Semiconductor Devices

p-*n* Junctions: Part 4

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Some implications of the Shockley diode equation

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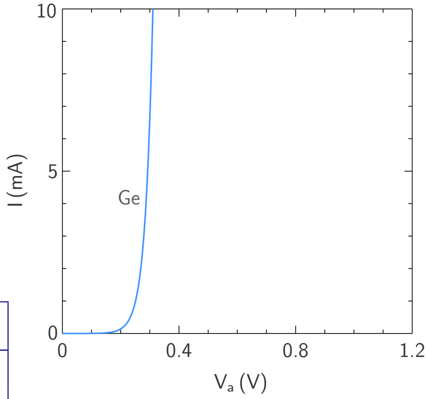

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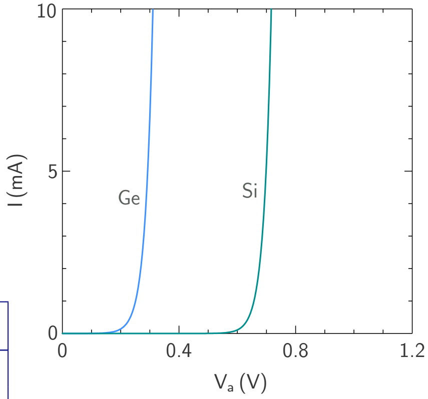

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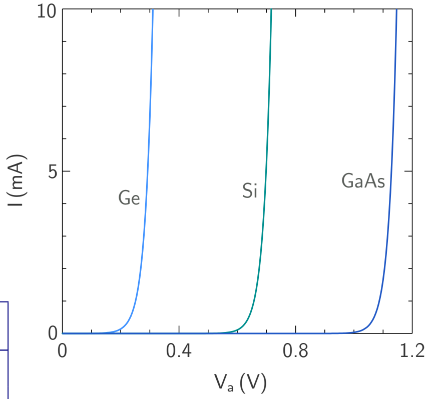

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Temperature dependence

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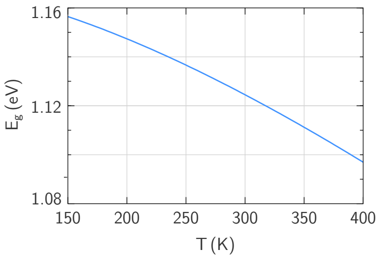

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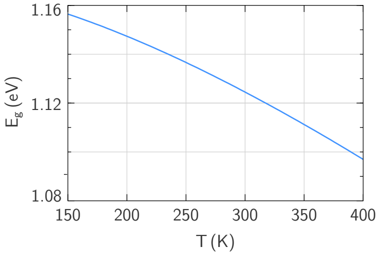

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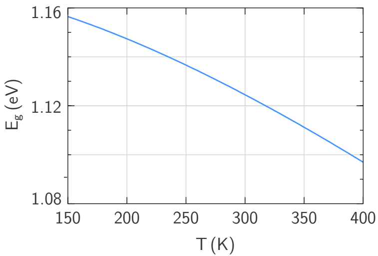

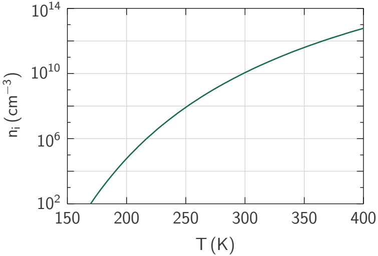

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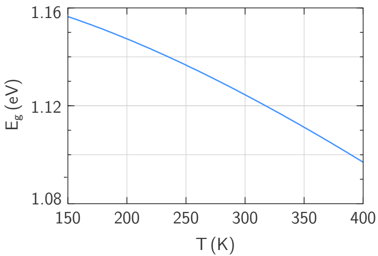

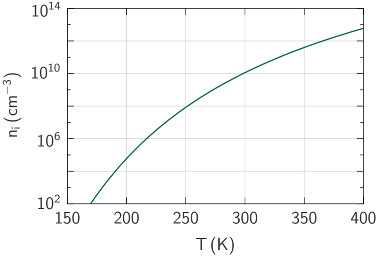

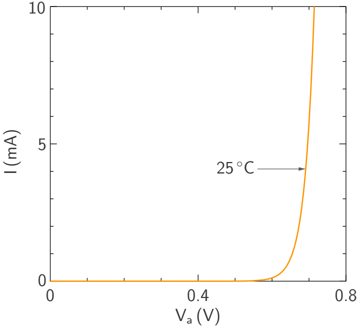

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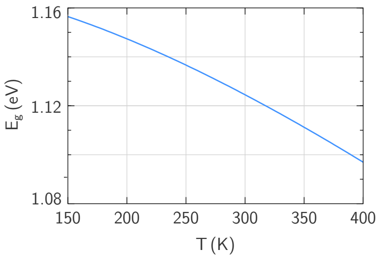

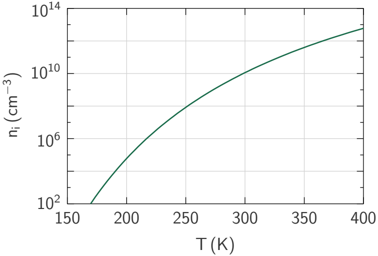

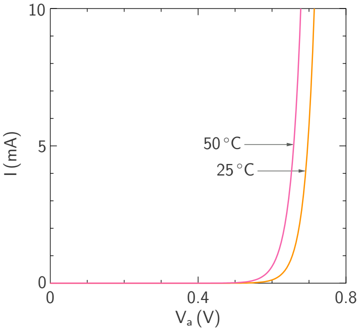

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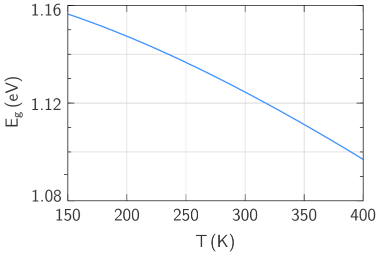

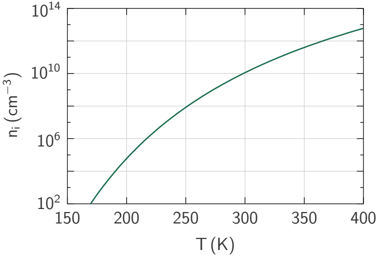

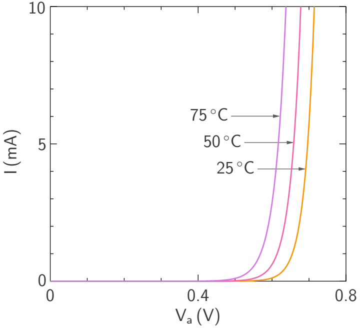

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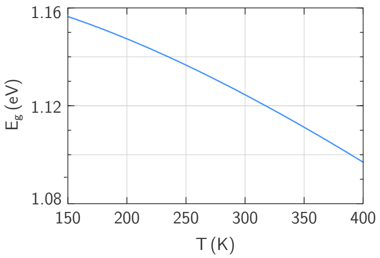

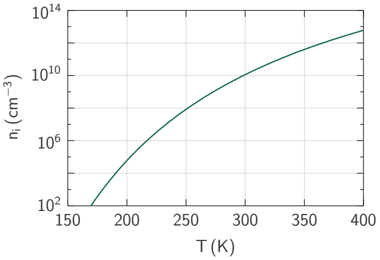

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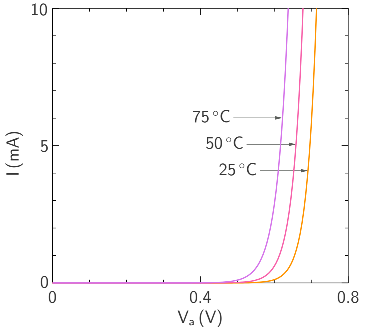
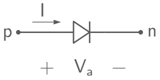
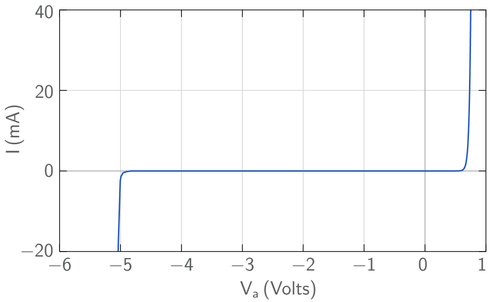
For silicon, the I-V curve shifts by about $-2\,\text{mV}/^\circ\text{C}$ as the temperature is increased.



Reverse breakdown





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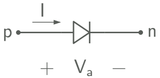
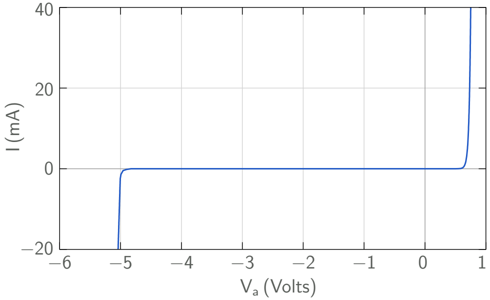
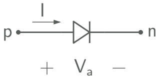
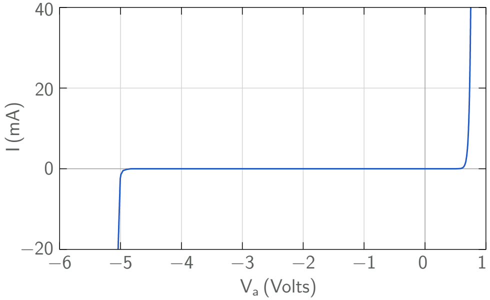




* A real diode cannot withstand indefinitely large reverse voltages and "breaks down" at some point as V_R is increased.

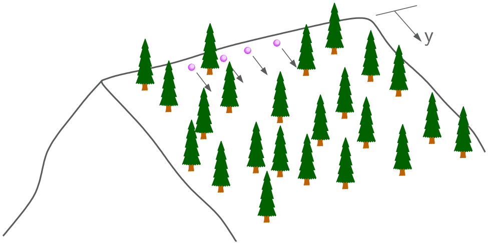
Reverse breakdown

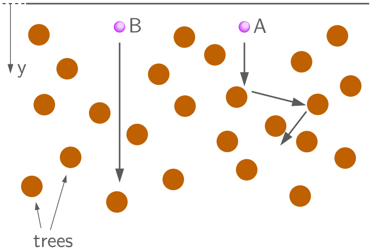




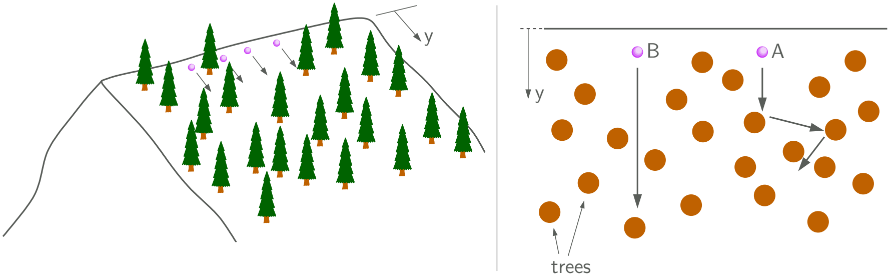
* A real diode cannot withstand indefinitely large reverse voltages and "breaks down" at some point as V_R is increased.
* Reverse breakdown can be due to
  - impact ionisation (avalanche breakdown)
  - tunneling (Zener breakdown)

Avalanche breakdown: impact ionisation





Consider spherical objects starting down from the top.



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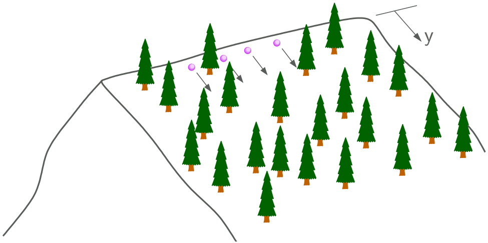
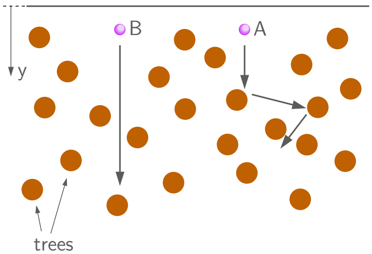
* When an objects hits a tree, it loses some of its kinetic energy and starts downhill again with a reduced kinetic energy.





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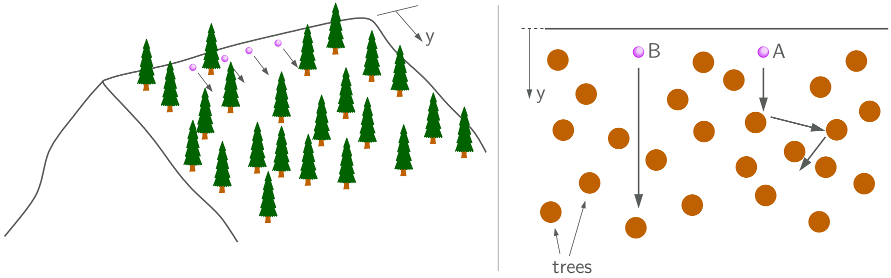
* There could be a "lucky" object which does not encounter a collision and therefore gains a higher kinetic energy as compared to other objects.

Avalanche breakdown: impact ionisation



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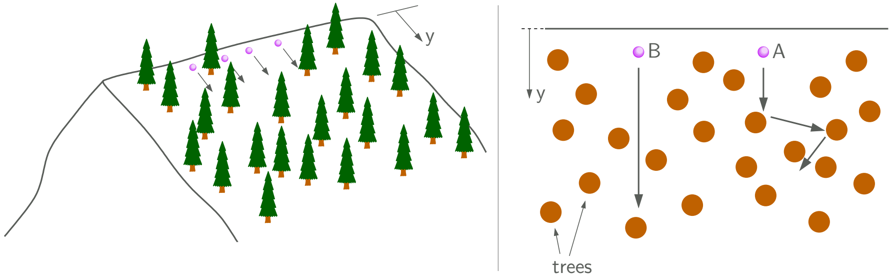

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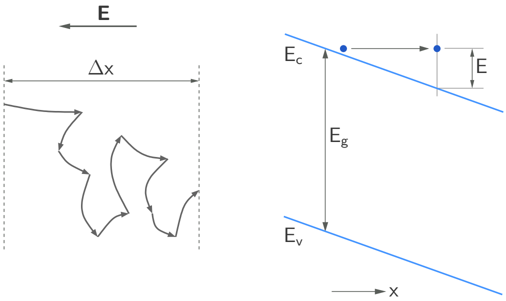
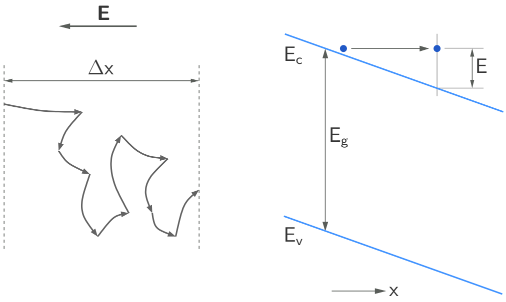
With this situation in mind, let us look at carrier transport in a semiconductor.

Avalanche breakdown: impact ionisation



* If an electron moves some distance without scattering, it gains an energy E with respect to E_c at that location. This energy can be thought of as the kinetic energy of the electron.

Avalanche breakdown: impact ionisation



* If an electron moves some distance without scattering, it gains an energy E with respect to E_c at that location. This energy can be thought of as the kinetic energy of the electron.
* Because of scattering events (phonons, impurity ions, etc.), an electron keeps losing the energy gained from the electric field, and it is constrained to stay near E_c.

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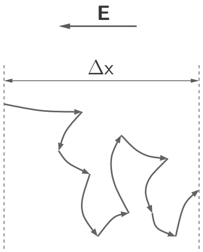

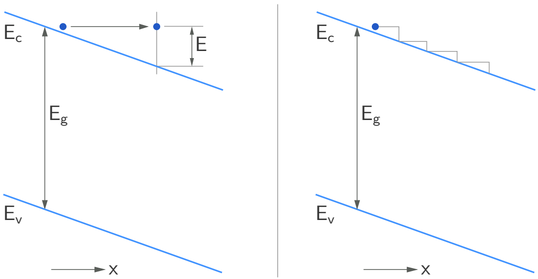

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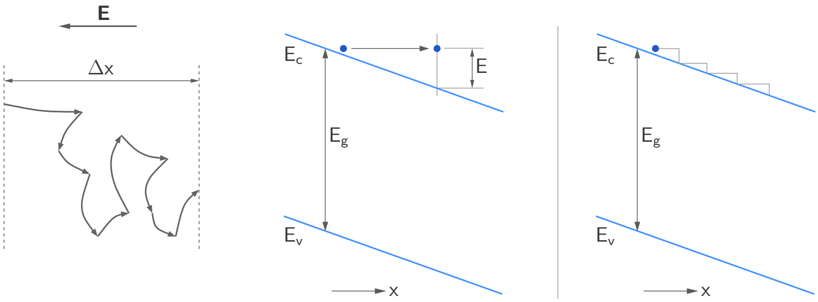

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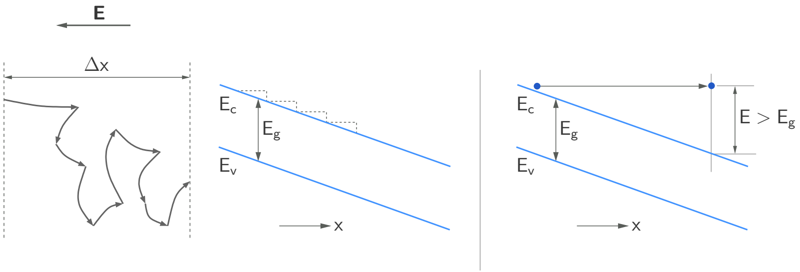
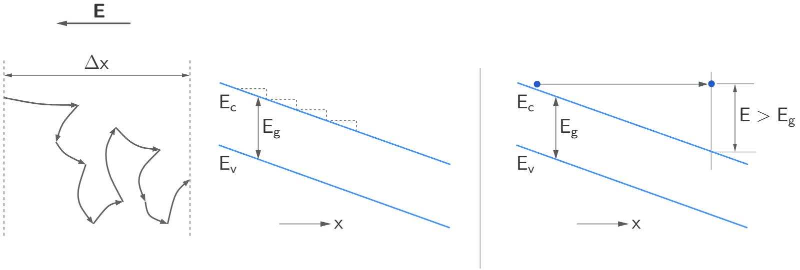
  (Note: For simplicity, we have not discussed the changes in the electron momentum in the other two directions.)

Avalanche breakdown: impact ionisation



* A "lucky" electron which undergoes fewer scattering events can gain substantial energy.

Avalanche breakdown: impact ionisation



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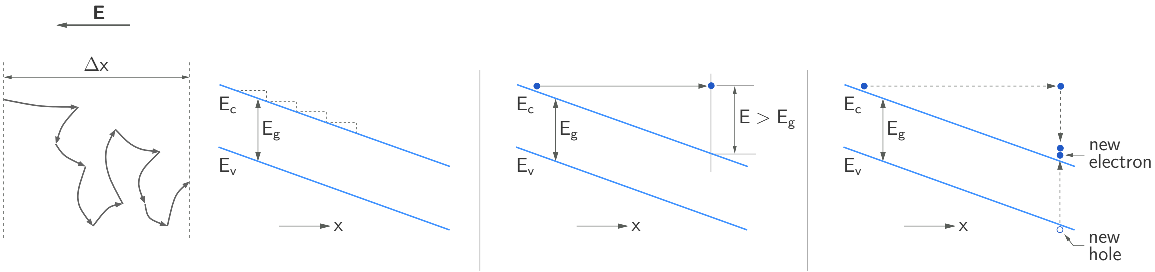

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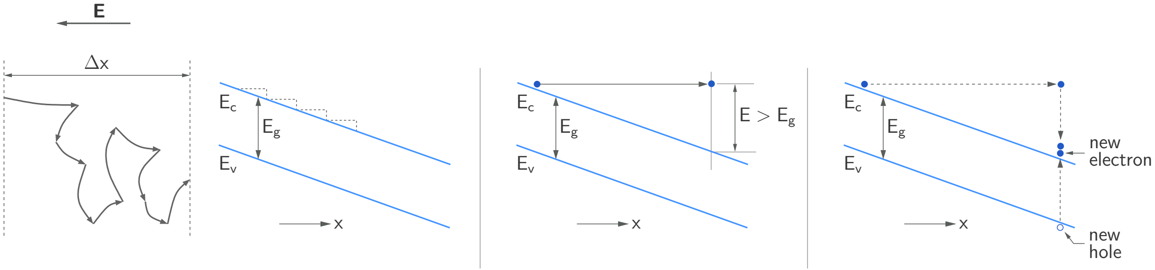

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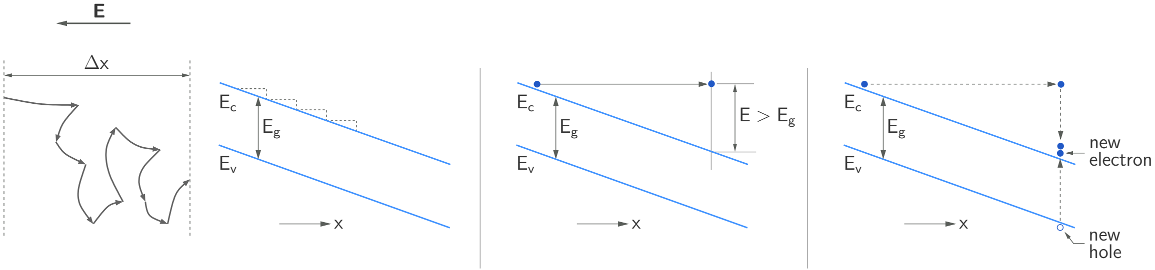

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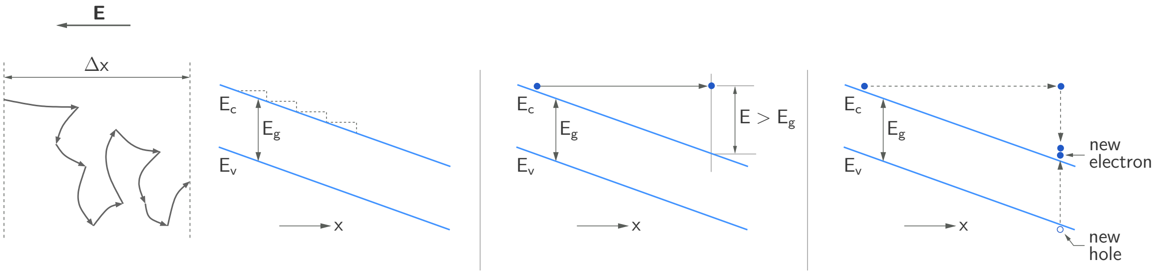

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  Before impact ionisation: one electron

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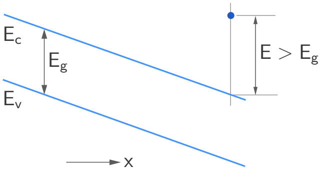
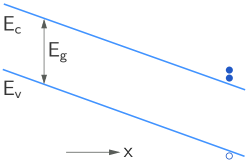
* The key requirement for impact ionisation to occur is a high electric field.

Avalanche breakdown: impact ionisation

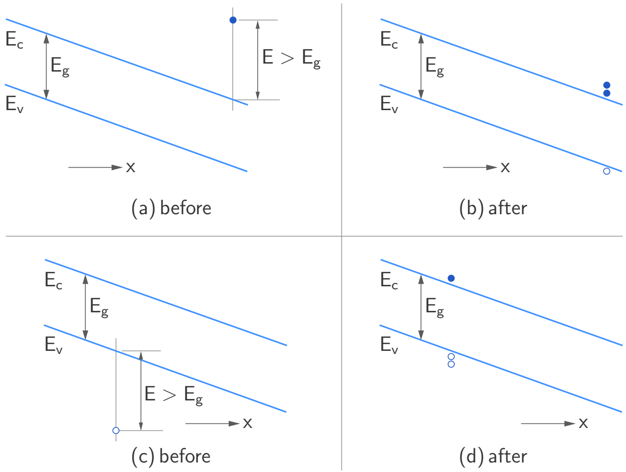


(a) before



(b) after

Avalanche breakdown: impact ionisation



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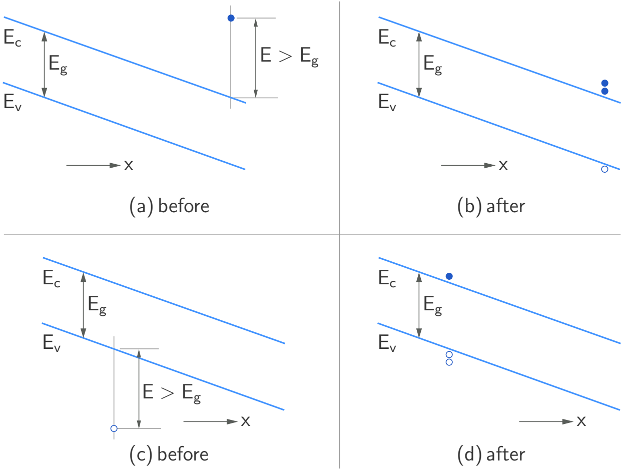
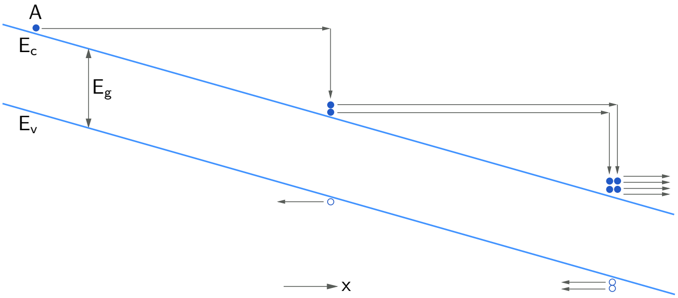


* Impact ionisation can be caused by a high-energy electron or a high-energy hole.

Avalanche breakdown: impact ionisation



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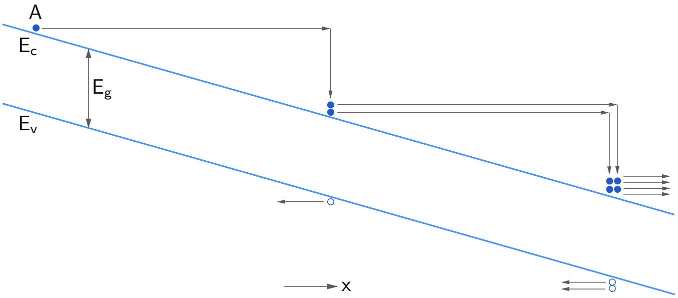

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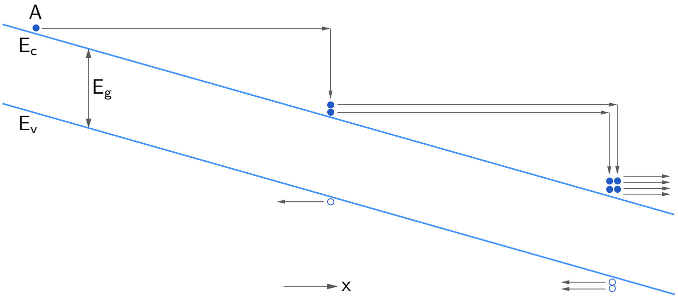

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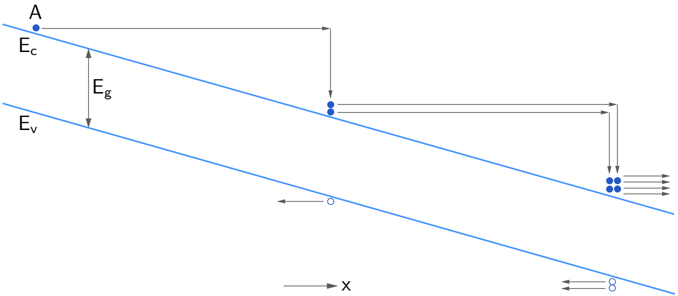

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* The avalanche multiplication process is obviously very complicated, but it can be characterised in a simple manner by a "critical field" $\mathcal{E}_c$ — if the electric field in the device exceeds $\mathcal{E}_c$, we can expect avalanche multiplication, leading to large currents.

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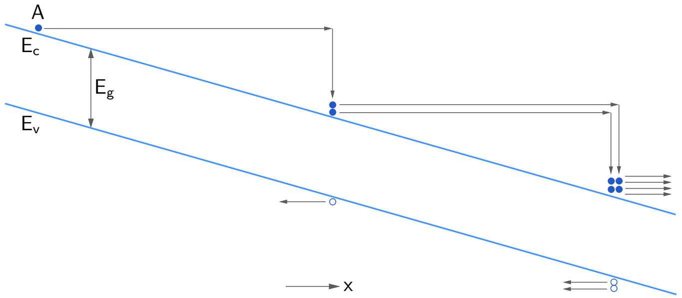

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* For Ge, Si, and GaAs, the critical field at room temperature is about 100, 300, and 400 kV/cm, respectively.

Example

For a p^+n silicon diode, estimate the doping density required on the n side for a breakdown voltage of 50 V, given that $\mathcal{E}_c = 250\,\text{kV/cm}$.

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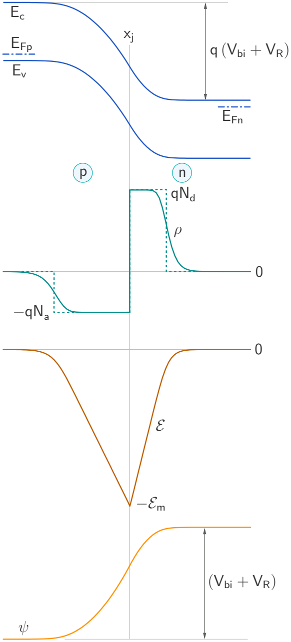

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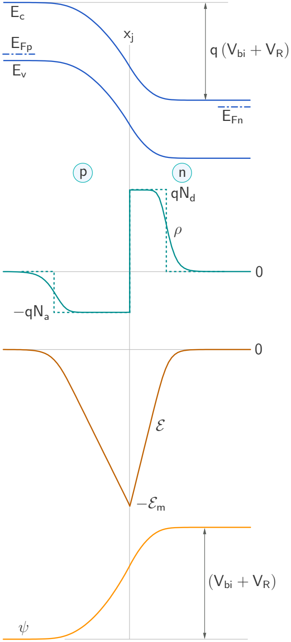

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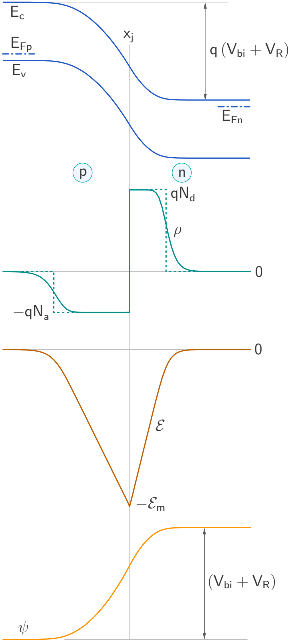

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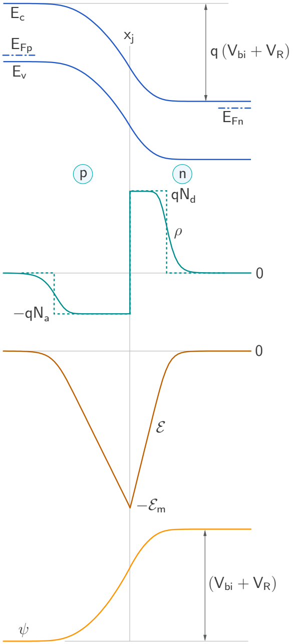
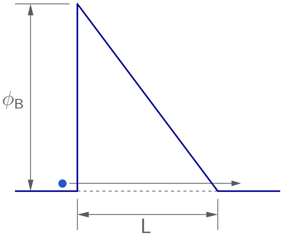


Zener breakdown



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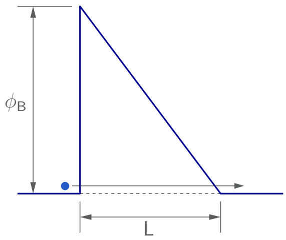

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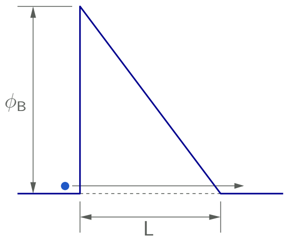

* Another mechanism which can cause reverse breakdown of a *pn* junction is quantum-mechanical tunneling.
* For a significant tunneling current,
  - The barrier width (L) must be small, typically few nanometers.
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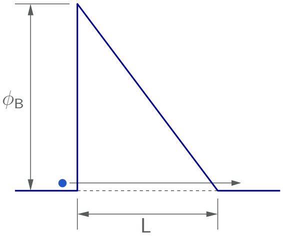
Zener breakdown



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* For a significant tunneling current,
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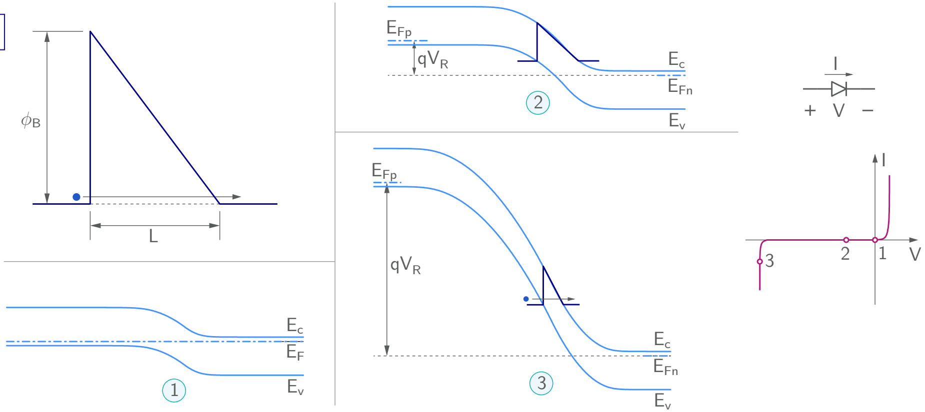
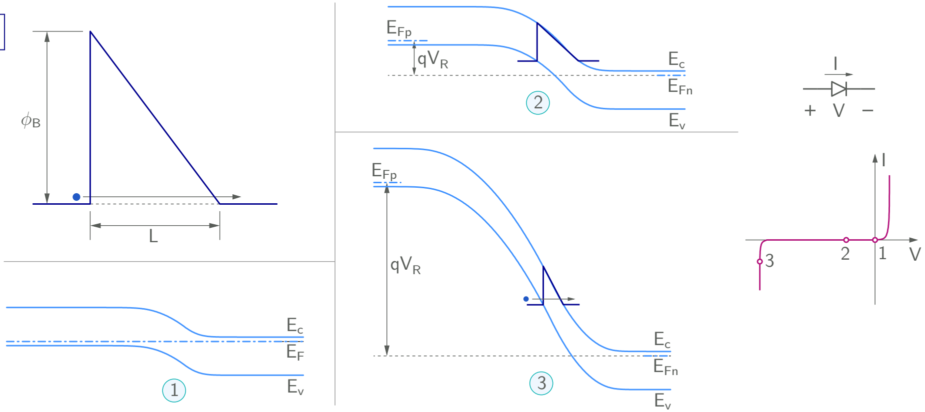
* With these points in mind, let us now look at a reverse-biased *pn* junction.

Zener breakdown

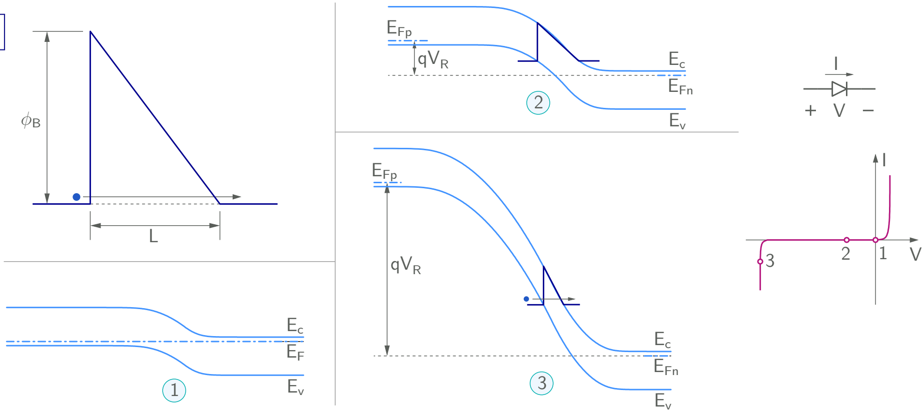


Zener breakdown



* The depletion width is given by $W = \sqrt{\dfrac{2\epsilon}{q}\left(\dfrac{1}{N_a}+\dfrac{1}{N_d}\right)(V_{bi}+V_R)}\,.$

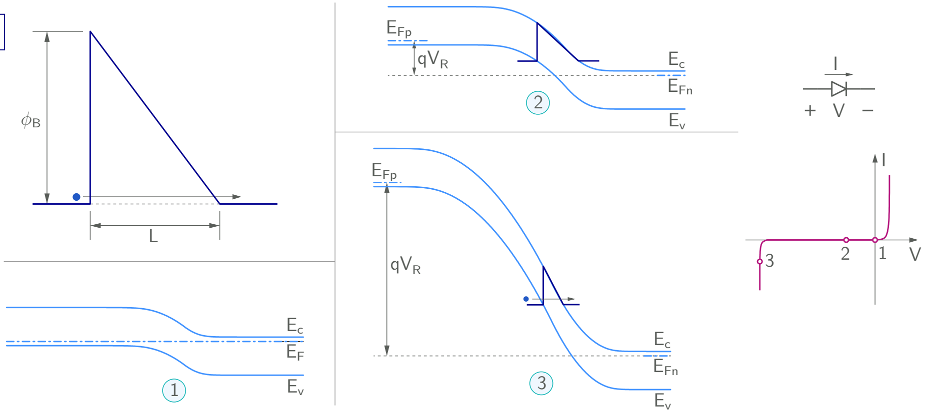
Zener breakdown



* The depletion width is given by $W = \sqrt{\dfrac{2\epsilon}{q}\left(\dfrac{1}{N_a}+\dfrac{1}{N_d}\right)(V_{bi}+V_R)}\,.$

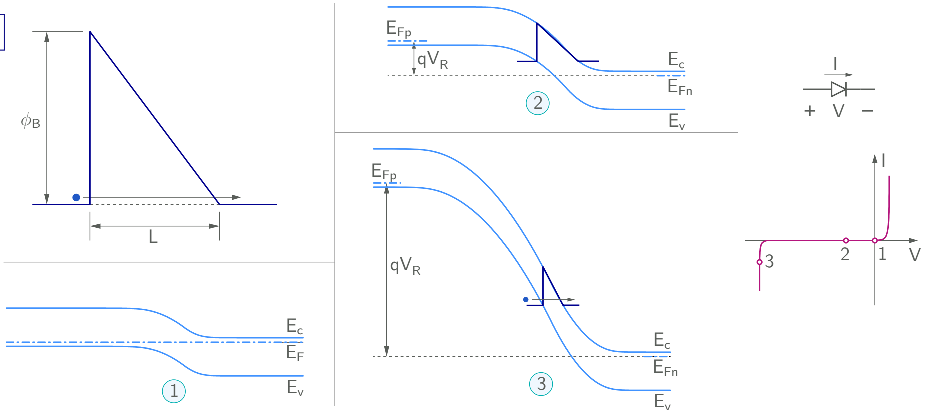
* As the reverse bias is increased, the barrier becomes thinner.

Zener breakdown



* The depletion width is given by $W = \sqrt{\dfrac{2\epsilon}{q}\left(\dfrac{1}{N_a}+\dfrac{1}{N_d}\right)(V_{bi}+V_R)}$.
* As the reverse bias is increased, the barrier becomes thinner.
* There is a large number of electrons in the valence band on the *p* side and a large number of states (vacancies) in the conduction band on the *n* side.

Zener breakdown



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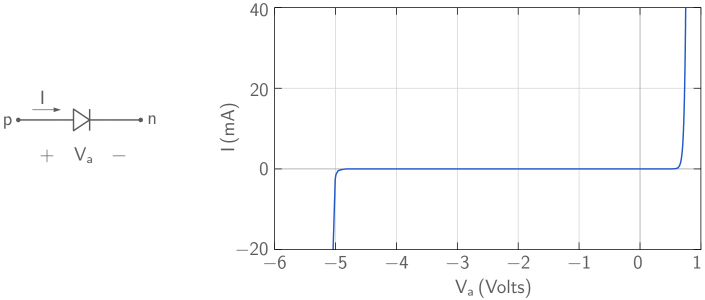
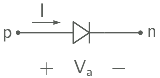
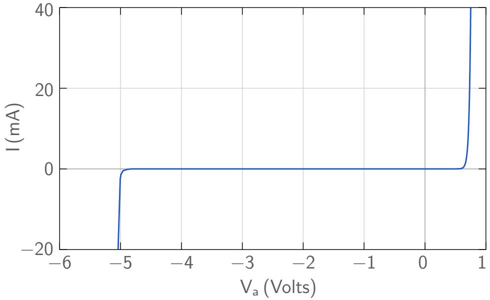
* As the reverse bias is increased, the barrier becomes thinner.
* There is a large number of electrons in the valence band on the *p* side and a large number of states (vacancies) in the conduction band on the *n* side.
* Relatively large doping densities are required to ensure that the barrier is sufficiently thin for tunneling to occur.

Reverse breakdown

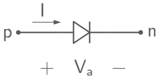


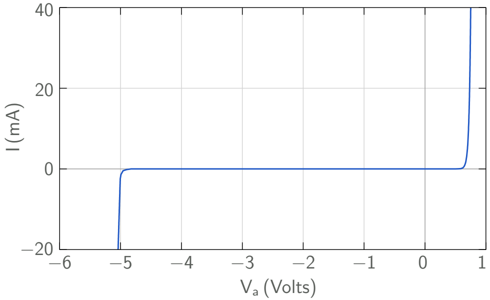
Reverse breakdown





* Silicon diodes with breakdown voltage V_{BR} ranging from a few volts to a thousand volts are commercially available.





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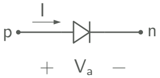
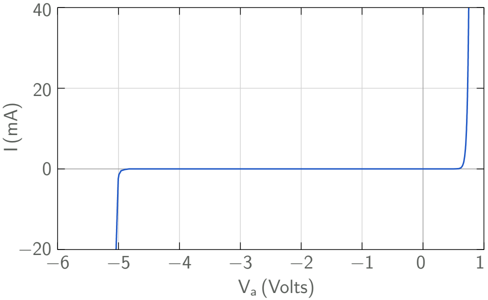
Reverse breakdown





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* In diodes with $V_{BR} < 5\,V$, the breakdown is generally due to tunnelling; for higher values of V_{BR}, it is due to avalanche multiplication.
* In some diodes (with $V_{BR} \simeq 5\,V$), it is possible that both mechanisms are active simultaneously.

Heterojunctions

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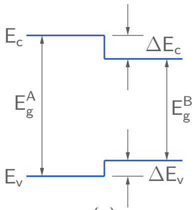
* The two semiconductors must be lattice-matched, i.e., they must have the same lattice constant to avoid dislocations and device degradation.

Heterojunctions



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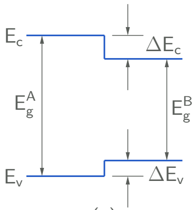

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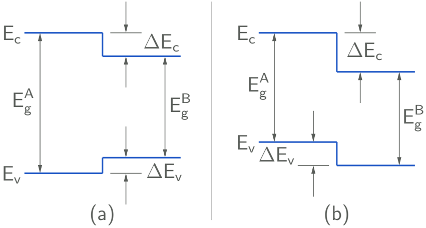

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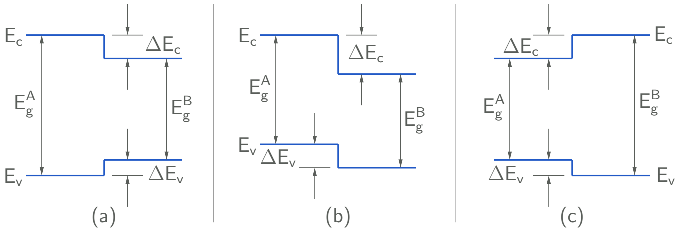

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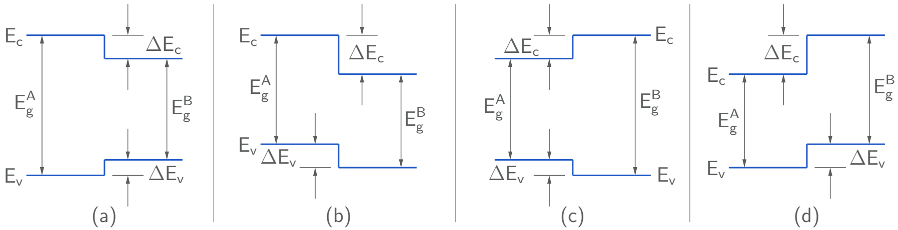

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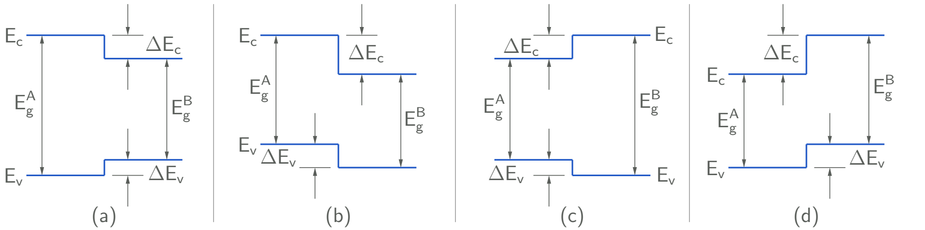

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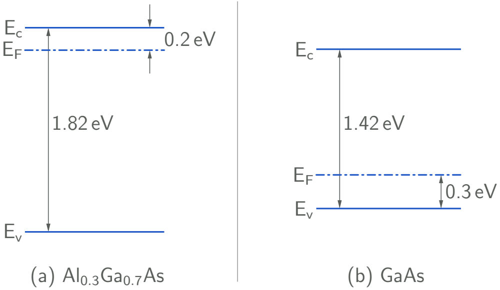
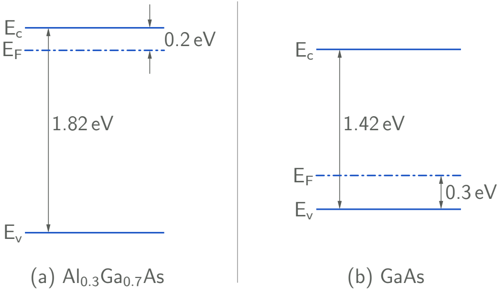
  (The bands are shown to be flat for simplicity. In practice, there will be some band bending due to the presence of an electric field.)

Example



Consider a heterojunction between n-$Al_{0.3}Ga_{0.7}As$ and p-GaAs (which are lattice matched at 300 K).

Example



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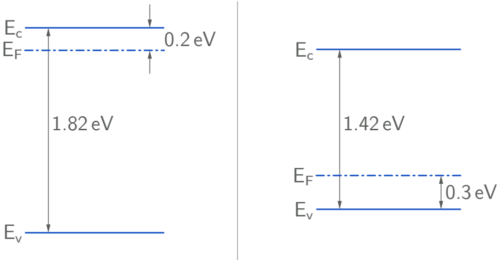

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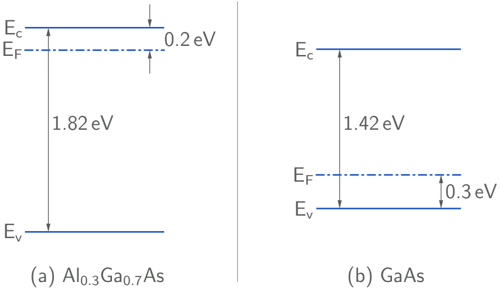

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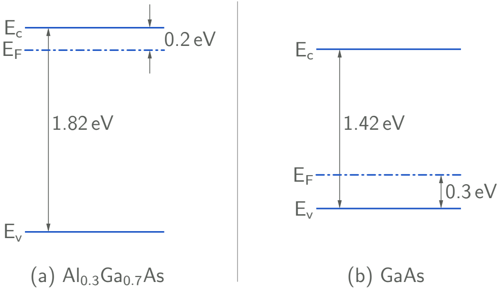

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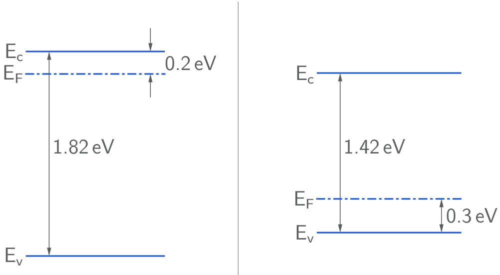
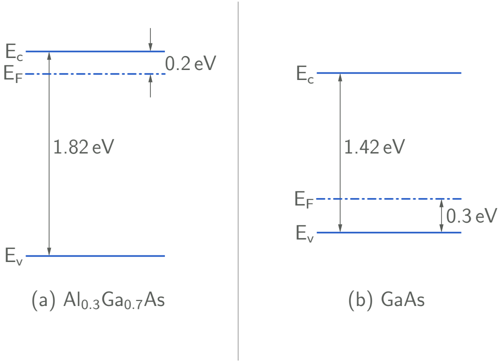
Sketch the band diagram of the pn junction in equilibrium.

Example



(a) $Al_{0.3}Ga_{0.7}As$ (b) GaAs

Example



* In equilibrium, the Fermi level must be constant.

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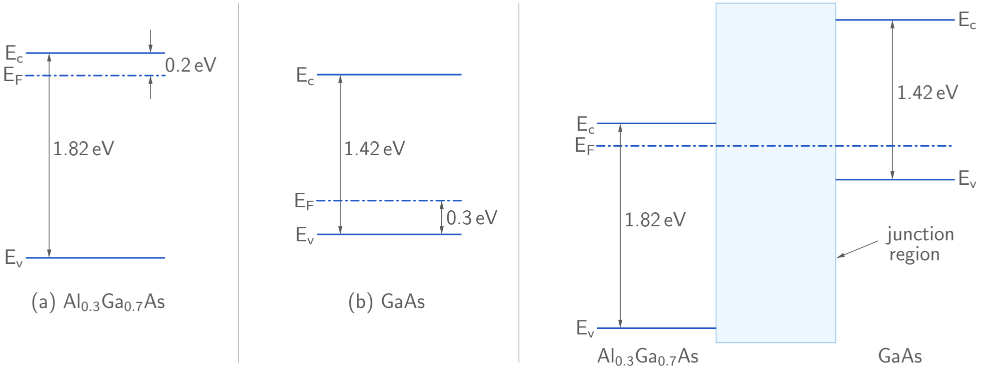

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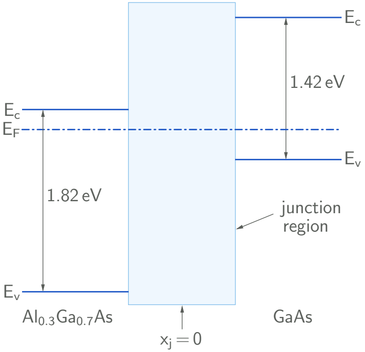
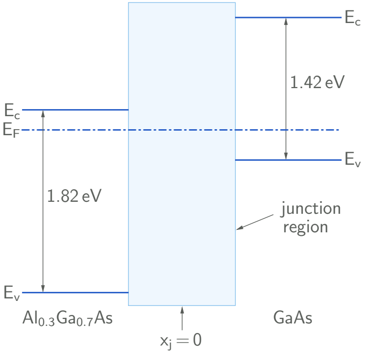
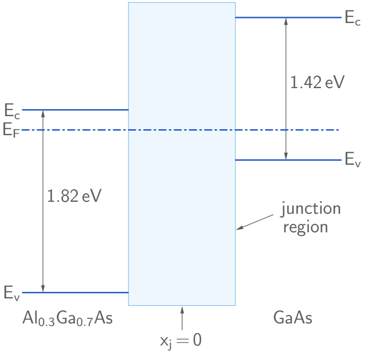


E_c
1.42 eV
E_c
E_F
E_v
1.82 eV
junction
region
E_v
$Al_{0.3}Ga_{0.7}As$
GaAs
$x_j = 0$



* The electric field must be continuous except at the interface (x_j) [where $\epsilon(0^-)\mathcal{E}(0^-) = \epsilon(0^+)\mathcal{E}(0^+)$]. We assume that there is no surface charge at the interface.



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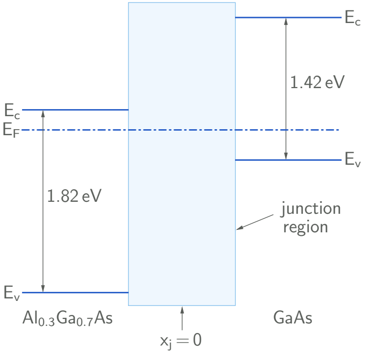

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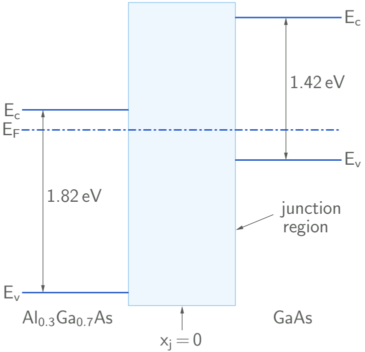

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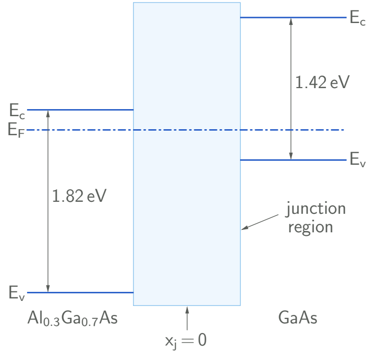

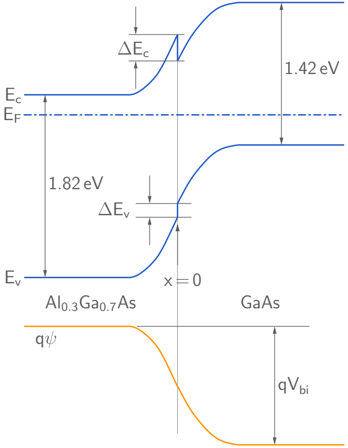

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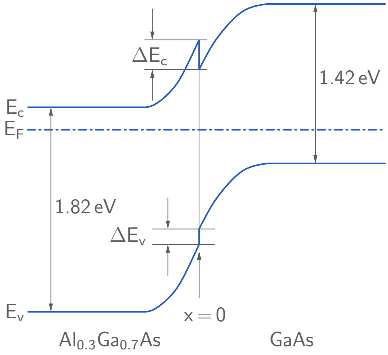

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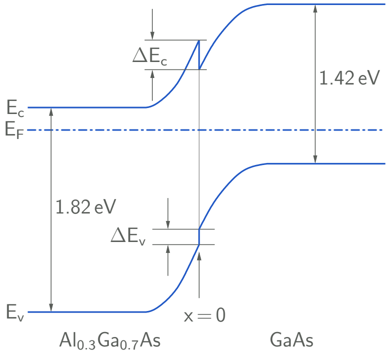

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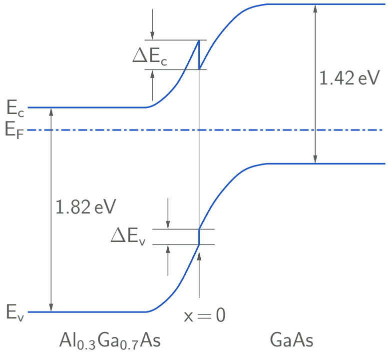

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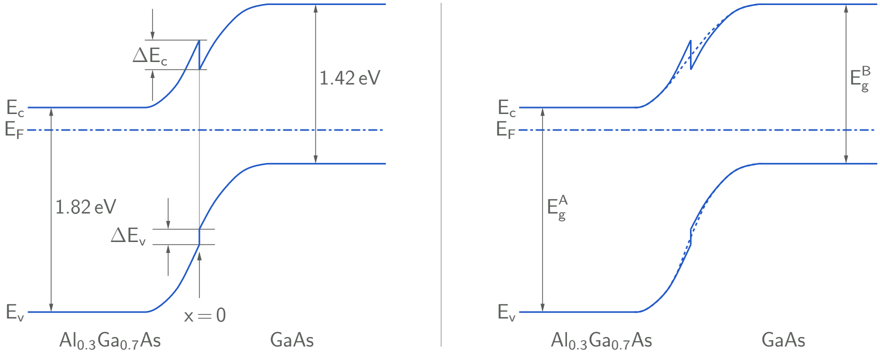

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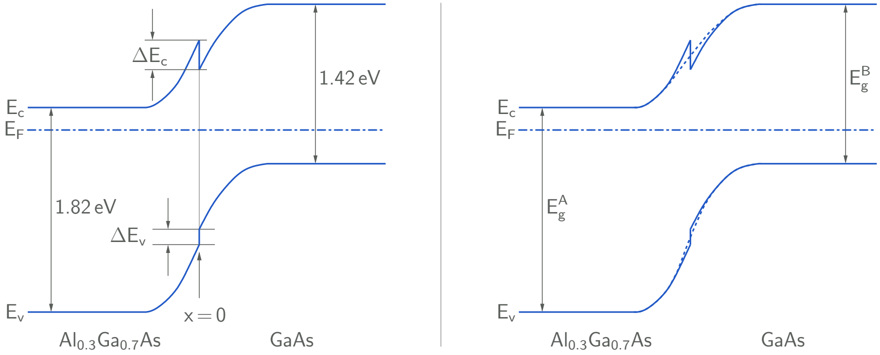

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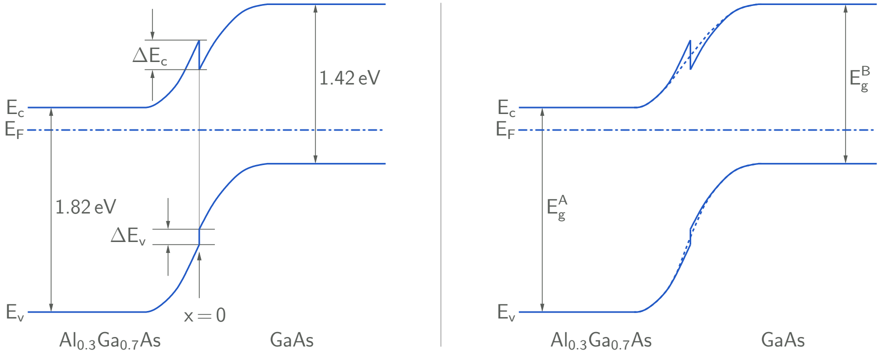

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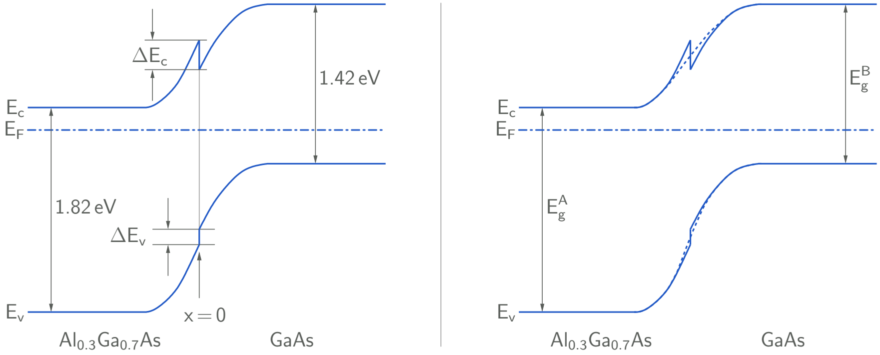

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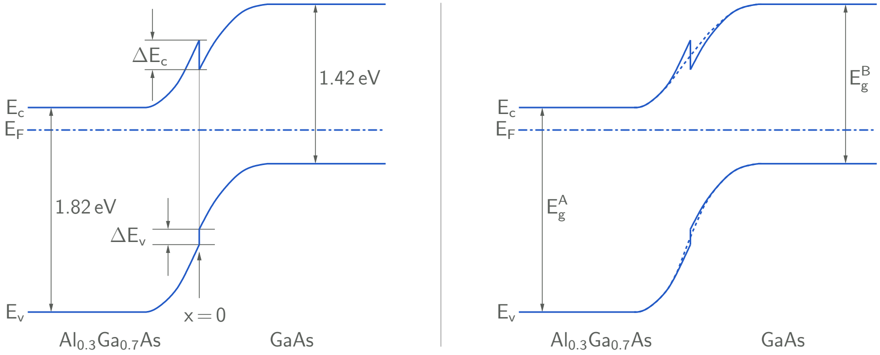
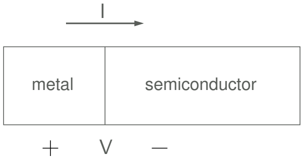
  With reverse bias, the depletion region expands. The current is negligibly small.

Effect of grading



* Graded heterojunctions are used to fabricate heterojunction bipolar transistors (HBT) in which a high current gain and a small device resistance are simultaneously made possible because of different semiconductors used for the emitter and base regoins of the device.

Metal-semiconductor junctions



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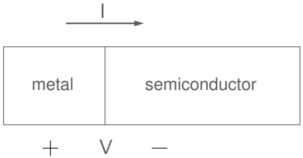

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* A metallic contact to a semiconductor device serves as the interface of the device with the external circuit. In this case, the M-S junction must be *ohmic*, i.e., it should be able to conduct a reasonably large current *in either direction* with a very small voltage drop across the junction.

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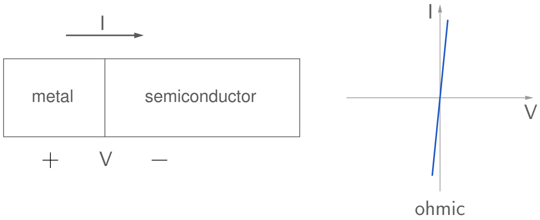

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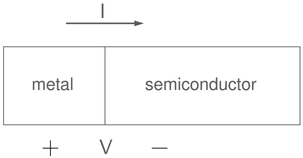

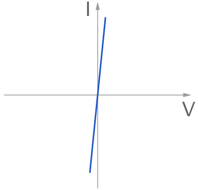

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* A *rectifying* M-S junction plays a key role in the operation of some semiconductor devices like the MESFET (Metal-Semiconductor Field-Effect Transistor). As the name implies, a rectifying M-S junction (also called a "Schottky contact") conducts well in one direction but blocks current in the other direction.

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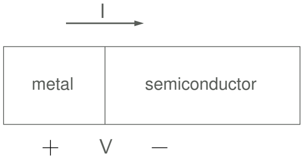

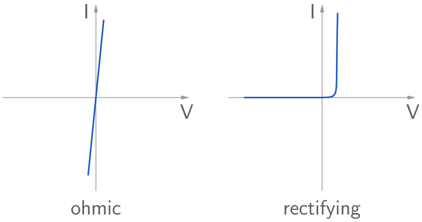

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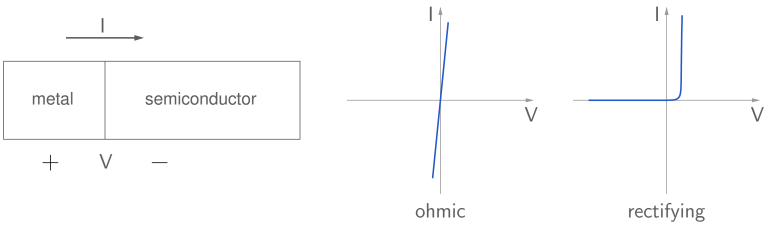
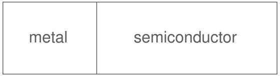


Metal-semiconductor (M-S) junctions serve two important purposes in semiconductor devices:

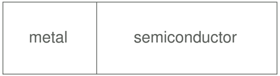
* A metallic contact to a semiconductor device serves as the interface of the device with the external circuit. In this case, the M-S junction must be *ohmic*, i.e., it should be able to conduct a reasonably large current *in either direction* with a very small voltage drop across the junction.

* A *rectifying* M-S junction plays a key role in the operation of some semiconductor devices like the MESFET (Metal-Semiconductor Field-Effect Transistor). As the name implies, a rectifying M-S junction (also called a "Schottky contact") conducts well in one direction but blocks current in the other direction.

What decides whether a given M-S junction is ohmic or rectifying?

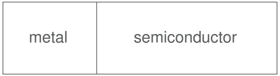


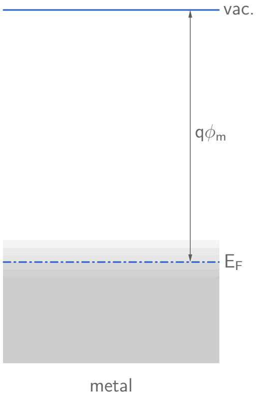
The band diagram of a metal-semiconductor junction is determined by



The band diagram of a metal-semiconductor junction is determined by

- metal work function ϕ_m (difference between the "vacuum level" and the Fermi level)





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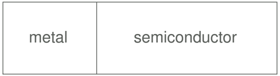

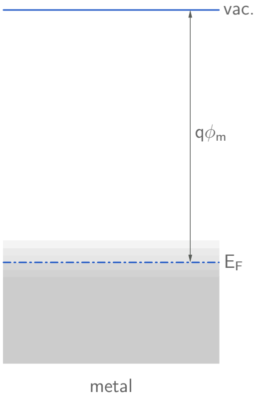

The band diagram of a metal-semiconductor junction is determined by

- metal work function ϕ_m (difference between the "vacuum level" and the Fermi level)
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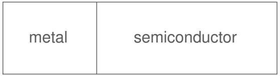

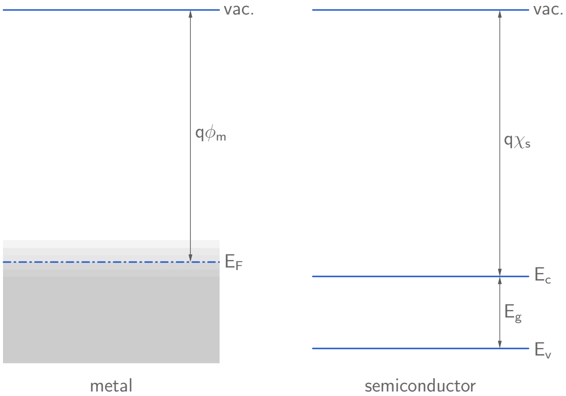

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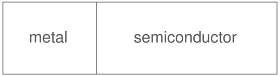

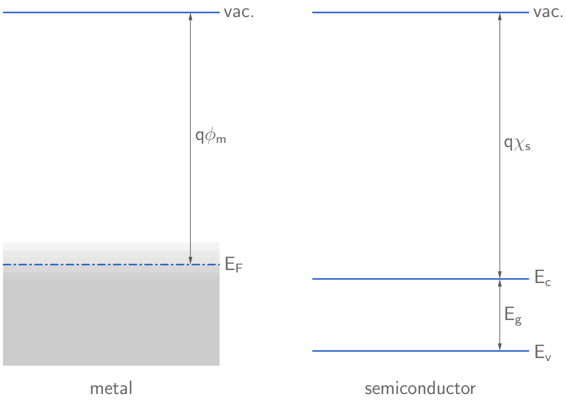

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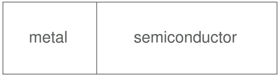

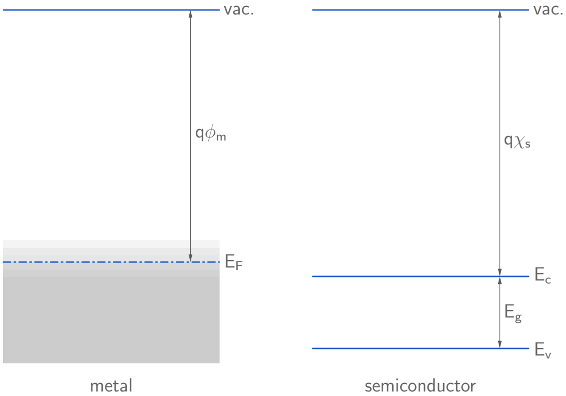

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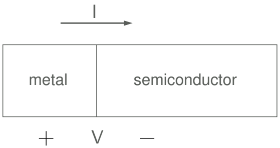
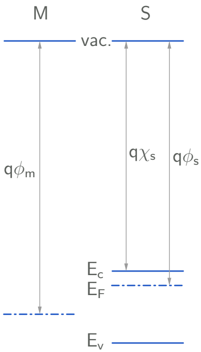
- doping density in the semiconductor (which sets the equilibrium Fermi level in the semiconductor)
- additional electron states within the band gap at the interface

  (We will ignore this effect, i.e., we will assume the M-S interface to be perfect.)

n-type semiconductor, $\phi_m > \phi_s$





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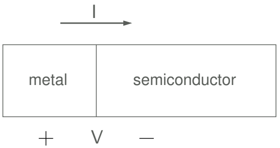

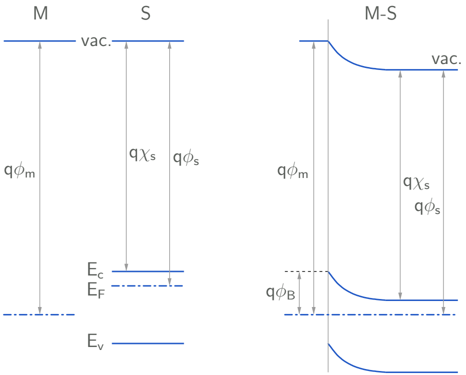

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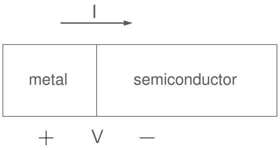

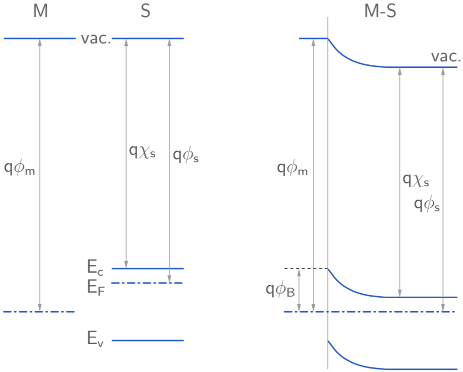

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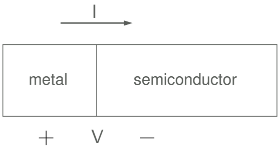

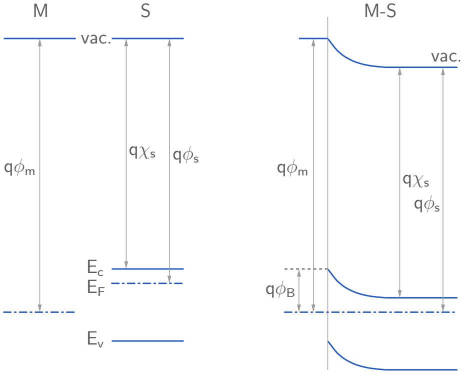

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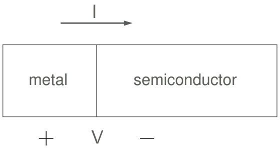

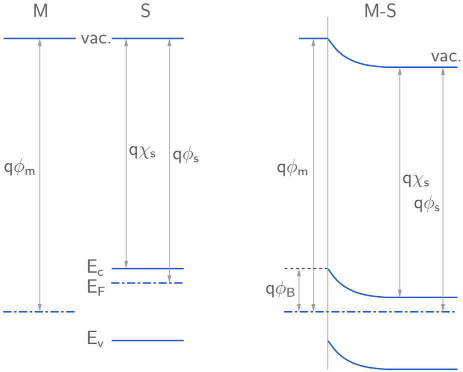

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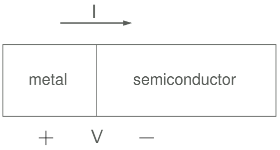

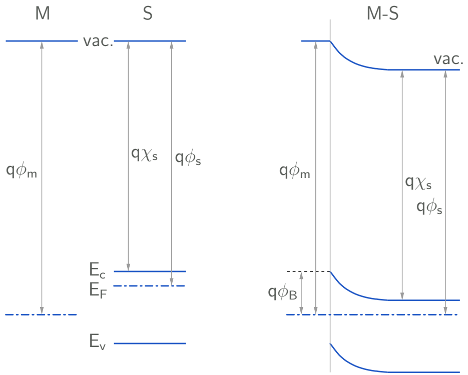

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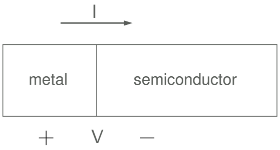

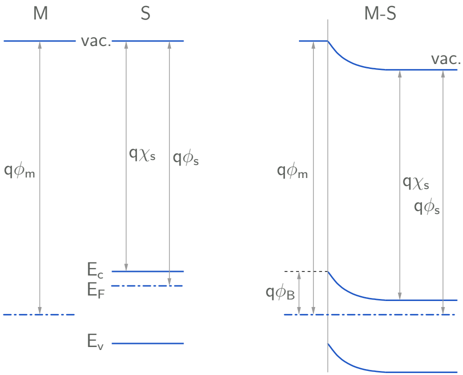

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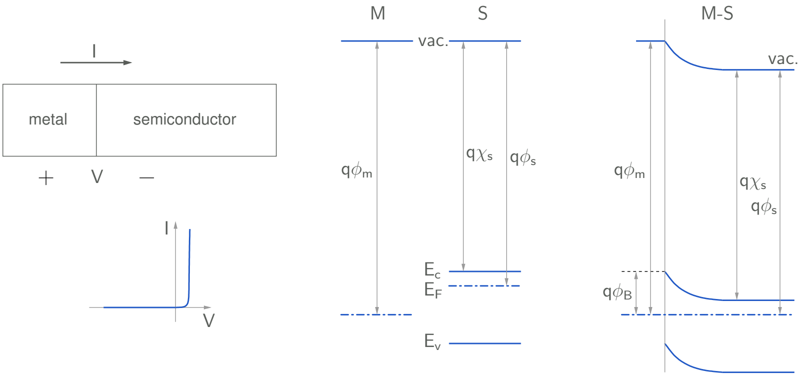
* This condition leads to a rectifying contact.

n-type semiconductor, $\phi_m > \phi_s$



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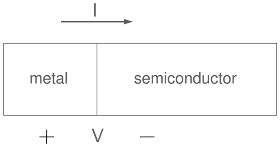

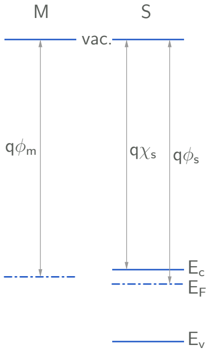

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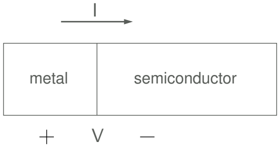

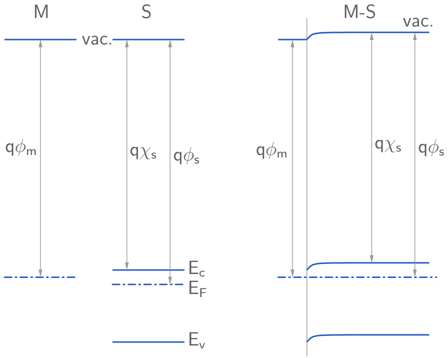

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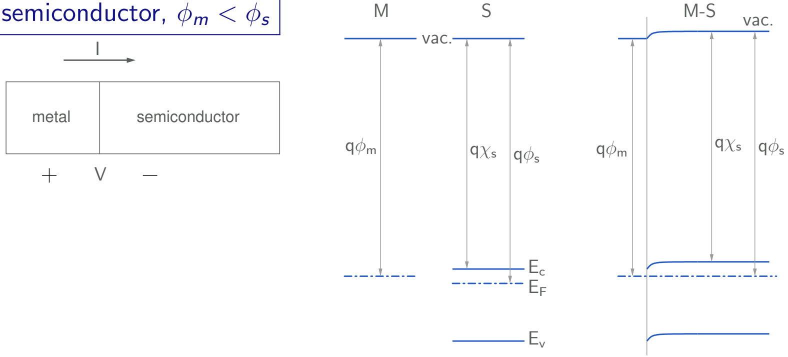
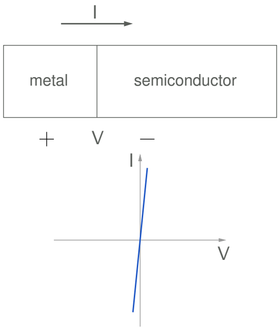
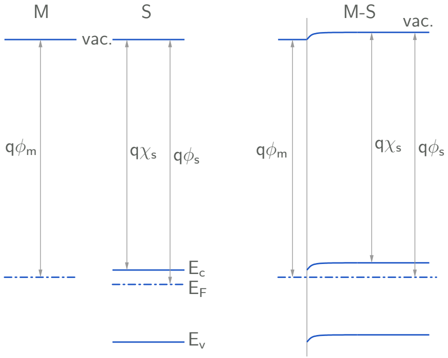


* There is a no barrier to electron flow from S to M $\rightarrow$ ohmic contact.

n-type semiconductor, $\phi_m < \phi_s$





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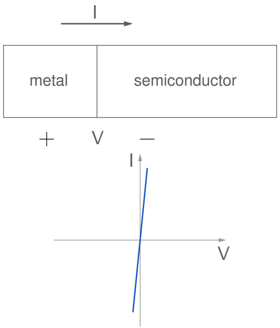

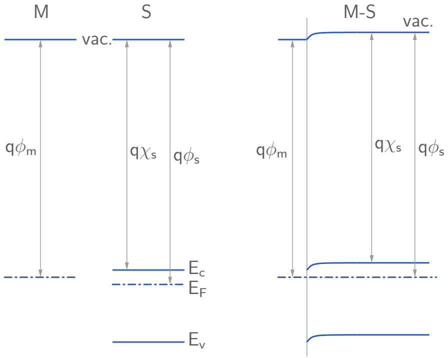

* There is a no barrier to electron flow from S to M $\rightarrow$ ohmic contact.
* In real semiconductors, there are significant departures from the ideal situation we have described.

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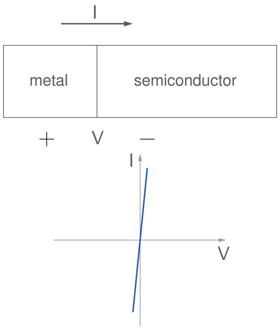
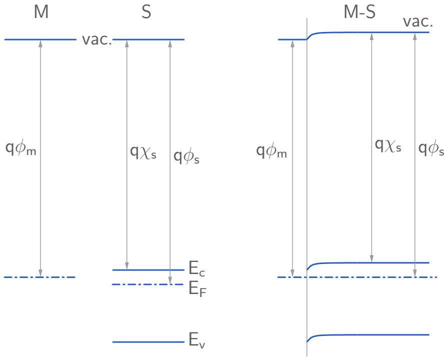
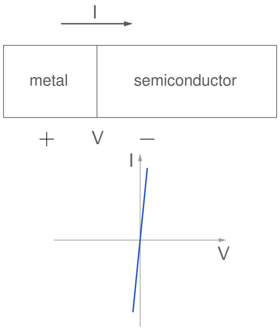
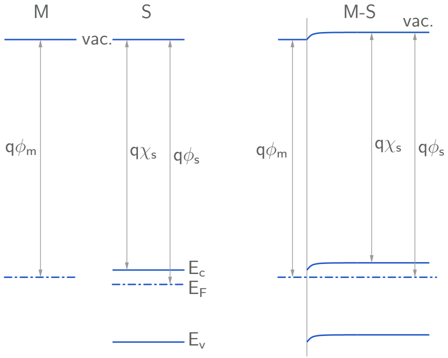




* There is a no barrier to electron flow from S to M $\rightarrow$ ohmic contact.
* In real semiconductors, there are significant departures from the ideal situation we have described.
  - At the M-S interface, the semiconductor crystal structure gets abruptly terminated, which results in incomplete ("dangling") covalent bonds or, in terms of the band picture, electron states within the forbidden gap.

n-type semiconductor, $\phi_m < \phi_s$





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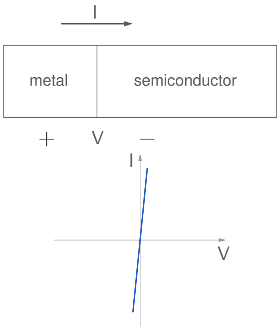
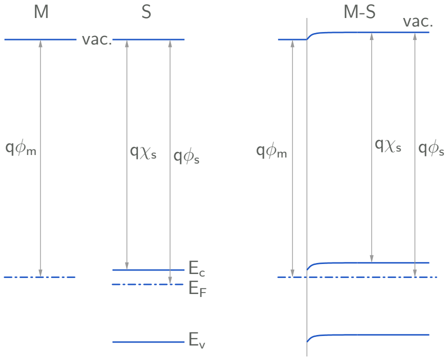
  - At the M-S interface, the semiconductor crystal structure gets abruptly terminated, which results in incomplete ("dangling") covalent bonds or, in terms of the band picture, electron states within the forbidden gap.
  - There may be a thin ($\sim 10\,\text{Å}$) oxide layer between the metal and the semiconductor.

n-type semiconductor, $\phi_m < \phi_s$





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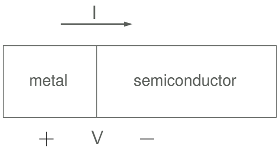
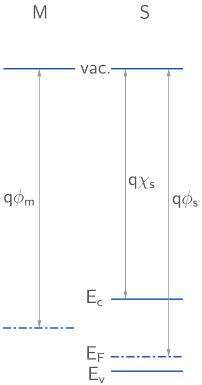
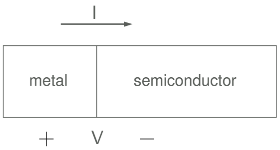
Because of these complications, the barrier heights get modified. However, the qualitative picture remains valid as long as the actual experimentally measured barrier heights are used.

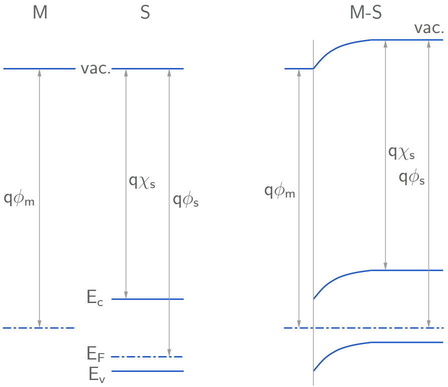
p-type semiconductor, $\phi_m < \phi_s$





p-type semiconductor, $\phi_m < \phi_s$





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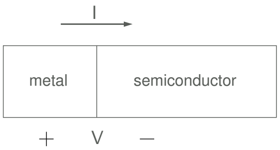

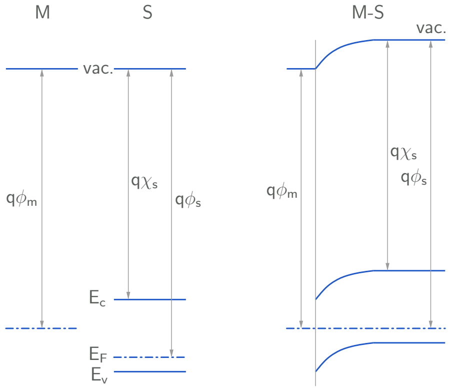

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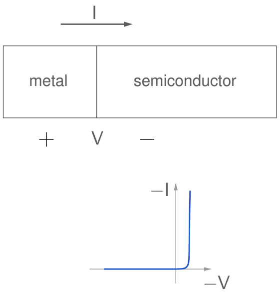
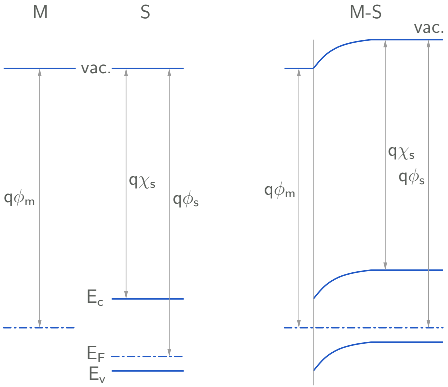
  In the opposite direction (from M to S), there is also a substantial barrier $q\phi_B = q\chi_s + E_g - q\phi_m$, and the contact is therefore rectifying.

p-type semiconductor, $\phi_m < \phi_s$





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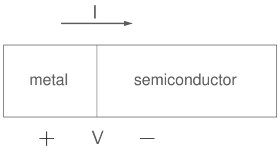

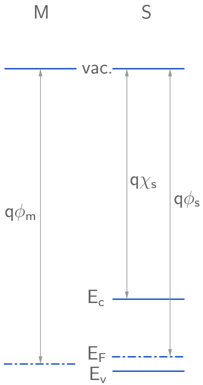

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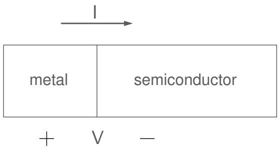

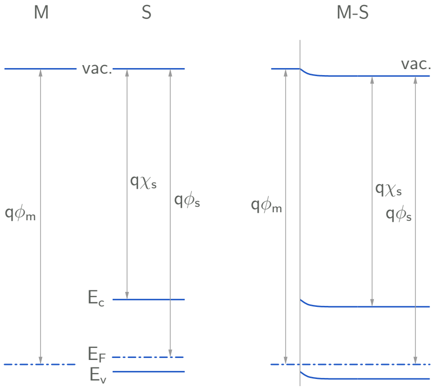

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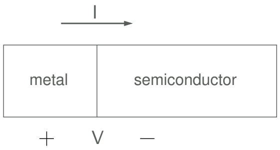

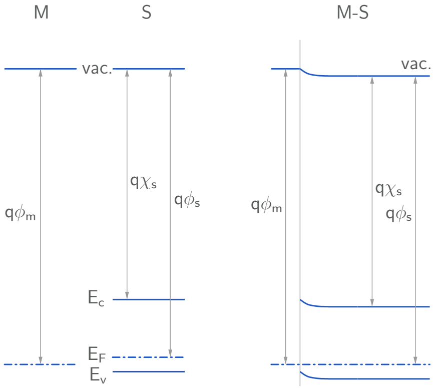

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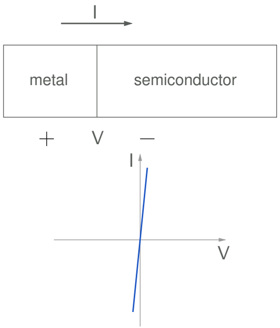

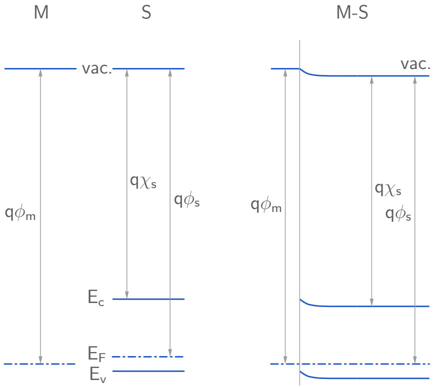

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Current-voltage relationship for a rectifying M-S junction

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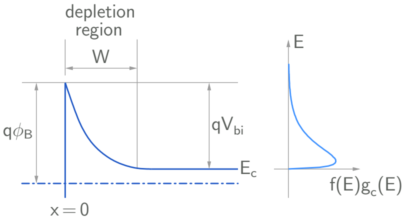
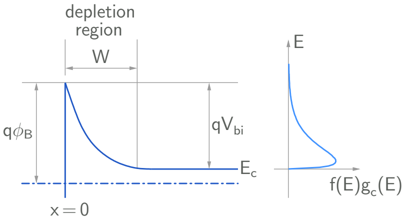
* In an M-S junction, minority carriers play no role in current conduction, and it is the injection of the majority carriers from semiconductor to metal which determines the current.



Consider a M-S junction in equilibrium.



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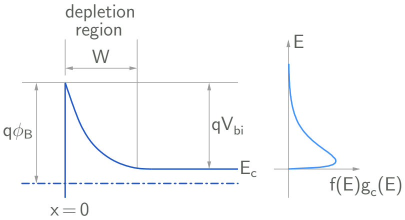

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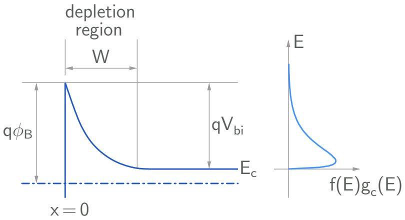

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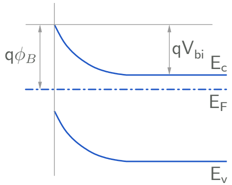
* In equilibrium, there is an equal and opposite current density, $J_{M \rightarrow S} = -J_{S \rightarrow M} = -A^* T^2 \, e^{-\phi_B/V_T}$, resulting in a net current density $J=0$.

Current-voltage relationship for a rectifying M-S junction



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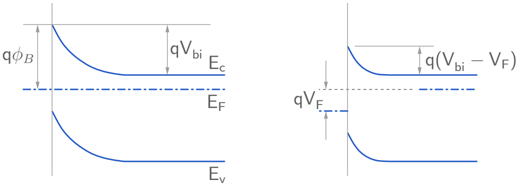

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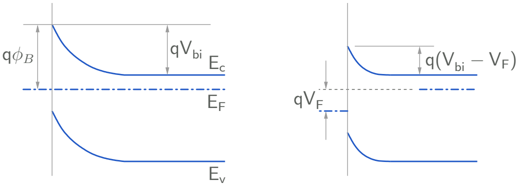

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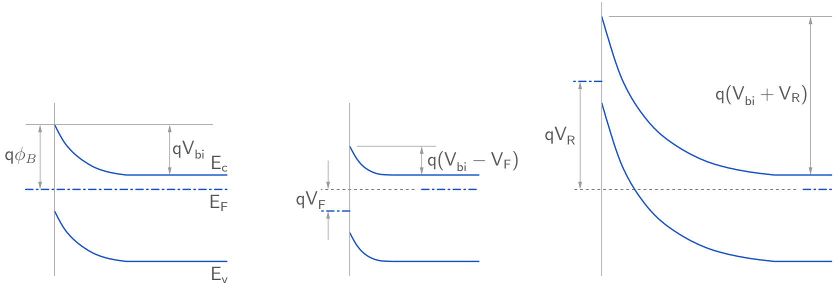

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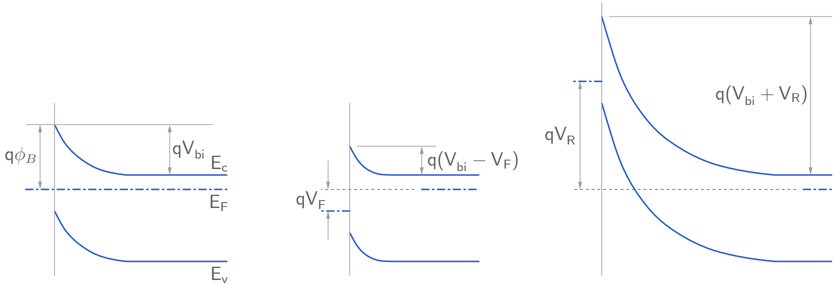

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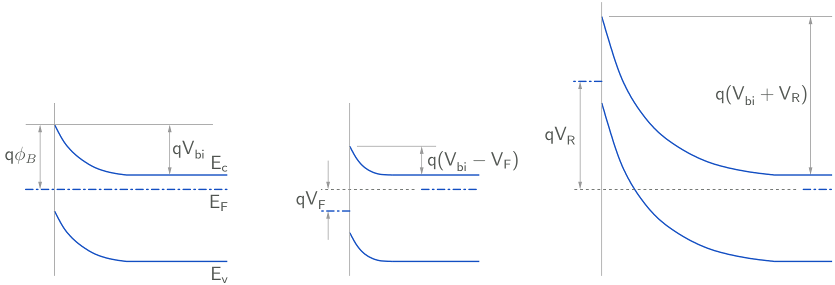

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In summary, $J = J_s \left[e^{V/V_T} - 1 \right]$, where $J_s = A^* T^2 \, e^{-\phi_B/V_T}$.

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* Remark: The process of thermionic emission also takes place in a *p-n* junction, but it can be ignored.

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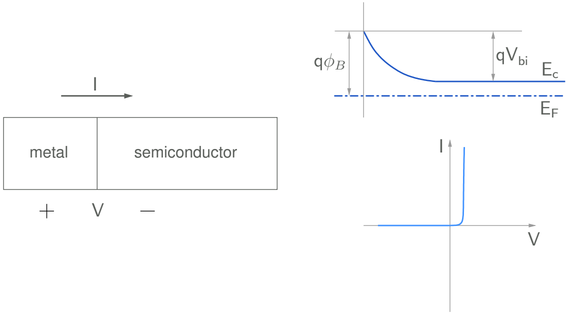
Effect of high doping density



(a)

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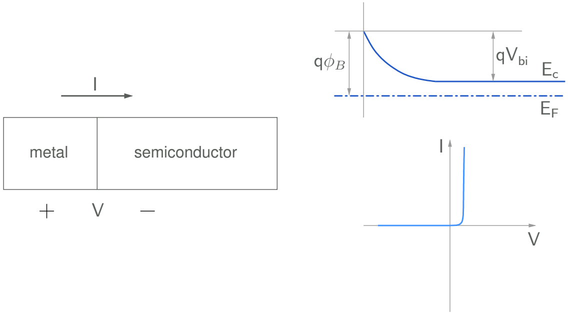

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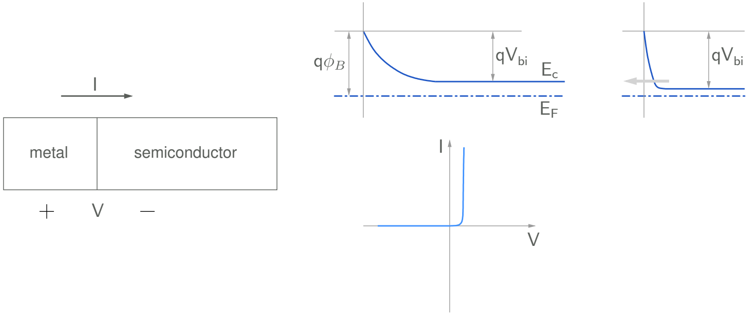

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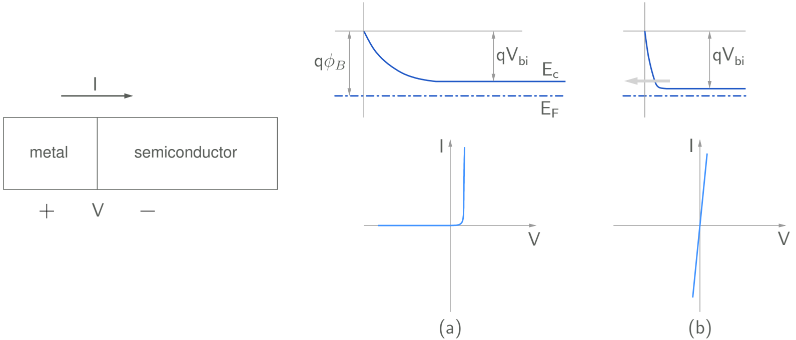

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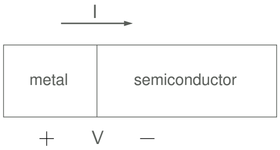

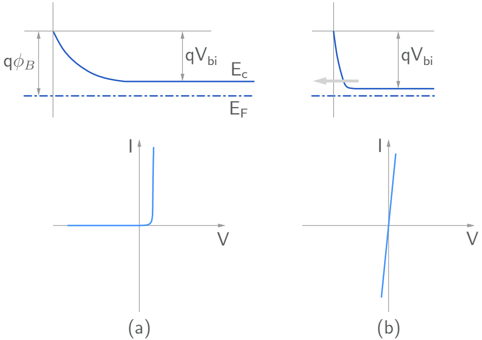

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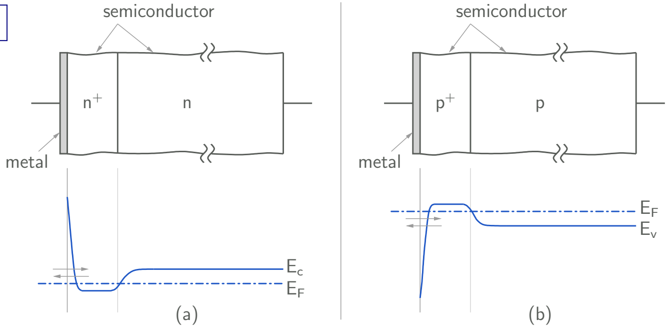
Practical ohmic contacts



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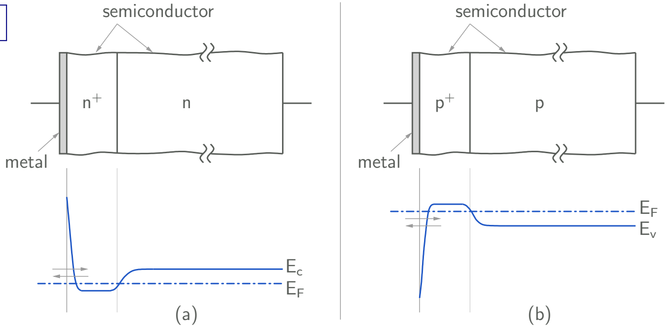

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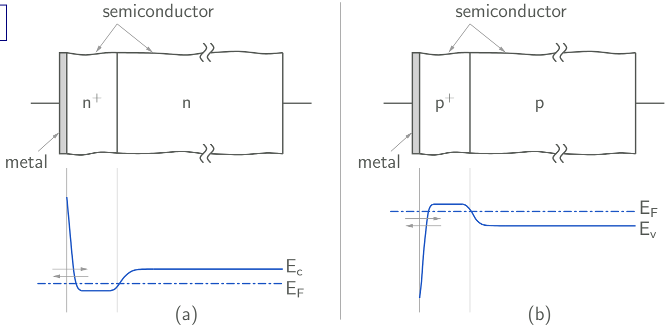

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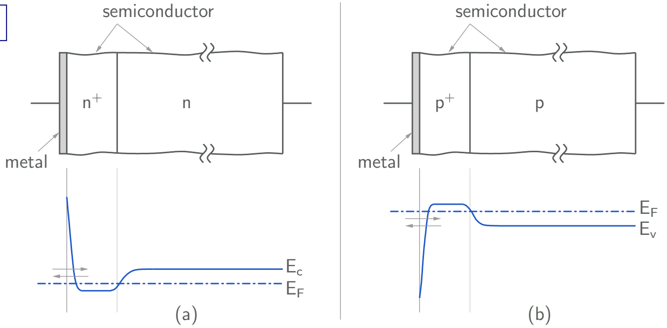

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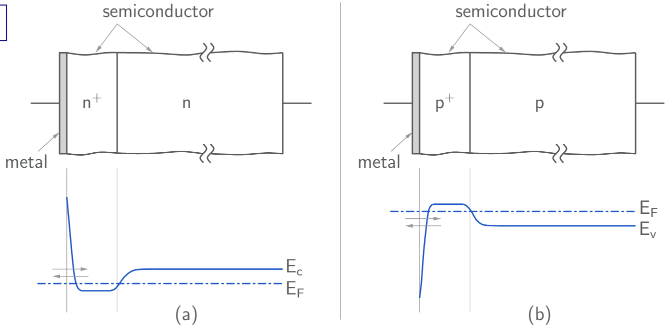

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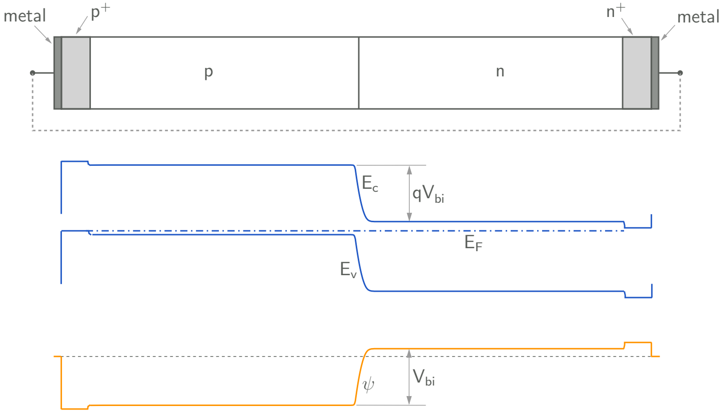
* Next, metal is deposited to make a metal-n^+ or metal-p^+ junction, which is ohmic — irrespective of the barrier ϕ_B — because of tunnelling. In this manner, the objective of making a low-resistance metallic contact is achieved. (In practice, metallic contacts also need to be "alloyed" by subjecting them to temperatures of $\sim 450\,^\circ$C for a few minutes.)

pn junction: band diagram with contact regions



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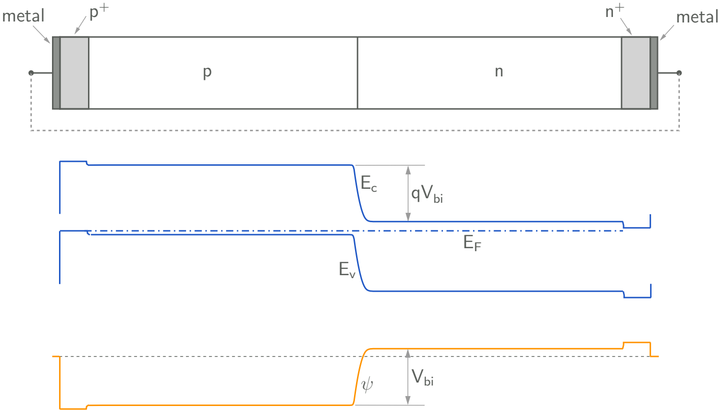

* Equilibrium: The net voltage drop is zero; the voltage drop (V_{bi}) across the depletion region is equal and opposite to the sum of the other voltage drops.

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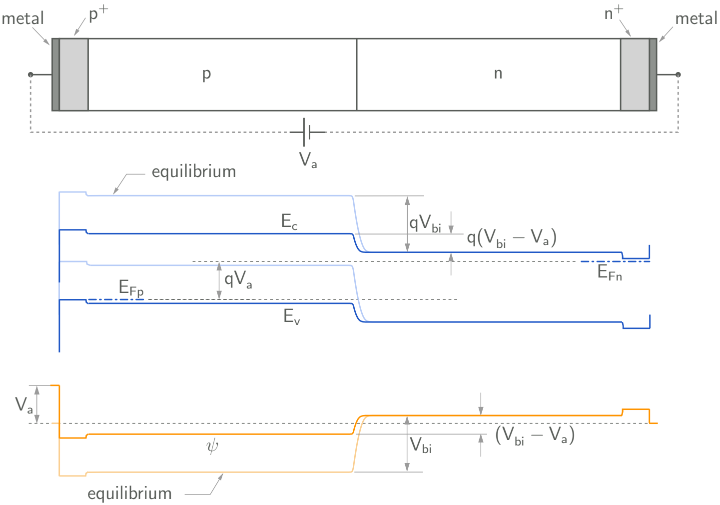

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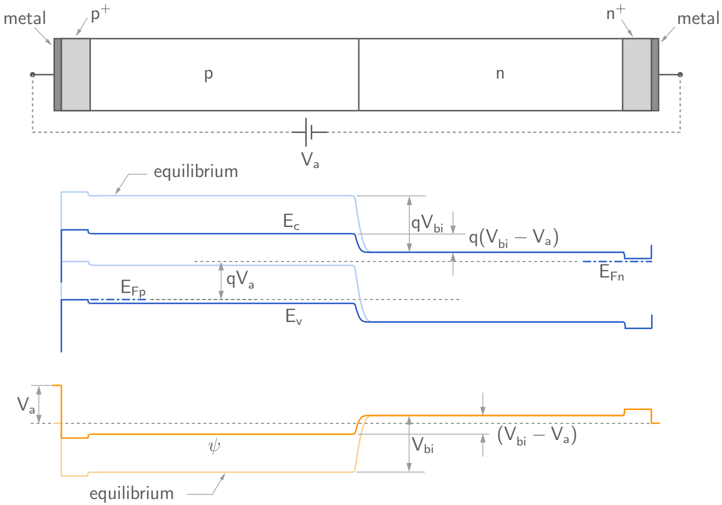
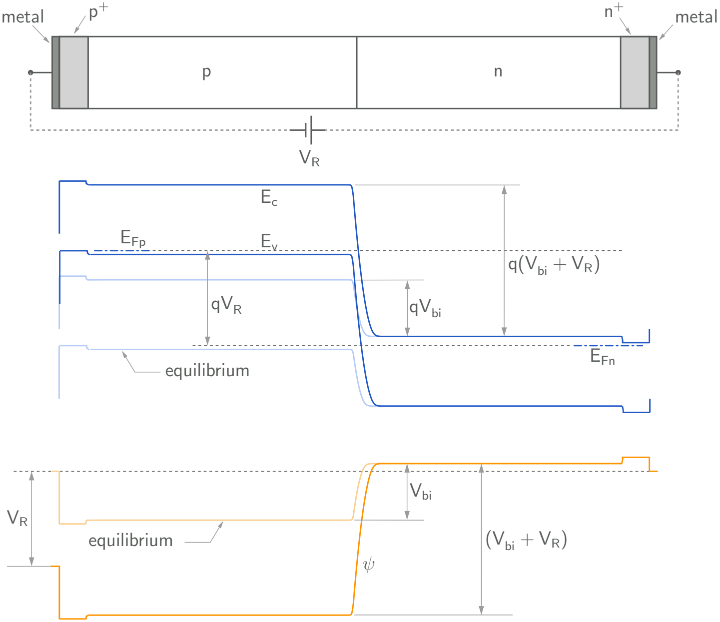
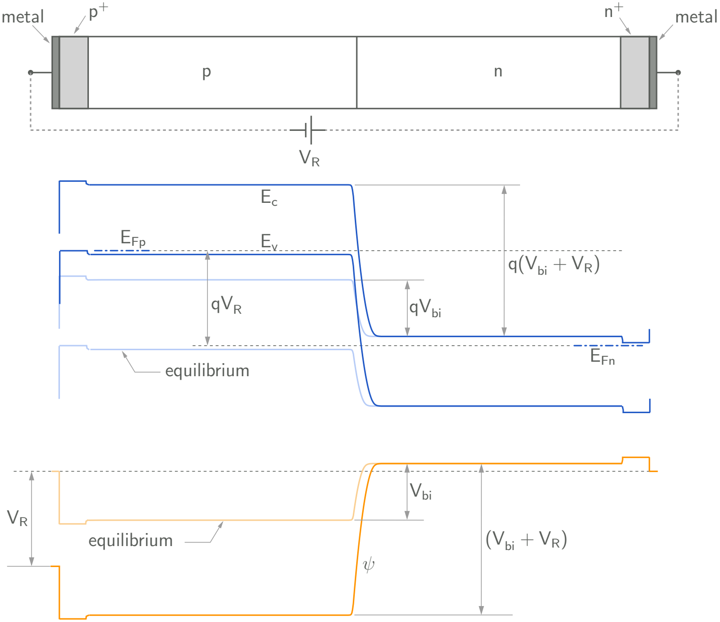


* Forward bias: The voltage drops across the M-S junctions, the n^+-n junction, and the p^+-p junction remain the same as in equilibrium; the applied forward voltage appears across the depletion region ($V_{\mathrm{bi}} \rightarrow V_{\mathrm{bi}} - V_a$).


metal
p+
n+
metal
p
n
V_R
E_c
E_Fp
E_v
q(V_bi + V_R)
qV_R
qV_bi
E_Fn
equilibrium
V_R
V_bi
equilibrium
(V_bi + V_R)
ψ



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