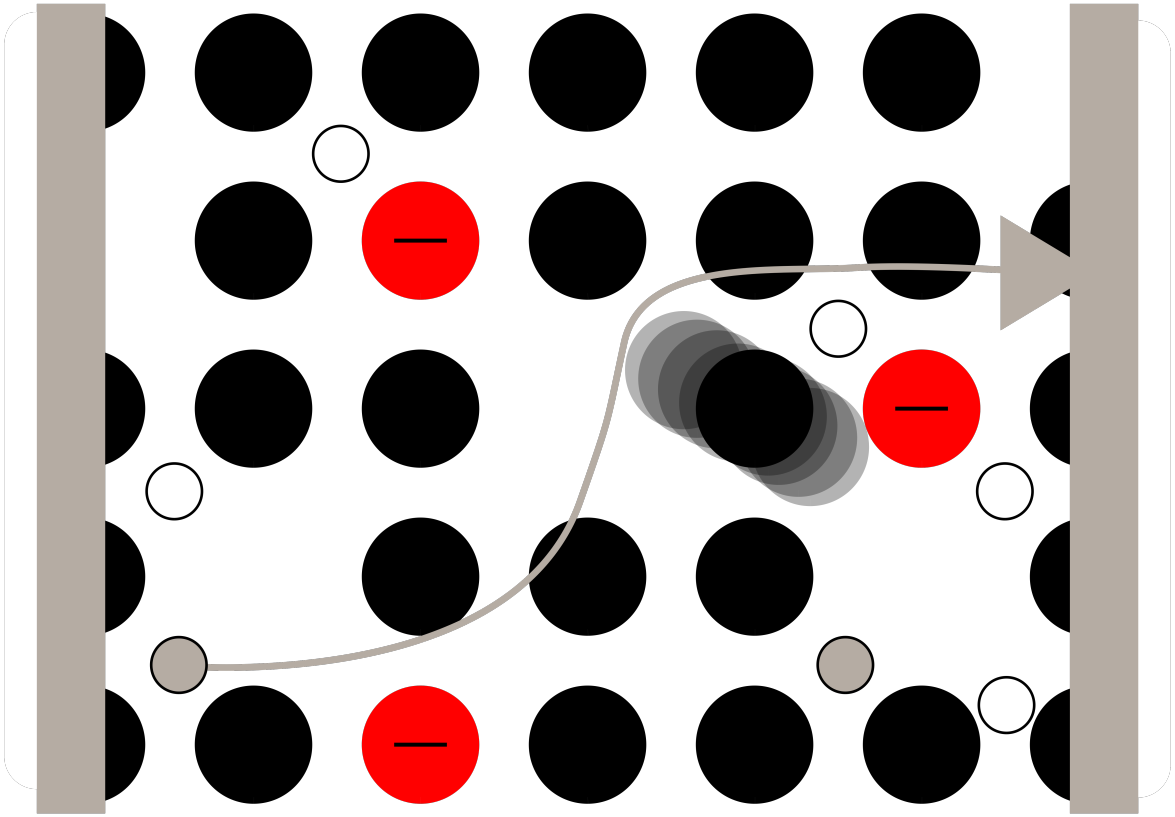
p-n junctions: Equivalent circuit

$$j = j_S\left(e^{\frac{eV_{bias} - jR_S}{n_{ideal}kT}} - 1\right)$$





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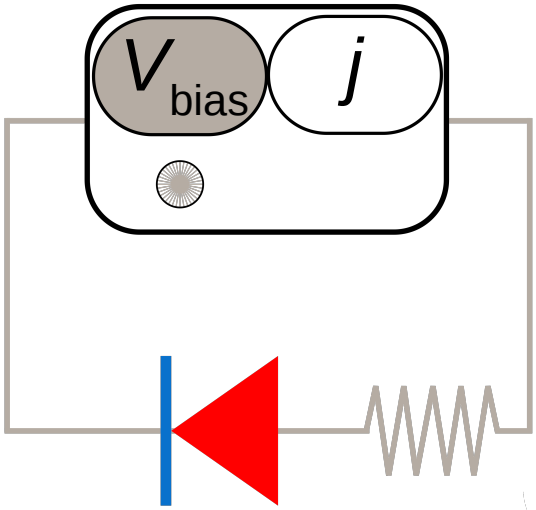

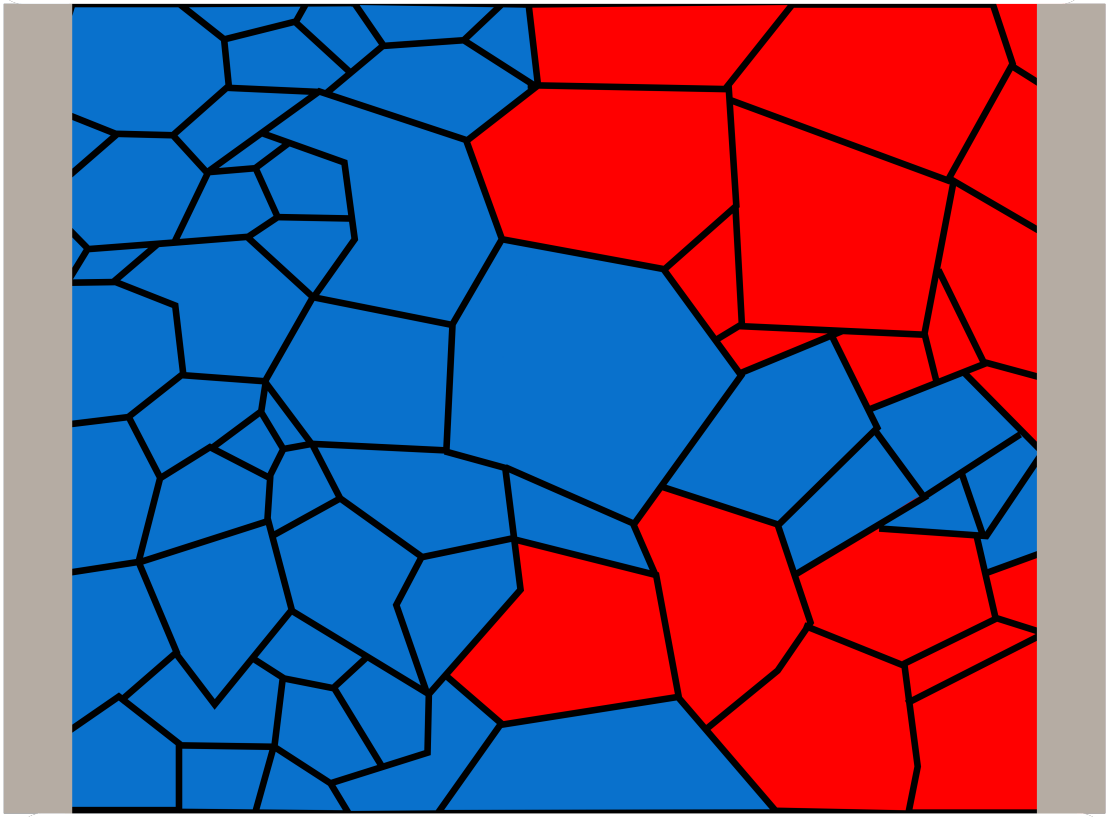

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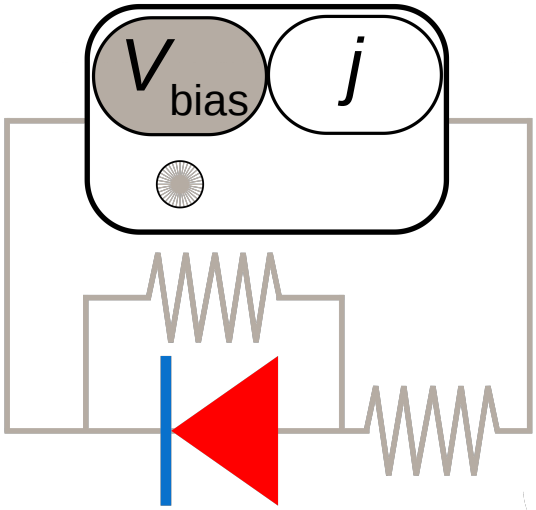

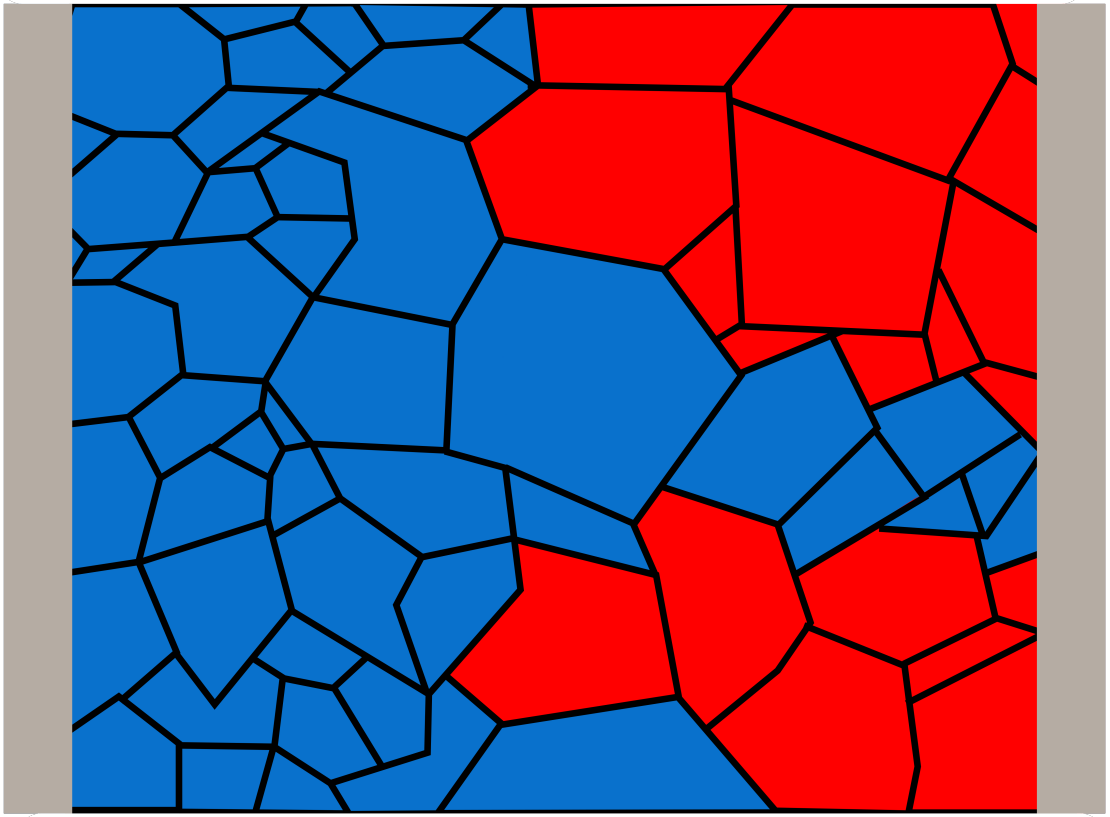

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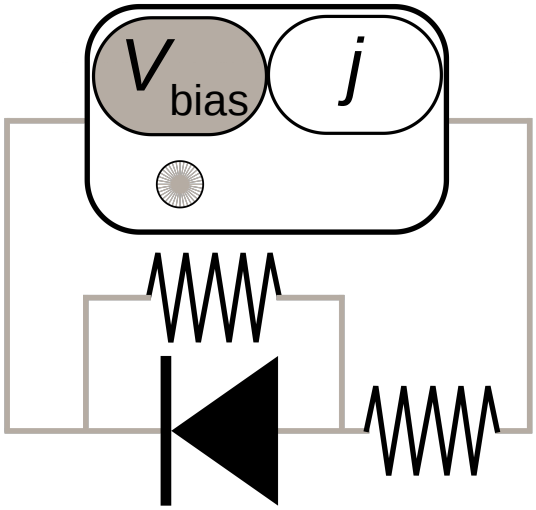

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Current-Voltage Characteristics

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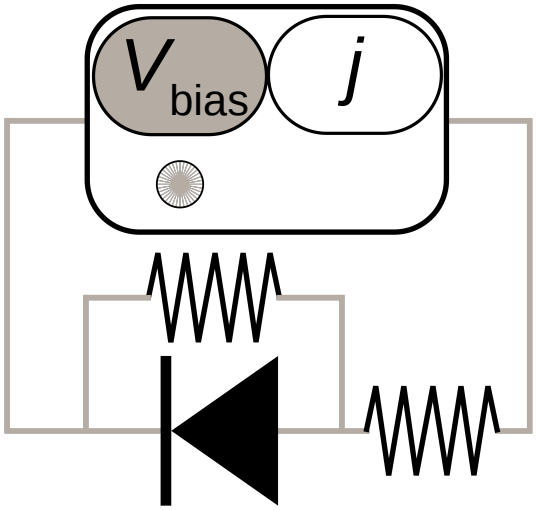

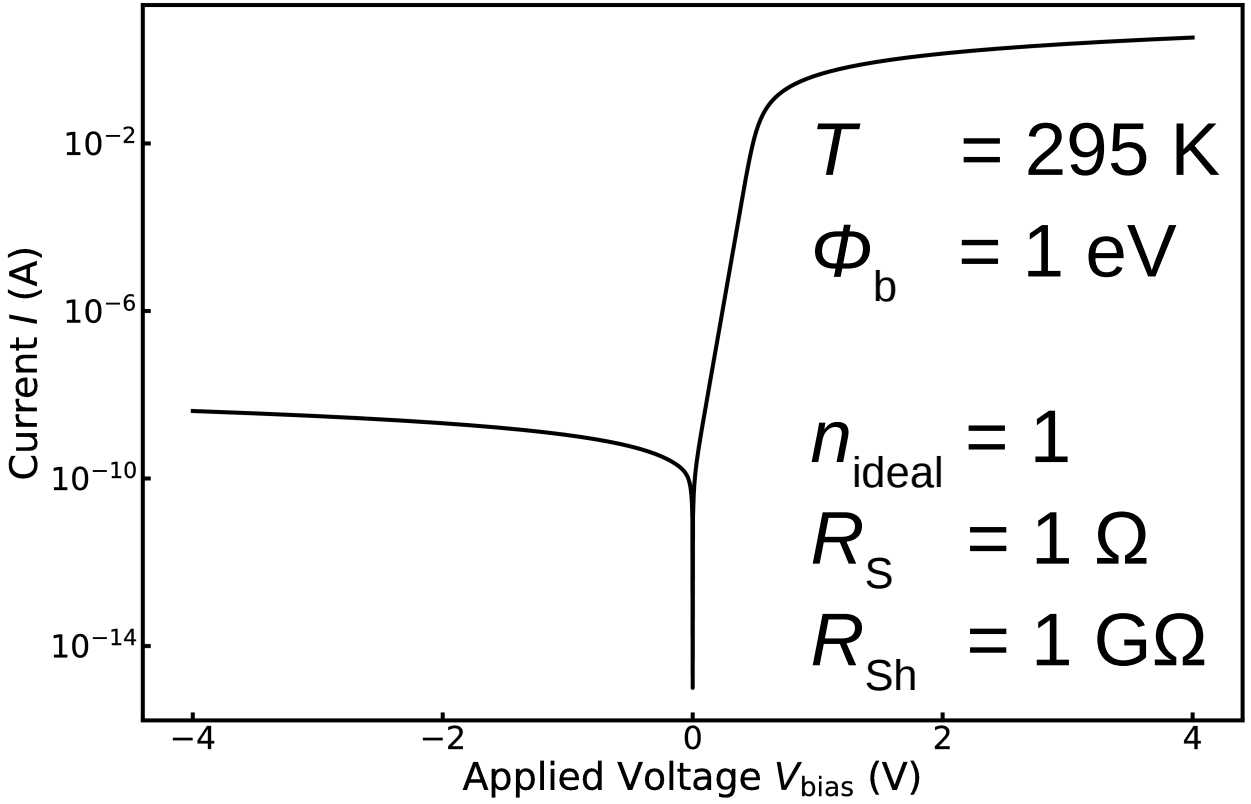

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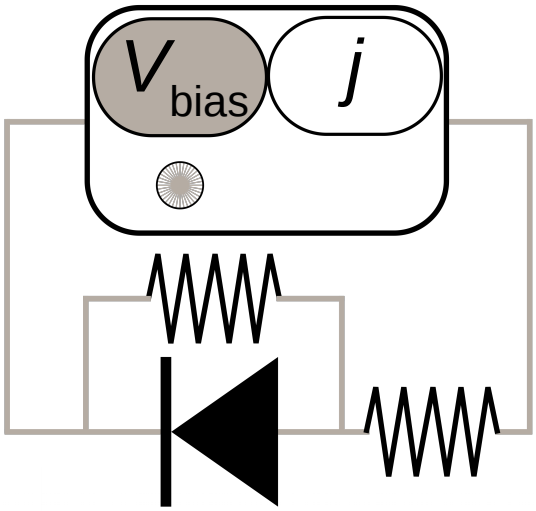
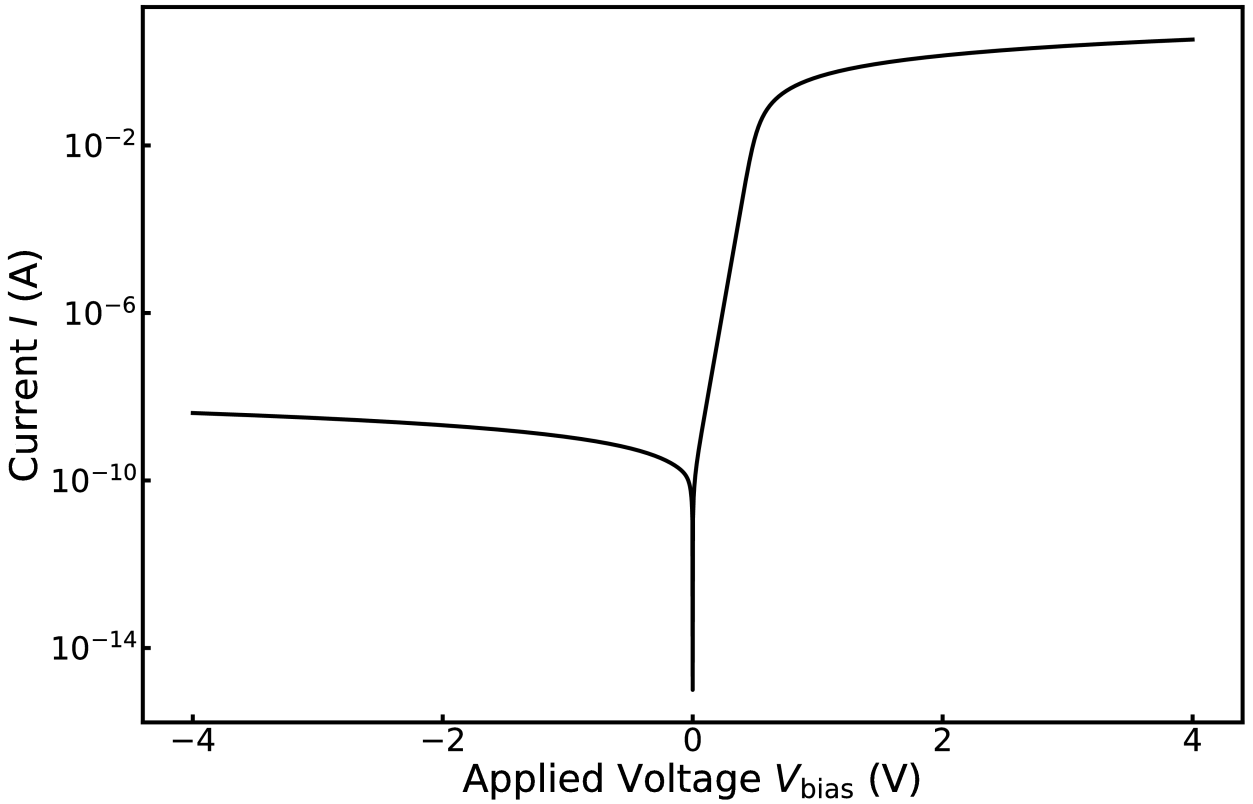
Current-Voltage Characteristics

T = 295 K
Φ_b = 1 eV

n_{ideal} = 1
R_S = 1 Ω
R_{Sh} = 1 GΩ



$$j = j_S\left(e^{\frac{eV_{bias} - jR_S}{n_{ideal}kT}} - 1\right) + \frac{V_{bias} - jR_S}{R_{Sh}}$$



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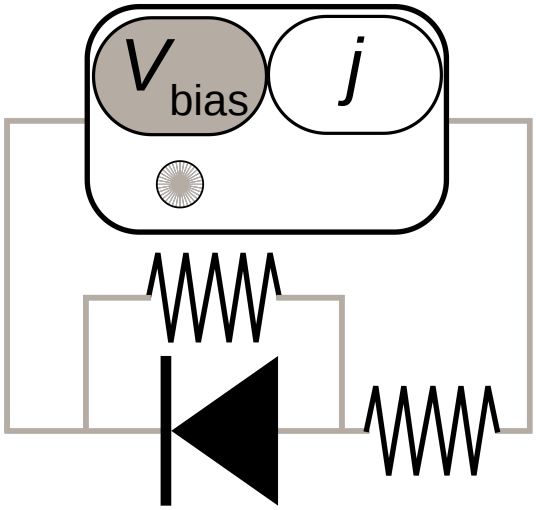
Current-Voltage Characteristics

T = 295 K
Φ_b = 1 eV

n_{ideal} = 1
R_S = 1 Ω
R_{Sh} = [1 GΩ, 1 kΩ, 1Ω]



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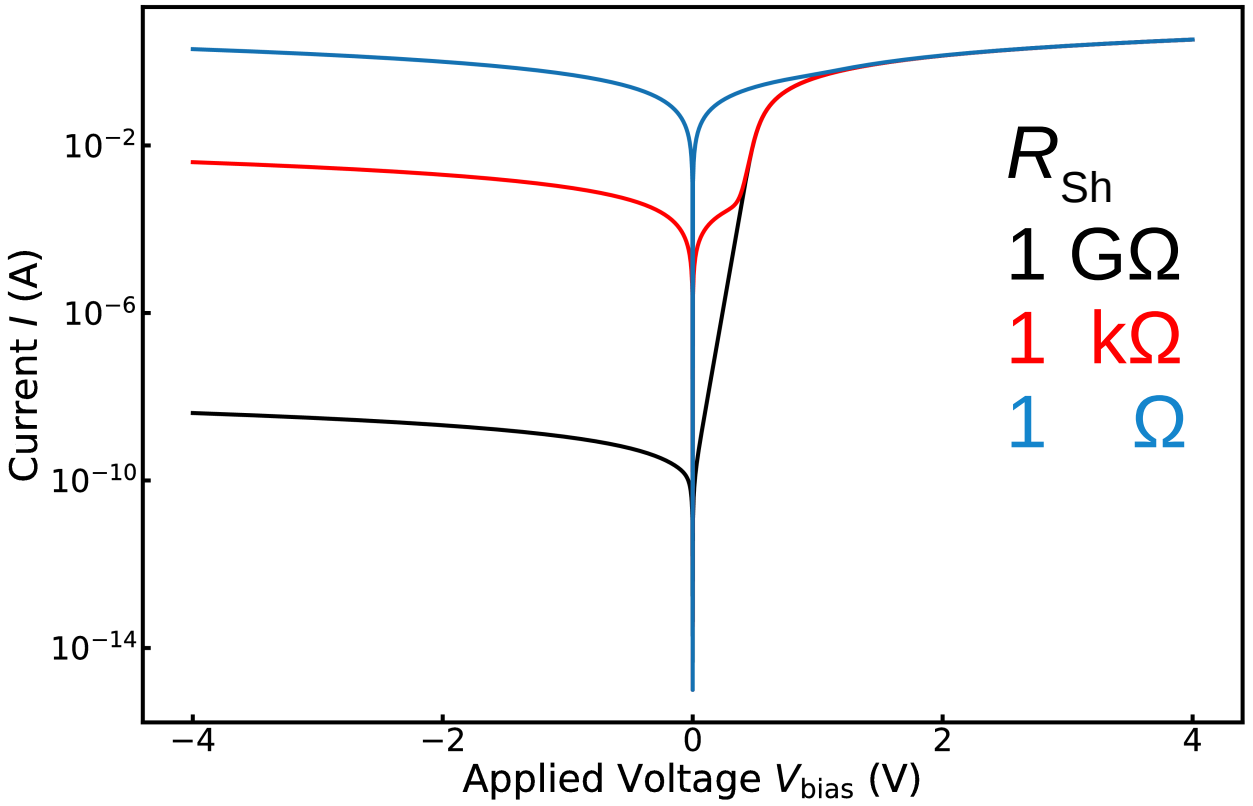

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Current-Voltage Characteristics

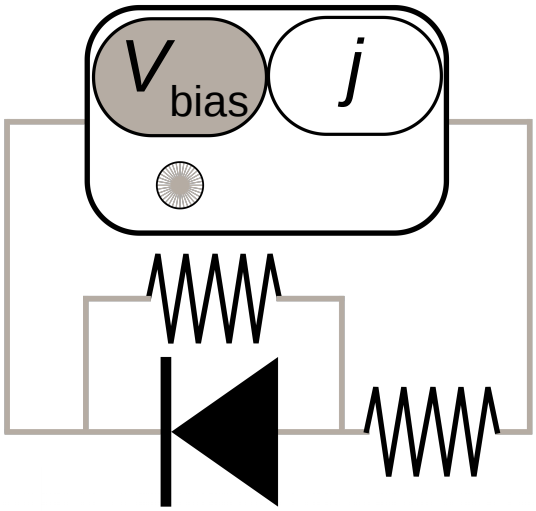
T = 295 K

Φ_b = 1 eV

n_{ideal} = 1

R_S = [1 Ω, 1 kΩ, 1 MΩ]

R_{Sh} = 1 GΩ



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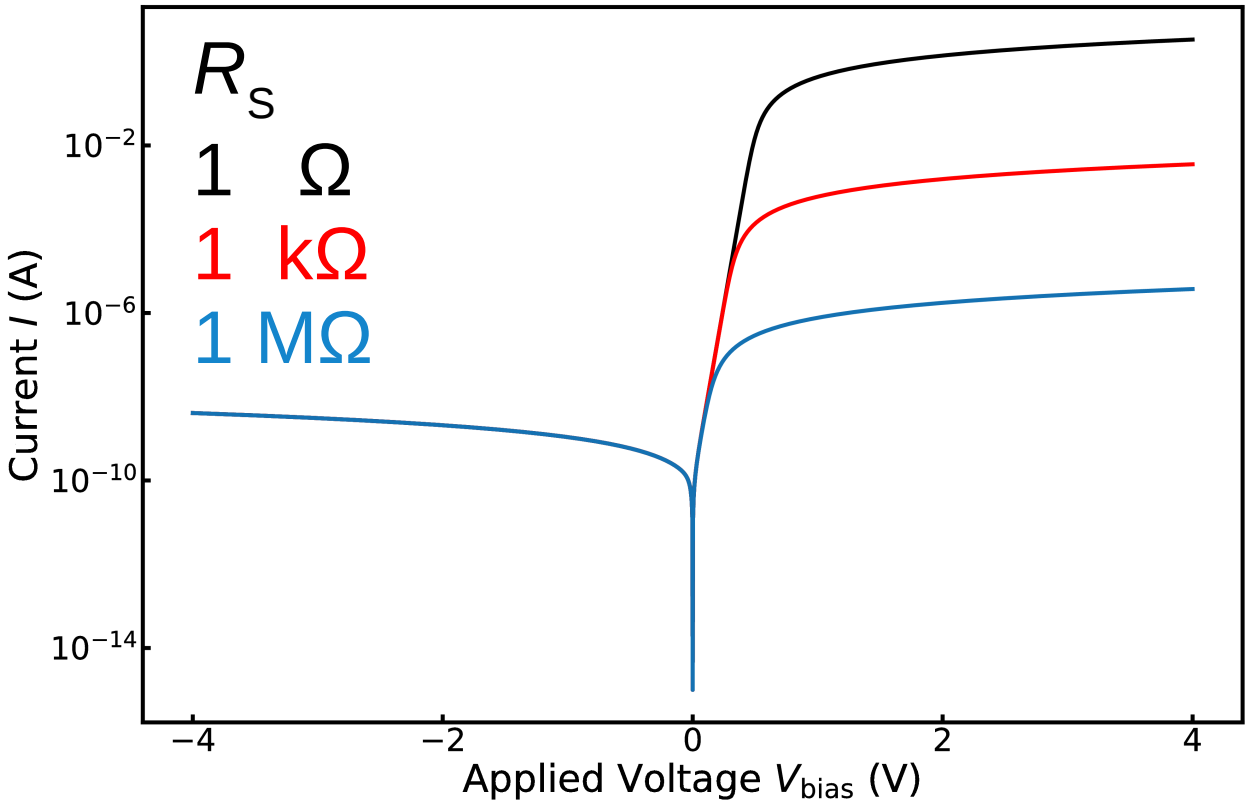

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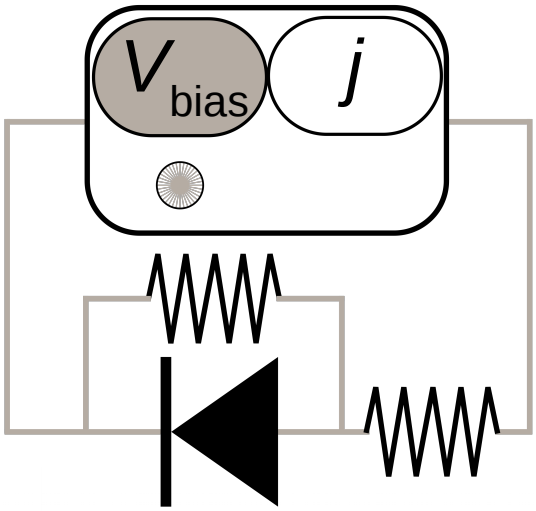
Current-Voltage Characteristics

T = 295 K
Φ_b = 1 eV

n_{ideal} = [1, 2, 3]
R_S = 1 Ω
R_{Sh} = 1 GΩ



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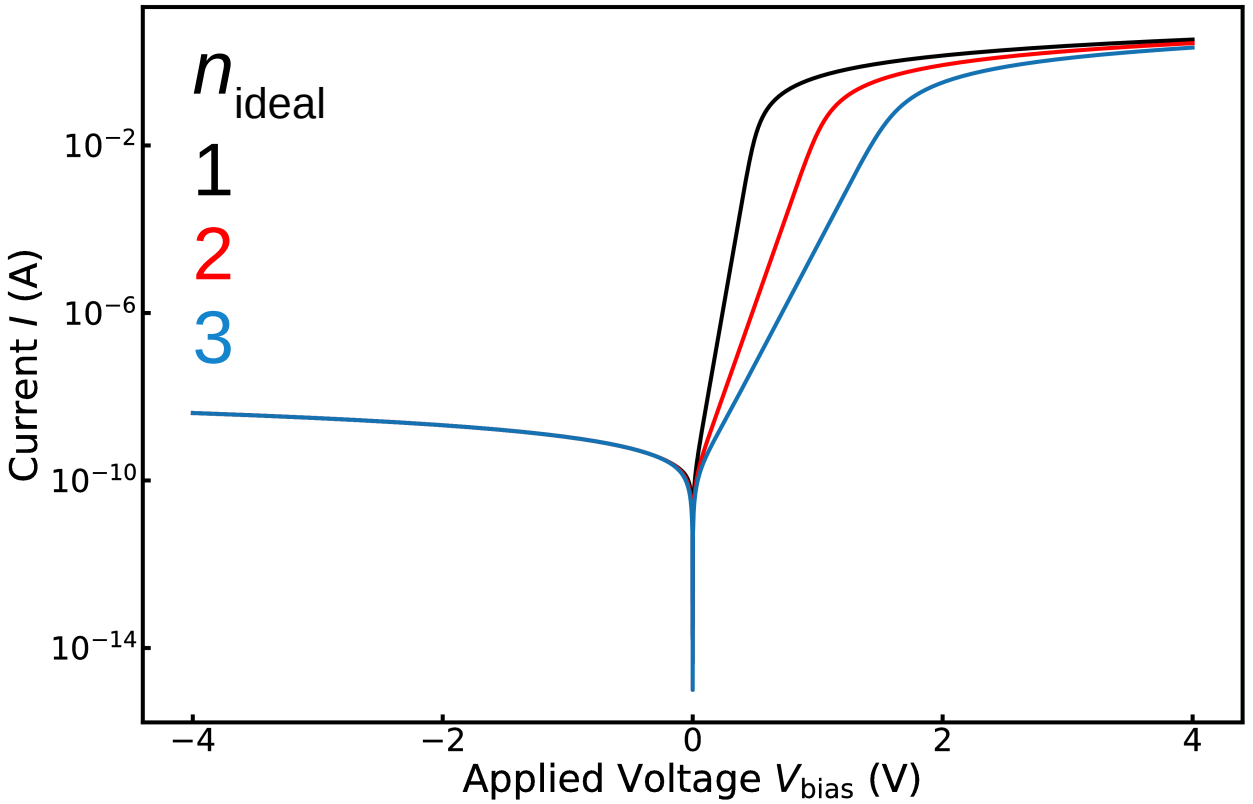

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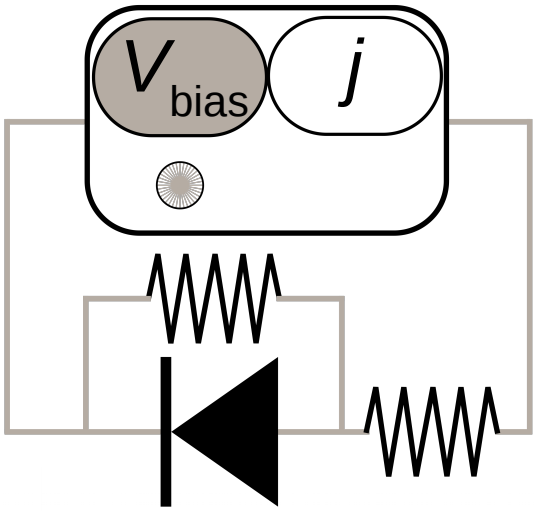
Current-Voltage Characteristics

T = [295 K, 450 K, 600 K]
Φ_b = 1 eV

n_{ideal} = 1
R_S = 1 Ω
R_{Sh} = 1 GΩ



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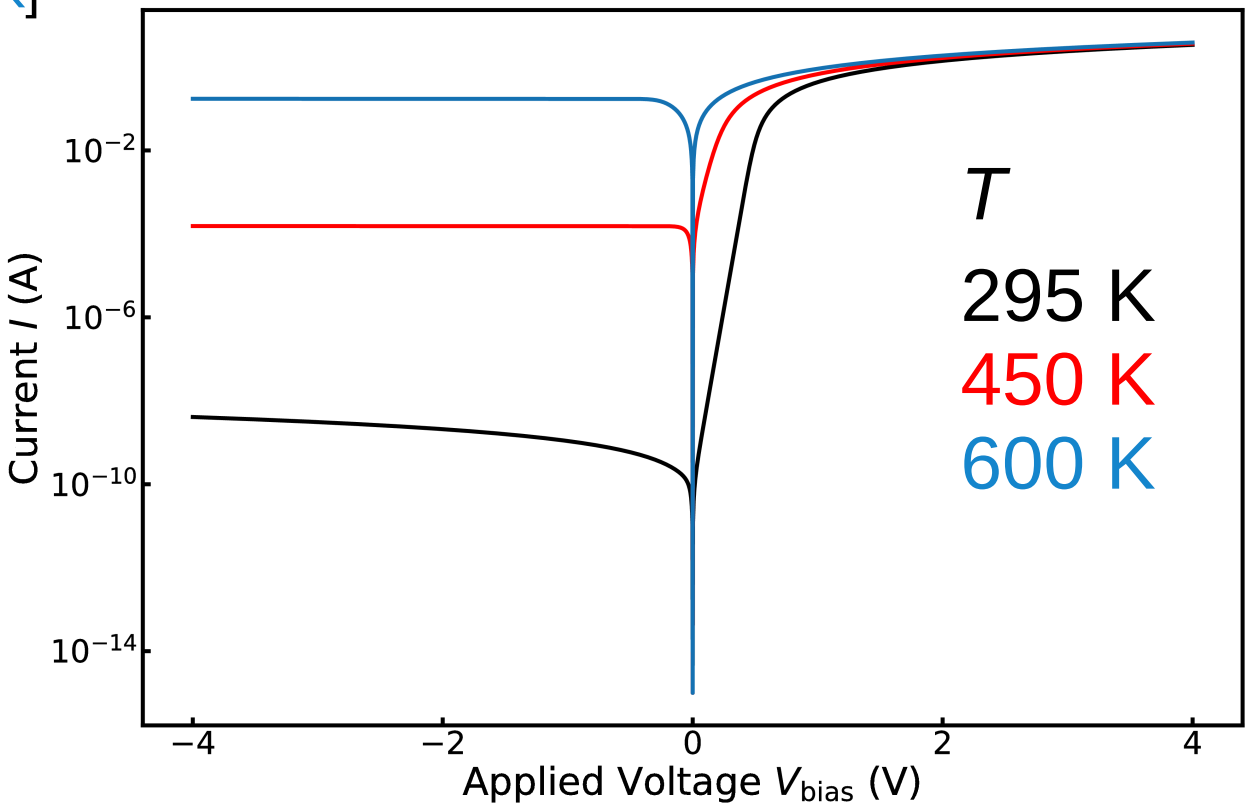

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Current-Voltage Characteristics

T = 295 K

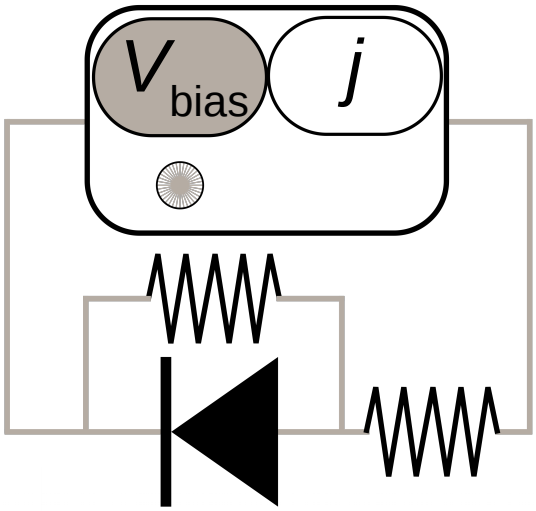
Si *p*-*n* junction with:

n_{ideal} = 1.72

R_S = 94 Ω

R_{Sh} = 1.64 GΩ

j_S = 0.61 nA



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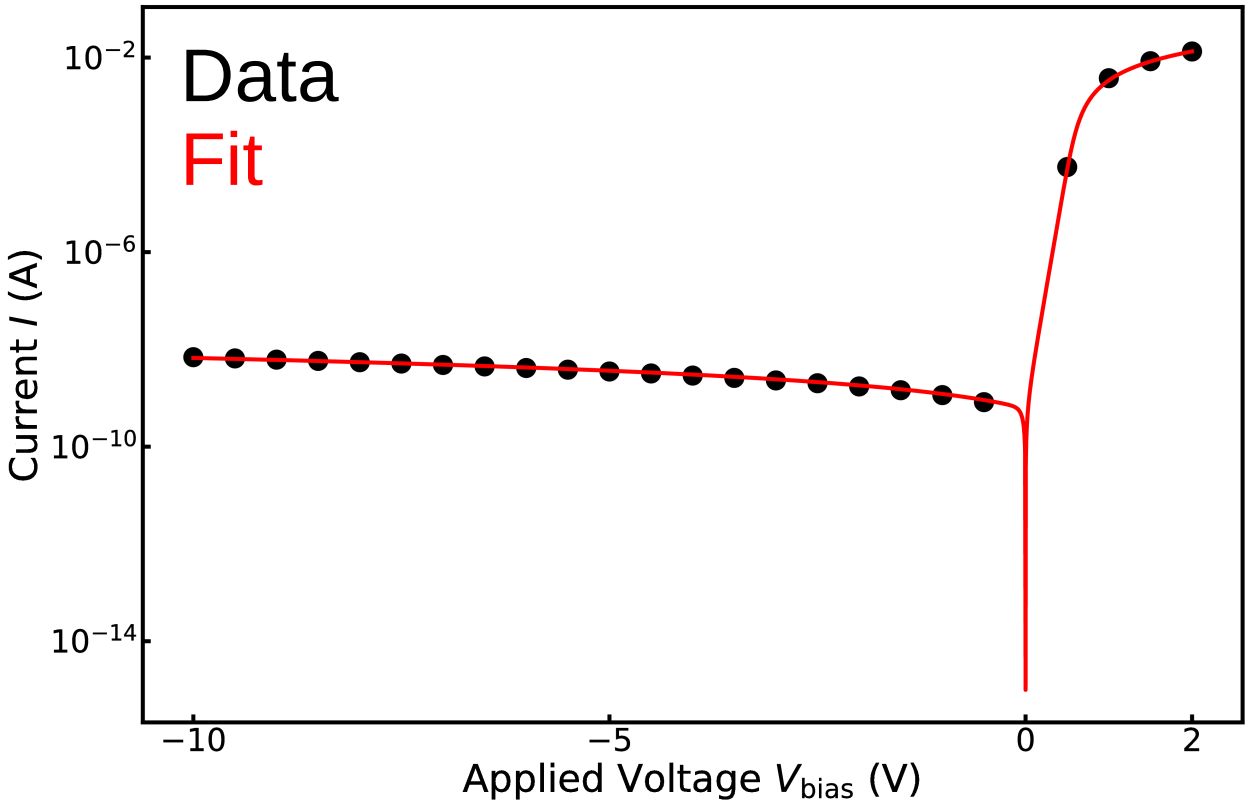

Data: Courtesy of Aleksei Andreevich Grigorev

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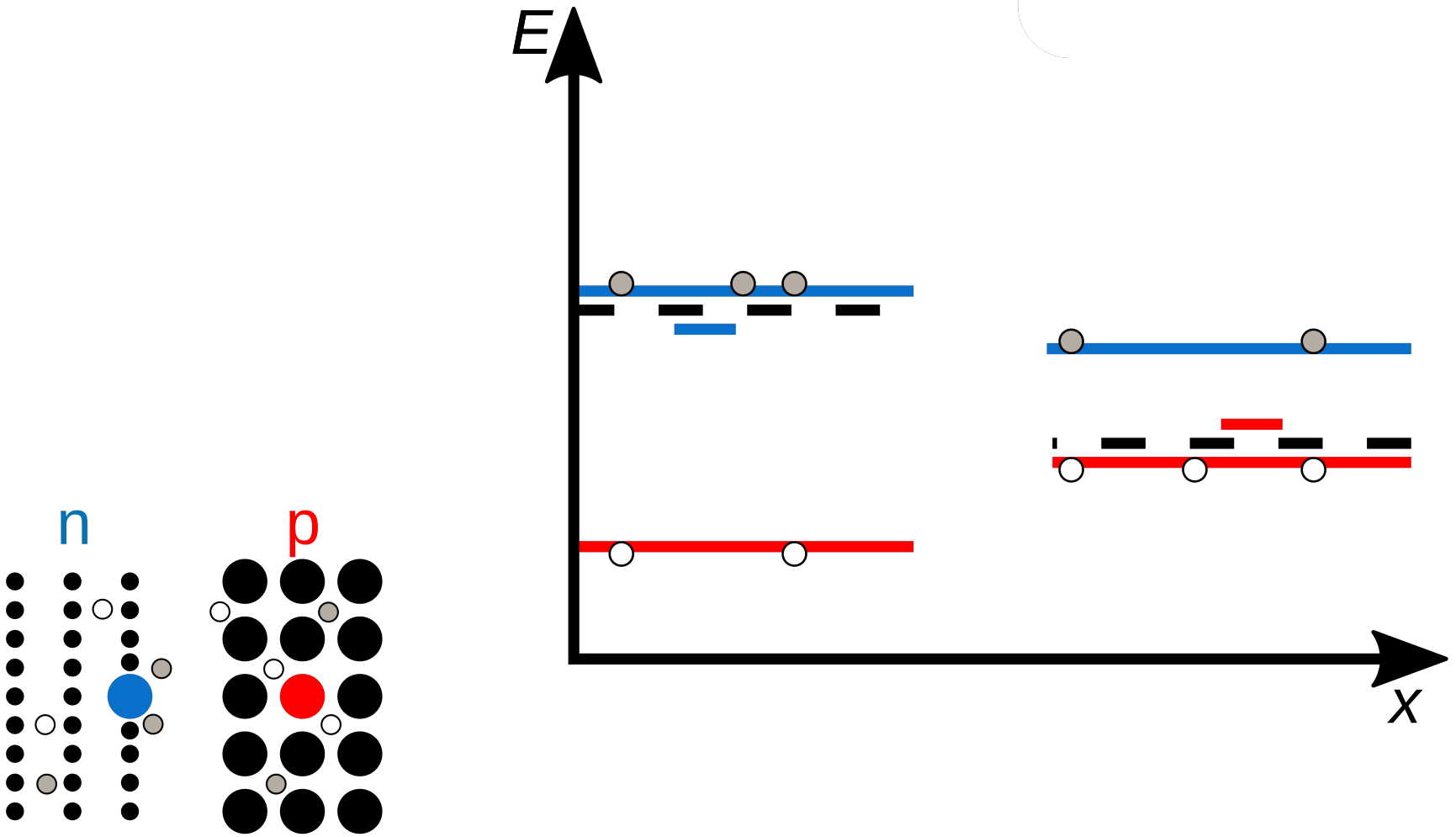
The band diagram of *p-n* **hetero**junctions



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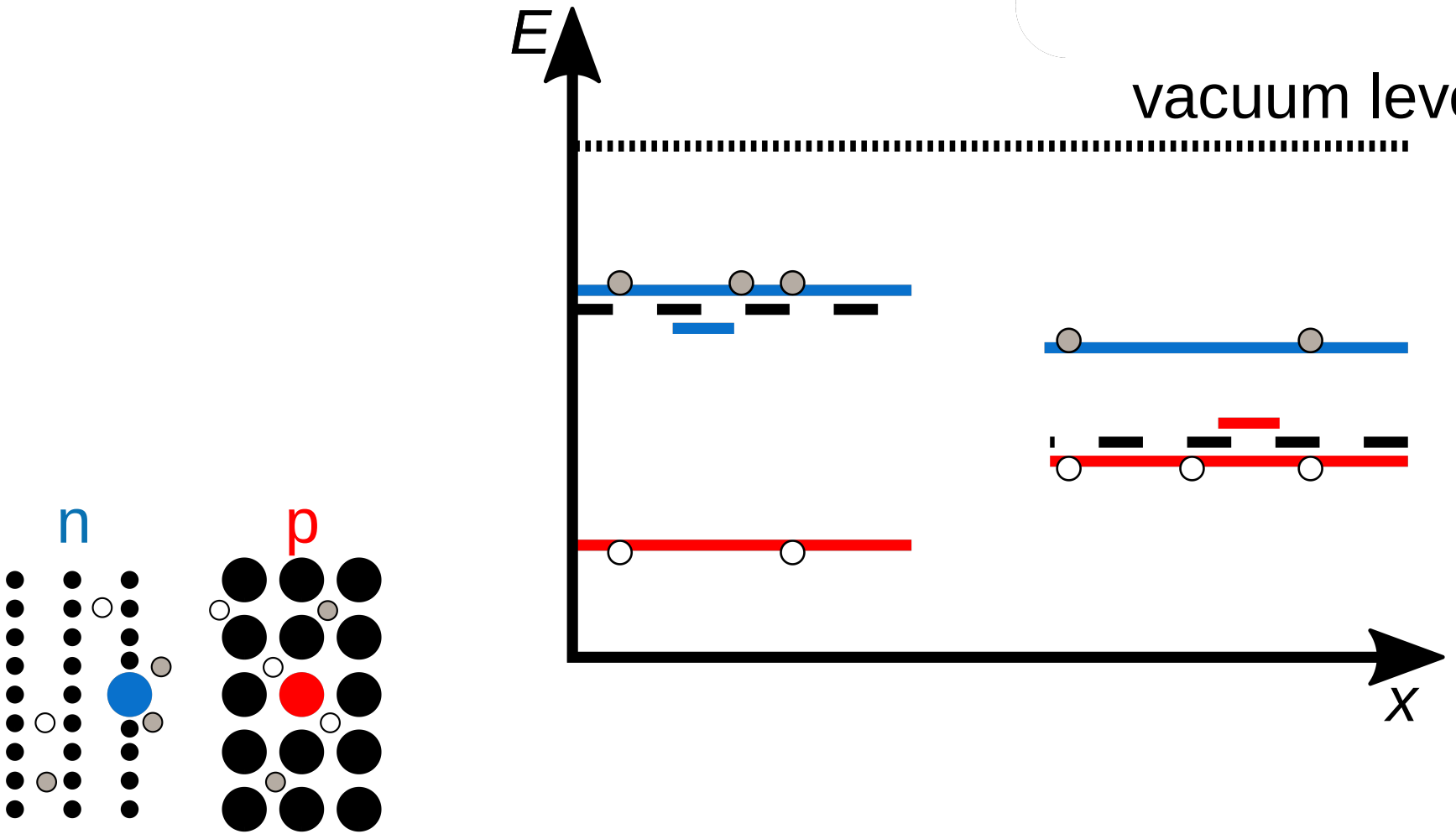

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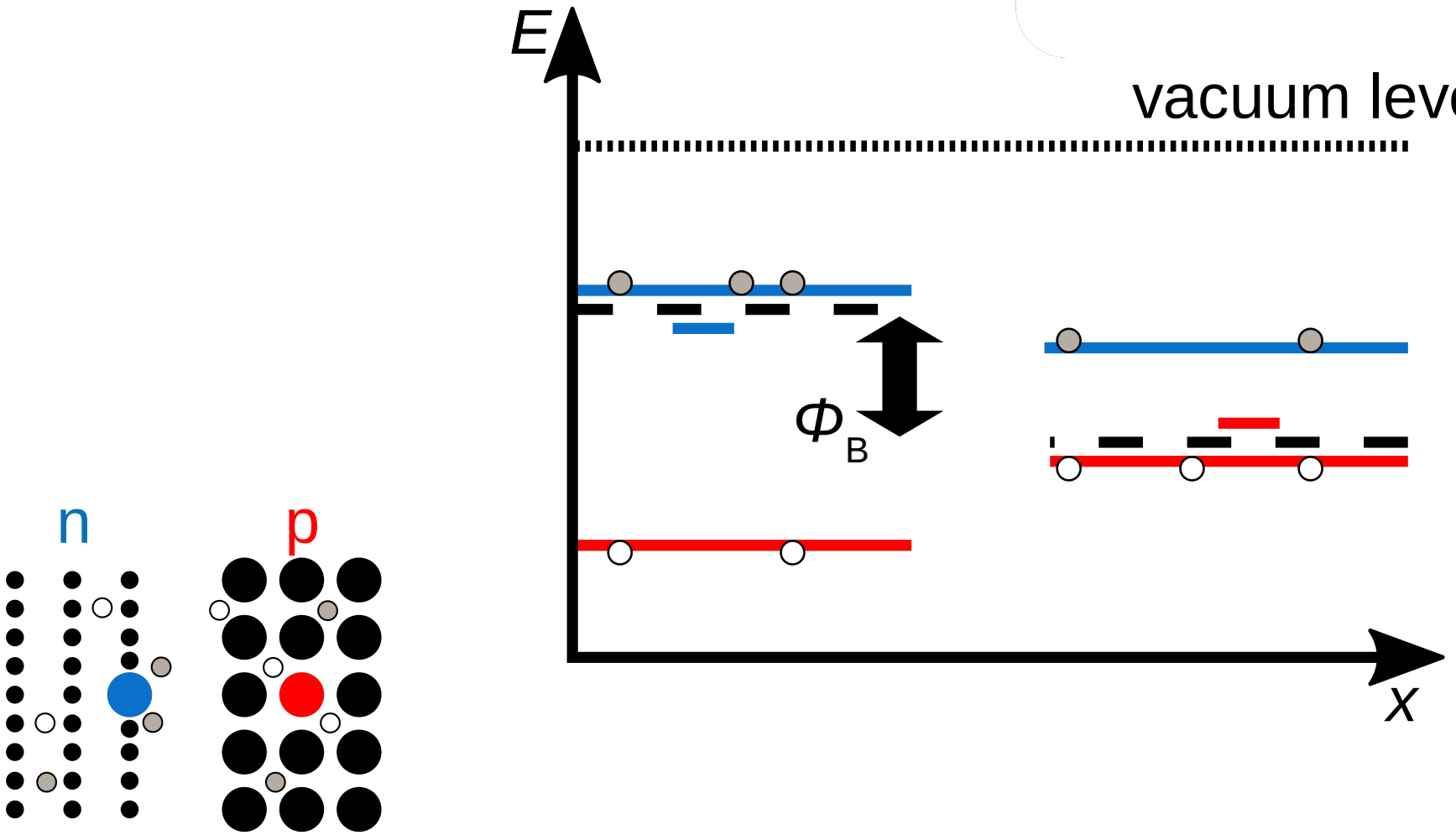

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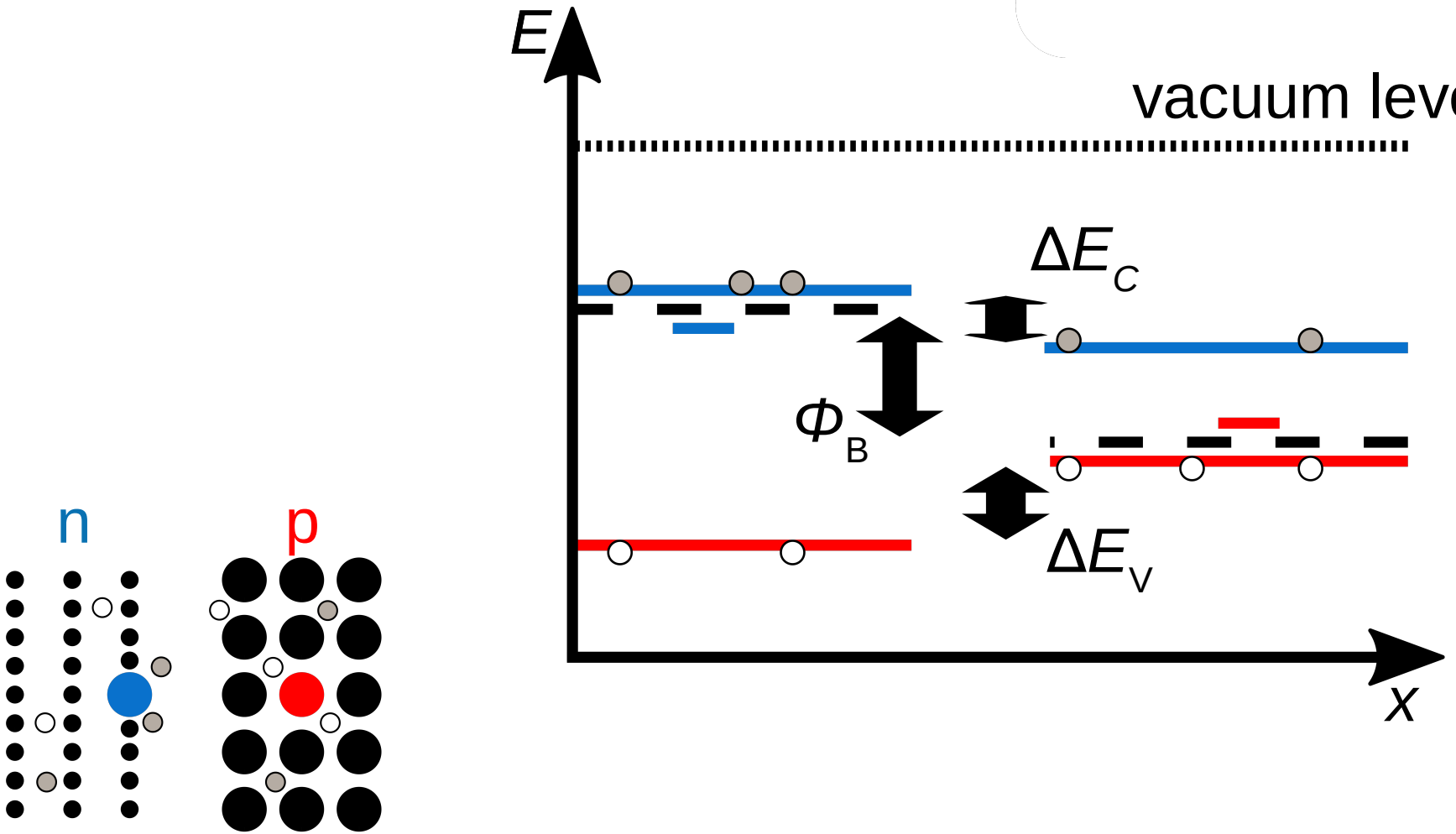

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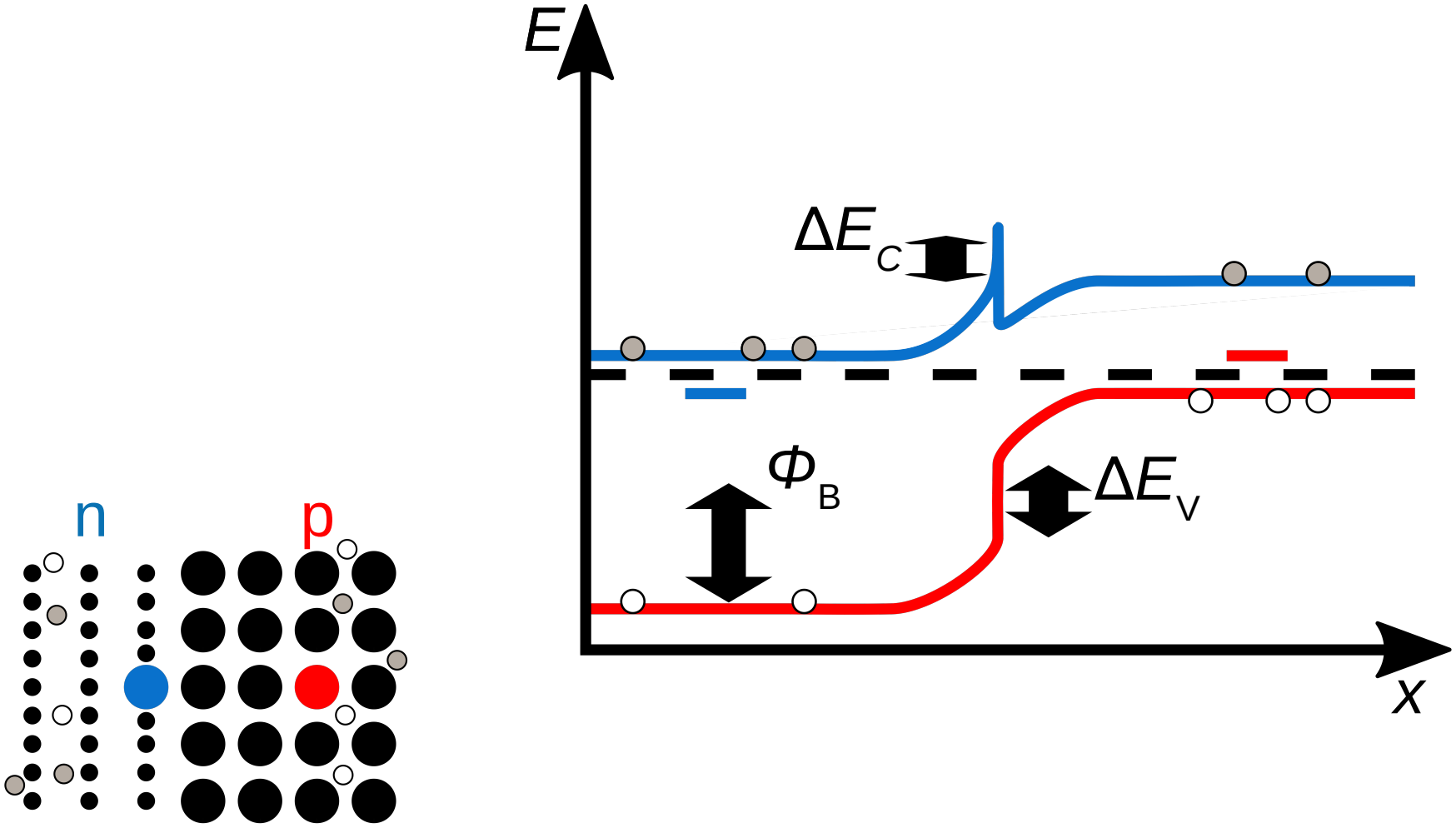

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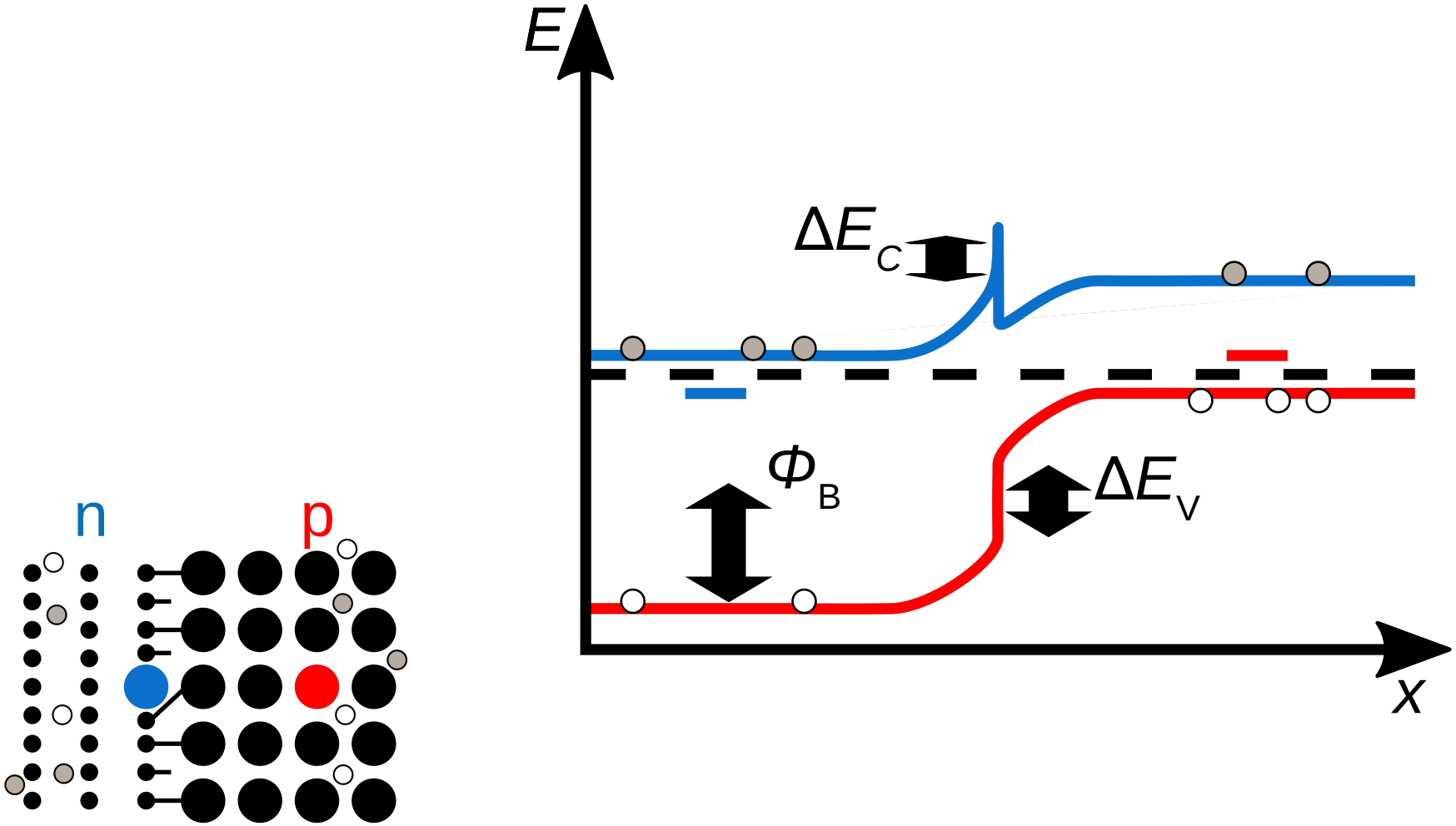

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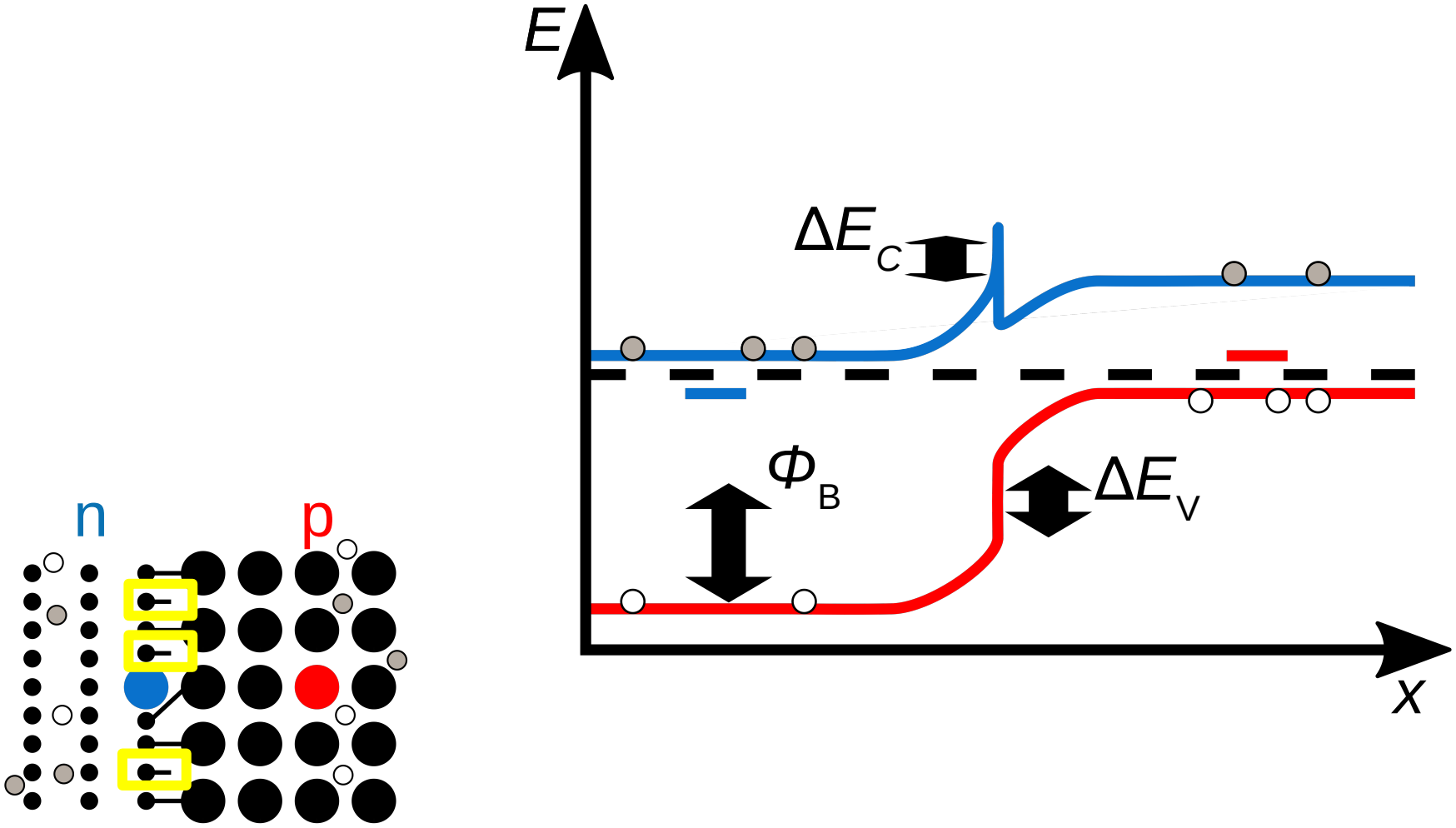

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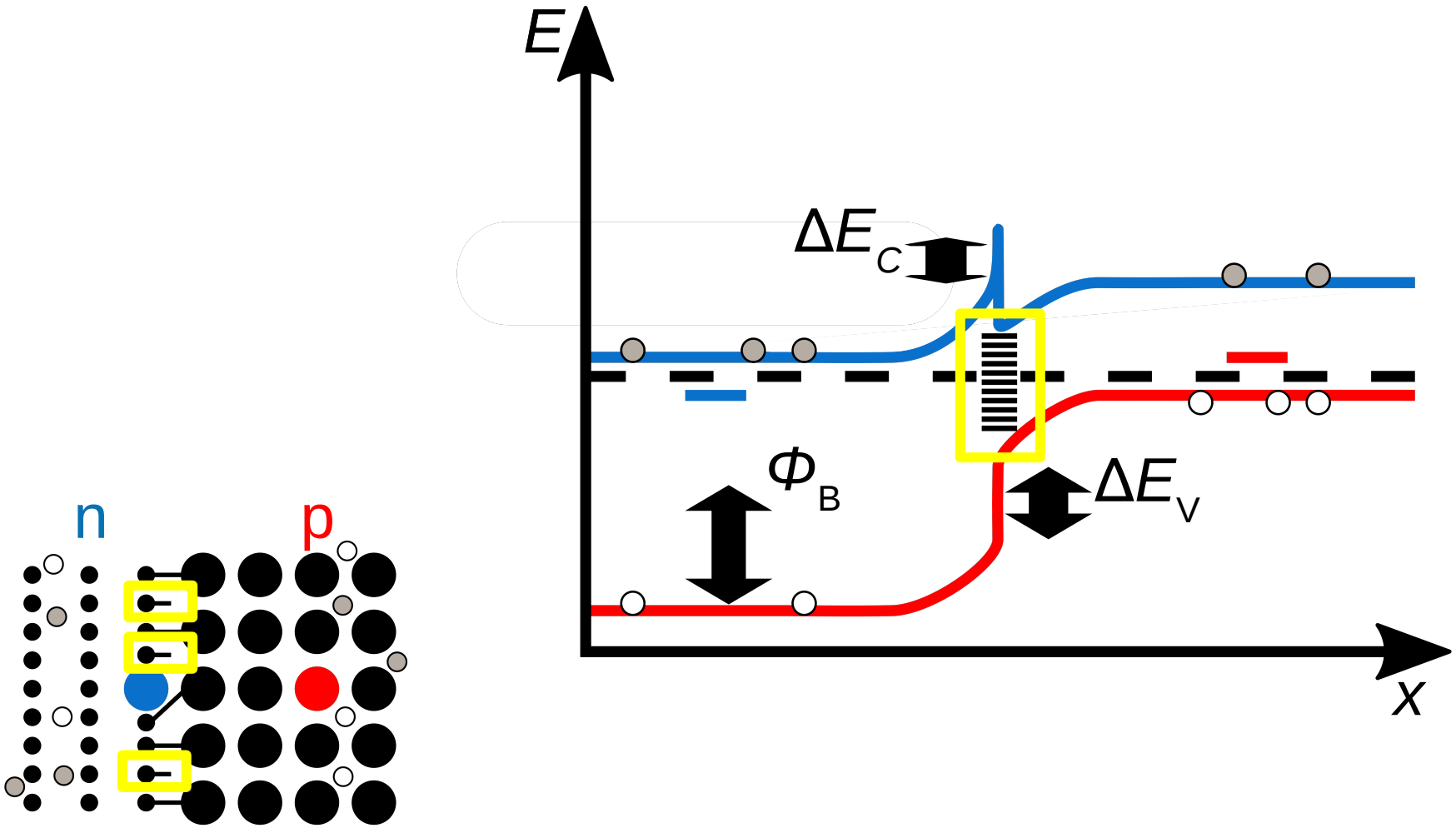

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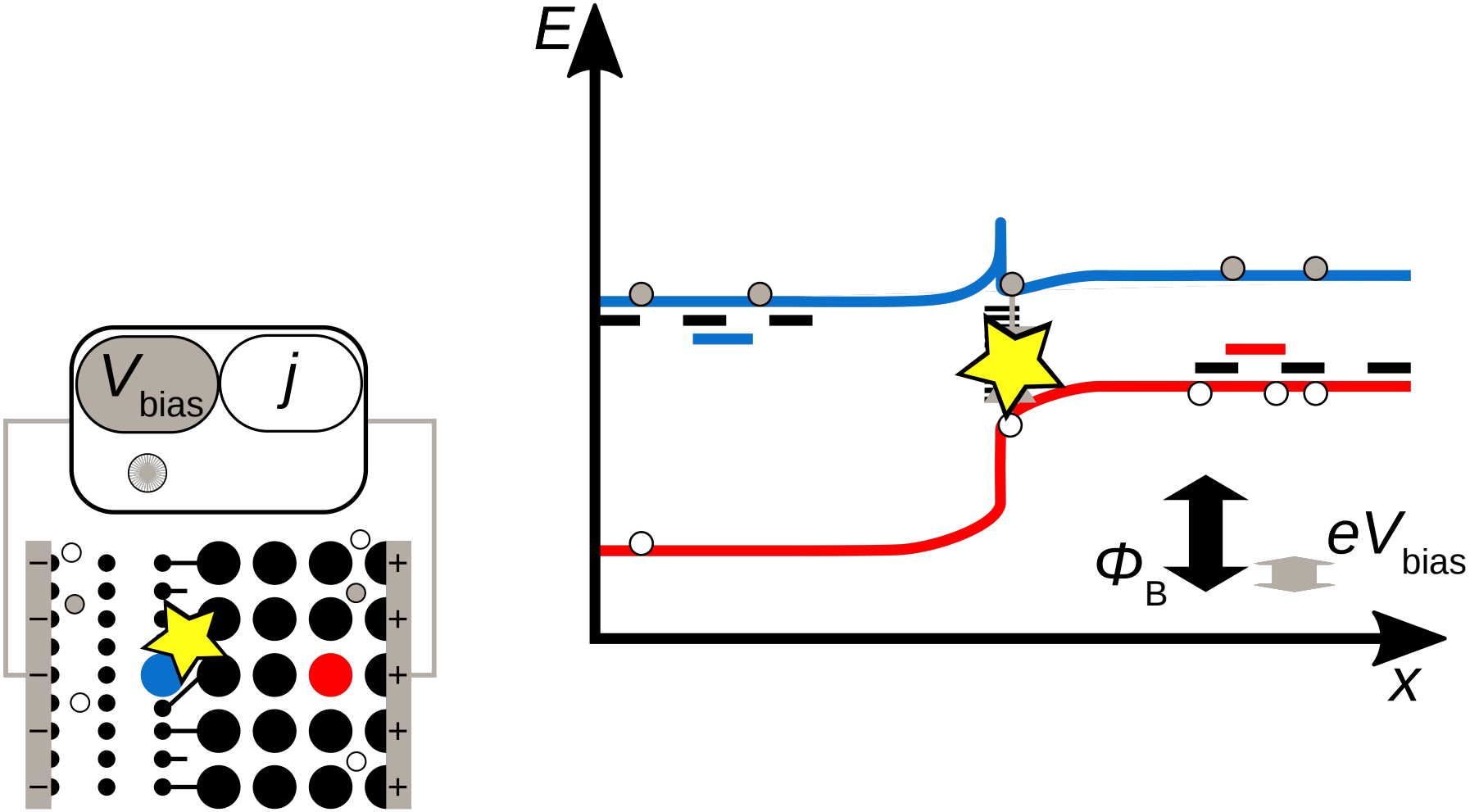

UiO : Centre for Materials Science and Nanotechnology
University of Oslo

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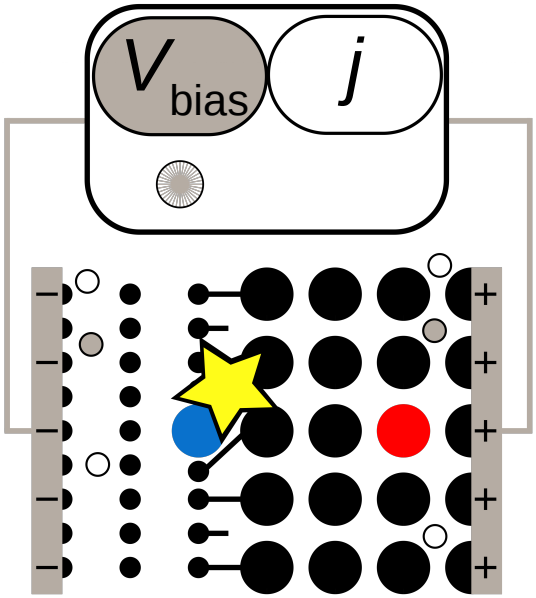
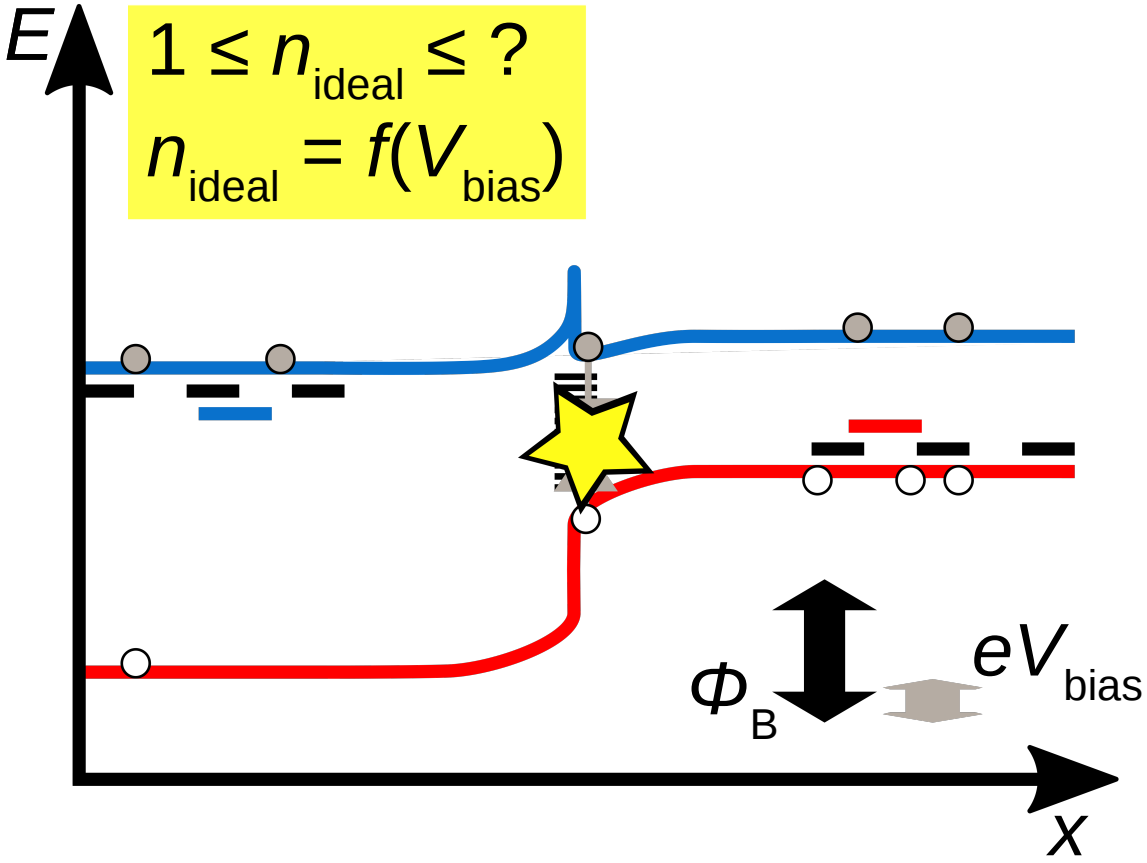
The band diagram of *p-n* heterojunctions

$$j = j_S\left(e^{\frac{eV_{bias} - jR_S}{n_{ideal}kT}} - 1\right) + \frac{V_{bias} - jR_S}{R_{Sh}}$$





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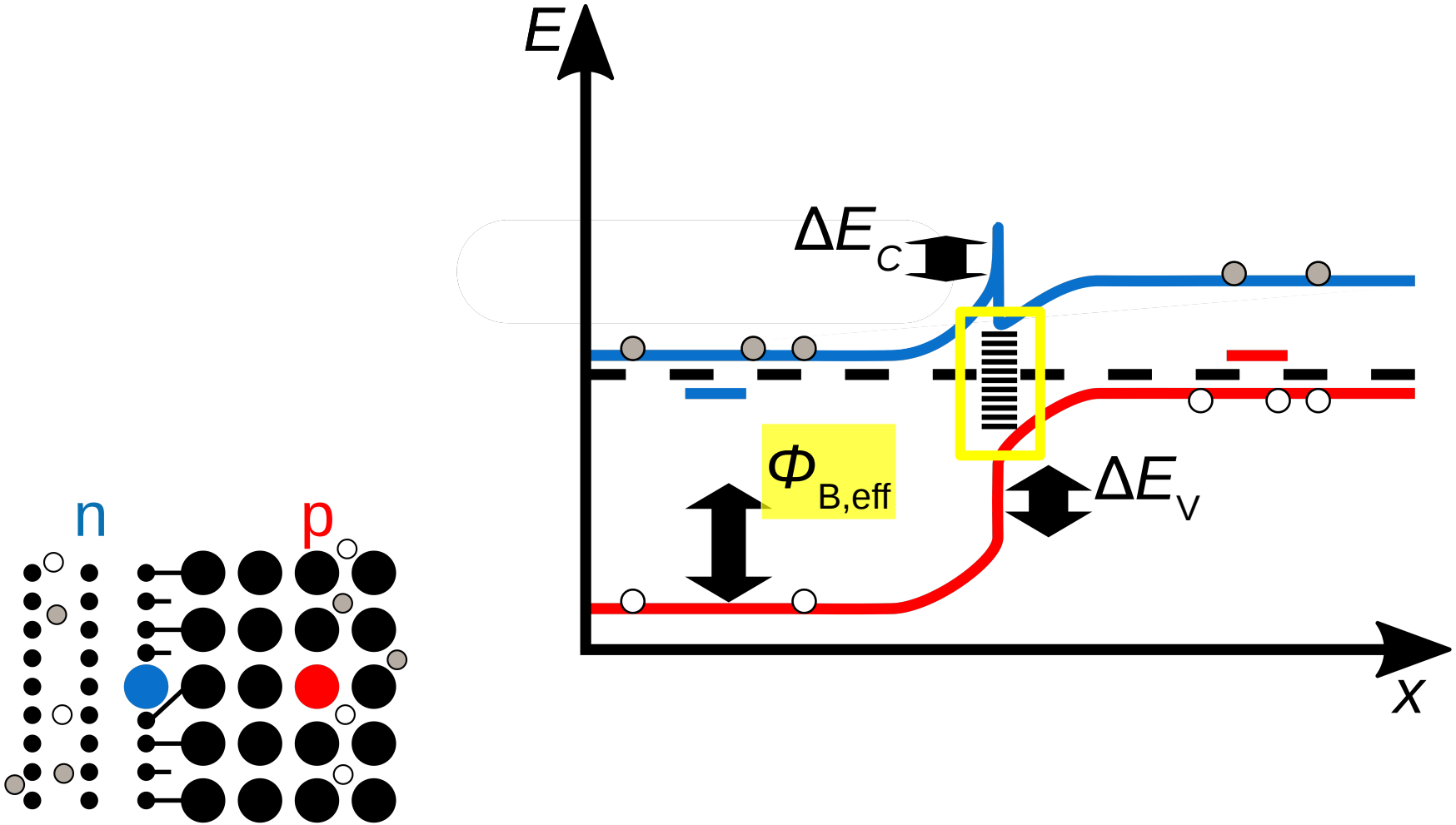

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Blood, P. and Orton, J.W., *The electrical Characterization of semiconductors* (1992)

Current-Voltage Characteristics

T = 295 K

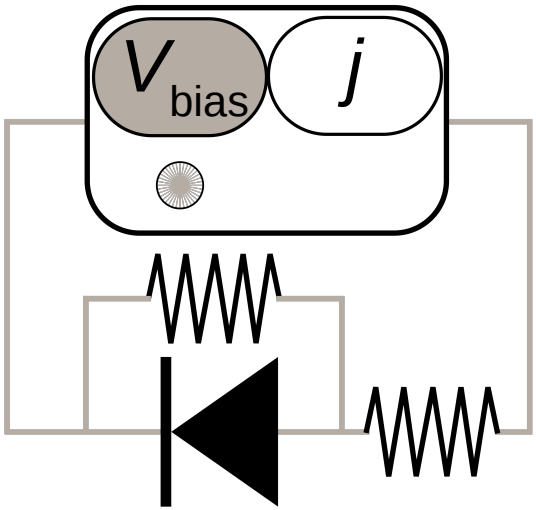
ZnO/CdS/CZTS junction:

n_{ideal} = 1.86

R_S = 6.4 kΩ

R_{Sh} = 284 MΩ

j_S = 3.6 pA



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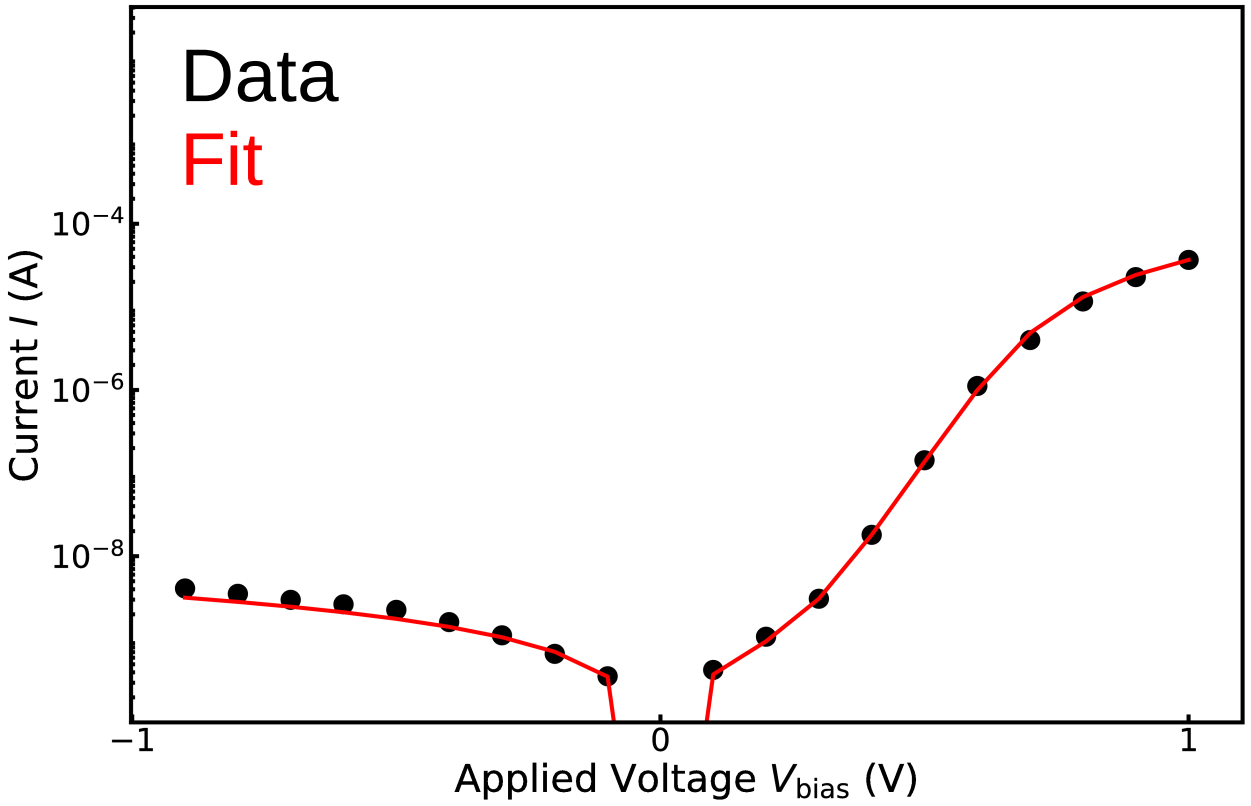
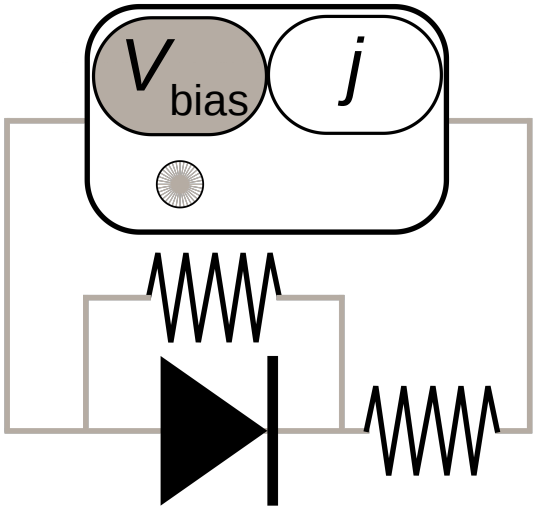
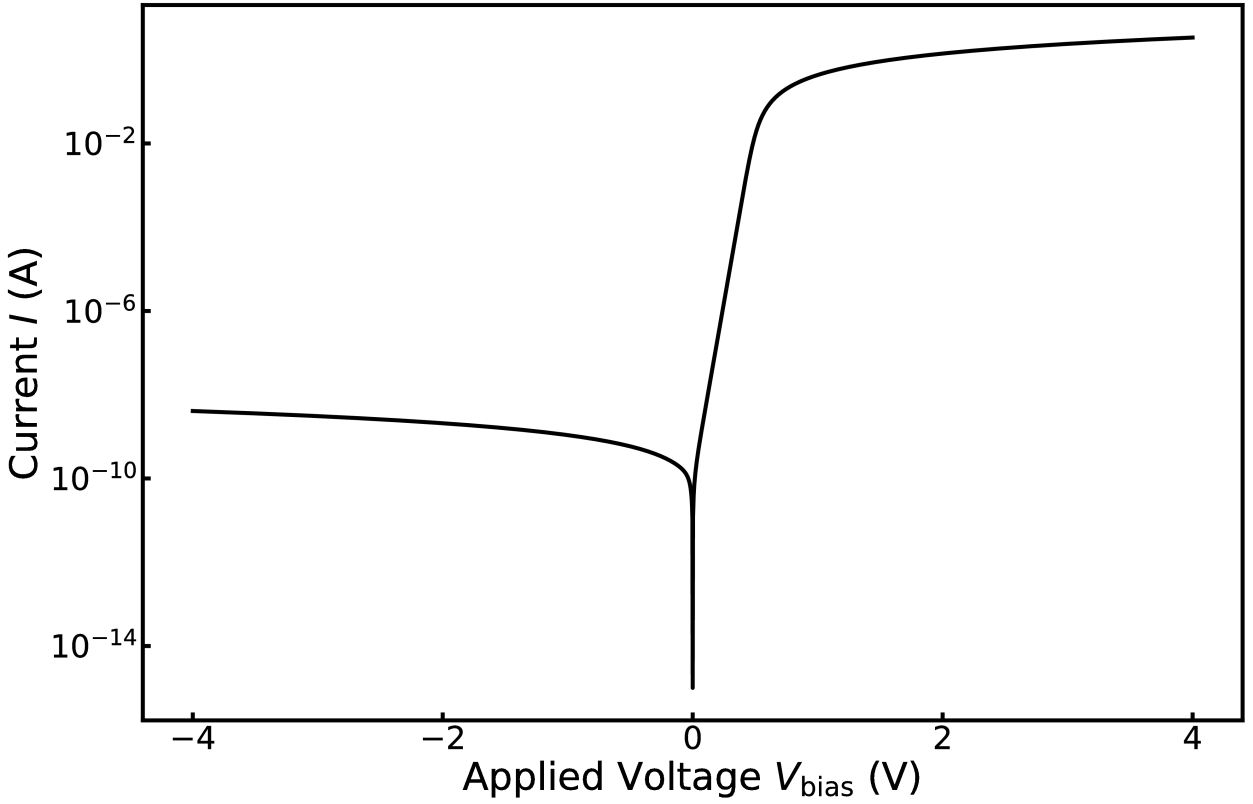


Data: Courtesy of Sigbjørn Grini

Fundamentals pf *p-n* junctions

$$j = j_S\left(e^{\frac{eV_{bias} - jR_S}{n_{ideal}kT}} - 1\right) + \frac{V_{bias} - jR_S}{R_{Sh}}$$





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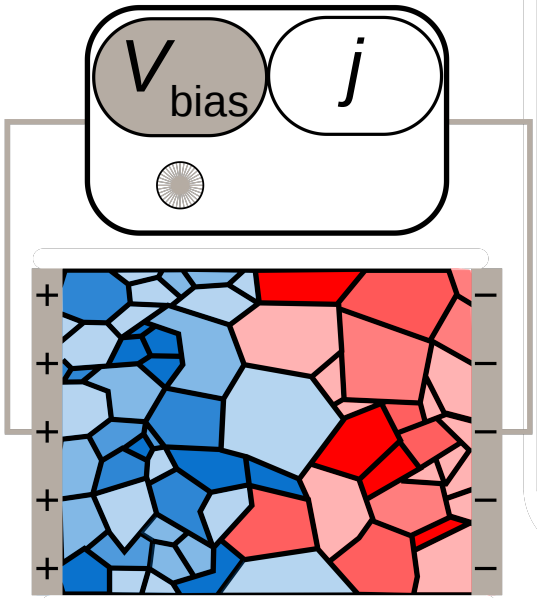
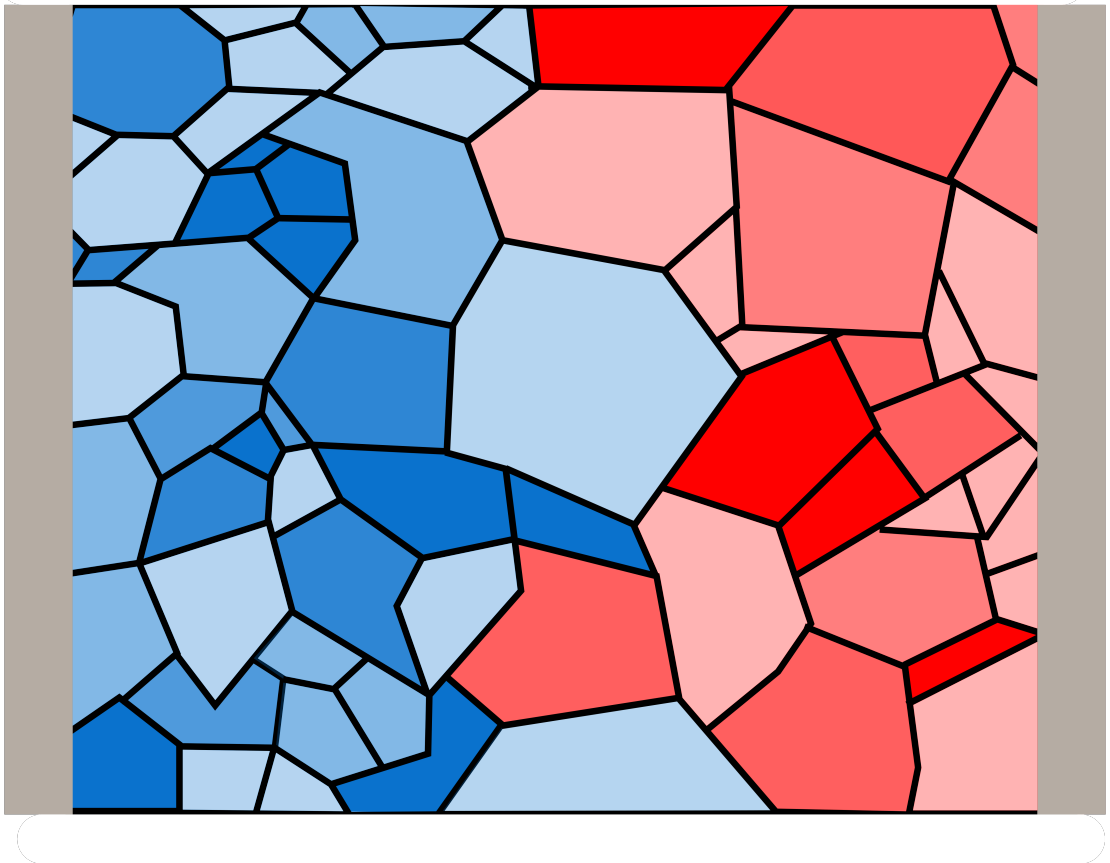
Sullivan, J.P., *J. Appl. Phys.* **70** (1991)

p-n junctions: Inhomogeneous barrier height





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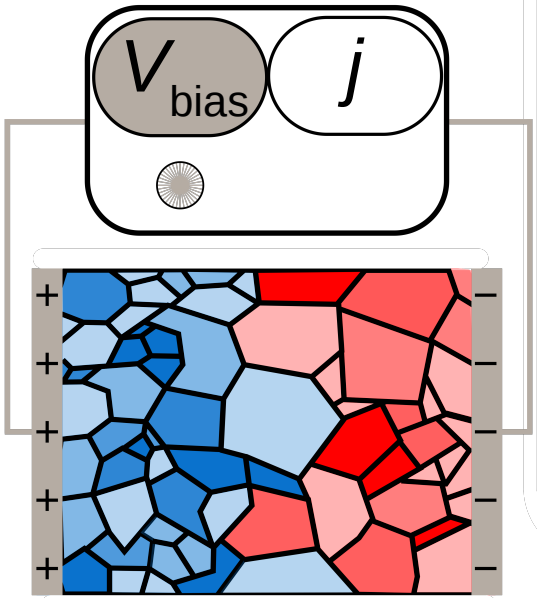

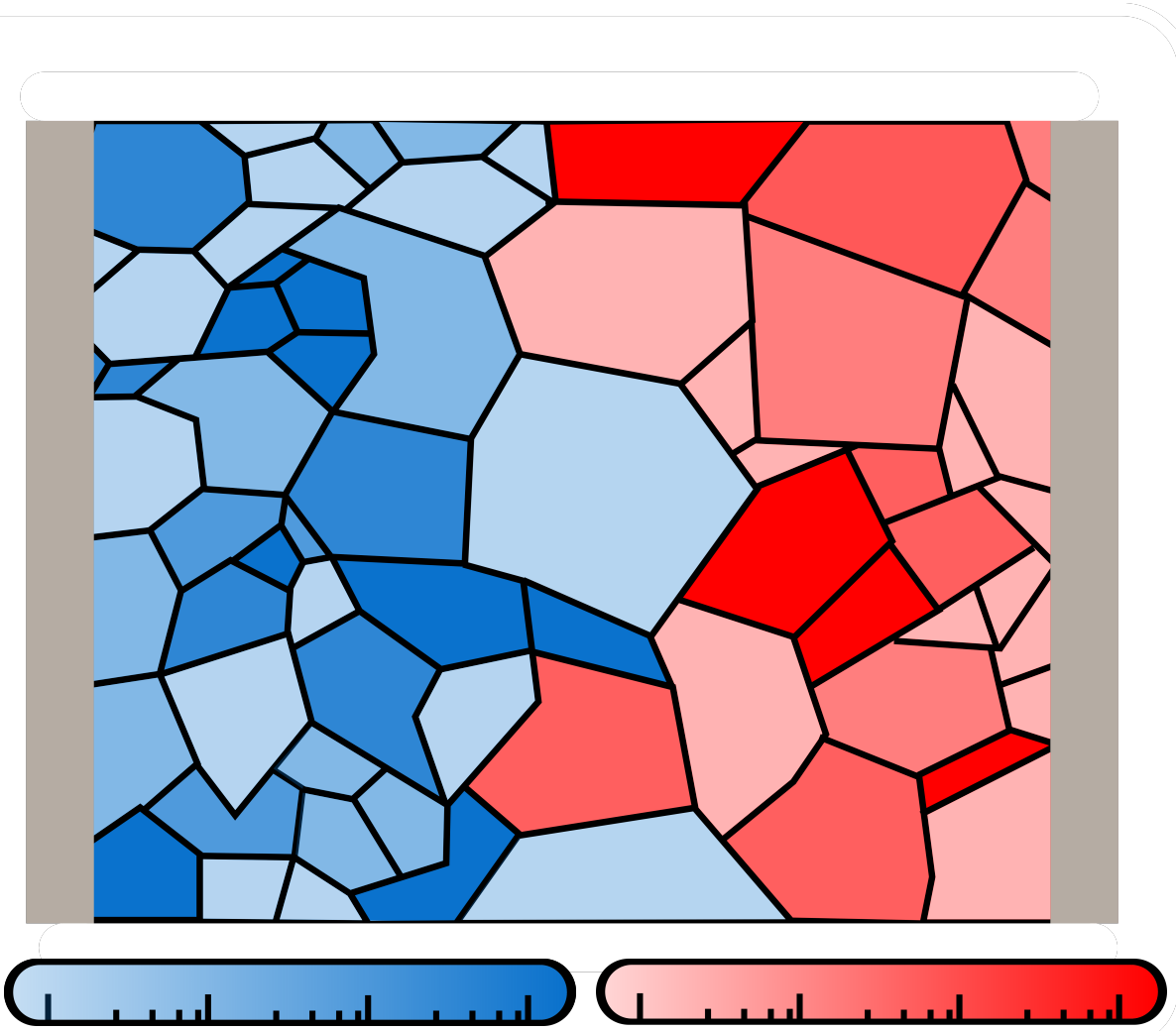

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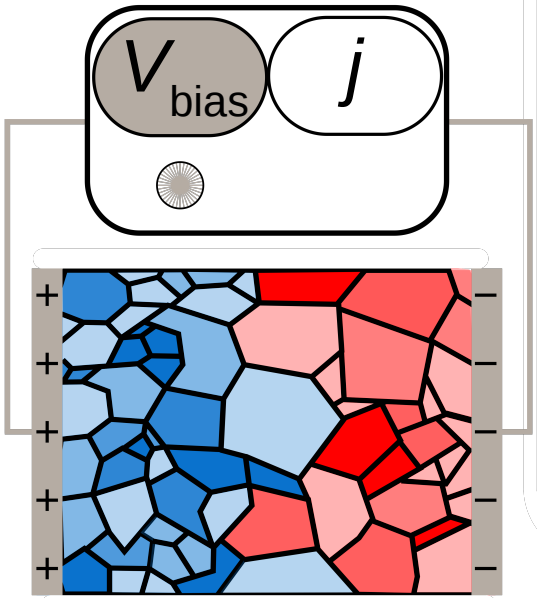

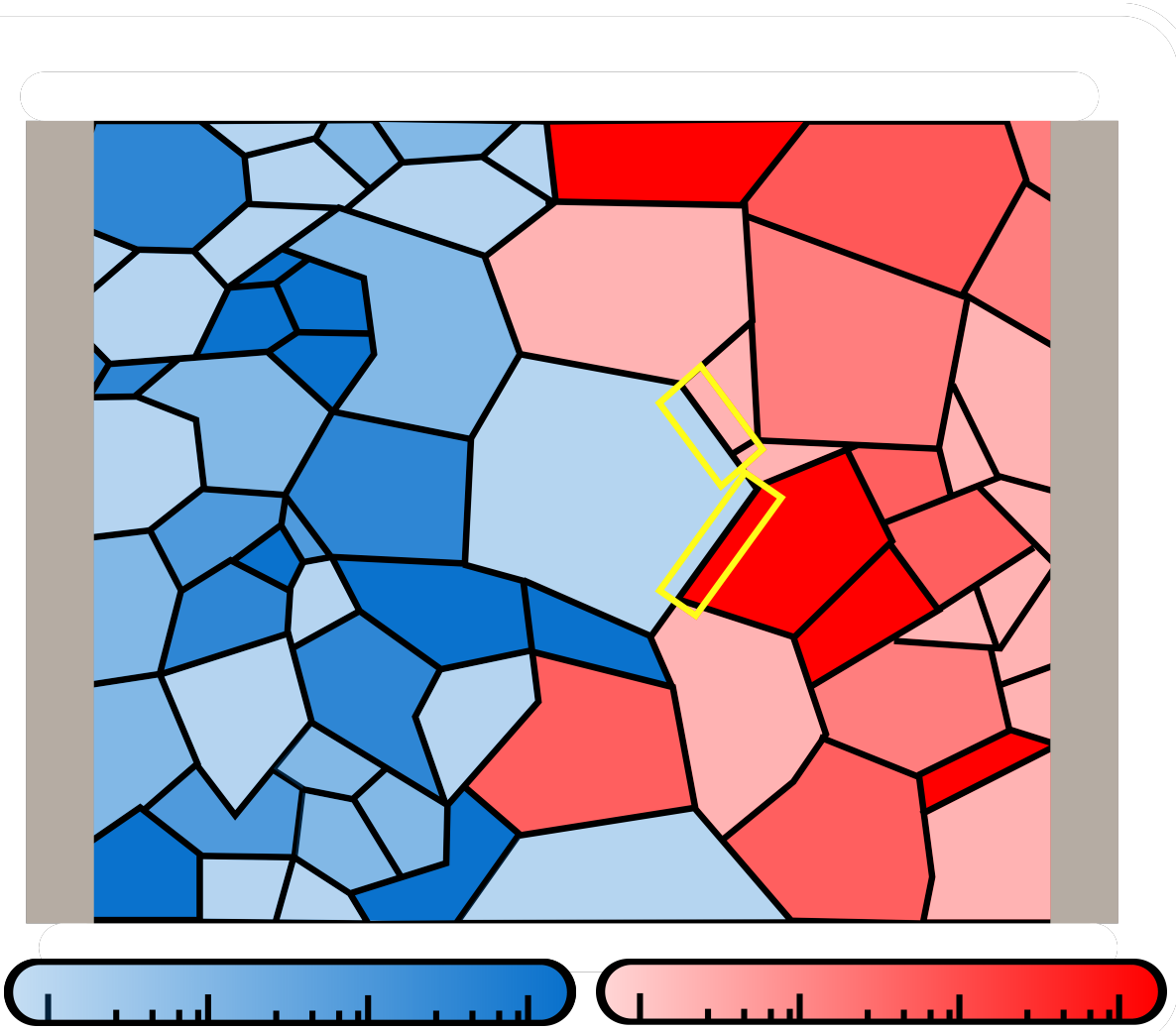

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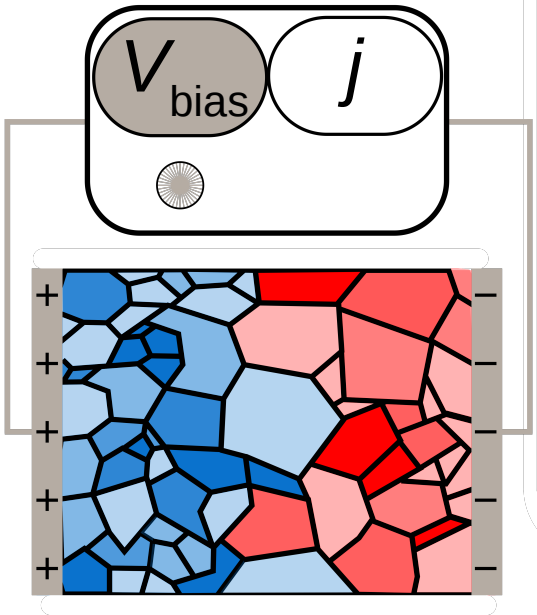

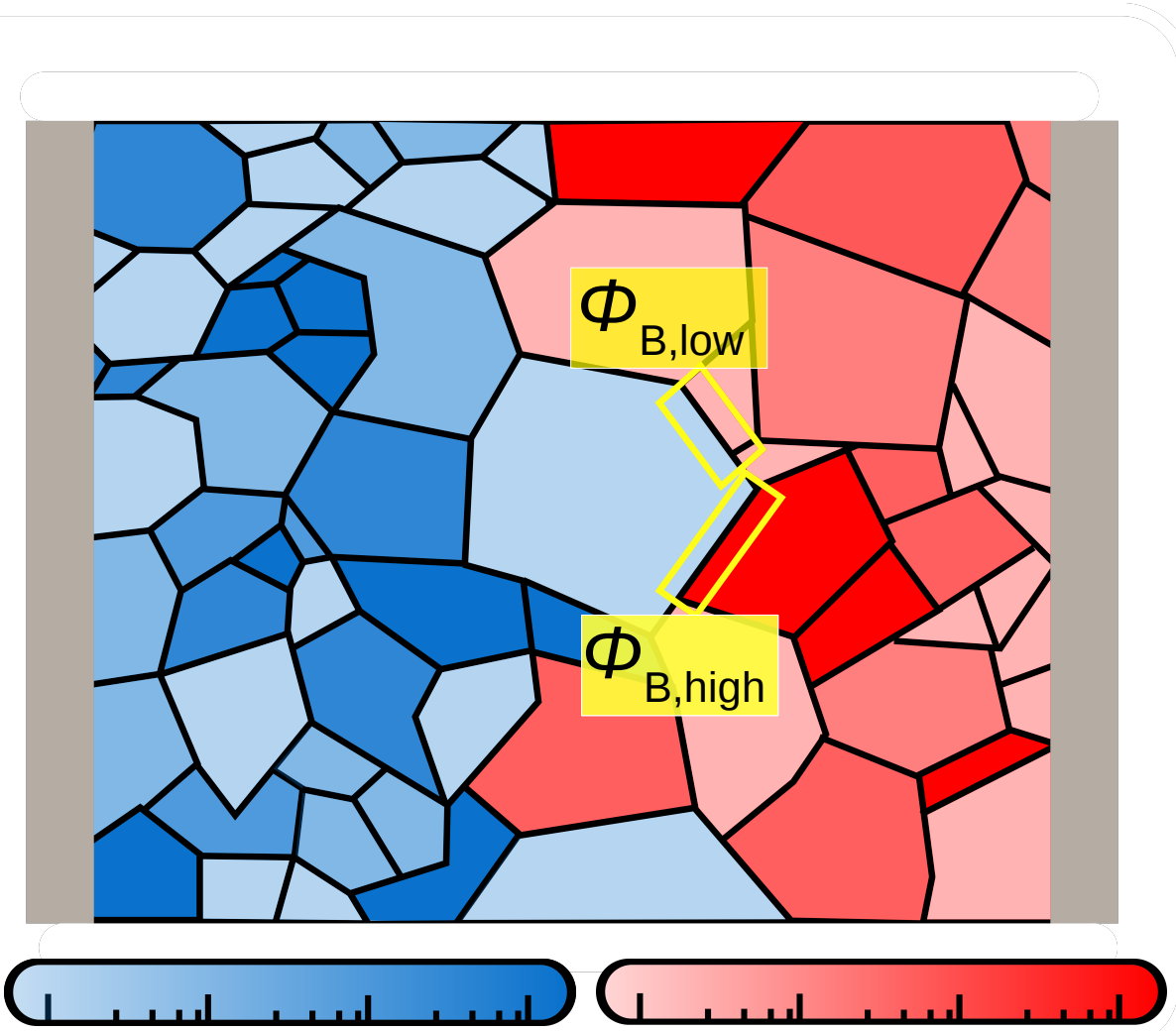

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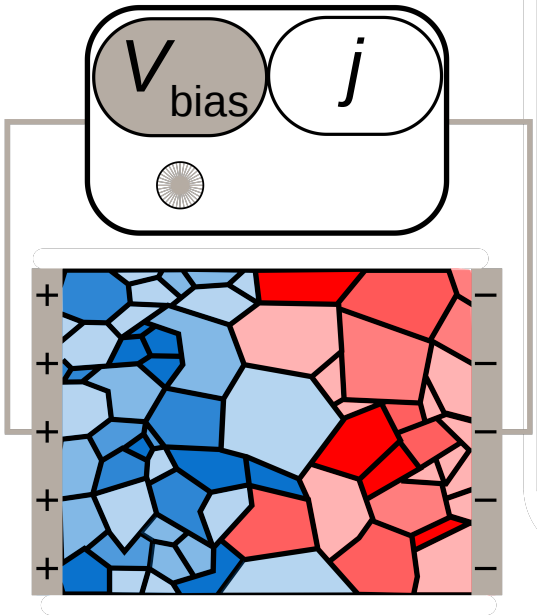
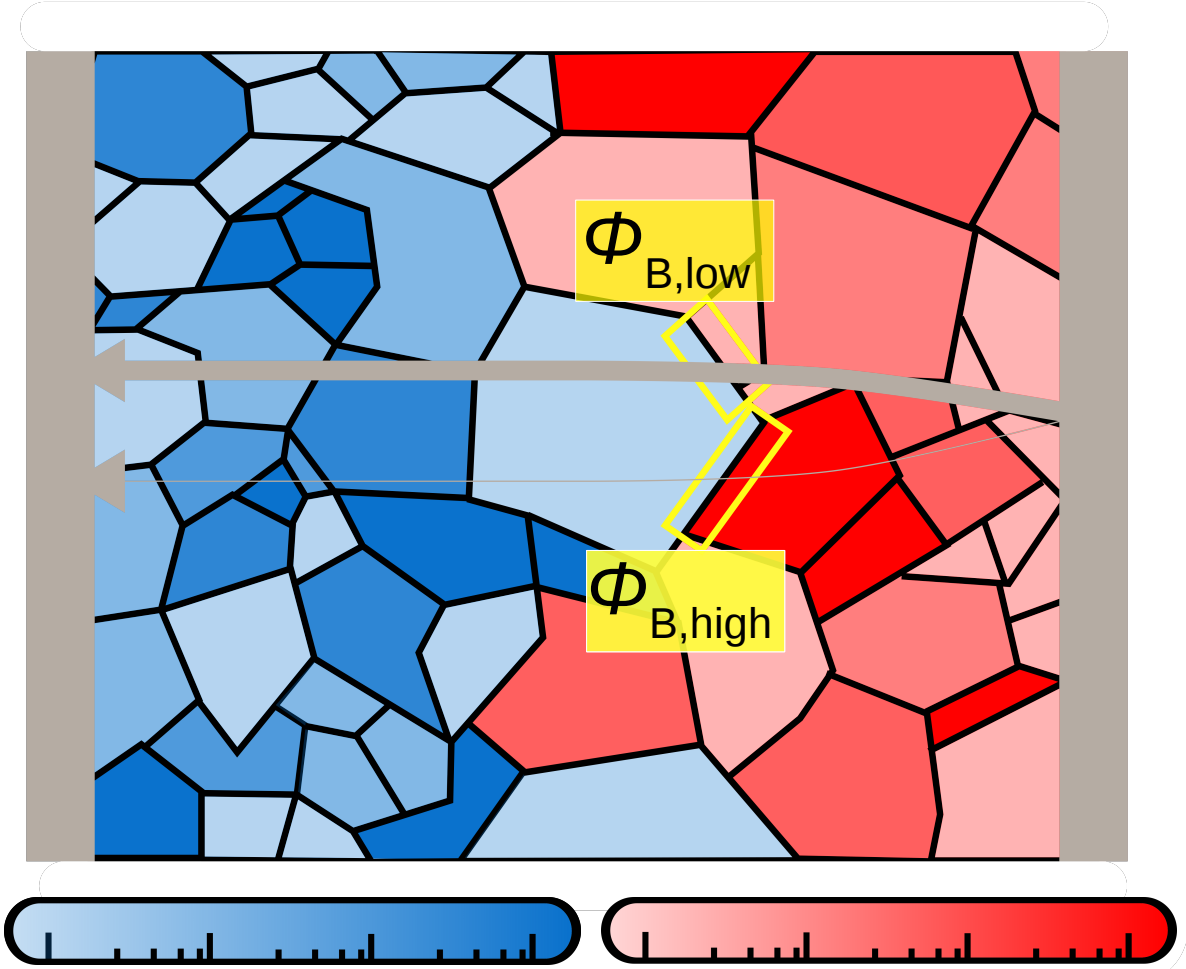
p-n junctions: Inhomogeneous barrier height

Current will see more of low Φ_B





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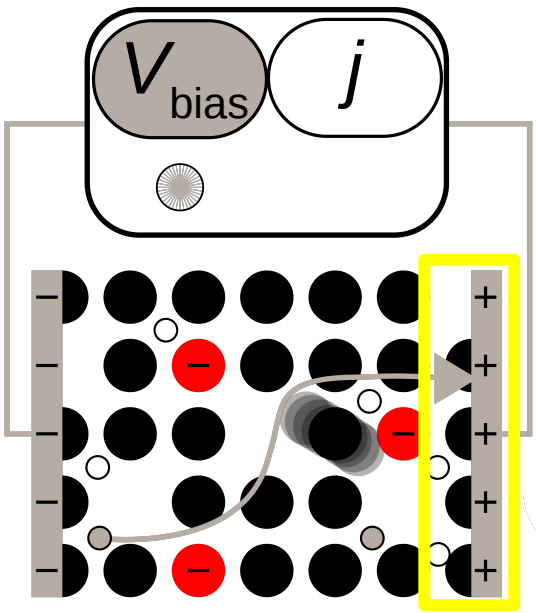
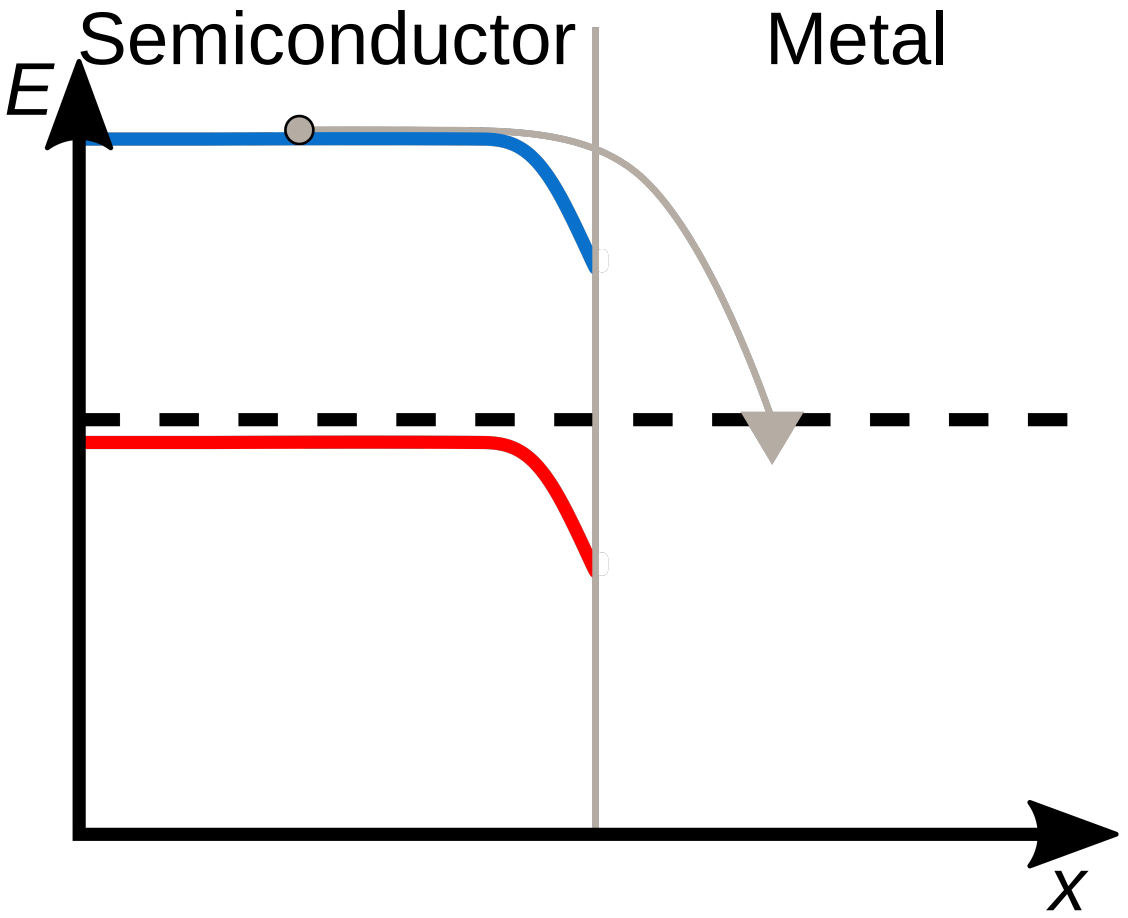
p-n junctions: Series resistance

Intrinsic Mobility
Scattering
Contacts





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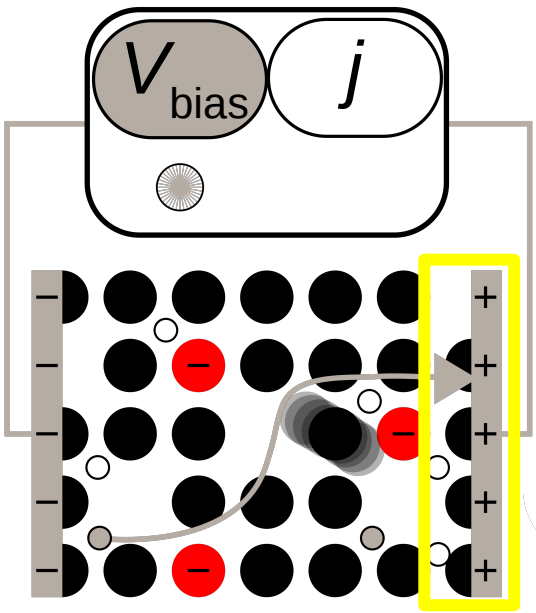

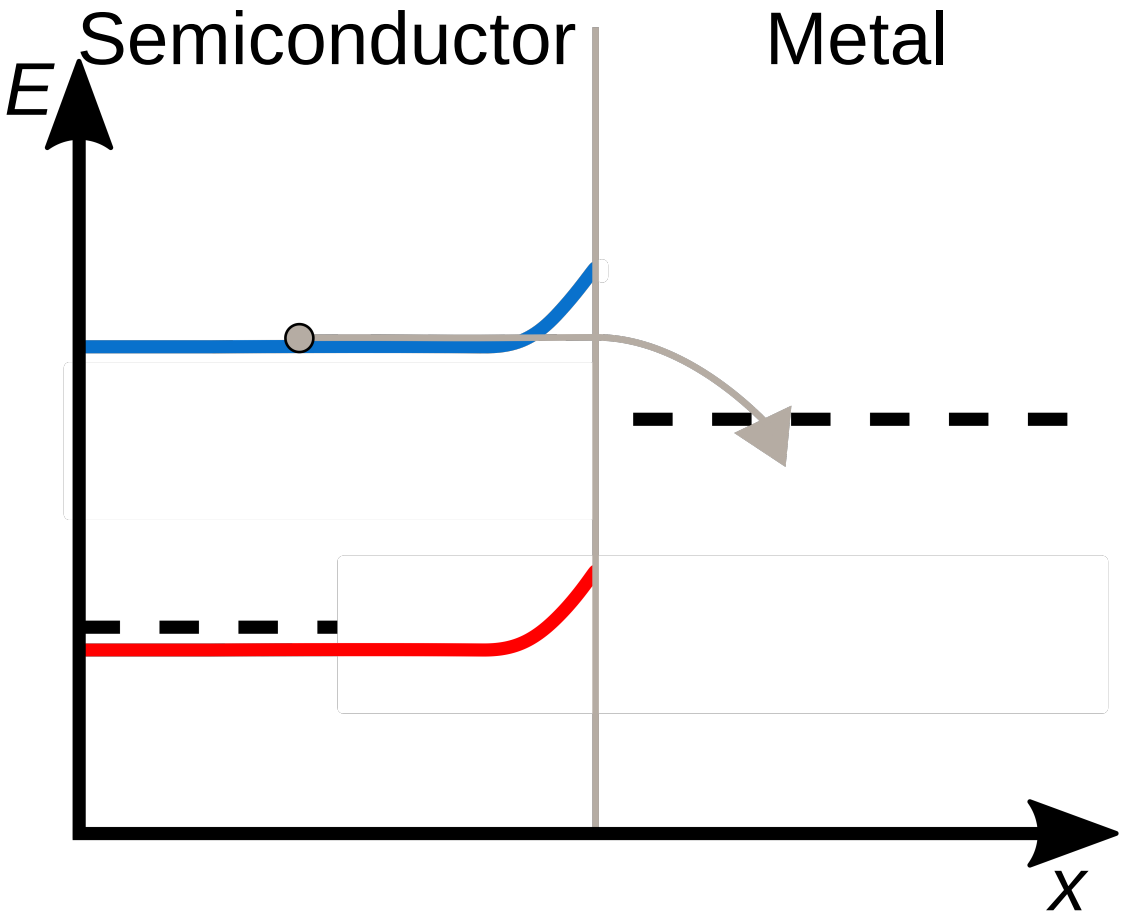

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