Semiconductor Devices

p-*n* Junctions: Part 4

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Some implications of the Shockley diode equation

$$I = qA\left(\frac{D_p p_{n0}}{L_p} + \frac{D_n n_{p0}}{L_n}\right)\left(e^{V_a/V_T} - 1\right)$$

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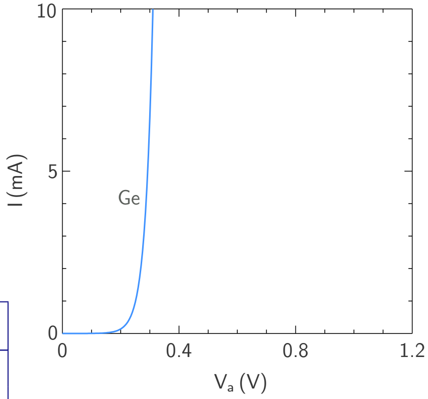

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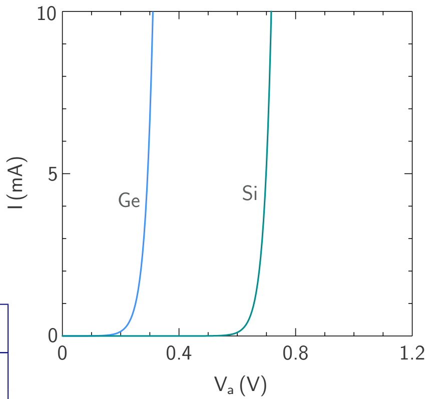

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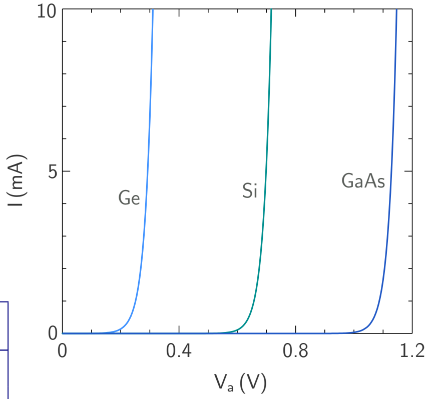

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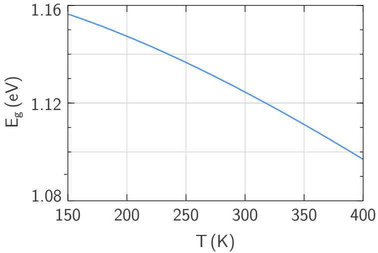

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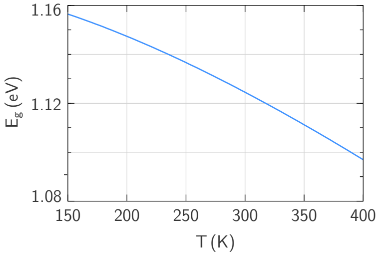

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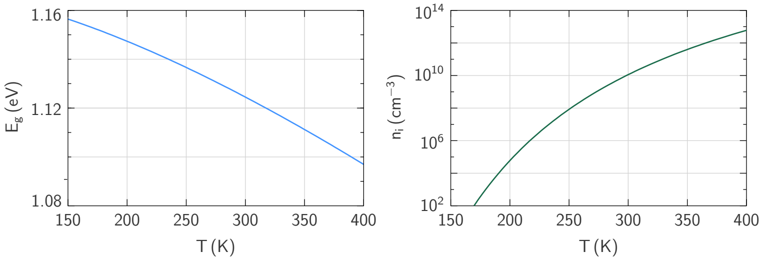

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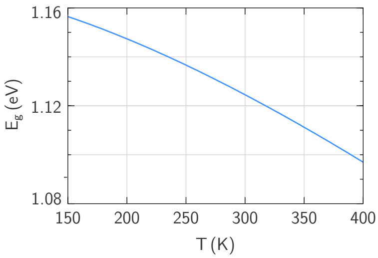

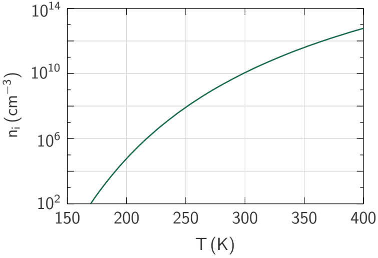

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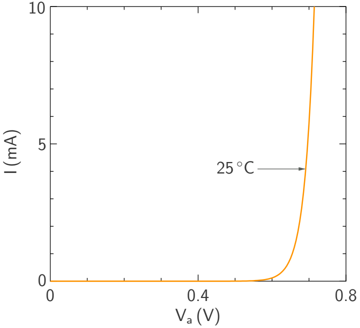

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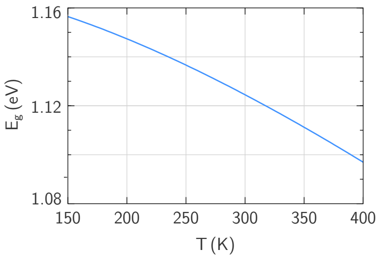

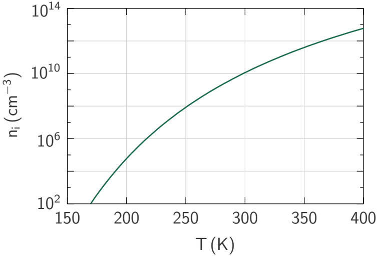

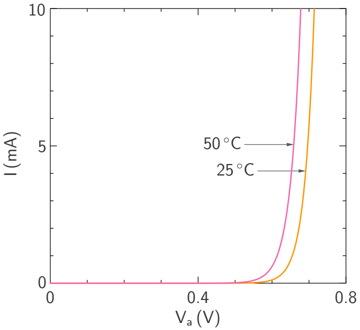

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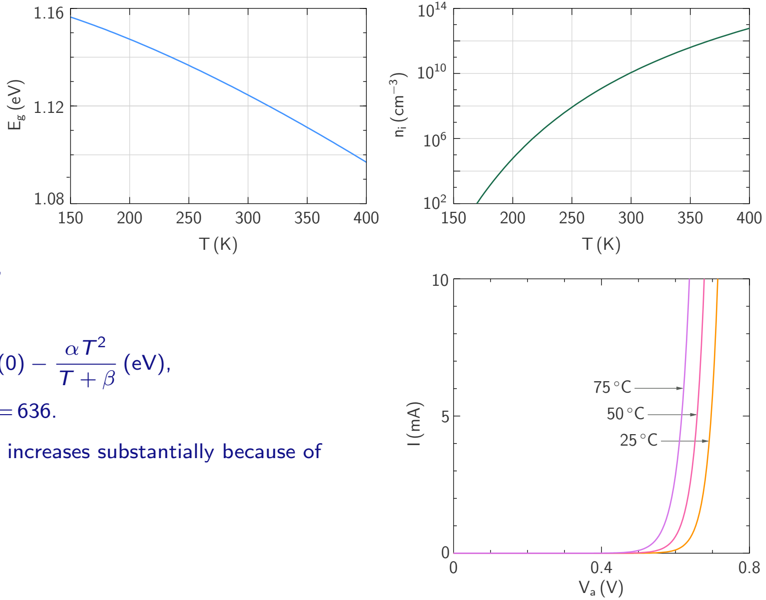

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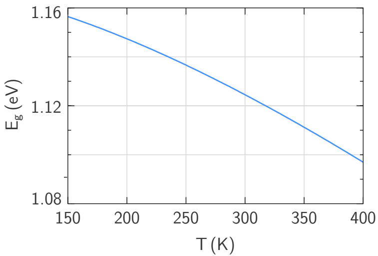

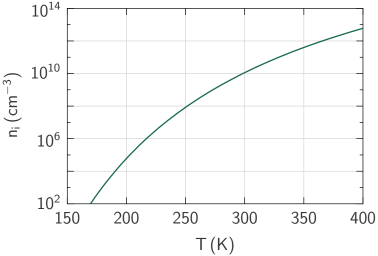

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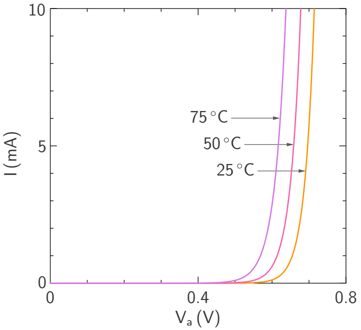
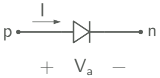
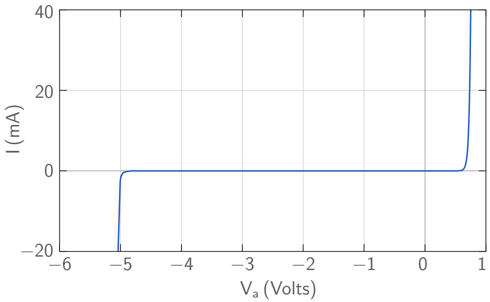
For silicon, the I-V curve shifts by about $-2\,\text{mV}/^\circ\text{C}$ as the temperature is increased.



Reverse breakdown





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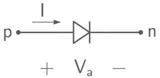

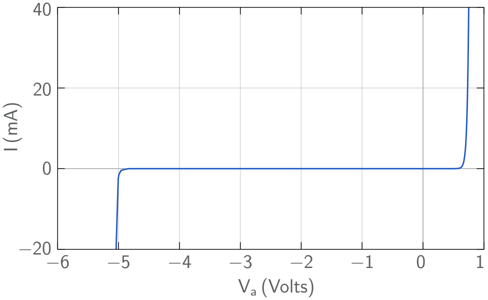

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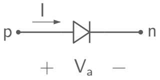

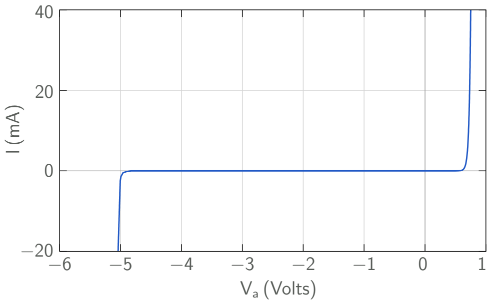

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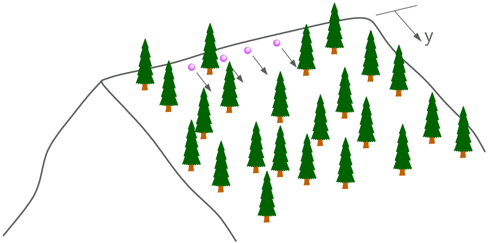
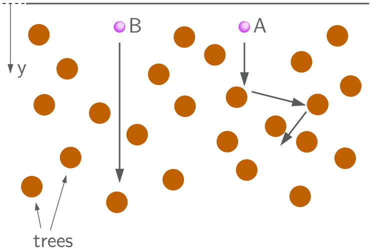
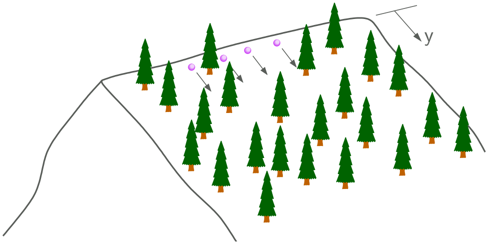
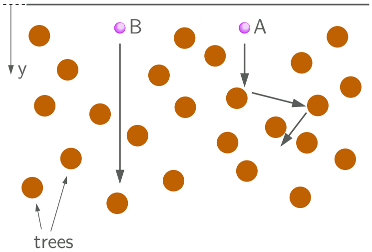
* Reverse breakdown can be due to
  - impact ionisation (avalanche breakdown)
  - tunneling (Zener breakdown)





Consider spherical objects srarting down from the top.





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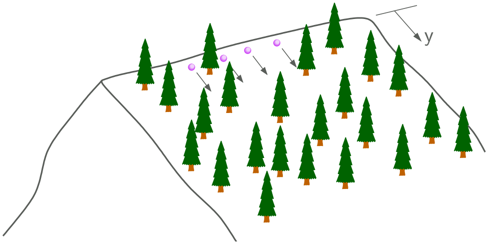
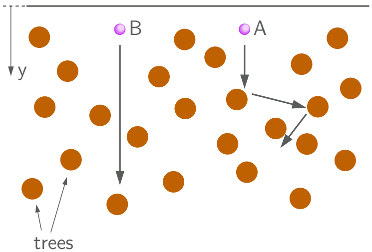
Avalanche breakdown: impact ionisation





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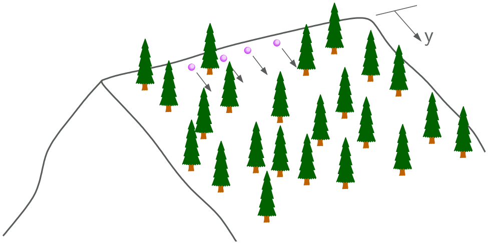

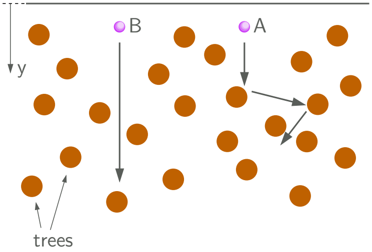

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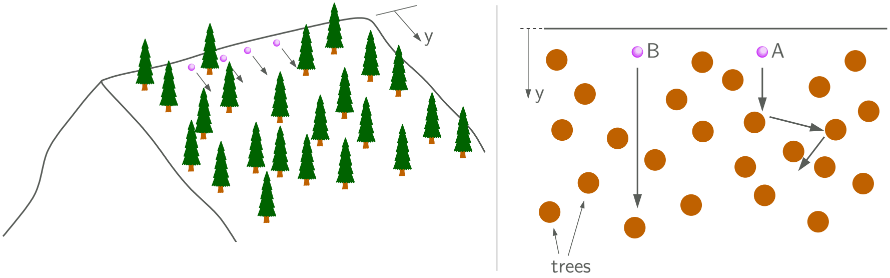
Avalanche breakdown: impact ionisation



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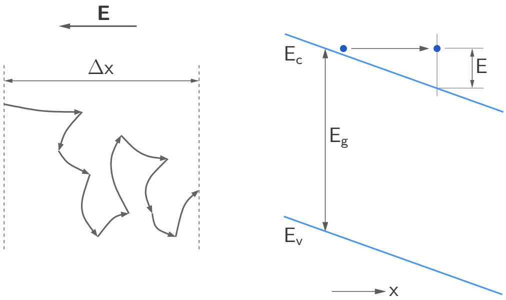
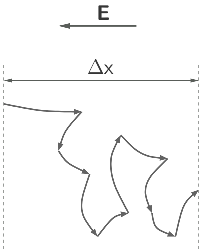
With this situation in mind, let us look at carrier transport in a semiconductor.

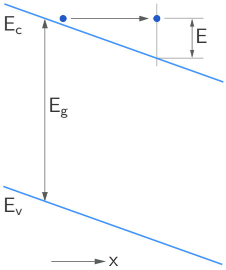
Avalanche breakdown: impact ionisation



* 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.

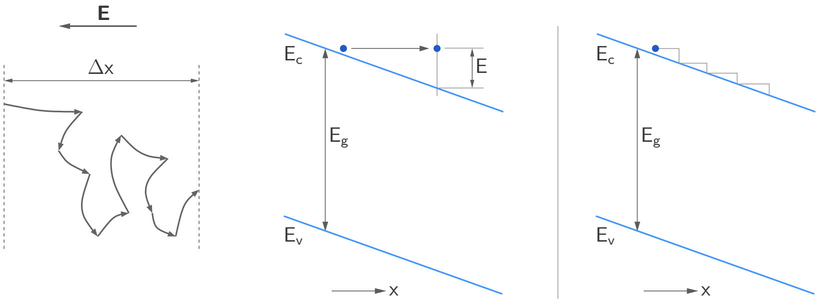
Avalanche breakdown: impact ionisation





* 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.

Avalanche breakdown: impact ionisation



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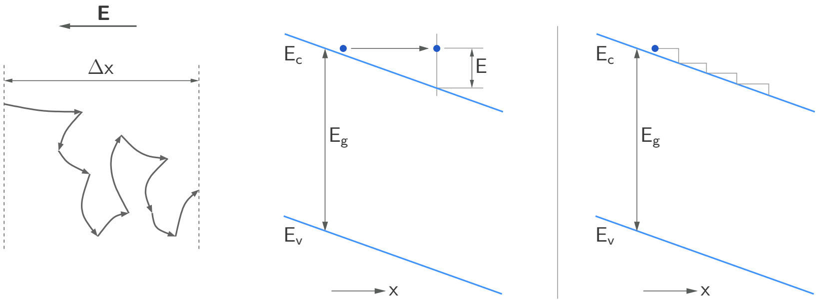

* If an electron moves some distance without scattering, it gains an energy E with respect to E_c at that location. This energy can be thought of as the kinetic energy of the electron.

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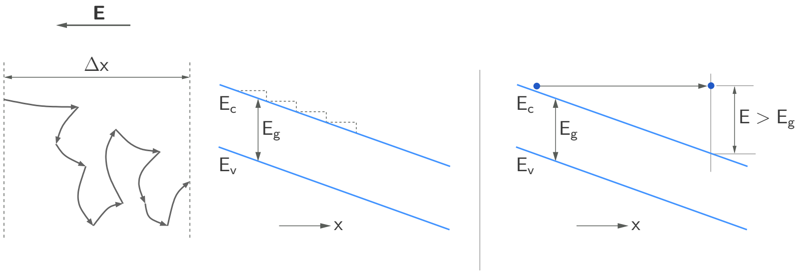
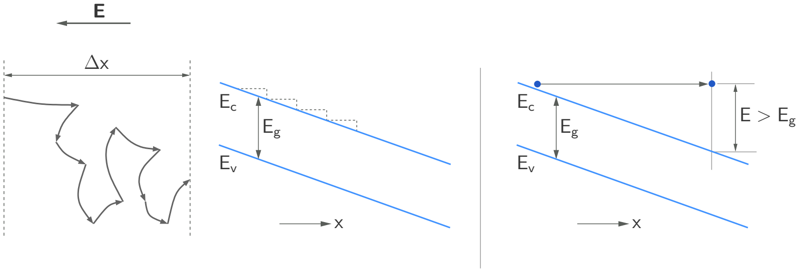
  (Note: For simplicity, we have not discussed the changes in the electron momentum in the other two directions.)

Avalanche breakdown: impact ionisation



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

Avalanche breakdown: impact ionisation



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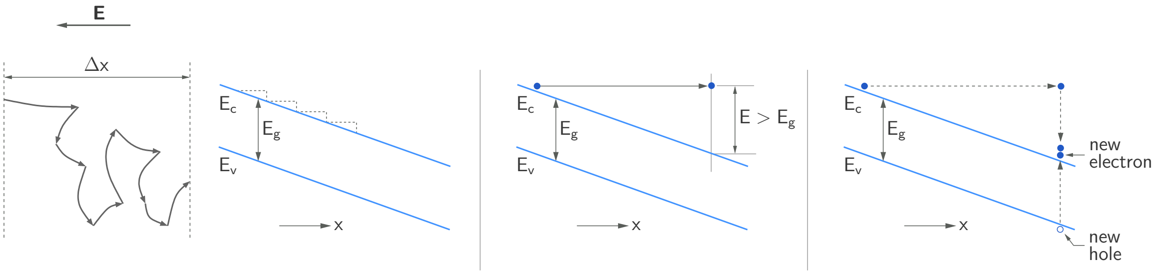

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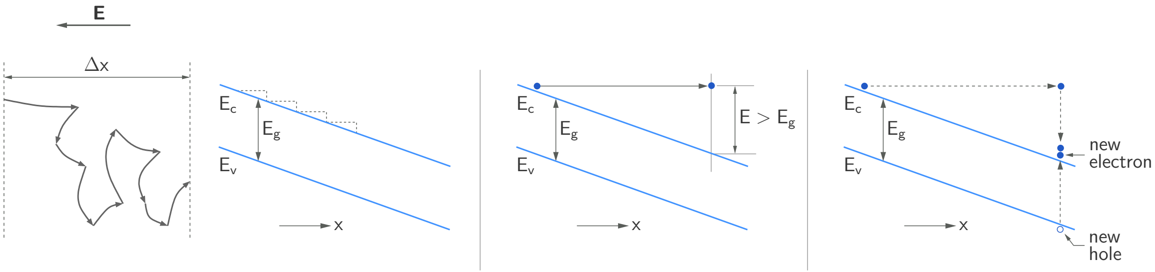

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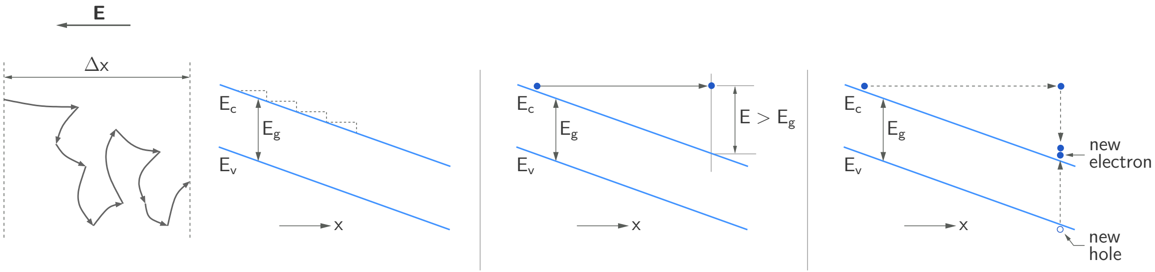

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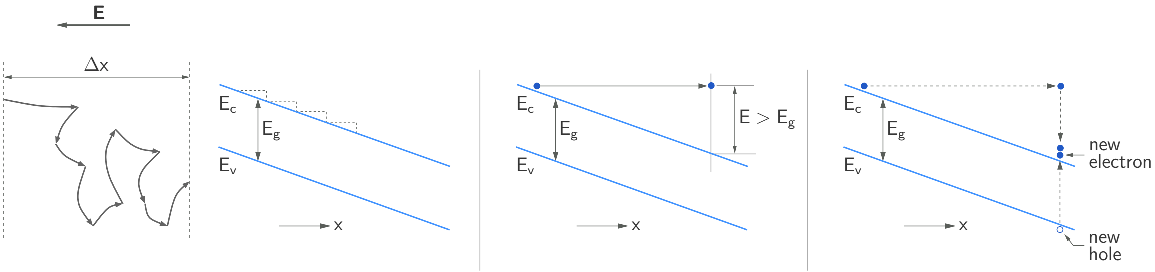

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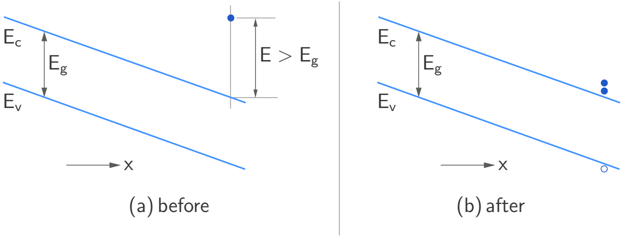
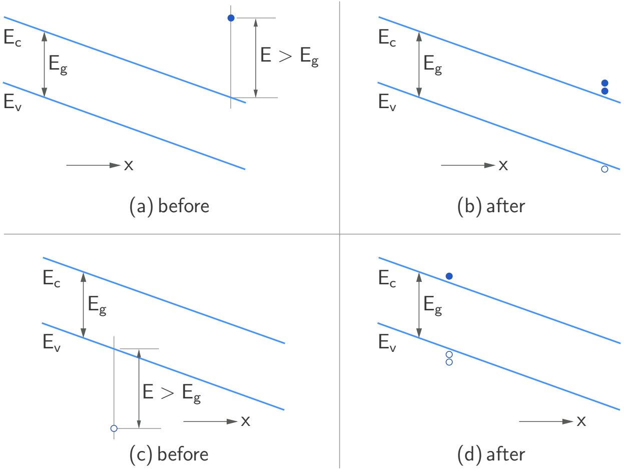
* The key requirement for impact ionisation to occur is a high electric field.

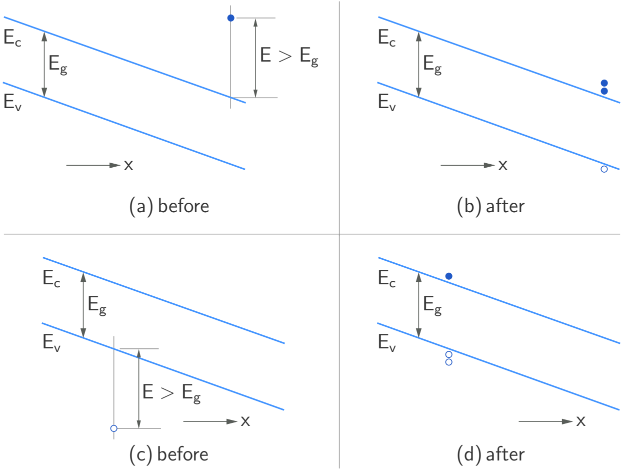
Avalanche breakdown: impact ionisation



(a) before (b) after

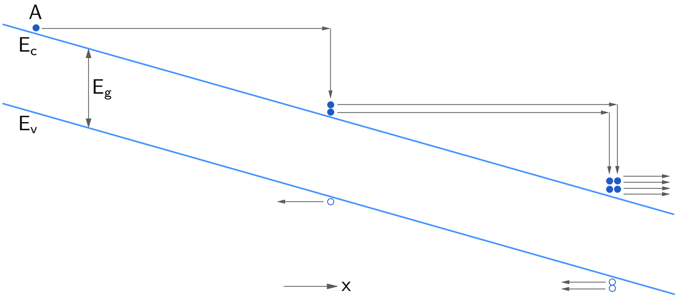
Avalanche breakdown: impact ionisation





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

Avalanche breakdown: impact ionisation



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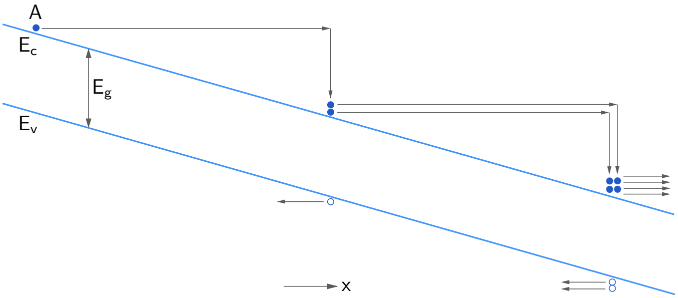

∗ A lucky electron gains energy, causes impact ionisation and gives rise to two electrons and one hole.

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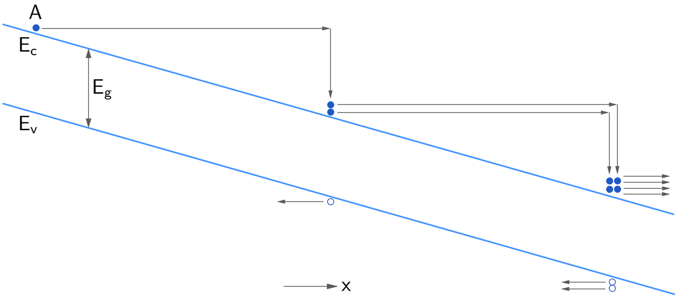

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* Each of these carriers can potentially cause impact ionisation because of the high electric field (if they travel without scattering) $\rightarrow$ "avalanche" multiplication.

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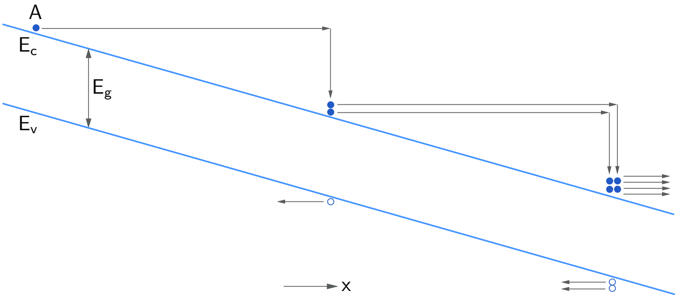

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* The avalanche multiplication process is obviously very complicated, but it can be characterised in a simple manner by a "critical field" $\mathcal{E}_c$ — if the electric field in the device exceeds $\mathcal{E}_c$, we can expect avalanche multiplication,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

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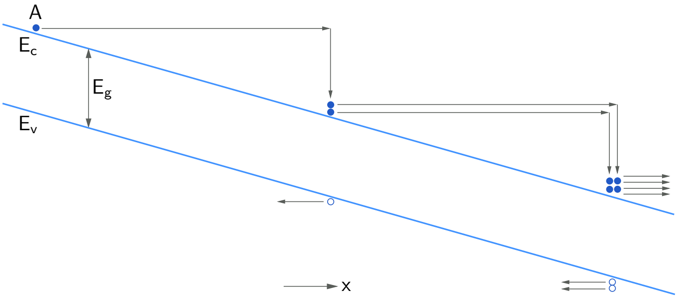

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* For Ge, Si, and GaAs, the critical field at room temperature is about 100, 300, and 400 kV/cm, respectively.

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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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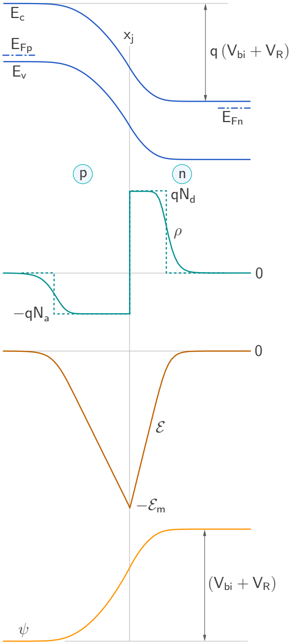

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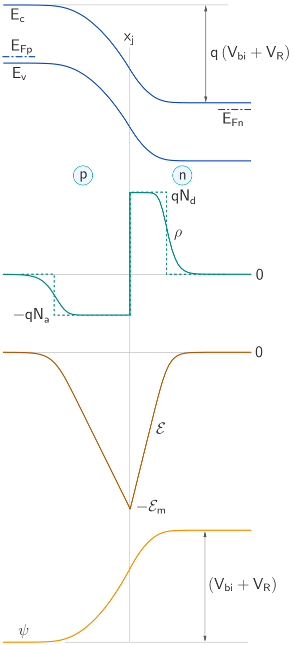

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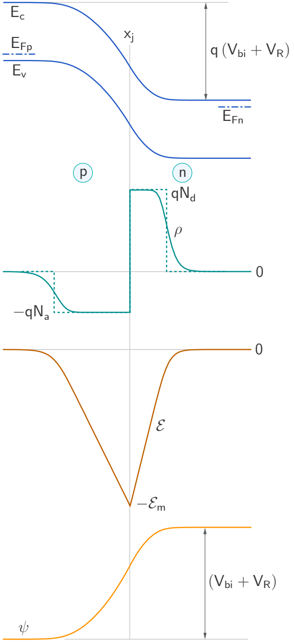

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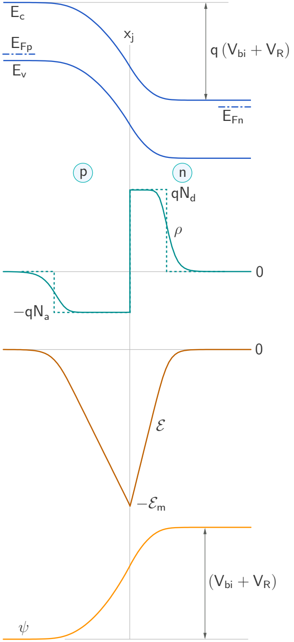
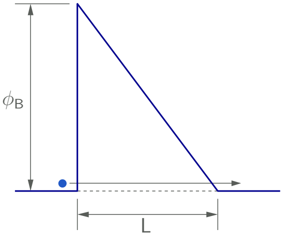
Units: $\dfrac{\text{F}}{\text{cm}}\left(\dfrac{\text{V}}{\text{cm}}\right)^2 \dfrac{1}{\text{C}}\,\dfrac{1}{\text{V}} = \dfrac{\text{C}}{\text{V}\cdot\text{cm}}\left(\dfrac{\text{V}}{\text{cm}}\right)^2 \dfrac{1}{\text{C}}\,\dfrac{1}{\text{V}} = \dfrac{1}{\text{cm}^3}.$





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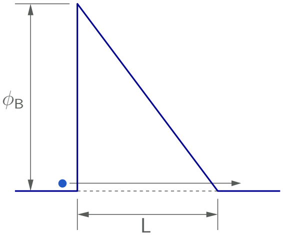
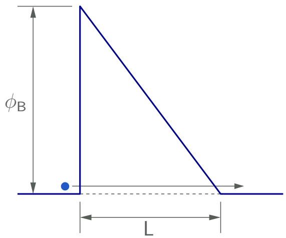


* Another mechanism which can cause reverse breakdown of a *pn* junction is quantum-mechanical tunneling.



* Another mechanism which can cause reverse breakdown of a *pn* junction is quantum-mechanical tunneling.
* For a significant tunneling current,
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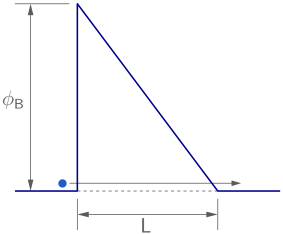
  - There must be a large number of electrons on one side and a large number of available states on the other side.



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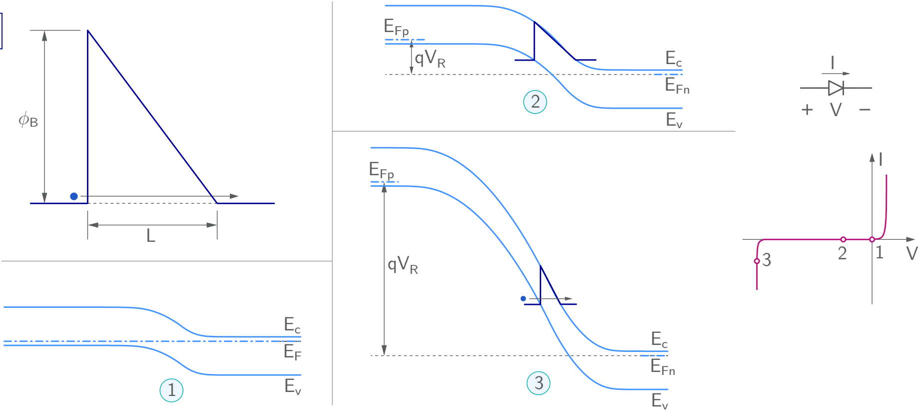
* With these points in mind, let us now look at a reverse-biased *pn* junction.

Zener breakdown



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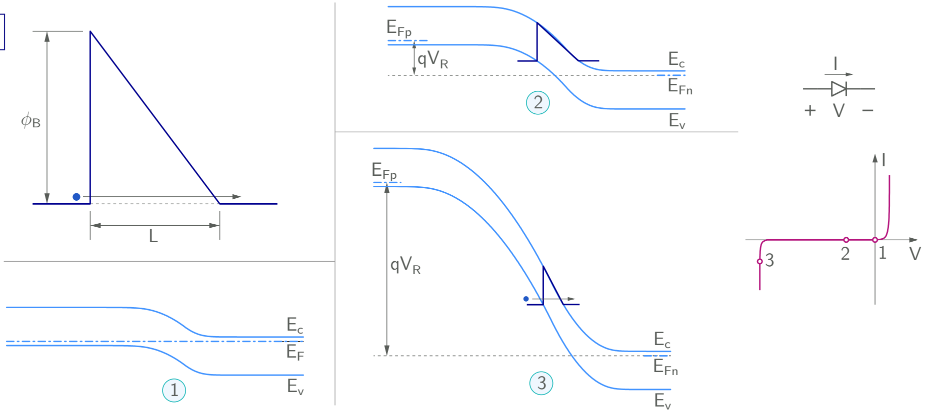
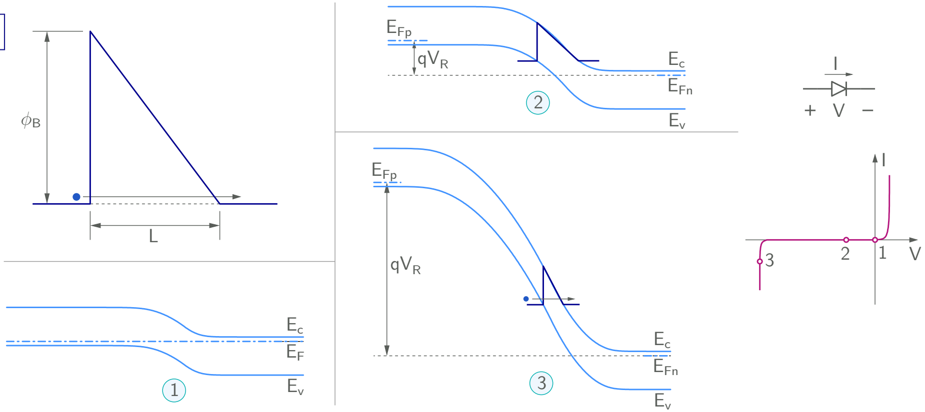


* The depletion width is given by $W = \sqrt{\dfrac{2\epsilon}{q}\left(\dfrac{1}{N_a}+\dfrac{1}{N_d}\right)(V_{\text{bi}}+V_R)}\,.$

Zener breakdown



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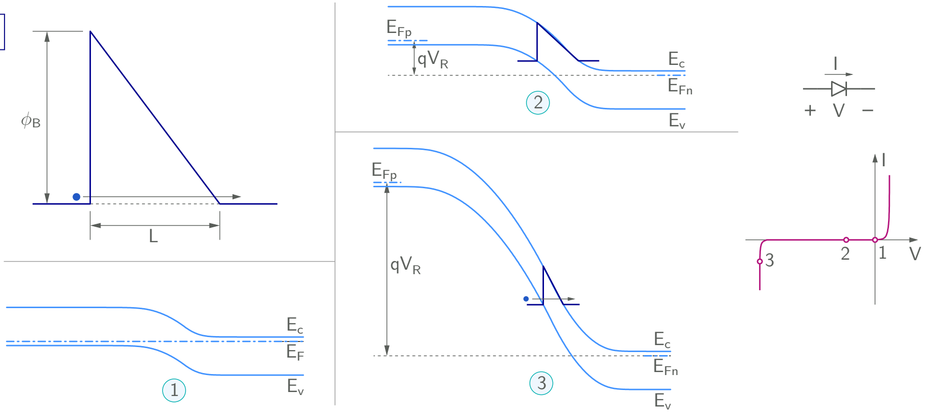

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* There is a large number of electrons in the valence band on the *p* side and a large number of states (vacancies) in the conduction band on the *n* side.

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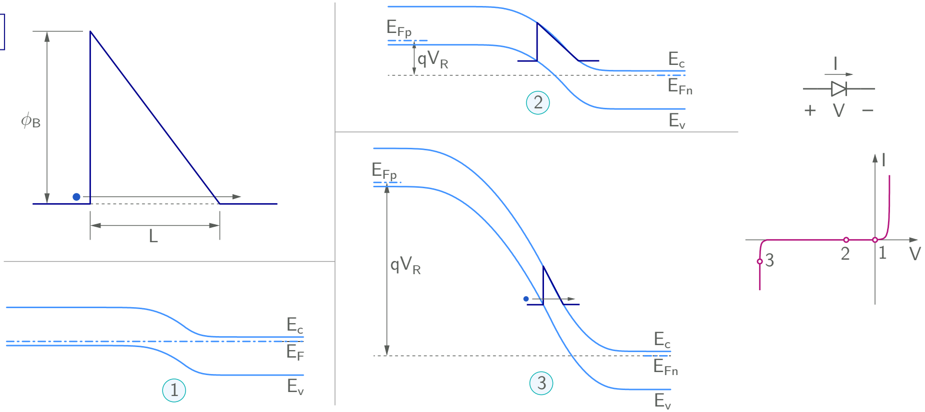

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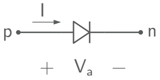
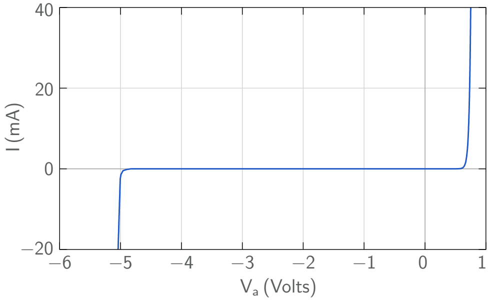
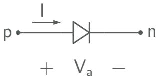
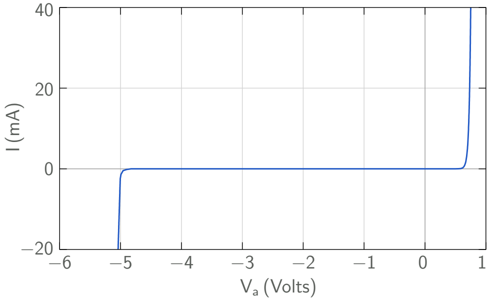
* As the reverse bias is increased, the barrier becomes thinner.
* There is a large number of electrons in the valence band on the p side and a large number of states (vacancies) in the conduction band on the n side.
* Relatively large doping densities are required to ensure that the barrier is sufficiently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

Reverse breakdown









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

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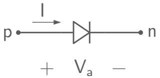
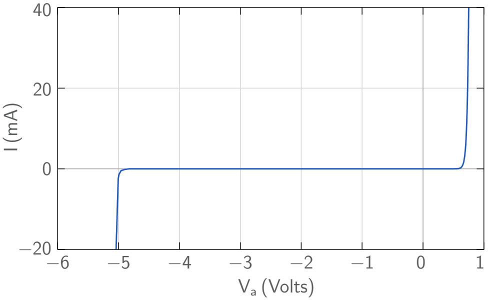
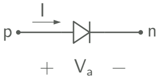
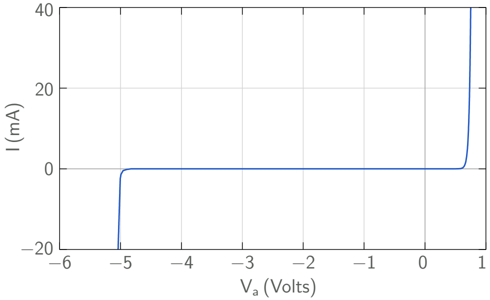




* Silicon diodes with breakdown voltage V_{BR} ranging from a few volts to a thousand volts are commercially available.
* In diodes with $V_{BR} < 5\,V$, the breakdown is generally due to tunnelling; for higher values of V_{BR}, it is due to avalanche multiplication.

Reverse breakdown





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


p
n

Heterojunctions

* The *pn* junctions we have considered so far are called "homojunctions," i.e., junctions between similar (same) semiconductors on the *p* and *n* sides.

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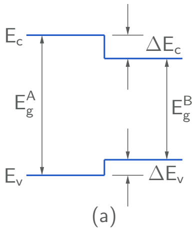
* In a *pn* “heterojunction,” two different semiconductors A and B are involved, where A is doped *p*-type, and B is doped *n*-type.
* The two semiconductors must be lattice-matched, i.e., they must have the same lattice constant to avoid dislocations and device degradation.



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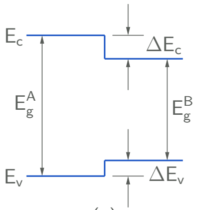
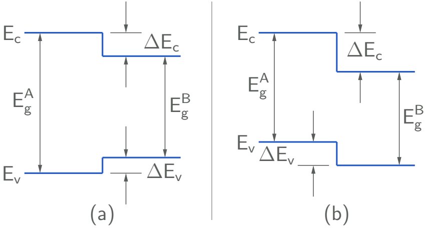
Heterojunctions



(a)

* Because A and B are different semiconductors, there are discontinuities in the band edges (ΔE_c and ΔE_v).
* Depending on the material properties of A and B, different signs for ΔE_c and ΔE_v are possible.



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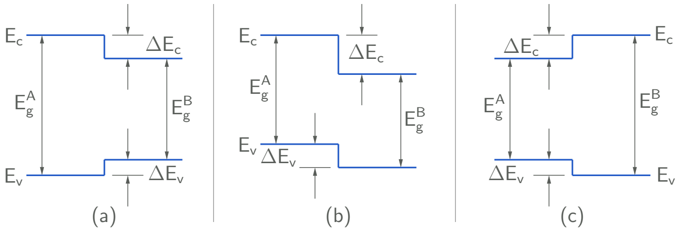

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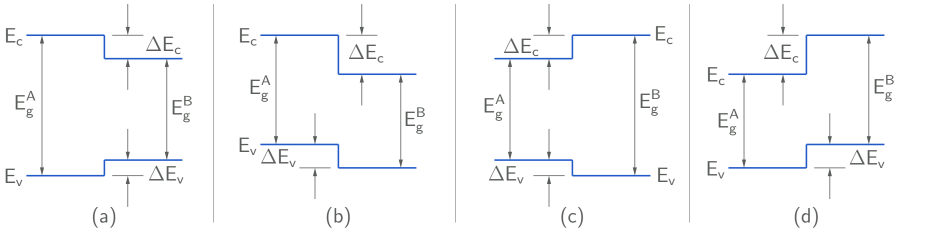

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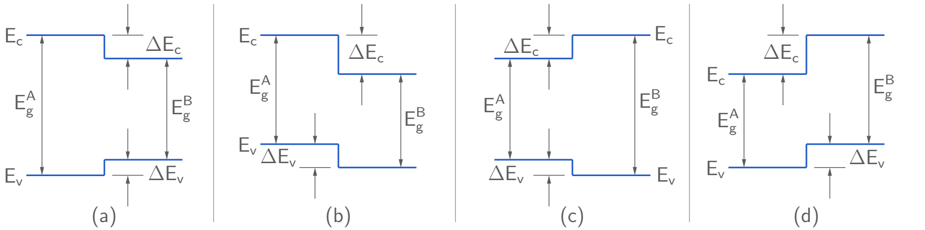

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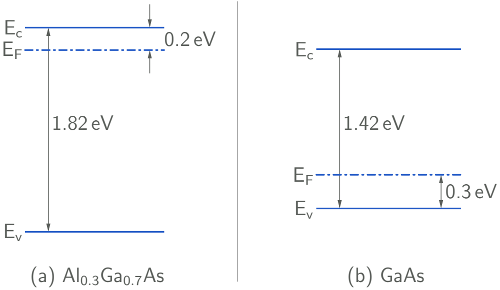
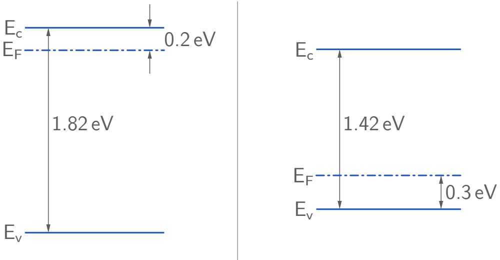
  (The bands are shown to be flat for simplicity. In practice, there will be some band bending due to the presence of an electric field.)

Example



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

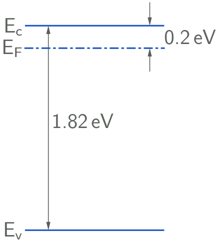


(a) $Al_{0.3}Ga_{0.7}As$ (b) GaAs

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

The doping densities are such that the Fermi levels in the isolated materials are $E_F = E_c - 0.2\,\text{eV}$ and $E_F = E_v + 0.3\,\text{eV}$ on the n and p sides, respectively.

Example



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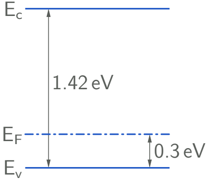

(b) GaAs

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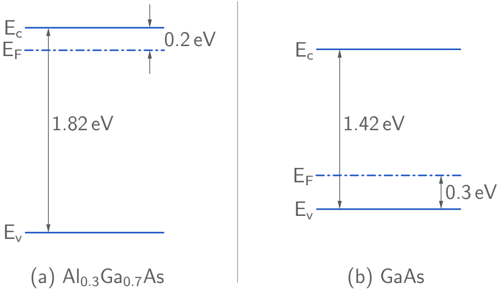
At the junction, E_c for $Al_{0.3}Ga_{0.7}As$ is higher than E_c for GaAs by $\Delta E_c = 0.27\,\text{eV}$, and E_v for $Al_{0.3}Ga_{0.7}As$ is lower than E_v for GaAs by $\Delta E_c = 0.13\,\text{eV}$.

Example



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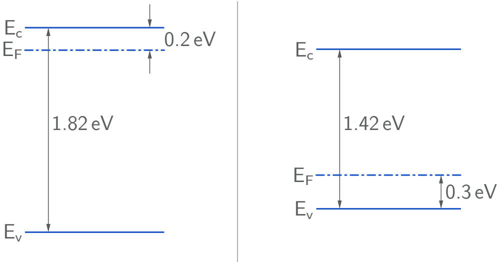
Example



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

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

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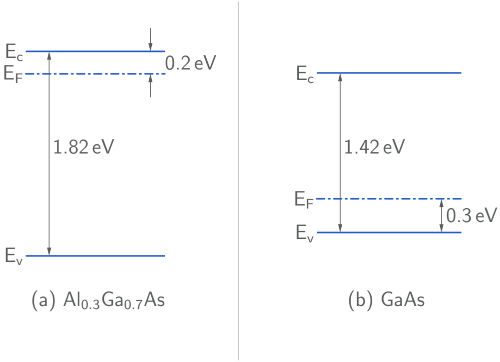
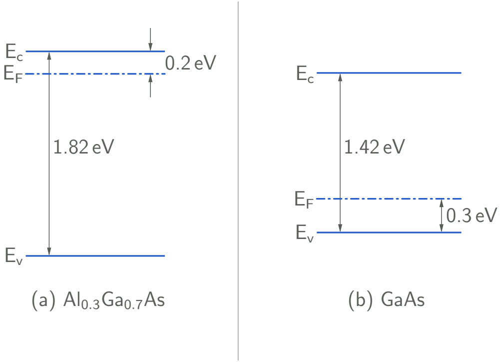
Sketch the band diagram of the *pn* junction in equilibrium.

Example

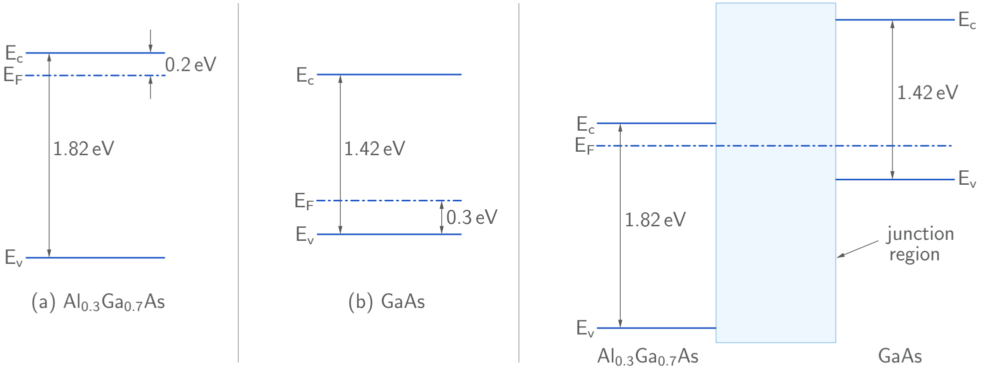


Example



* In equilibrium, the Fermi level must be constant.

Example



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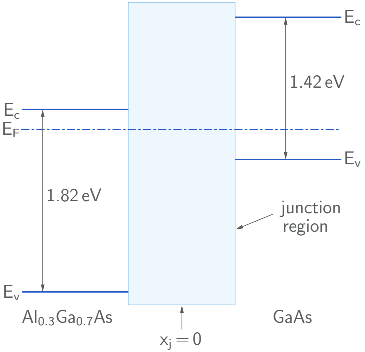
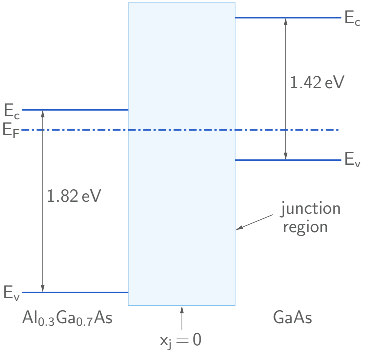
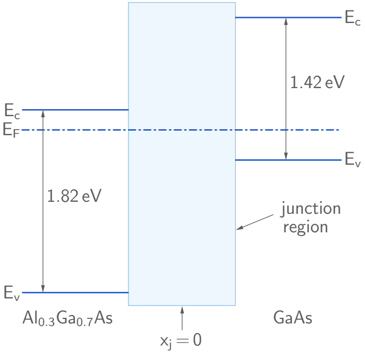

E_c
1.42 eV
E_c
E_F
E_v
1.82 eV
junction
region
E_v
$Al_{0.3}Ga_{0.7}As$
GaAs
$x_j = 0$



* 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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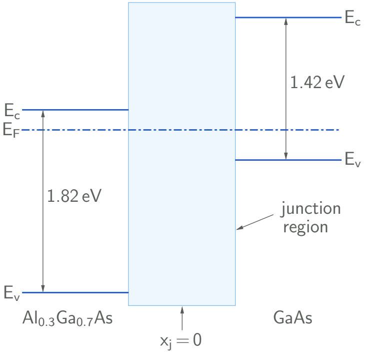

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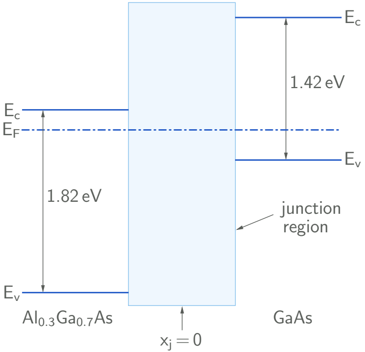

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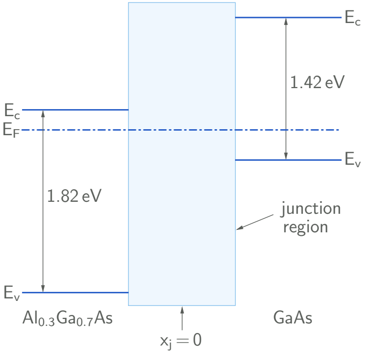
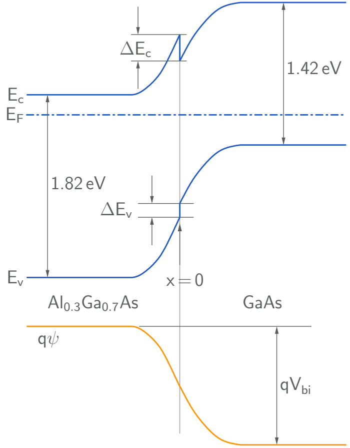
* The charge density variation is similar to that of a *pn* homojunction $\rightarrow$ the potential variation is also similar in the two cases.





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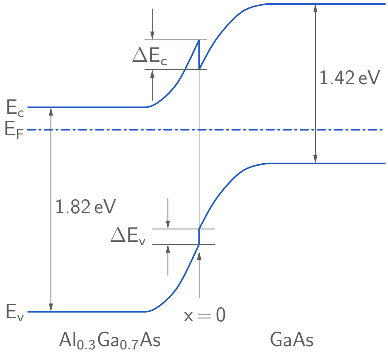
Effect of grading



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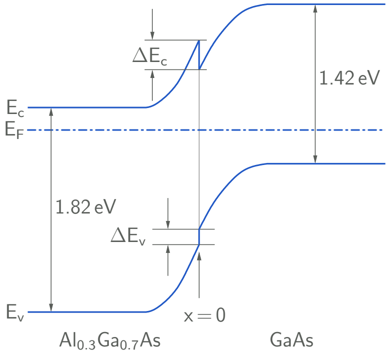

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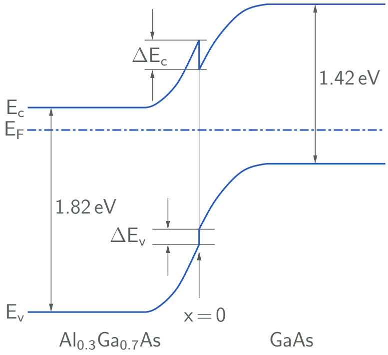

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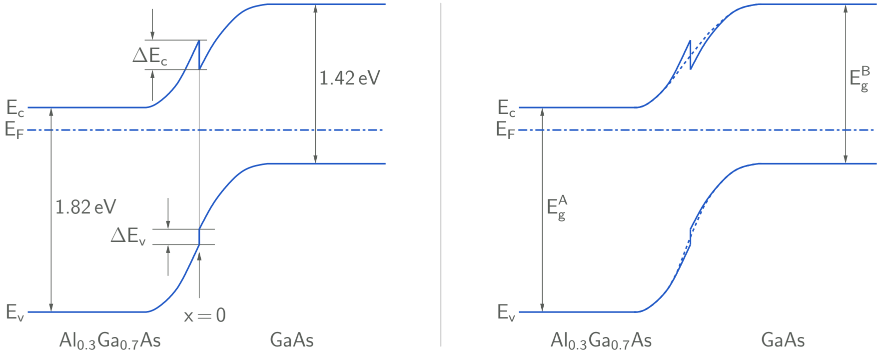

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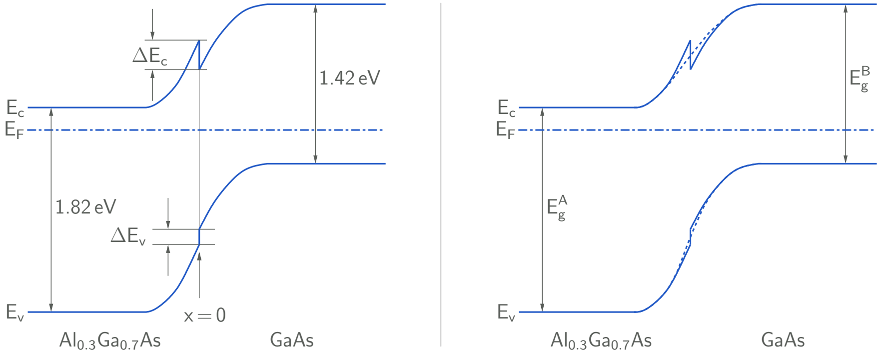

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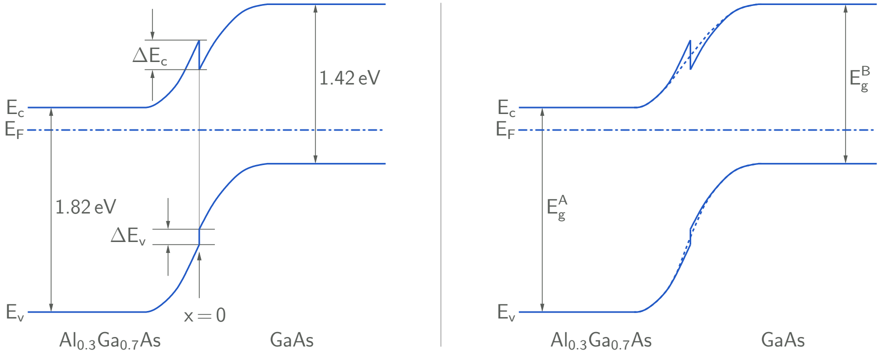

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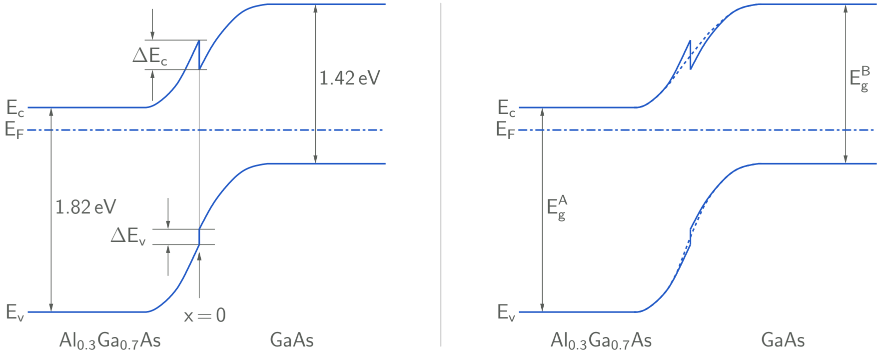

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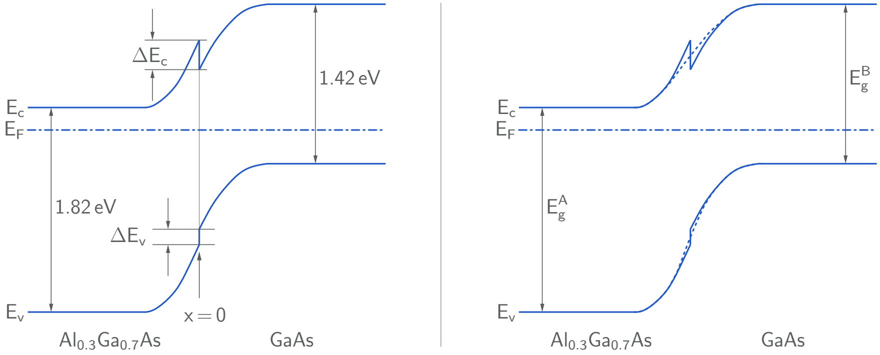
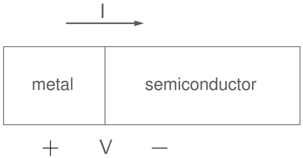
  With forward bias, the depletion region shrinks. The current increases exponentially with forward bias.
  With reverse bias, the depletion region expands. The current is negligibly small.

Effect of grading

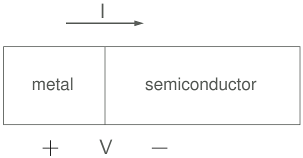


* Graded heterojunctions are used to fabricate heterojunction bipolar transistors (HBT) in which a high current gain and a small device resistance are simultaneously made possible because of different semiconductors used for the emitter and base regoins of the device.



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

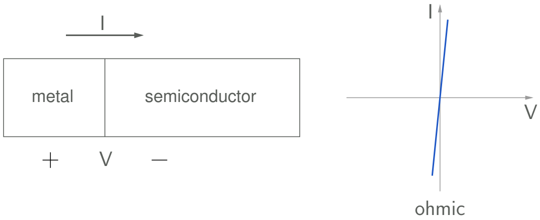
Metal-semiconductor junctions



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.

Metal-semiconductor junctions



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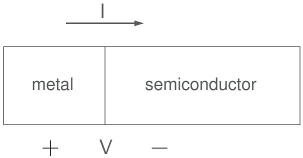

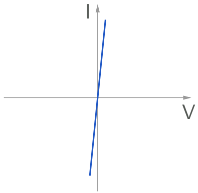

ohmic

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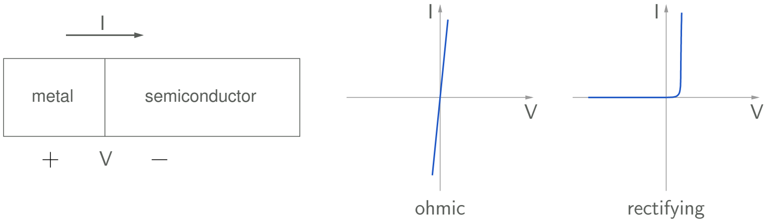
* A *rectifying* M-S junction plays a key role in the operation of some semiconductor devices like the MESFET (Metal-Semiconductor Field-Effect Transistor). As the name implies, a rectifying M-S junction (also called a "Schottky contact") conducts well in one direction but blocks current in the other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



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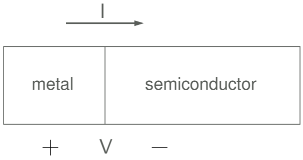
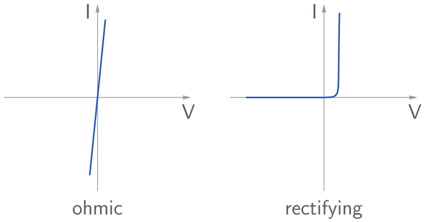
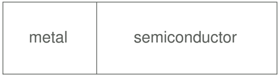




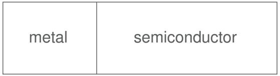
Metal-semiconductor (M-S) junctions serve two important purposes in semiconductor devices:

* 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



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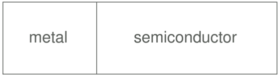
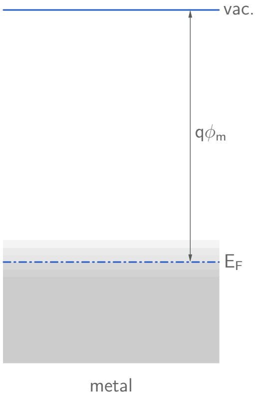
- metal work function ϕ_m (difference between the "vacuum level" and the Fermi level)





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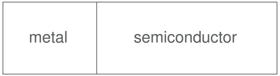

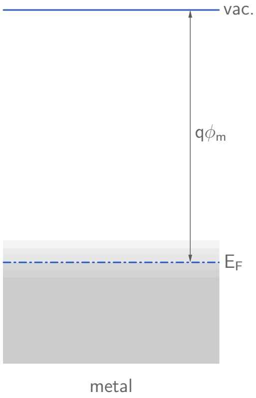

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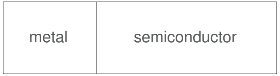

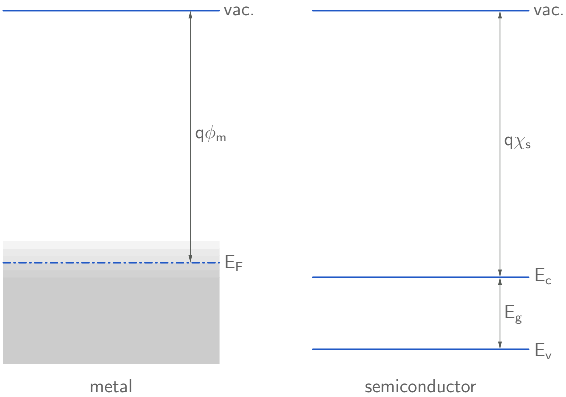

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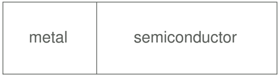

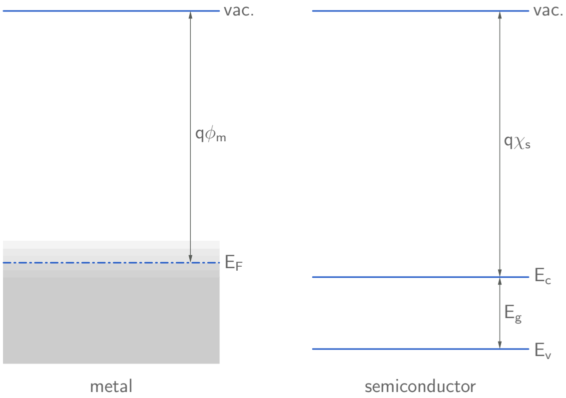

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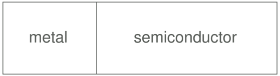

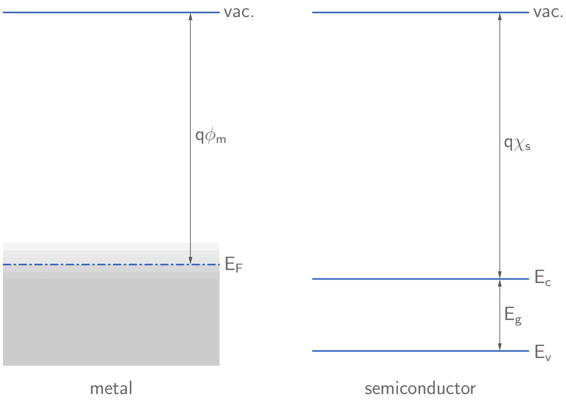

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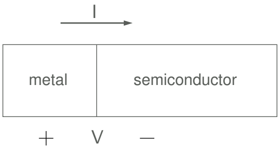
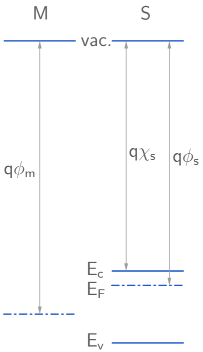
- additional electron states within the band gap at the interface
  (We will ignore this effect, i.e., we will assume the M-S interface to be perfect.)

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





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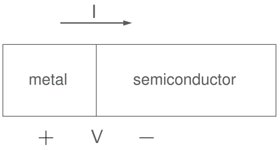

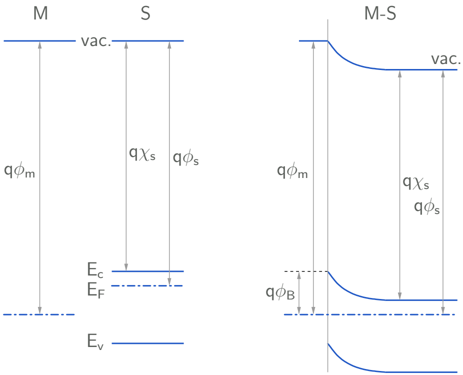

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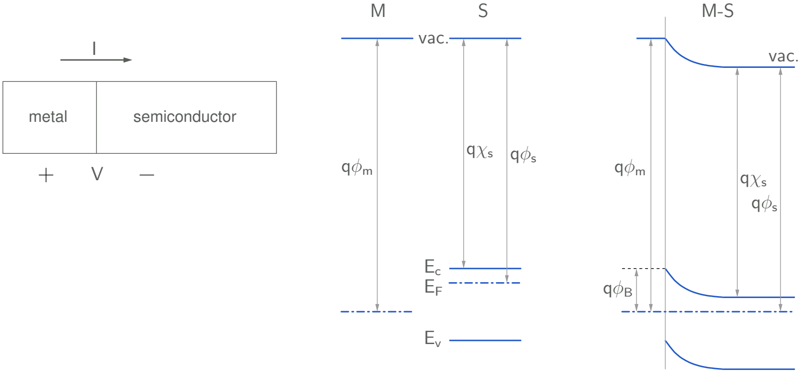

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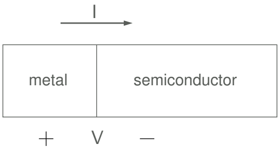

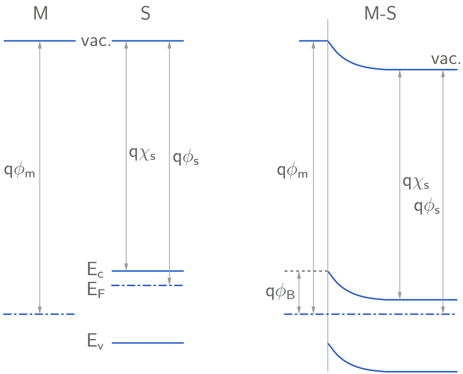

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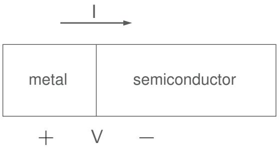

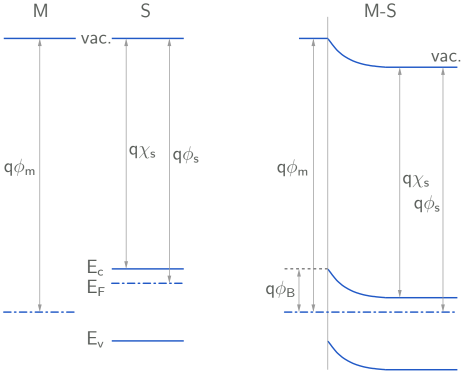

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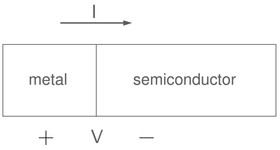

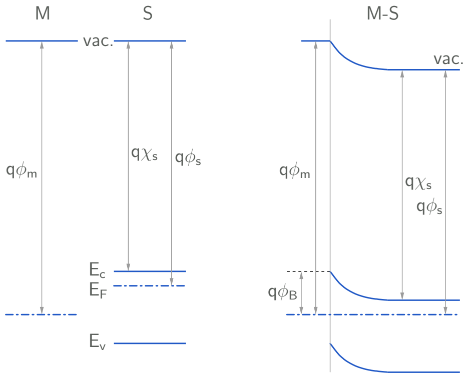

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* If a positive voltage is applied to the metal (w.r.t. the semiconductor), the barrier to electron flow from S to M reduces $\rightarrow$ current can flow.
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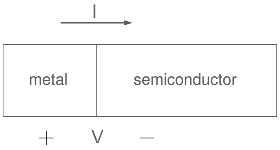

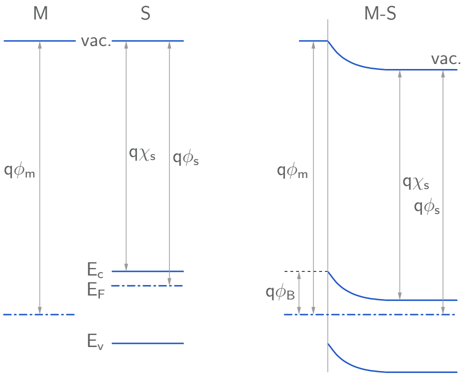

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* This condition leads to a rectifying contact.

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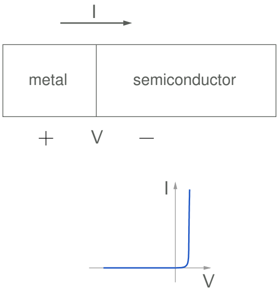

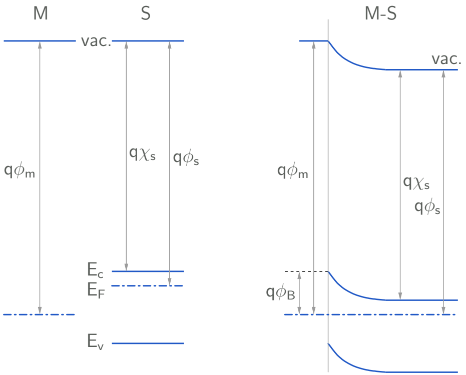

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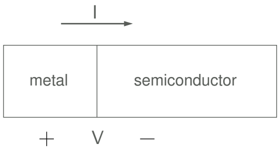

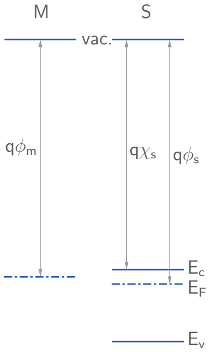

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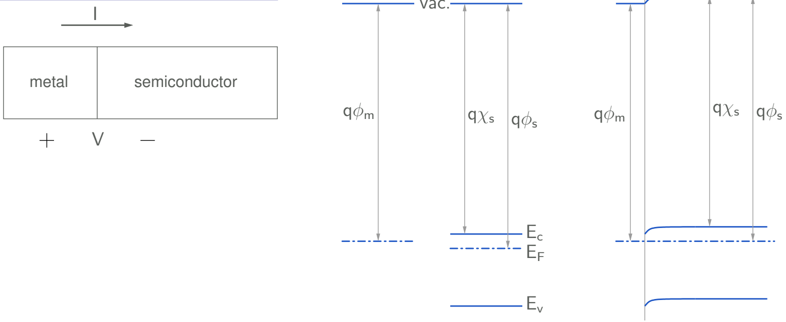

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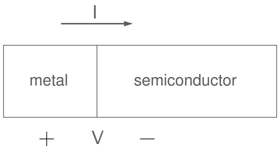

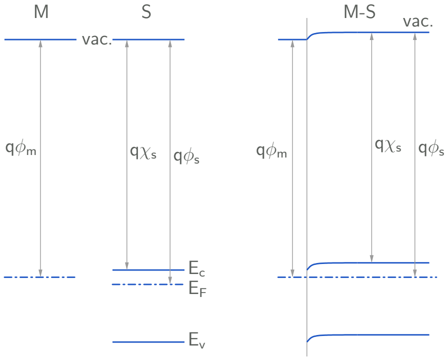

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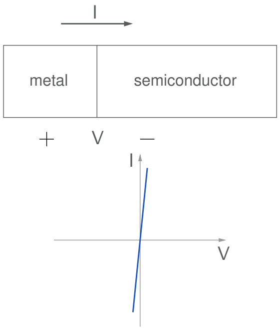

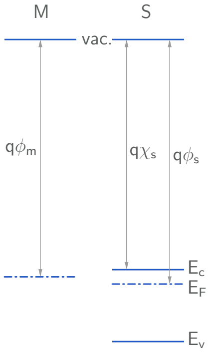

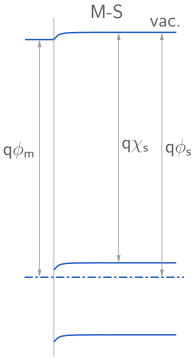

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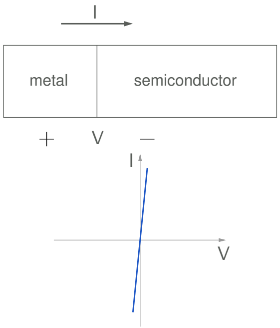

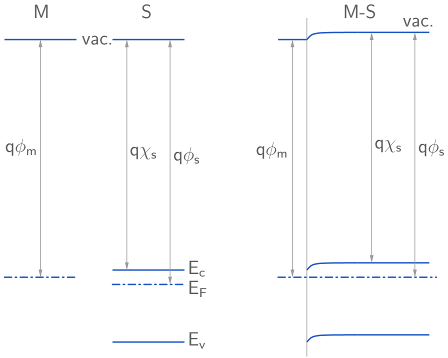

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* In real semiconductors, there are significant departures from the ideal situation we have described.

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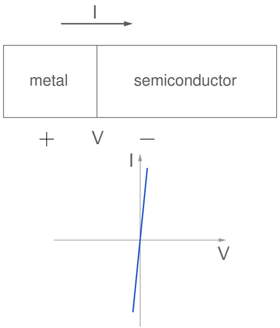
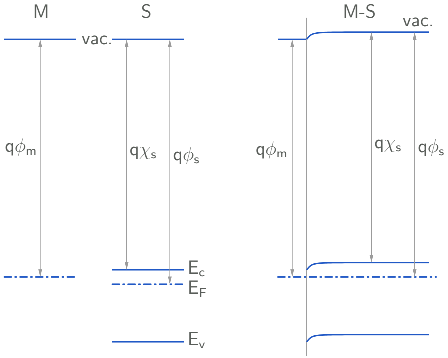
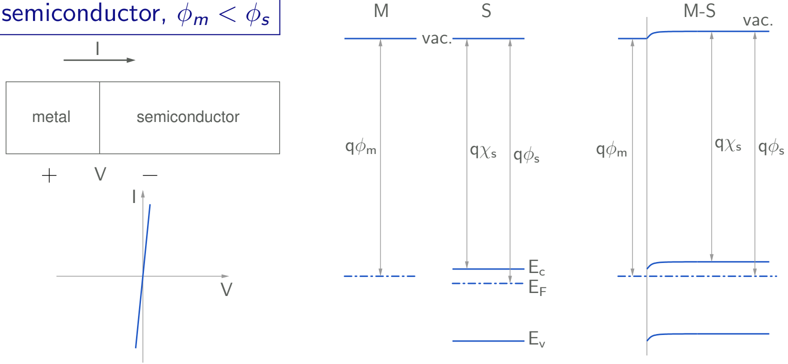




* There is a no barrier to electron flow from S to M $\rightarrow$ ohmic contact.
* In real semiconductors, there are significant departures from the ideal situation we have described.
  - At the M-S interface, the semiconductor crystal structure gets abruptly terminated, which results in incomplete ("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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  - There may be a thin ($\sim 10\,\text{Å}$) oxide layer between the metal and the semiconductor.

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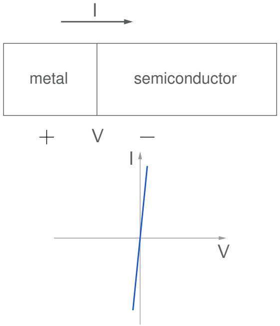

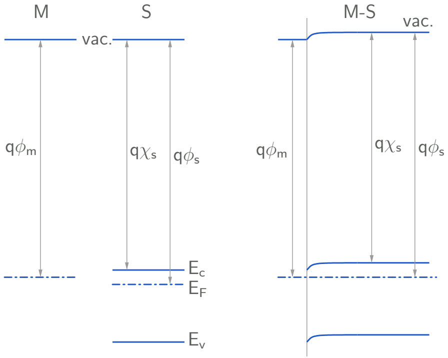

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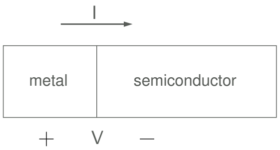
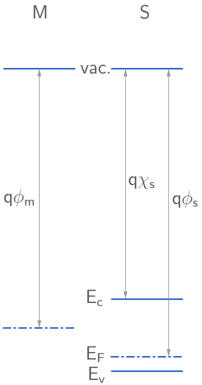
  - There may be a thin (~ 10 Å) oxide layer between the metal and the semiconductor.

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, $\phi_m < \phi_s$





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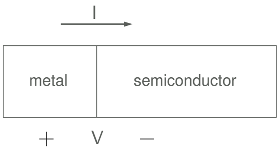

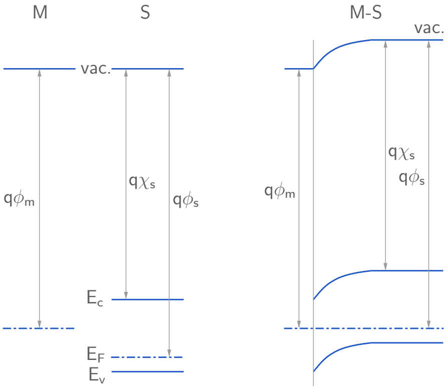

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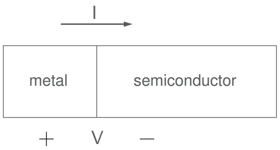

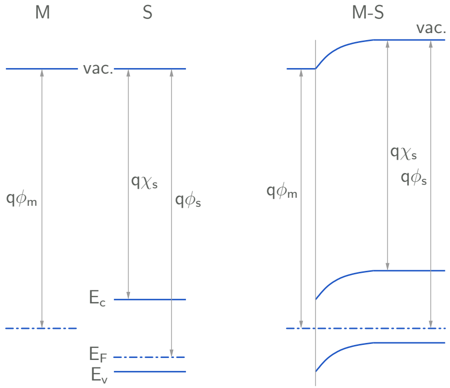

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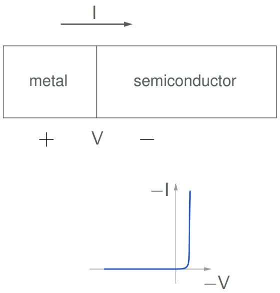

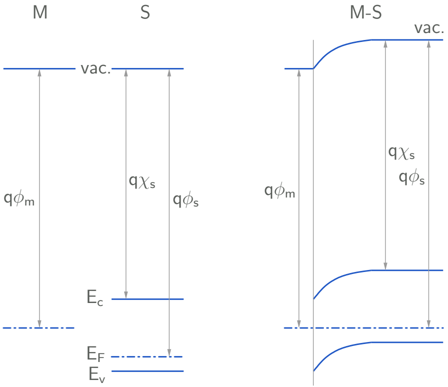

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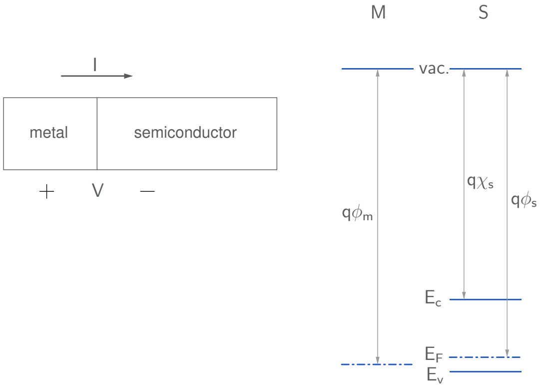

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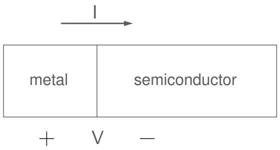

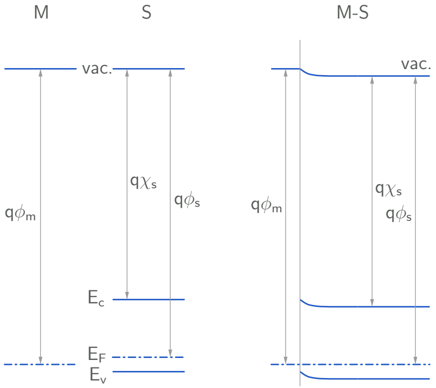

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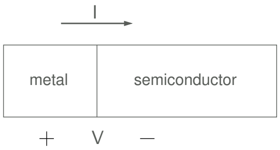

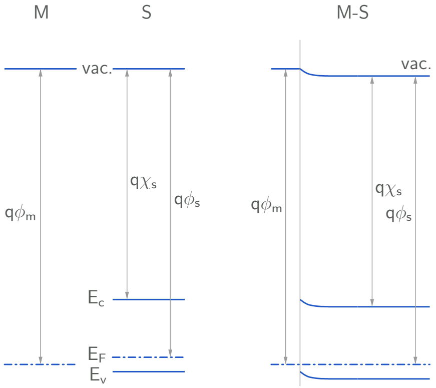

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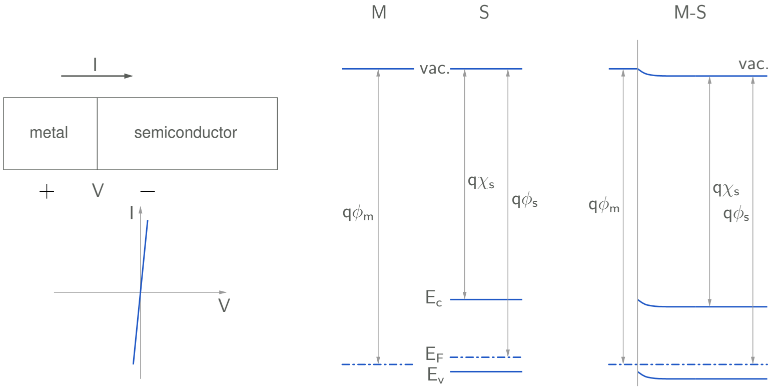

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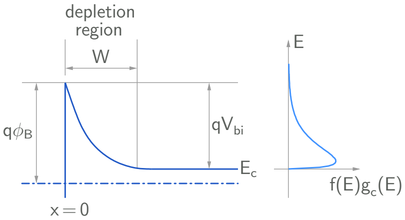
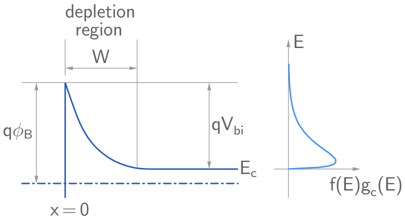
* In an M-S junction, minority carriers play no role in current conduction, and it is the injection of the majority carriers from semiconductor to metal which determines the current.



Consider a M-S junction in equilibrium.

Current-voltage relationship for a rectifying M-S junction



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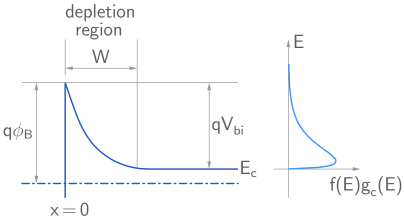

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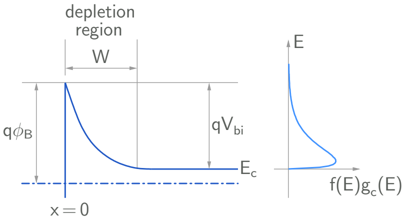

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* In equilibrium, there is an equal and opposite current density,
  $J_{M\rightarrow S} = -J_{S\rightarrow M} = -A^* T^2 \, e^{-\phi_B/V_T}$,
  resulting in a net current density $J = 0$.

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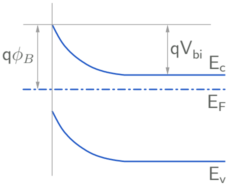

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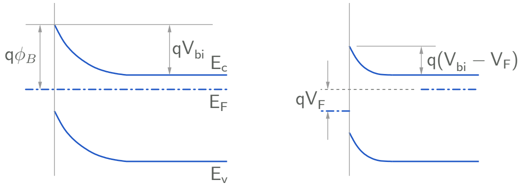

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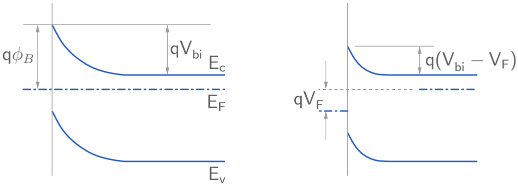

With a forward voltage, the barrier to electron flow from S to M decreases by V_F while that for M to S remains the same, and the net current density is

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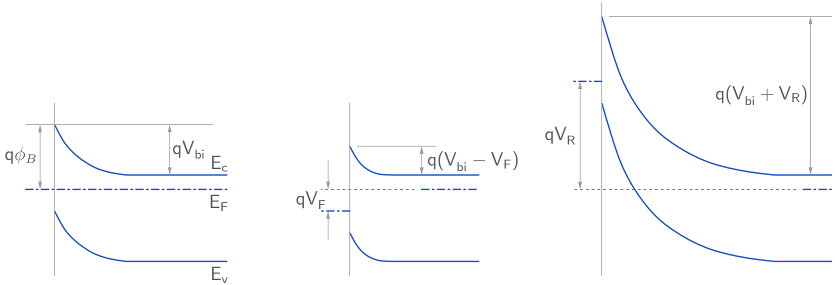

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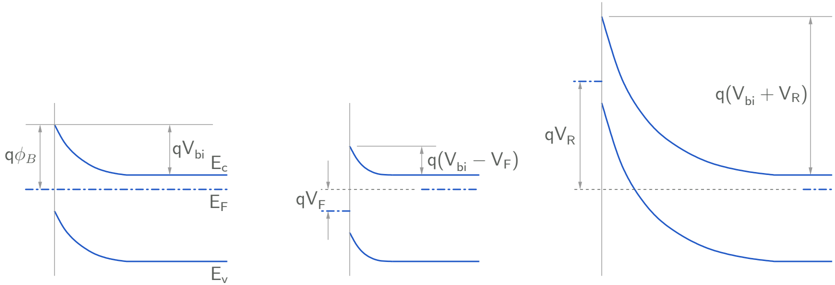

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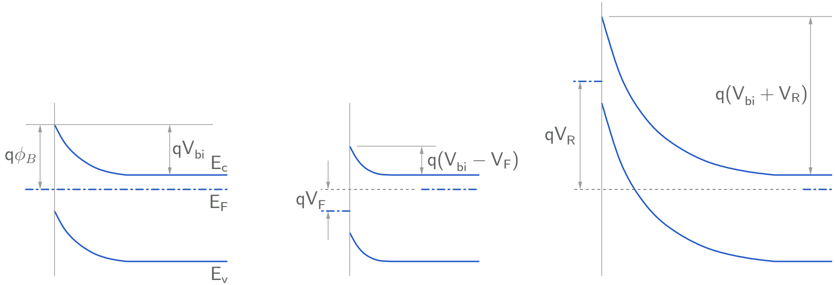

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In summary, $J = J_s \left[e^{V/V_T} - 1\right]$, where $J_s = A^* T^2 \, e^{-\phi_B/V_T}$.

* For both *pn* and rectifying M-S junctions, we have $J = J_s \left(e^{V_a/V_T} - 1 \right)$.

Rectifying M-S junction

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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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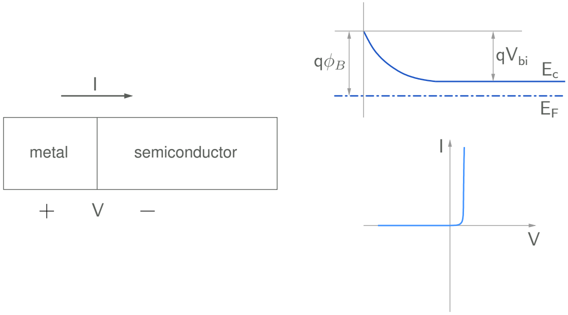
Effect of high doping density



(a)

* The contact in (a) is rectifying because of the potential barrier.

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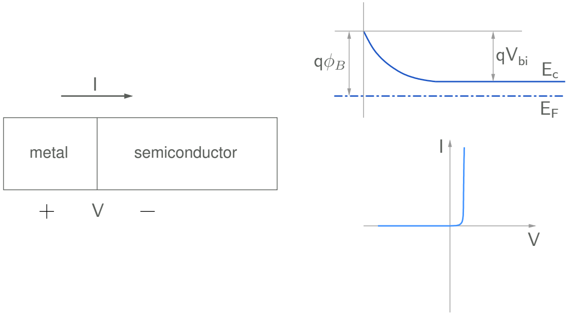

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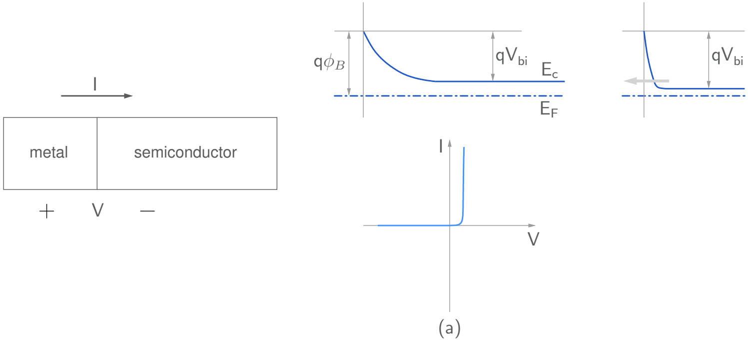

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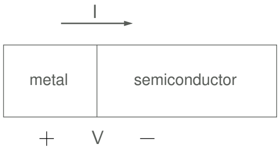

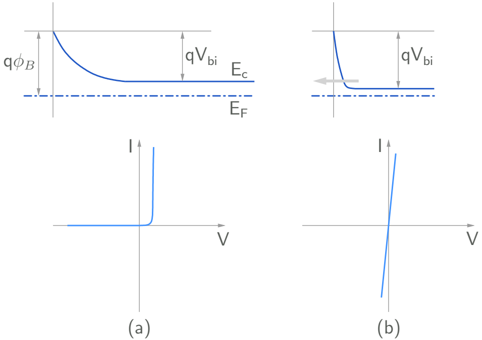

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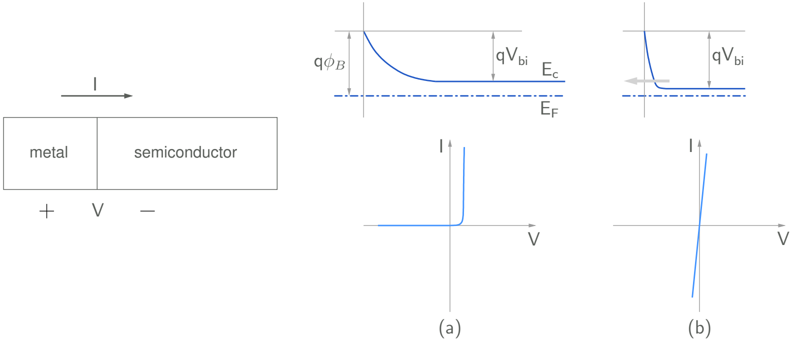

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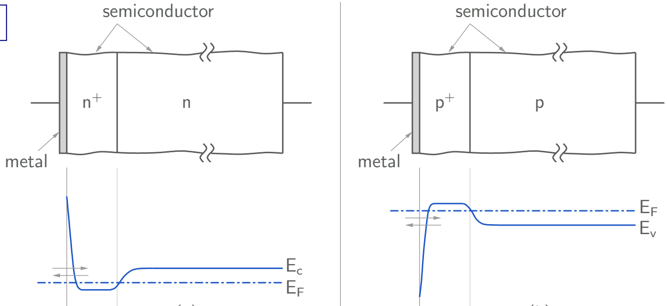
* If the doping density is increased, the barrier width (depletion region width) decreases, and tunneling of electrons becomes possible even with a small applied voltage (of either polarity) $\rightarrow$ an ohmic contact.

Practical ohmic contacts



(a) (b)

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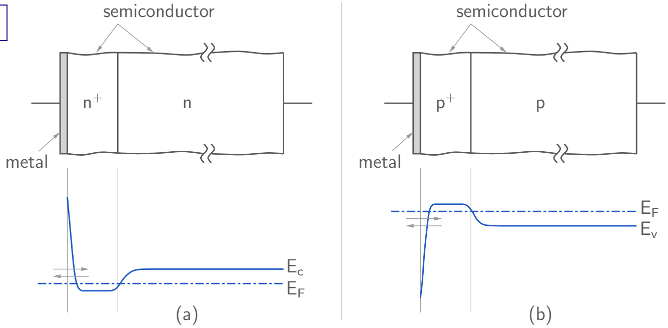

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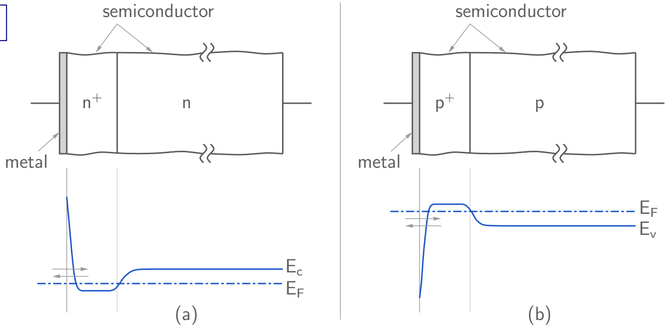

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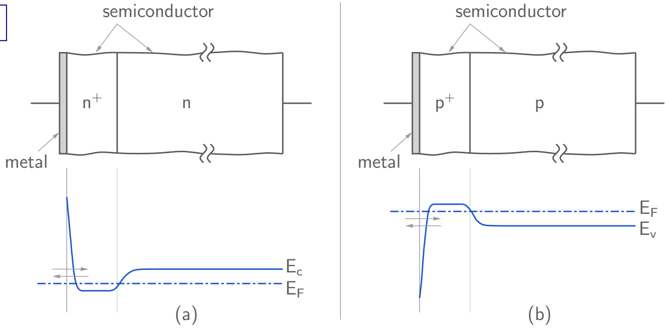

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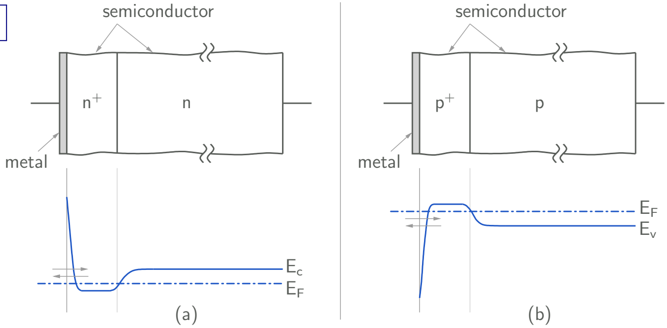

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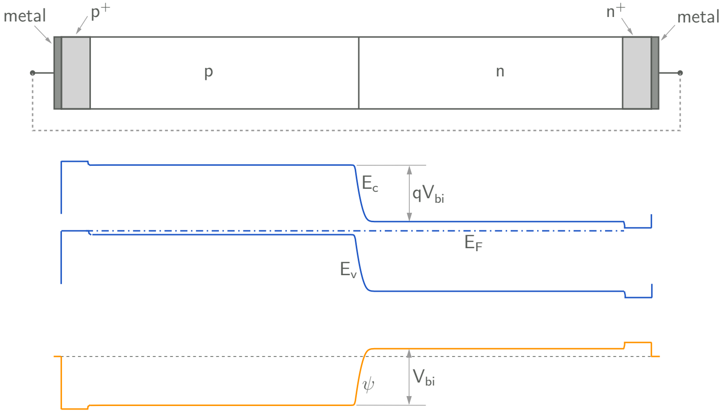
* These n^+n or p^+p junctions are essentially ohmic since a large number of majority carriers (of the same type) are available for conduction on both sides of the junction.
* Next, metal is deposited to make a metal-n^+ or metal-p^+ junction, which is ohmic — irrespective of the barrier ϕ_B — because 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 $\sim 450\,^{\circ}\mathrm{C}$ for a few minutes.)

pn junction: band diagram with contact regions



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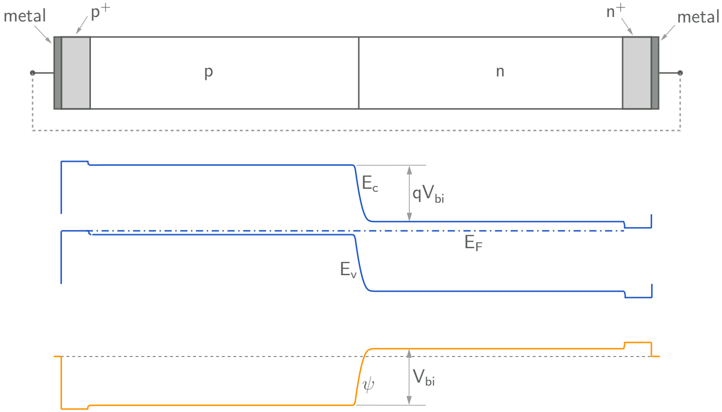

* Equilibrium: The net voltage drop is zero; the voltage drop (V_{bi}) across the depletion region is equal and opposite to the sum of the other voltage drops.

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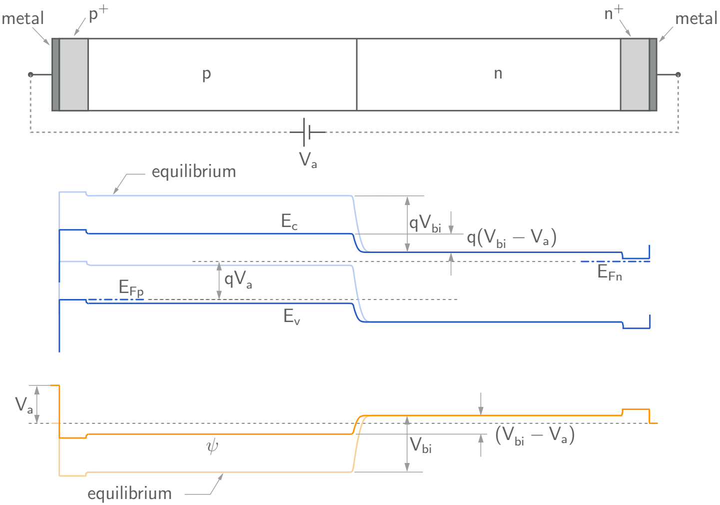

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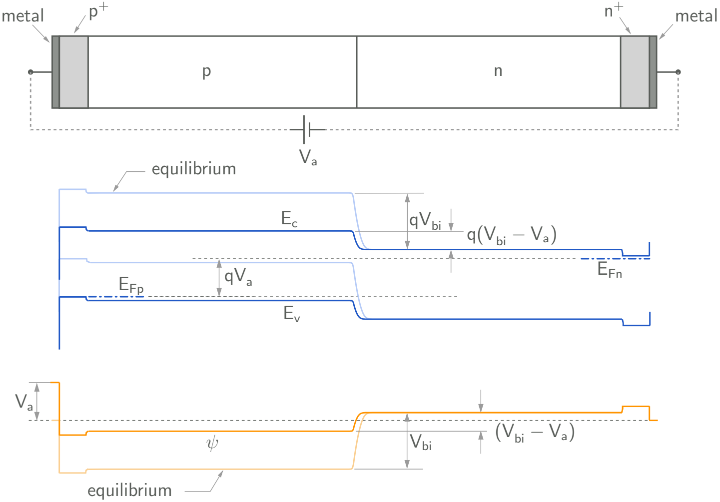
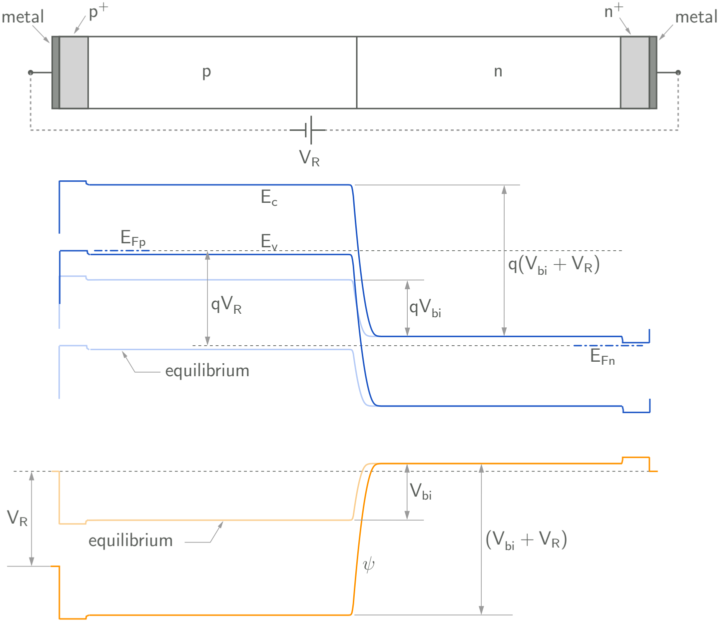
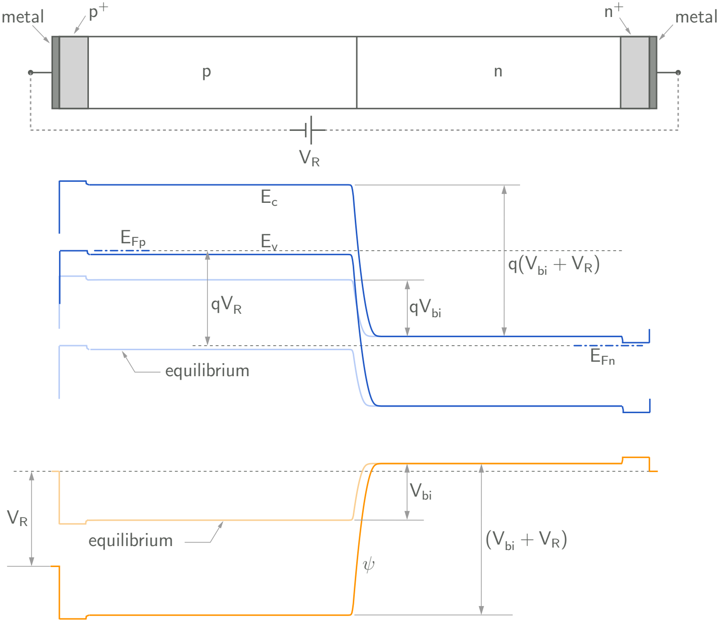


* Forward bias: The voltage drops across the M-S junctions, the n^+-n junction, and the p^+-p junction remain the same as in equilibrium; the applied forward voltage appears across the depletion region ($V_{\text{bi}} \rightarrow V_{\text{bi}} - V_a$).


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
(V_bi + V_R)
equilibrium
ψ



* Reverse 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 reverse voltage appears across the depletion region ($V_{\mathrm{bi}} \rightarrow V_{\mathrm{bi}} + V_R$).