3G rule for attending in person lectures at KIT:

- ***geimpft*** **– vaccinated**
- ***genesen*** **– recovered**
- ***getestet*** **– tested**

“Solar Energy” WS 2021/2022

Karlsruher Institut für Technologie

Lecture 5: Semiconductor Junctions (*p*–*n* Junction Diode)

Tenure-Track-Prof. Dr. Ulrich W. Paetzold

Institute of Microstructure Technology (IMT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen
Light Technology Institute (LTI), Engesserstrasse 13, Building 30.34, 76131 Karlsruhe

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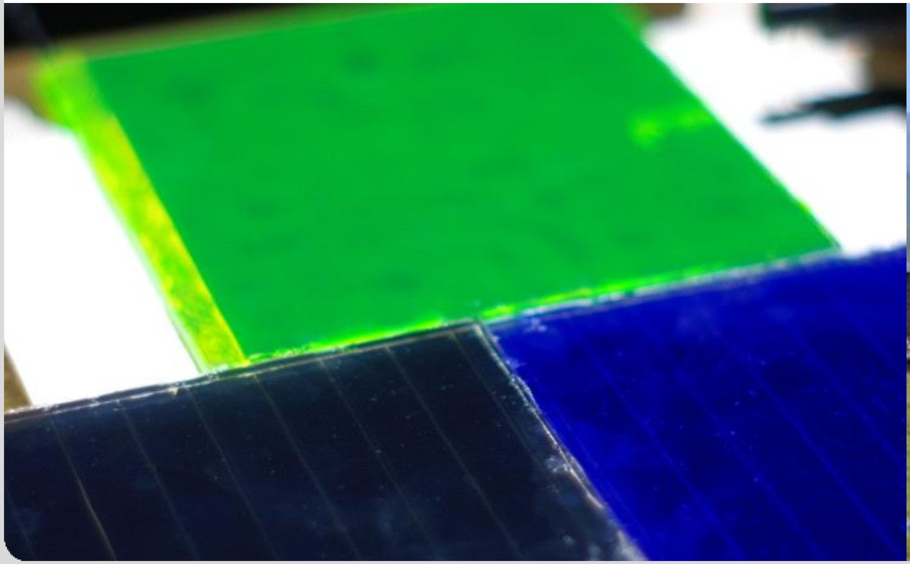
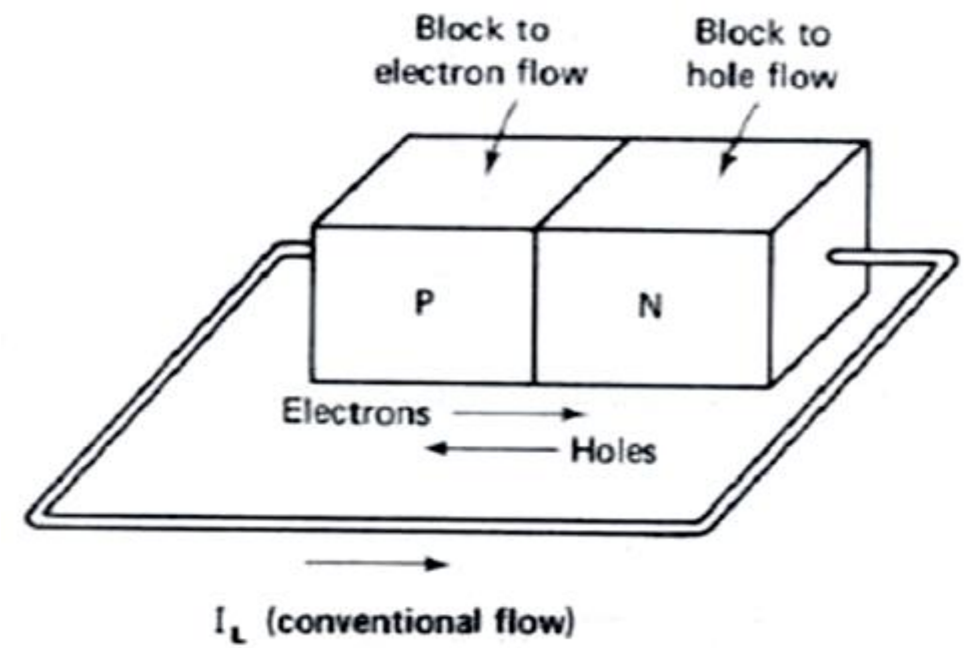
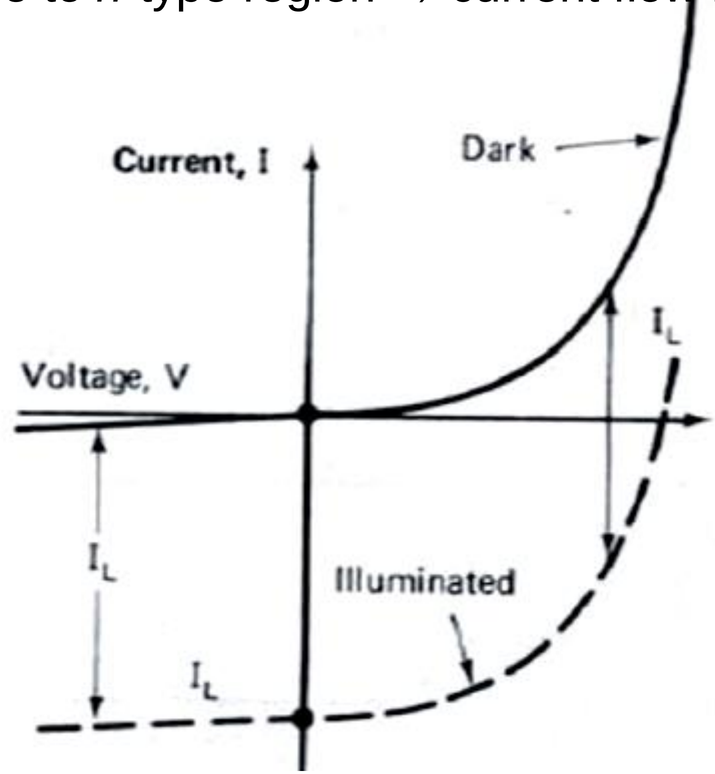


p–n Junction Diodes

The market dominating PV technology (c-Si solar cells) can be described in first approximation simply as large diodes, formed by making a junction between *n*- and *p*-type material.

Basic requirement of electronic asymmetry: *n*-type regions have large e^- densities but small h^+ densities ⇒ e^- flow easily but h^+ find it difficult. When illuminated, excess e^--h^+ pairs are generated, with a flow of e^- from *p*-type to *n*-type region ⇒ current flow in the lead!





Source: *Green, “Solar Cells”, Prentice Hall 1998*

Outline

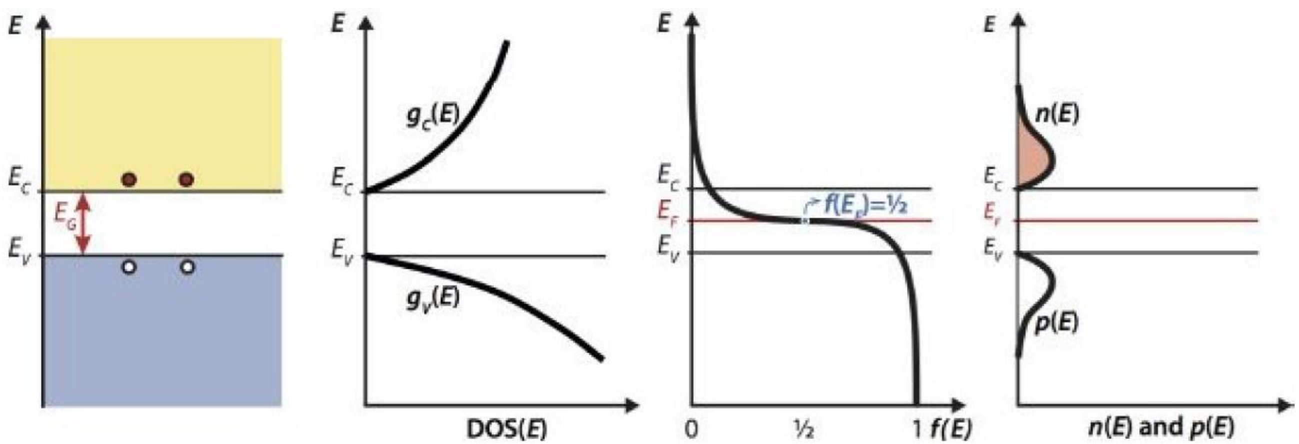
- RECAP: Charge concentration, doped semiconductor
- Part I: pn-junction in thermal equilibrium
- Part II: pn-junction under applied bias
- Part III: pn-junction under light
- Part IV: Heterojunctions (extra materials)

Recapitulation - Carrier concentrations

<u>Intrinsic semiconductor in thermal equilibrium:</u>

The carrier concentrations n(E) and p(E) are a product of:

1. The *density of states* function DoS(*E*) per unit volume and energy. Given for conduction band (CB) close to *EC* and in the valence band (VB) close to *EV* by $g_c(E)$ and $g_v(E)$, respectively.
2. The occupation function is the Fermi–Dirac distribution function, *f* (*E*), which describes the ratio of states filled with an electron to total allowed states at given energy *E*.



$$n(E) = g_C(E) f(E),$$

$$p(E) = g_V(E)\,[1 - f(E)]$$

$$n = \int_{E_C}^{E_{top}} n(E)\,dE,$$

$$p = \int_{E_{bottom}}^{E_V} p(E)\,dE.$$

Source: textbook

Recapitulation - Carrier concentrations

<u>Intrinsic semiconductor in thermal equilibrium:</u> Effective density of states of electrons *n* in E_c *and p in* E_V is given by

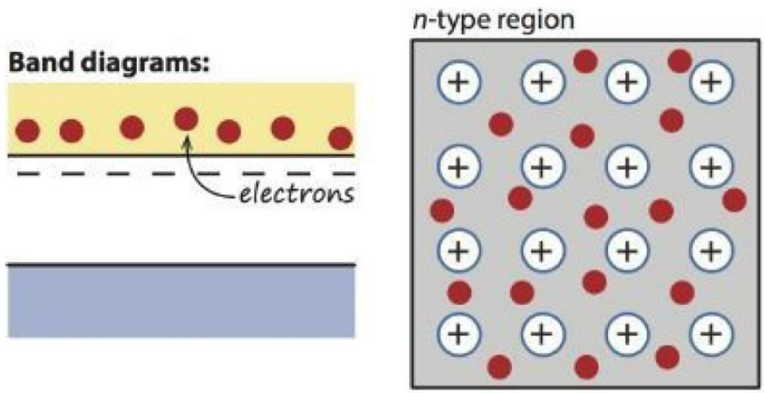
$$n = N_c e^{((E_F - E_c)/kT)} \quad \text{and} \quad p = N_v e^{((E_v - E_F)/kT)}$$

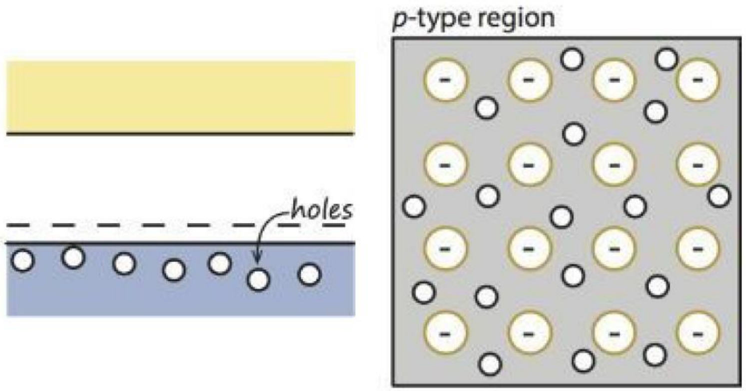
Hence, consider n = p = n_i^2, the Fermi level in an undoped semiconductor lies close to the midgap, being offset by differences in the effective density of states in E_c and E_v

$$E_F = \frac{E_c + E_v}{2} + \frac{k_B T}{2} \ln\left(\frac{N_v}{N_c}\right)$$

Recapitulation

Doped semiconductor: Charge neutrality preserved, but charge carrier concentrations dominated by doping.





Majority carrier: $n_n \approx N_D$

Minority carrier: $p_n = n_i^2/N_D << n$

$$\Rightarrow \; E_F - EC = \; kBT \ln\left(\frac{N_C}{N_D}\right)$$

Majority carrier: $p_p \approx N_A$

Minority carrier: $n_p = n_i^2/N_A << p$

$$\Rightarrow \; E_F - EV = \; kBT \ln\left(\frac{N_V}{N_A}\right)$$

Source: textbook

Outline

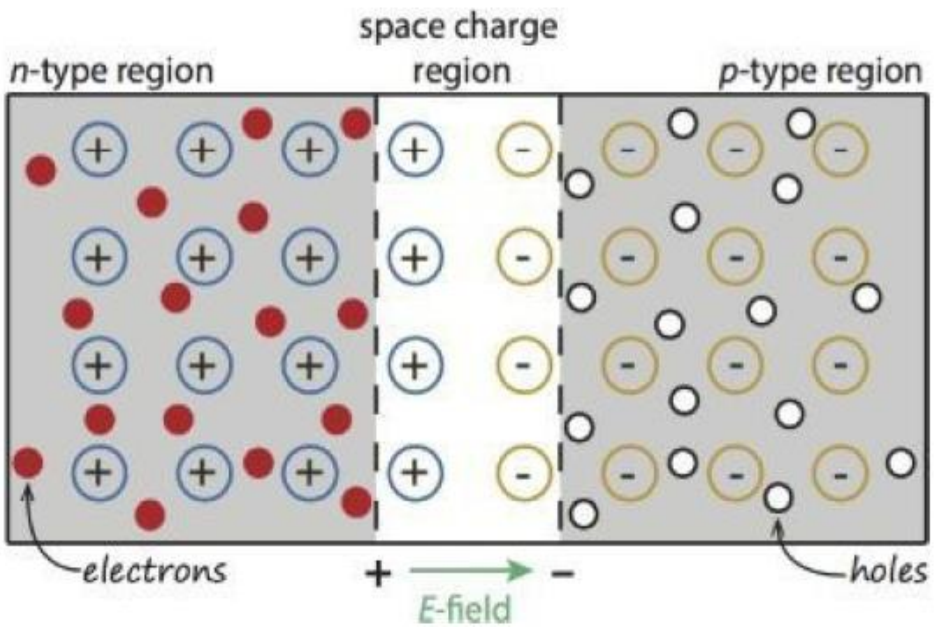
- RECAP: Charge concentration, doped semiconductor
- **Part I: pn-junction in thermal equilibrium**
- Part II: pn-junction under applied bias
- Part III: pn-junction under light
- Part IV: Heterojunctions (extra materials)

n-type and p-type regions in contact

In a p-n junction the doped n-region and p-region are brought in contact, a very high concentration gradient of majority charge carrier occurs.

=> Expected that excess e^{-} flow from region of high conc. (*n*-type) to regions of low conc. (*p*-type), and similarly for h^{+}

- But, e^{-} leaving *n*-type side leave behind ionised donors (positive charge), and h^{+} leaving *p*-type region will ionised acceptors (negative charges).
- A **space charge region** free of mobile charge carriers appears. It “extends” until the force resulting from the electric field between ionised background charges compensates the concentration gradient.

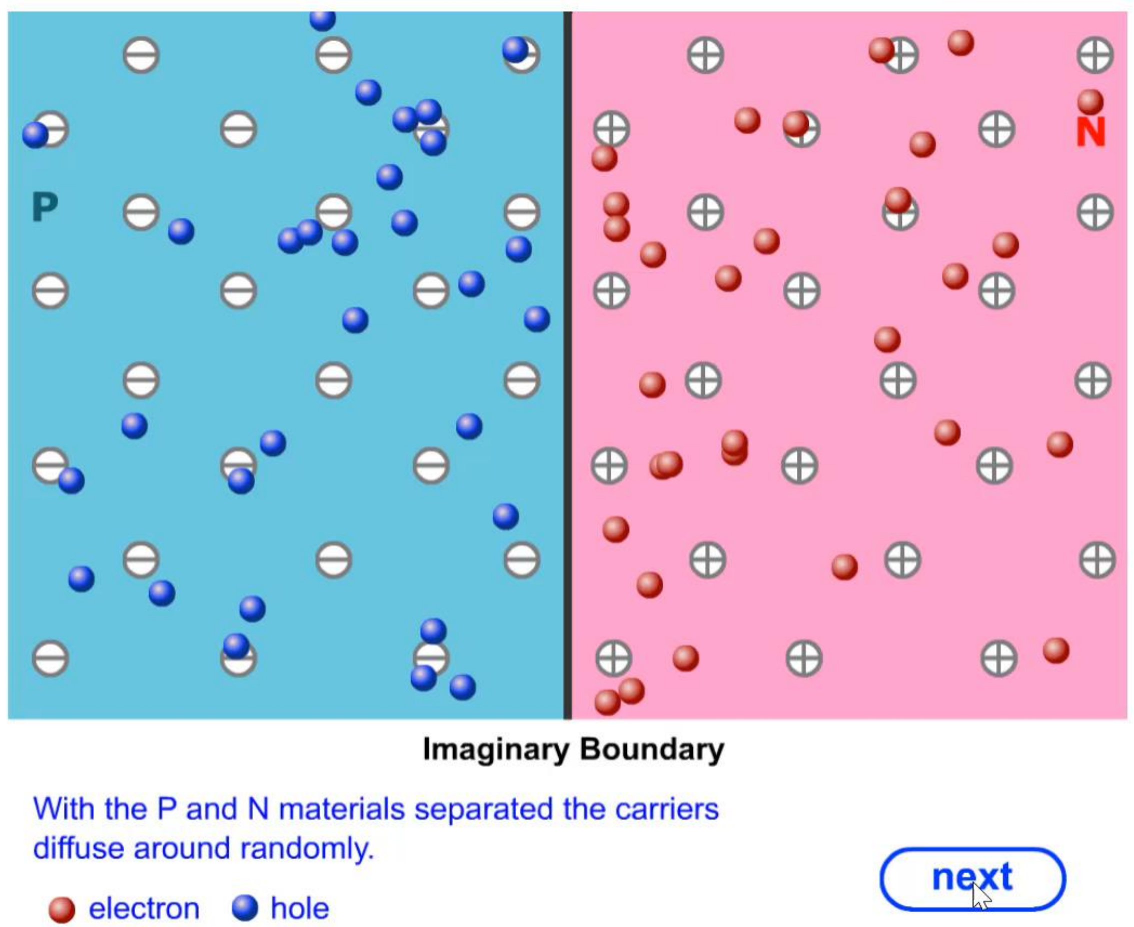


Source: textbook

p–n Junction Diode Under Equilibrium

In equilibrium, the net current from the device is zero.

Electron drift current and electron diffusion current exactly balance out (same for holes)

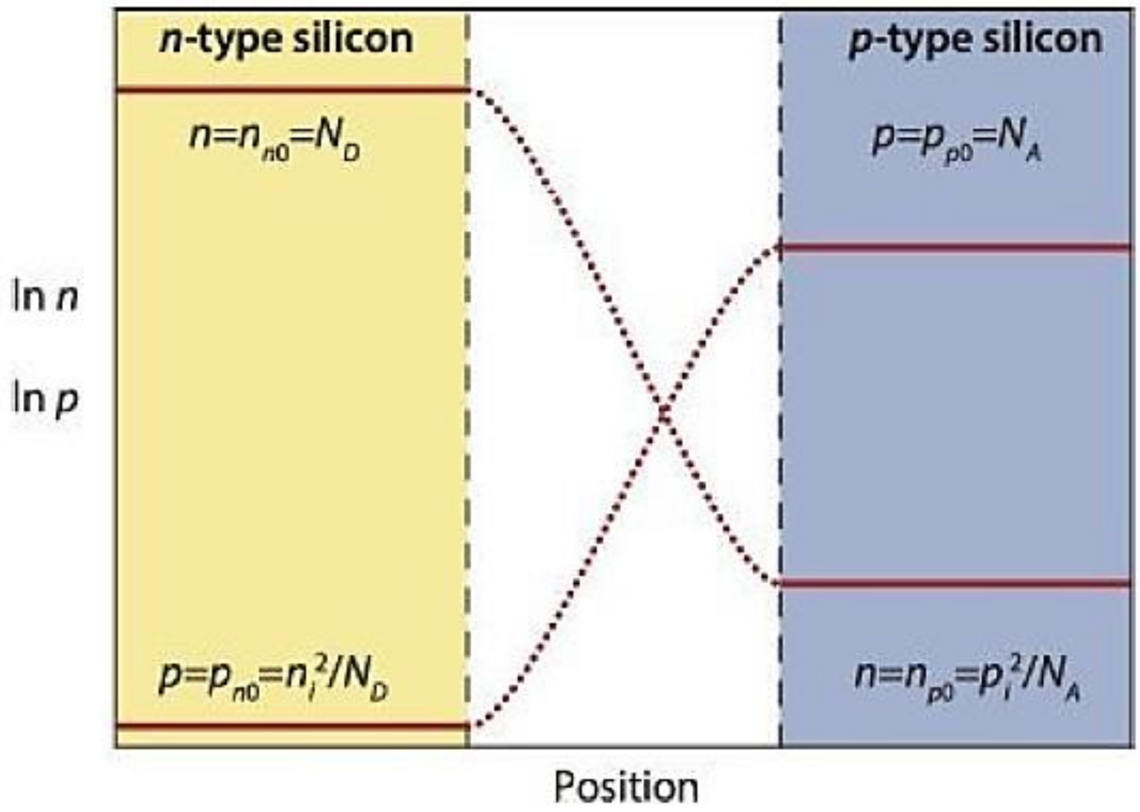


Source: http://www.pveducation.org/pvcdrom/pn-junction/pn-junction-diodes

Source: textbook

p–n Junction Diode Under Equilibrium

Concentrations profile of mobile charge carriers in a *p-n* junction under equilibrium



Source: textbook

p–n Junction Diode Under Equilibrium

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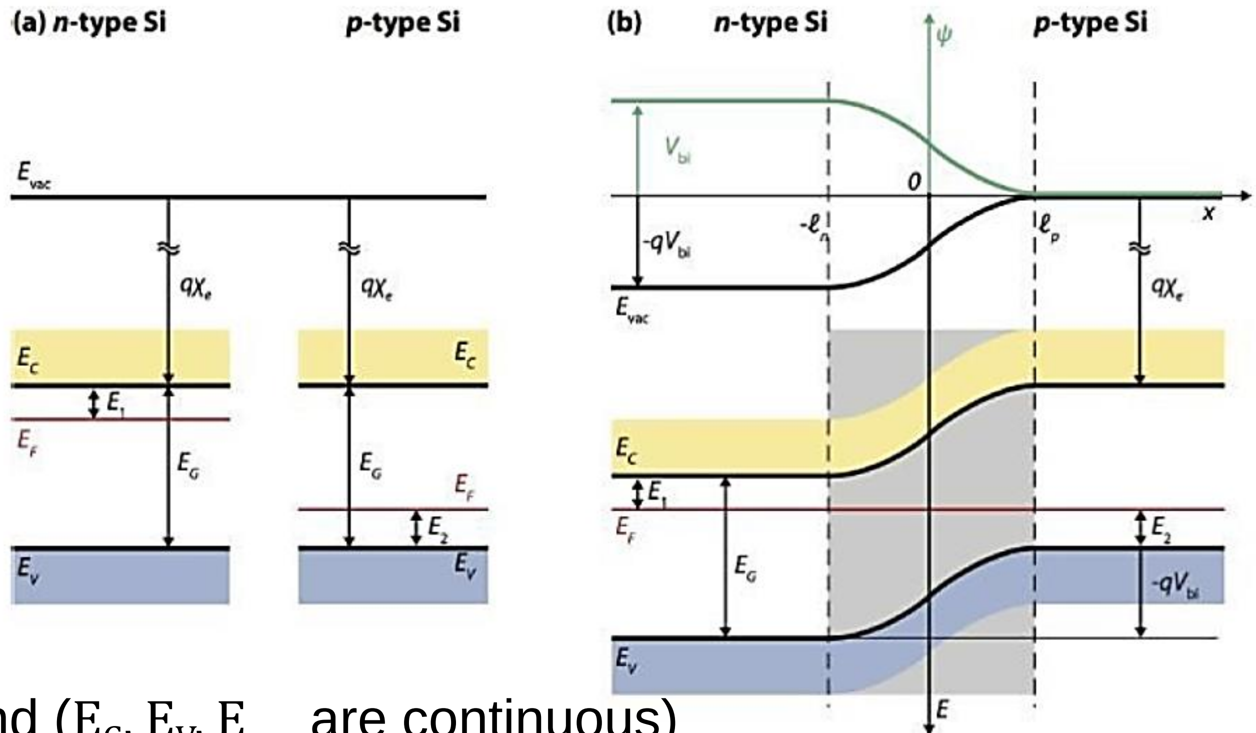
Based on these considerations, one obtains an idea of the band structure:

- Fermi Energy must be constant across the junction
  (“A system in equilibrium can only have one Fermi Energy”)
- Far away from the junction the diode behaves like a doped semicond.



⇒ bands bend (E_C, E_V, E_{vac} are continuous)

⇒ Internal E-field is determined by a so called *built-in-voltage*

Source: textbook

p–n Junction Diode Under Equilibrium

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Derivation of the build-in voltage / electrostatic potential difference across the space charge region (also called depletion region).

$$\mathrm{qV_{bi}} = \mathrm{E_C}(-\infty) - \mathrm{E_C}(+\infty)$$

consider $\mathrm{p_p} = \mathrm{N_V}\, e^{-\frac{E_F - EV(-\infty)}{k_B T}} = \mathrm{NA}$ and $\mathrm{n_n} = \mathrm{N_C}\, e^{-\frac{E_C(\infty) - EF}{k_B T}} = \mathrm{N_D}$

=> $\mathrm{p_p\ n_n} = \mathrm{N_A N_D} = \mathrm{N_C N_V}\, e^{-\frac{E_C(\infty) - EV(-\infty)}{k_B T}}$

$\Rightarrow \mathrm{N_A N_D} = \mathrm{N_C N_V} e^{-\frac{E_G}{k_B T}}\ e^{\frac{-E_C(\infty) + E_C(-\infty)}{k_B T}}$ with $\mathrm{E_G} = \mathrm{E_C}\text{-}\mathrm{E_V}$

$\Rightarrow \mathrm{V_{bi}} = \mathrm{V_T} \ln\left(\frac{N_A N_D}{n_i^2}\right)$ with $\mathrm{n_i}^2 = \mathrm{N_C N_V} e^{-\frac{E_G}{k_B T}}$ and $V_T = \mathrm{k_B T/q}$

Source: textbook

p–n Junction Diode Under Equilibrium

Built-in voltage for different semiconductors and doping concentrations

$$V_{bi} = V_T \ln\left(\frac{N_A N_D}{{n_i}^2}\right)$$

- depends only on intrinsic charge carrier concentration
- Increases moderately with doping concentrations (N_A, N_D).
- With increasing doping concentration: $V_{bi} \longrightarrow E_G/q$
- Note also dependence of n_i and T.

T = 300 K	Ge	Si	GaAs
n_i^2/cm^{-6}	$5,8 \cdot 10^{26}$	$2,1 \cdot 10^{20}$	$3,2 \cdot 10^{12}$
n_A/cm^{-3}	10^{15}	10^{15}	10^{15}
n_D/cm^{-3}	10^{15}	10^{15}	10^{15}
U_D/V	$0,18$	$0,56$	$1,0$
n_A/cm^{-3}	10^{15}	10^{15}	10^{15}
n_D/cm^{-3}	10^{18}	10^{18}	10^{18}
U_D/V	$0,36$	$0,73$	$1,18$
n_A/cm^{-3}	10^{18}	10^{18}	10^{18}
n_D/cm^{-3}	10^{18}	10^{18}	10^{18}
U_D/V	$0,53$	$0,90$	$1,35$

Courtesy U. Lemmer

Source: textbook

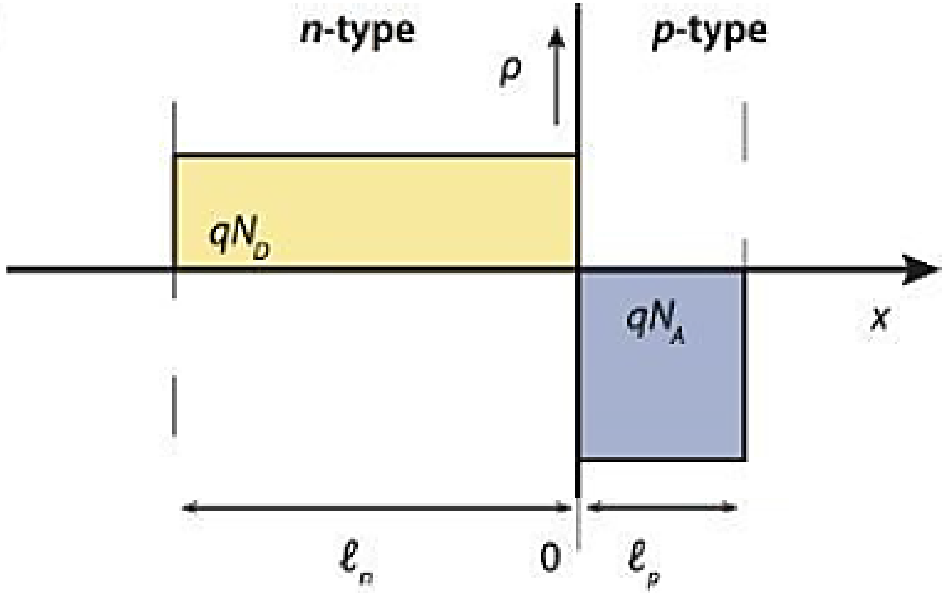
p–n Junction Diode Under Equilibrium

In order to derive more quantitative characteristics, we proceed with the simplified description of the diode in the *Shockley model"* also called *"abrupt junction approximation"* :

$$\rho(x) = \mathrm{qN_D} \quad \text{for} \quad -l_\mathrm{n} \le x \le 0$$

$$\rho(x) = \mathrm{qN_A} \quad \text{for} \quad 0 \le x \le l_p$$

Note, outside the space charge region, the charge density $\rho(x) = 0$.



Source: textbook

p–n Junction Diode Under Equilibrium

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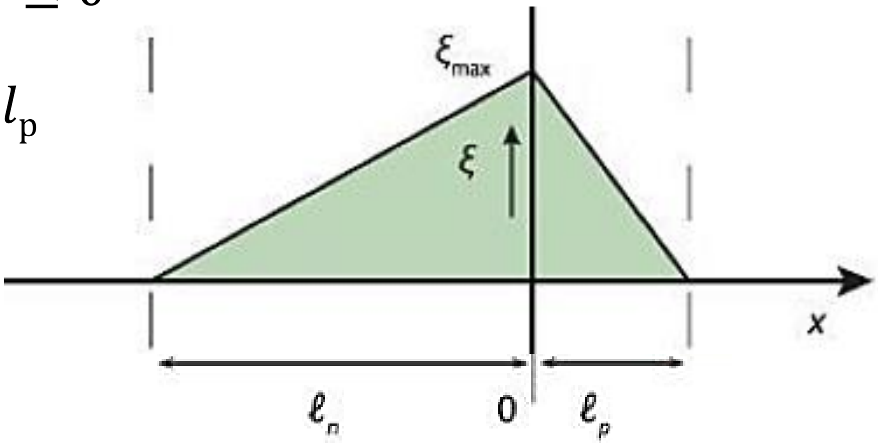
In the *abrupt junction approximation*, the electric field and the potential can be calculated simply with Poisson's equation: $\frac{d^2\psi}{dx^2} = -\frac{d\ E}{dx} = -\frac{\rho}{\varepsilon_0\varepsilon_r}$

where ψ is the electrostatic potential, E is the electric field, ρ is the space-charge density, ε_0 is the dielectric constant in vacuum, and ε_r the material specific dielectric constant.

Derivation $\mathrm{E} = \frac{1}{\varepsilon_0\varepsilon_r}\int \rho\, dx$ with $\mathrm{E}(-l_\mathrm{n}) = \mathrm{E}(l_\mathrm{p}) = 0$:

$$\mathrm{E}(x) = \frac{q}{\varepsilon_0\varepsilon_r}\mathrm{N_D}(-\mathrm{l_n} + x) \quad for \quad -l_\mathrm{n} \le x \le 0$$

$$\mathrm{E}(x) = \frac{q}{\varepsilon_0\varepsilon_r}\mathrm{N_A}(\mathrm{l_p} - x) \quad for \quad 0 \le x \le l_\mathrm{p}$$



Considering the continuity of E at the boundary we of the junction.

$$N_A l_p = N_D l_n$$

Source: textbook

p–n Junction Diode Under Equilibrium

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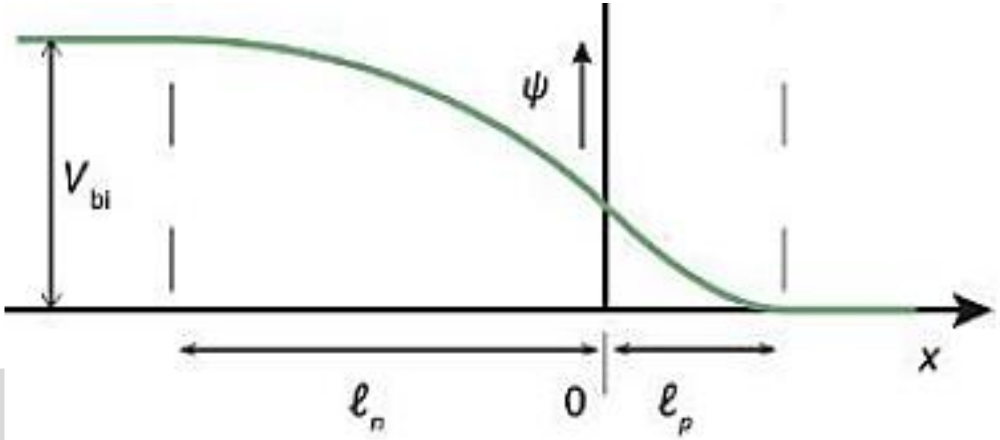
In the *abrupt junction approximation*, the electric field and the potential can be calculated simply with Poisson's equation: $\frac{d^2\psi}{dx^2} = -\frac{d^2E}{dx} = -\frac{\rho}{\varepsilon_0\varepsilon_r}$

where ψ is the electrostatic potential, E is the electric field, ρ is the space-charge density, ε_0 is dielectric constant in vacuum, and ε_r the material specific dielectric constant.

Derivation of $\psi(x) = \int E\,dx$ with $\psi(l_\mathrm{p}) = 0)$:

$$\psi(x) = \frac{q}{2\varepsilon_0\varepsilon_r} N_\mathrm{D}(x + l_\mathrm{n})^2 + \frac{q}{2\varepsilon_0\varepsilon_r}(N_D\,l_n{}^2 + N_A\,l_p{}^2)^2 \qquad for\ -l_\mathrm{n} \le x \le 0$$

$$\psi(x) = \frac{q}{2\varepsilon_0\varepsilon_r} N_\mathrm{A}(x + l_\mathrm{n})^2 \qquad for\ \ 0 \le x \le lp$$



Source: textbook

p–n Junction Diode Under Equilibrium

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Knowing the electrostatic potential ψ(x) across the junction, we see that the built-in voltage is key too the characteristics of the junction:

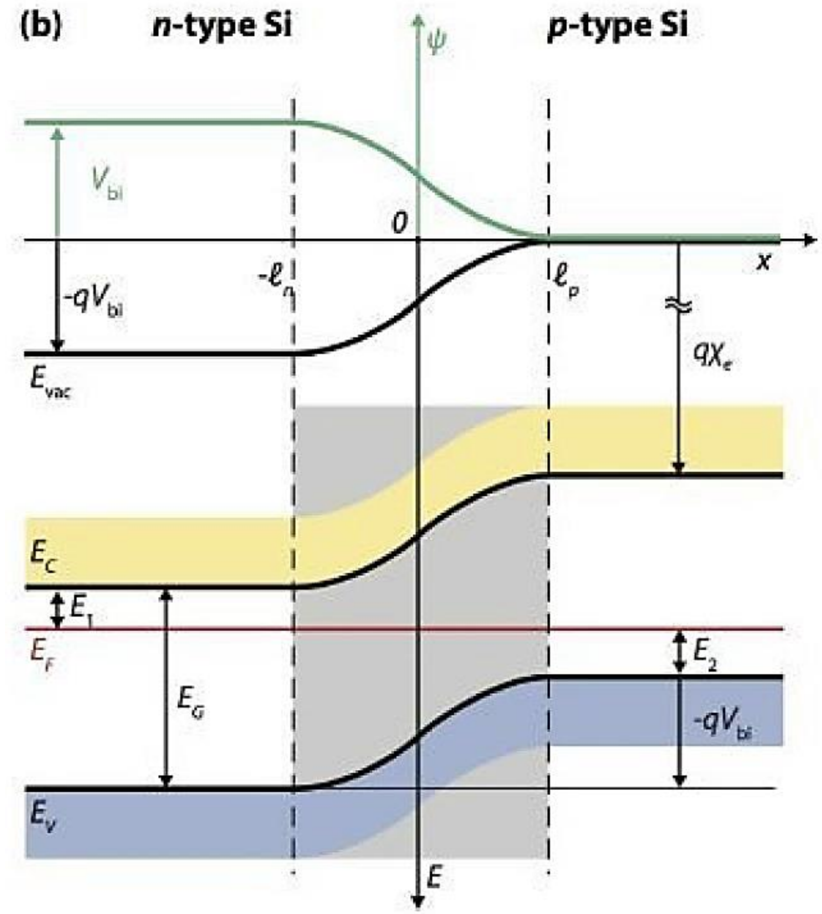
- $V_{bi} = \psi(-l_n) - \psi(l_p) = \psi(-l_n)$

  $= \frac{q}{2\varepsilon_0\varepsilon_r}(N_D\, l_n^2 + N_A\, l_p^2)$

- $V_{bi} = E_G - E_1 - E_2 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$

  with $n_i^2 = N_C N_V e^{-\frac{E_G}{k_B T}}$

  and $V_T = k_B T/q$



Source: textbook

p–n Junction Diode Under Equilibrium

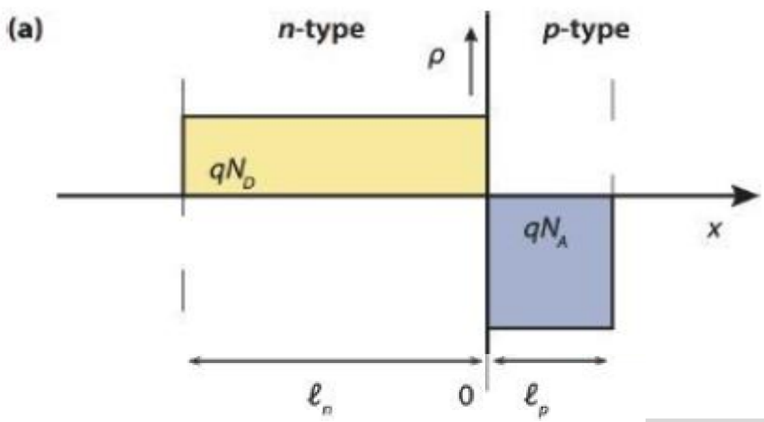
<u>The width of the space charge region</u> ($W = l_n + l_p$) is calculated next.

Consider $V_{bi} = \frac{q}{2\varepsilon_0\varepsilon_r}(N_D\, l_n{}^2 + N_A\, l_p{}^2)$

and $N_A l_p = N_D l_n$

=> $l_n{}^2 = \frac{2\varepsilon_0\varepsilon_r}{q}\frac{N_A}{N_D}\frac{V_{bi}}{(N_A+N_D)}$, $l_p{}^2 = \frac{2\varepsilon_0\varepsilon_r}{q}\frac{N_D}{N_A}\frac{V_{bi}}{(N_A+N_D)}$

=> $W = \sqrt{\frac{2\varepsilon_0\varepsilon_r}{q}V_{bi}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)}$



$T = 300$ K	Ge	Si	GaAs
ε_r	16	11,9	13,1
n_A/cm^{-3}	10^{15}	10^{15}	10^{15}
n_D/cm^{-3}	10^{15}	10^{15}	10^{15}
U_D/V	0,18	0,56	1,0
$l_p/\mu\text{m}$	0,4	0,6	0,85
$l_n/\mu\text{m}$	0,4	0,6	0,85
n_A/cm^{-3}	10^{15}	10^{15}	10^{15}
n_D/cm^{-3}	10^{18}	10^{18}	10^{18}
U_D/V	0,36	0,73	1,18
$l_p/\mu\text{m}$	0,8	1	1,3
$l_n/\mu\text{m}$	0,0008	0,001	0,0013
n_A/cm^{-3}	10^{18}	10^{18}	10^{18}
n_D/cm^{-3}	10^{18}	10^{18}	10^{18}
U_D/V	0,53	0,9	1,35
$l_p/\mu\text{m}$	0,02	0,02	0,03
$l_n/\mu\text{m}$	0,02	0,02	0,03

Courtesy U. Lemmer

Source: textbook

p–n Junction Diode Under Equilibrium

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The width of the space charge region ($W = l_n + l_p$) is calculated next.

Consider $V_{bi} = \frac{q}{2\varepsilon_0\varepsilon_r}(N_D\, l_n{}^2 + N_A\, l_p{}^2)$

and $N_A l_p = N_D l_n$

=> $l_n{}^2 = \frac{2\varepsilon_0\varepsilon_r}{q}\frac{N_A}{N_D}\frac{V_{bi}}{(N_A+N_D)}$, $l_p{}^2 = \frac{2\varepsilon_0\varepsilon_r}{q}\frac{N_D}{N_A}\frac{V_{bi}}{(N_A+N_D)}$

Thus, we can also derive the maximum electric field strength by:

$$E(x=0) = \frac{q}{\varepsilon_0\varepsilon_r}N_D(-l_n) = \sqrt{\frac{2q}{\varepsilon_0\varepsilon_r}V_{bi}\left(\frac{N_A N_D}{N_A+N_D}\right)}$$

Outline

- RECAP: Charge concentration, doped semiconductor
- Part I: pn-junction in thermal equilibrium
- **Part II: pn-junction under applied bias**
- Part III: pn-junction under light
- Part IV: Heterojunctions (extra materials)

p–n Junction Diode Under Applied Bias

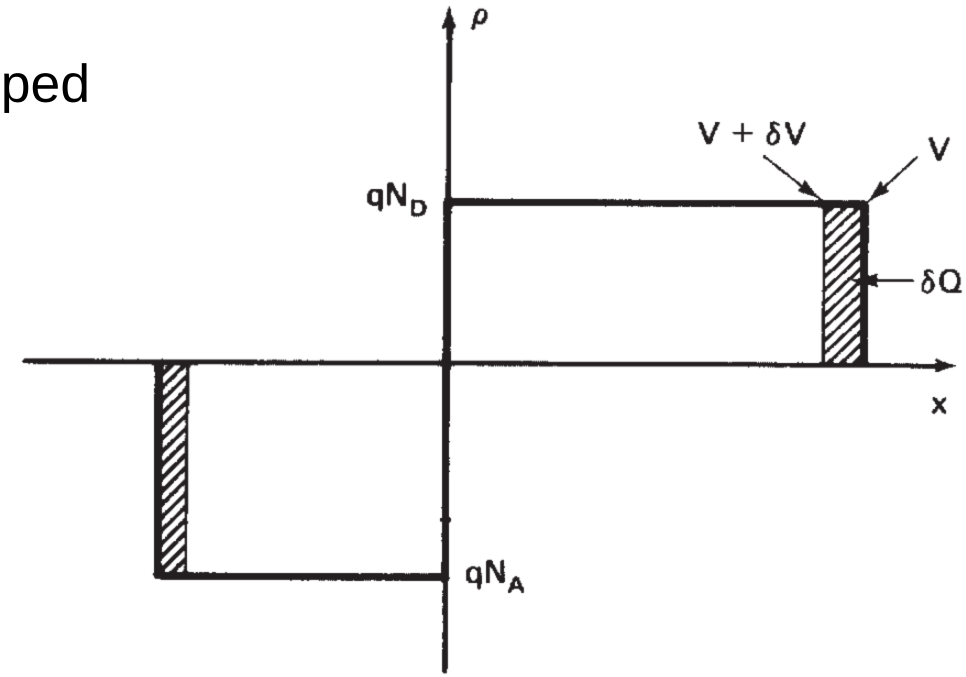
Presence and width of depletion region can be measured. Change in applied voltage V_a causes a change in stored charge at the edges of the region. Identical situation to a parallel-plate capacitor with separation *W*, thus the depletion region capacitance is:

$$C = \frac{\epsilon A}{W}$$

and if one side of diode is heavily doped (normally the case) then

$$\frac{C}{A} = \left[\frac{q\epsilon N}{2(\psi_0 - V_a)}\right]^{1/2}$$

where *N* is the smaller of N_D or N_A



Source: Green, “Solar Cells”, Prentice Hall 1998

p–n Junction Diode Under Applied Bias

So far, we considered the p-n junction in equilibrium (i.e. no net currents). However, if an external bias V_a is applied, the system is not any longer in equilibrium, but steady state (i.e. charge density does not change w. time).

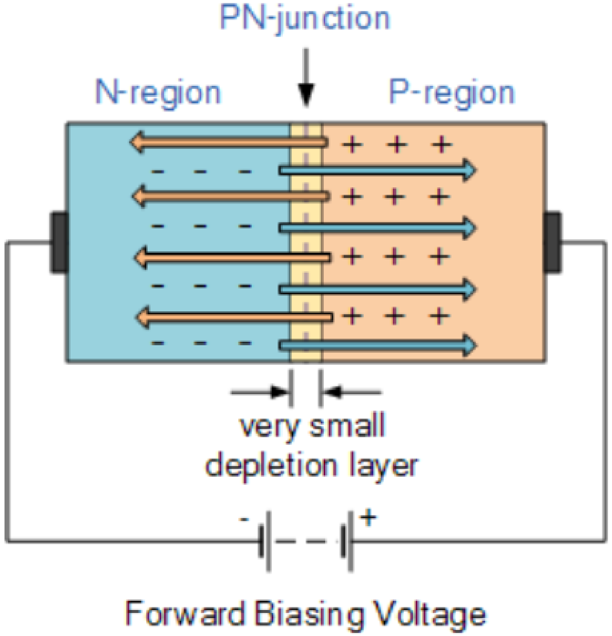
First, consider „forward-bias voltage“:

- P-type connected to positive pole
- N-type connected to negative pole

What happens?

- Free (majority) charge carriers will be pushed into the space charge region.
  - h^+ towards n-type
  - e^- towards p-type
- Reaching the opposite neutral region, they recombine with the local majority charge carrier.

=> A (drift) current flow is induced



p–n Junction Diode Under Applied Bias

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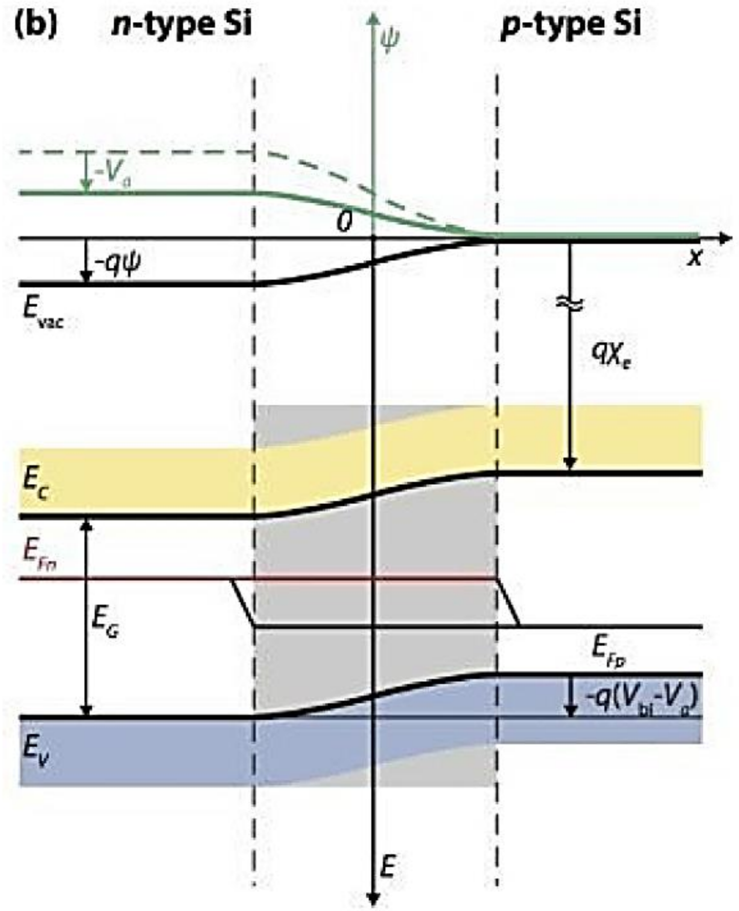
The band diagram under forward-bias voltage:

- The applied V_a reduces the potential difference between n-type and p-type
- Change of electrostatic potential across junction ($V_{bi} - V_a$)
- Fermi-level splits up into a Fermi-levels E_{Fp} and E_{Fn} of holes and electrons, respe
- Reduction of the width of the space charge region



forward-bias voltage

Source: textbook

p–n Junction Diode Under Applied Bias

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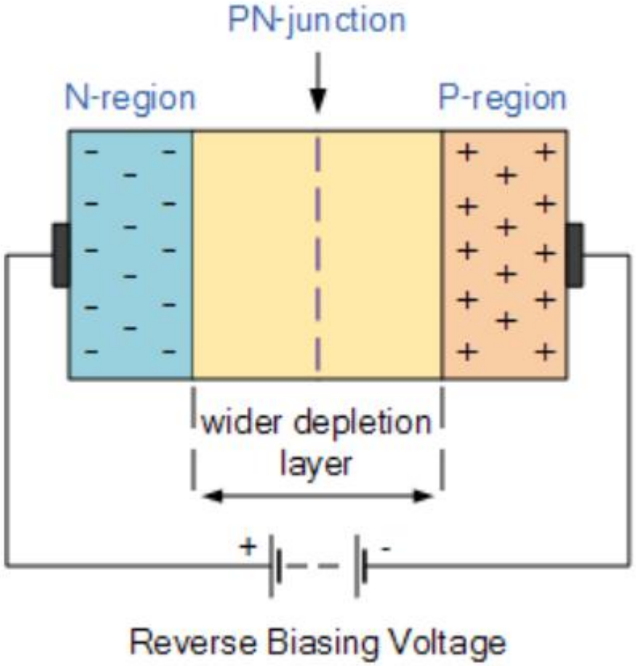
So far, we considered the p-n junction in equilibrium (i.e. no net currents). However, if an external bias V_a is applied, the system is not any longer in equilibrium, but steady state (i.e. charge density does not change w. time).

Second, consider „reverse-bias voltage“:

- P-type connected to negative pole
- N-type connected to positive pole

What happens?

- Free (majority) charge carriers will be pulled away from the junction.
  - h^+ in p-type away from junction
  - e^- in p-type away from junction
- The space charge region increases
- The thermal generation induces a remaining small current (called saturation current)



p–n Junction Diode Under Applied Bias

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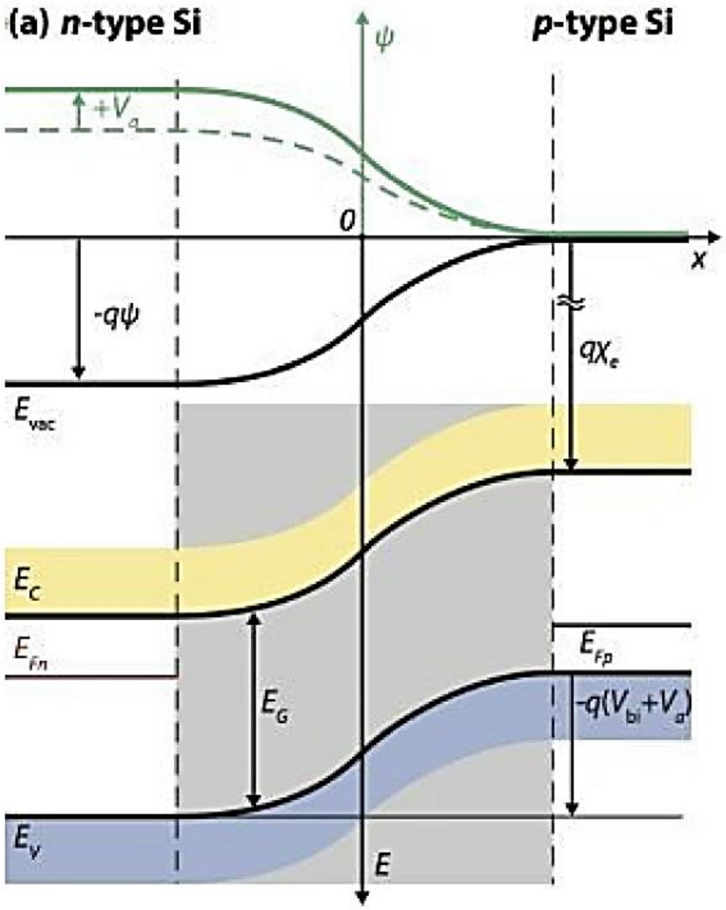
The band diagram:

- The applied V_a increases the potential difference between n-type and p-type
- Increase of electrostatic potential across junction ($V_{bi} - V_a$)
- Increase of the width W of the space charge region.



reverse-bias voltage

Source: textbook

p–n Junction Diode Under Applied Bias

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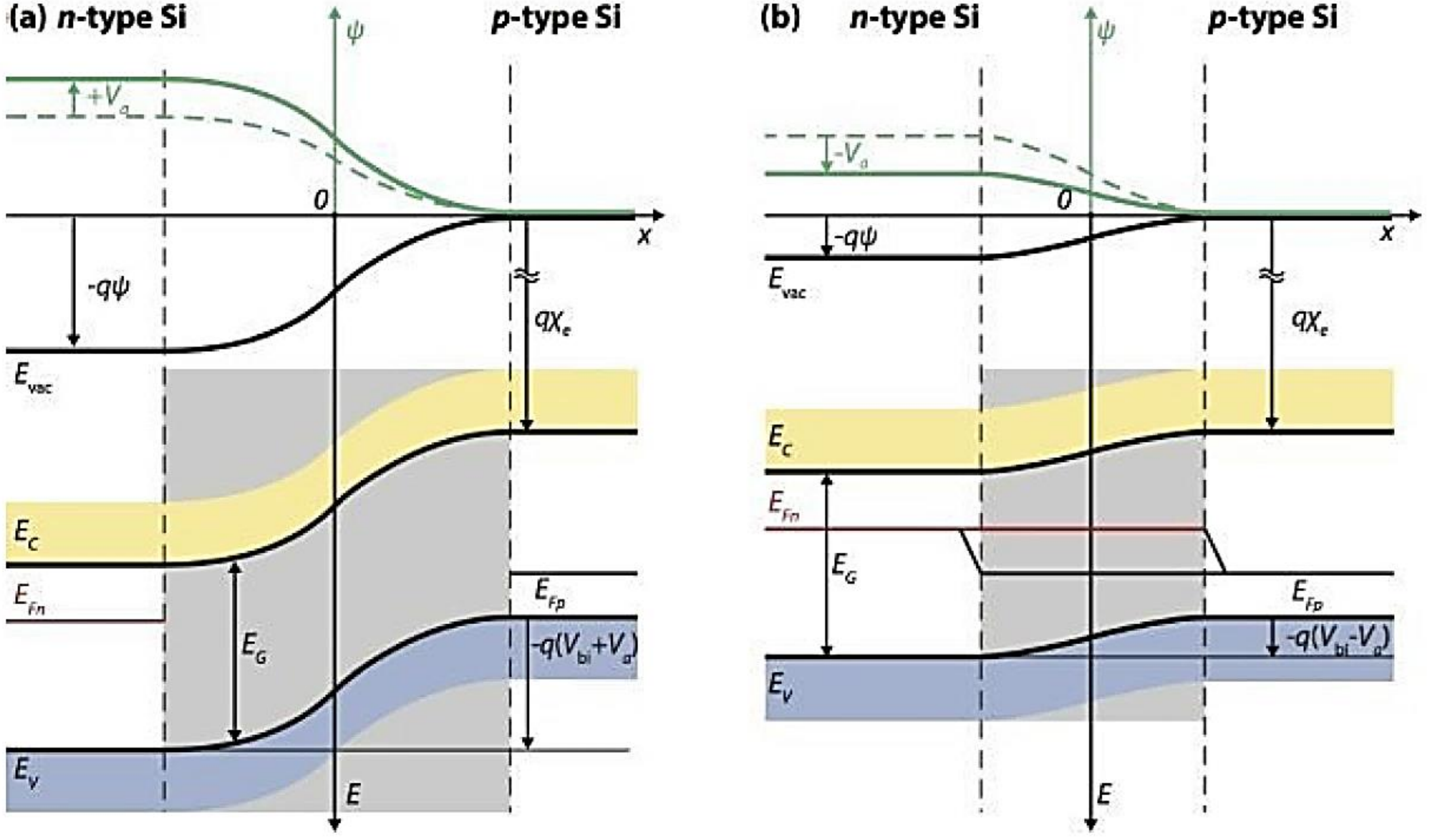
The band diagram:



reverse-bias voltage *forward-bias voltage*

Source: textbook

p–n Junction Diode Under Applied Bias

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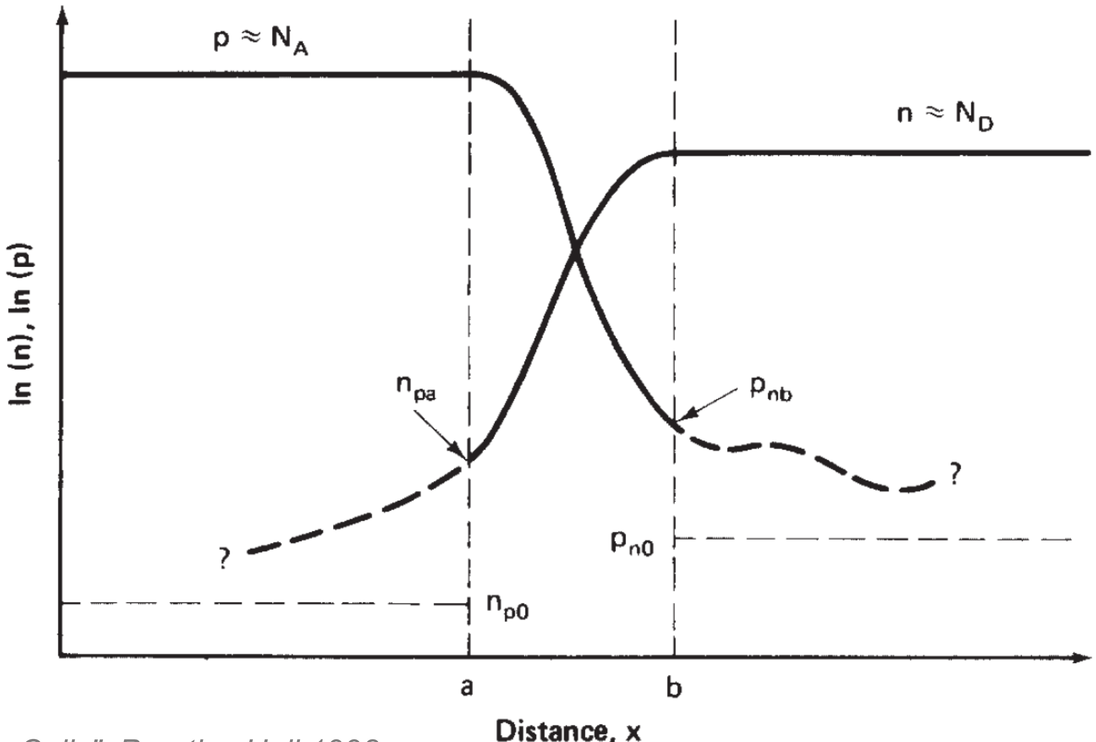
Derivation of the p–n Junction diode under applied bias. Let us start w. the „forward-bias voltage“:

- Starting point is so called *minority charge carrier injection*, which describes the excess of minority charge carriers that will be induced due to the previously described drift current induced by external voltage V_a.



Source: Green, “Solar Cells”, Prentice Hall 1998

p–n Junction Diode Under Applied Bias

Derivation of the p–n Junction diode under applied bias.

- Considering that the origin of the *minority charge carrier injection* is based on diffusion current through the p-n junction, we get:

$$J_{pD}(\mathrm{x}) = -\mathrm{q}D_p \frac{dp}{dx}$$

- The concentration of holes at the edge of the space-charge region is

$$p(\mathrm{x} = -l_{\mathrm{n}}) = \mathrm{N_V}\, e^{\frac{E_{Fp} - q\,(V_{bi} - V_a) - E_V}{k_B T}} = \mathrm{p_n}^0 \exp\left(\frac{qV_a}{k_B T}\right)$$

(use geometrical considerations w. figure on previous slide)

=> For the excess charge carrier concentration we get:

$$\Delta p(\mathrm{x} = -l_{\mathrm{n}}) = p(\mathrm{x} = -l_{\mathrm{n}}) - \mathrm{pn}^0 = p_n^0 \left(\exp\left(\frac{qV_a}{k_B T}\right) - 1\right)$$

This means that the minority carrier concentration at the edge of the depletion region increases with applied voltage => *minority carrier injection*

Note, $p_n^0 = n_i^2 / N_A$ and we know N_A and V_a

p–n Junction Diode Under Applied Bias

Derivation of the p–n Junction diode under applied bias.

- Considering that the origin of the *minority charge carrier injection* is based on diffusion current through the p-n junction, we get:

$$J_{pD(\mathrm{x})} = -\mathrm{q} D_p \frac{dp}{dx}$$

- Considering further the continuity equation:

$\frac{1}{\mathrm{q}} \frac{d}{dx} J_{pD}(x) - R + G = 0$ and $\mathrm{G} = 0$ in the dark and $\mathrm{R} = \Delta p / \tau_p$

- $D_p \frac{d^2 \Delta p}{dx2} = \Delta p \,/\, \mathrm{L_p}^2$ with $\mathrm{L_p} = \sqrt{D_p \tau_p}$

$$\Rightarrow p(\mathrm{x}) = p(\mathrm{x} = -l_{\mathrm{n}})\, exp\left(-\frac{x}{L_p}\right) = p_n^0 \left(\exp\left(\frac{qV_a}{k_B T}\right) - 1\right) exp\left(-\frac{x}{\sqrt{D_p \tau_p}}\right)$$

p–n Junction Diode Under Applied Bias

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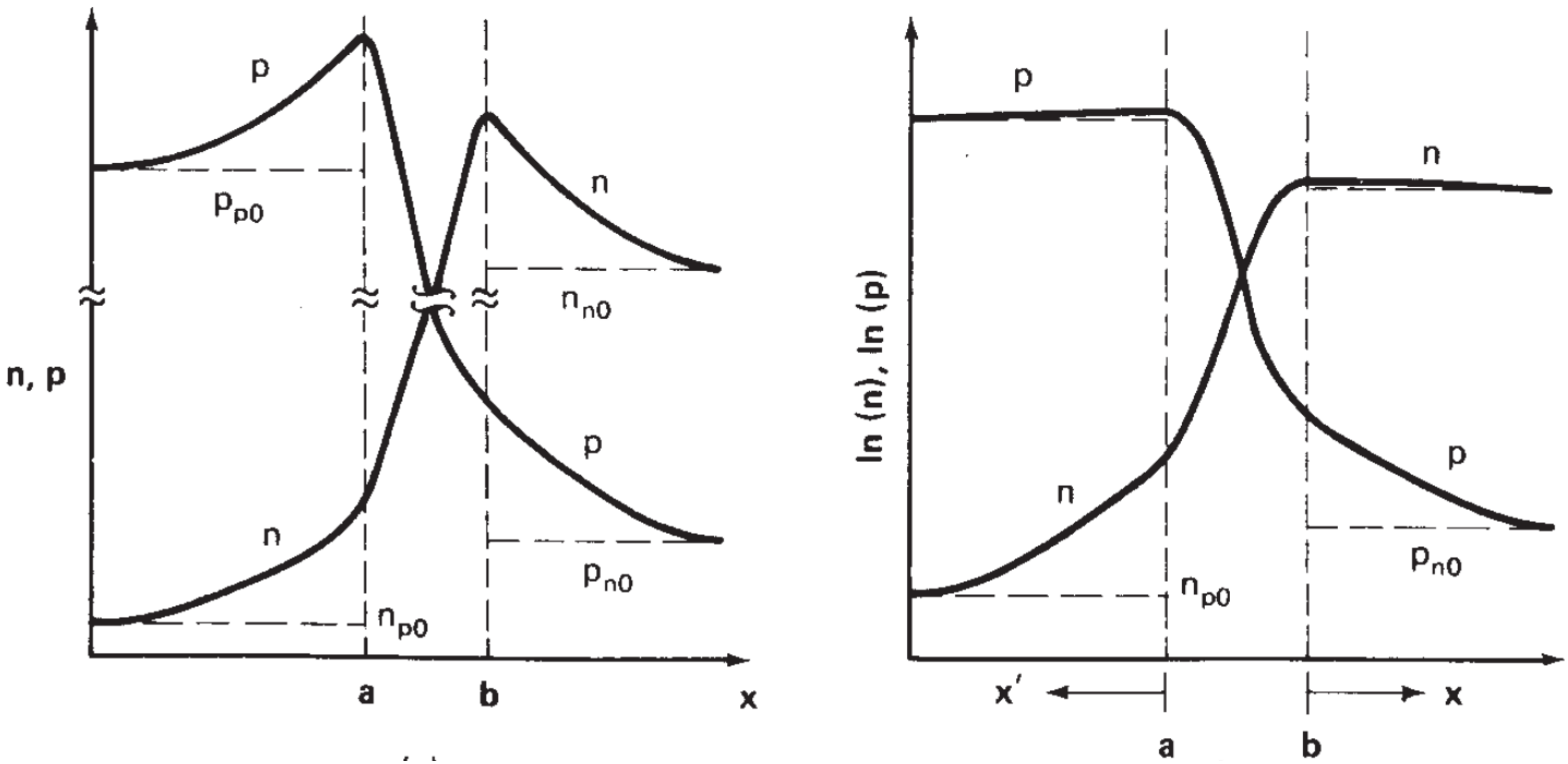

Source: Green, “Solar Cells”, Prentice Hall 1998

p–n Junction Diode Under Applied Bias

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Now we can derive the diffusion current:

$$J_{p,\,\mathrm{diff}}(\mathrm{x} = -l_{\mathrm{n}}) = -\mathrm{q}D_p \frac{\partial p}{\partial x}\Big|_{x=-ln} = -\mathrm{q}\;\mathrm{D}_p \frac{\partial}{\partial x}\left(p\;(x = -ln)\exp(-\frac{x}{L_p})\right)$$

$$J_{p,\,\mathrm{diff}}(\mathrm{x} = -l_{\mathrm{n}}) = \mathrm{q}\frac{\mathrm{D_p}}{L_p}\,\mathrm{p_n}\;\left(exp\left(\frac{qV_a}{k_BT}\right) - 1\right)$$

und analog:

$$J_{n,\,\mathrm{diff}\,(}\mathrm{x} = -l_{\mathrm{p}}) = \mathrm{q}\frac{\mathrm{D_n}}{L_n}\,\mathrm{n_p}\;\left(exp\left(\frac{qV_a}{k_BT}\right) - 1\right)$$

$$J = J_{n,\,\mathrm{diff}} + \mathrm{Jp}_{,\,\mathrm{diff}} = q\left(\frac{\mathrm{D_p}}{L_p}p_n{}^0 + \frac{\mathrm{D_p}}{L_p}n_p{}^0\right)\left(exp\left(\frac{qV_a}{k_BT}\right) - 1\right)$$

$$\mathrm{p_n}^0 = \mathrm{n_i}^2\,/\,\mathrm{N_A}$$

$$\mathrm{n_p}^0 = \mathrm{n_i}^2\,/\,\mathrm{N_D}$$

- This implies an exponential increase in current with V_a .
- In high reverse-bias voltage, the current saturates:

$$J_0 = q\left(\frac{\mathrm{D_p}}{L_p}p_n{}^0 + \frac{\mathrm{D_p}}{L_p}n_p{}^0\right)$$

p–n Junction Diode Under Applied Bias

The final form of the IV-characteristic (called also *Shockley equation*):

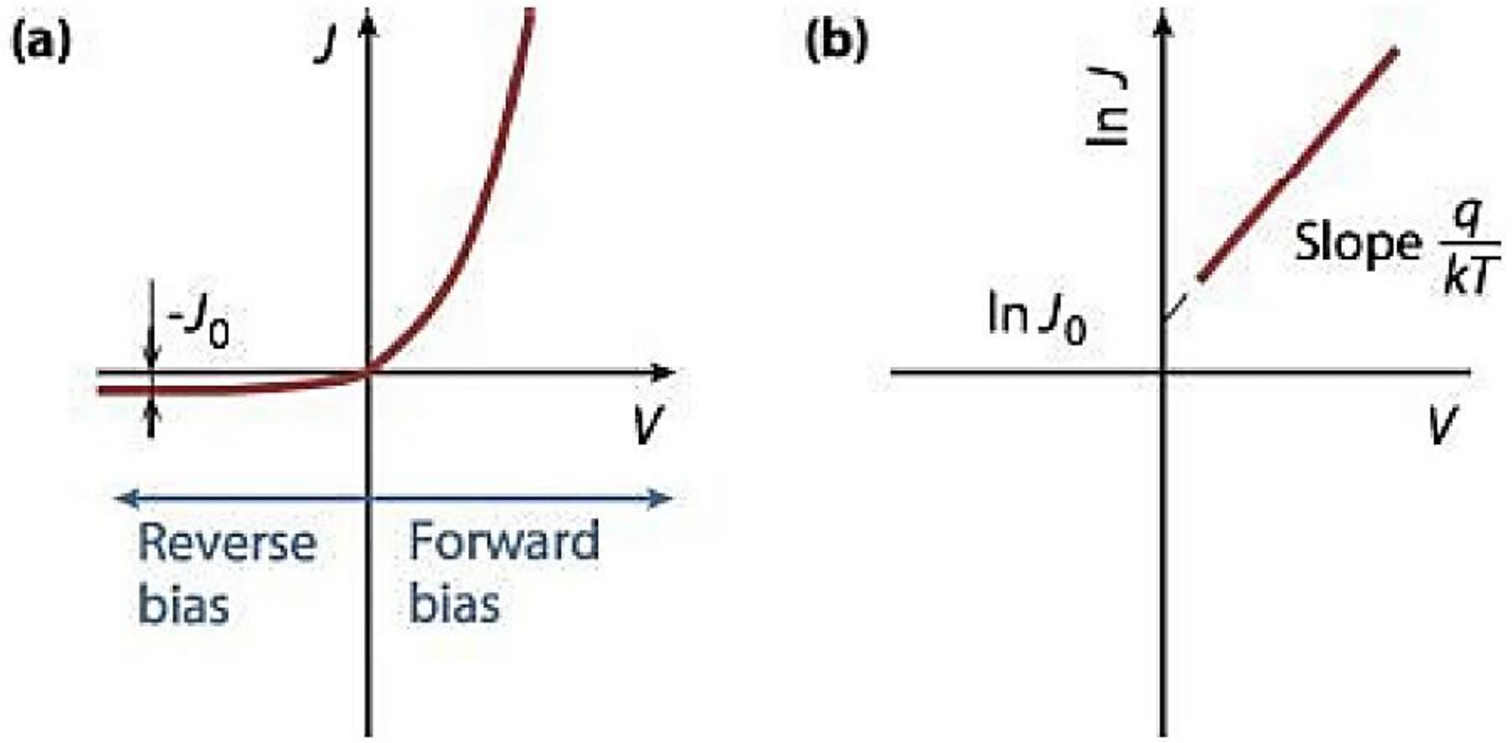
$$J = J_0\left(exp\left(\frac{qV_a}{k_B T}\right) - 1\right)$$

with $J_0 = q\left(\frac{D_p}{L_p} p_n{}^0 + \frac{D_p}{L_p} n_p{}^0\right)$

Note, this implies also the generation currents J_{gen} and recombination current J_{rec}.

- $J_0 = J_{rec}(V_a = 0) = J_{gen}(V_a = 0)$
- $J_{rec}(V_a) = J_0\, exp\left(\frac{qV_a}{k_B T}\right)$
- $J\,(V_a) = J_{rec}(V_a) - J_{gen}(V_a)$

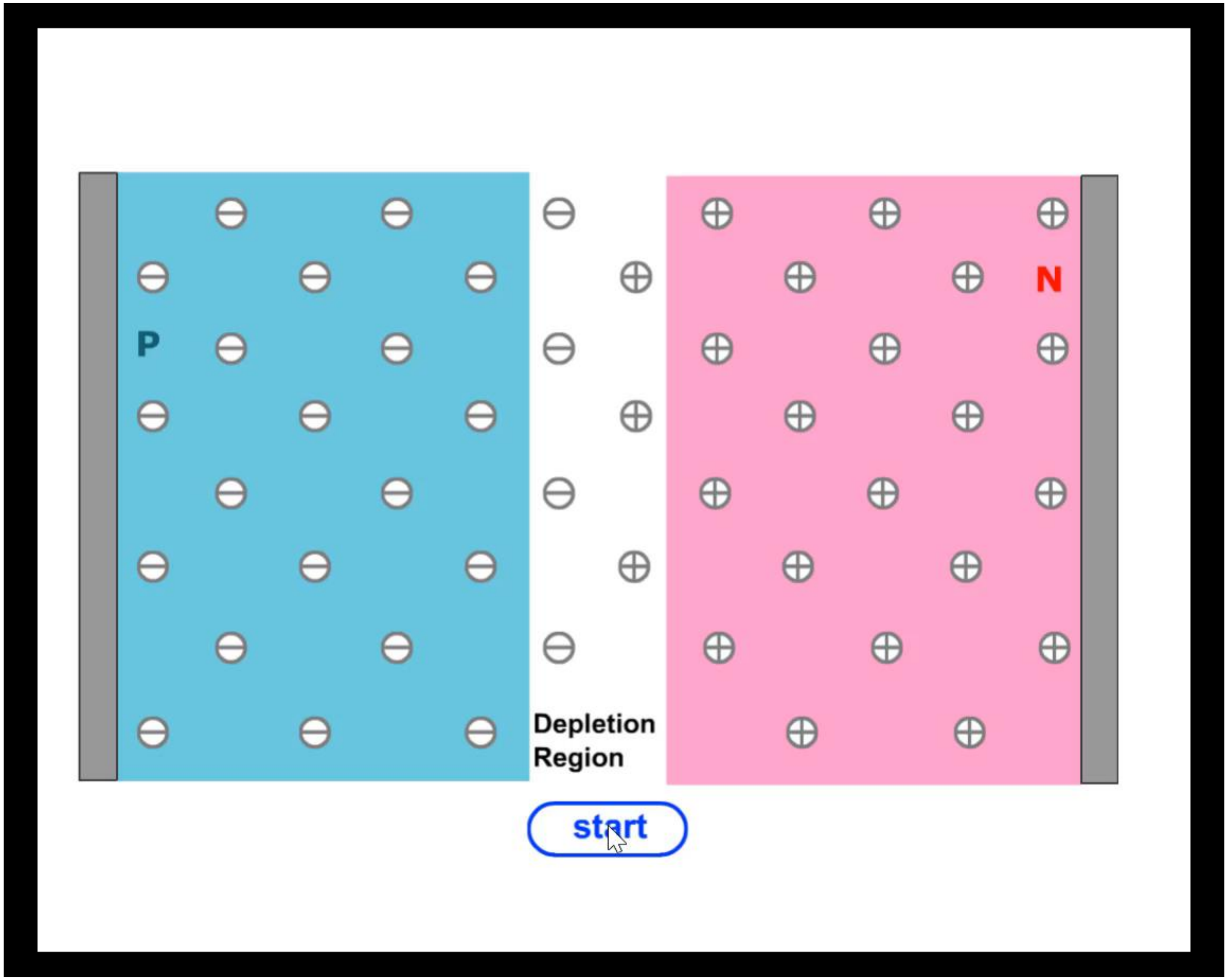
p–n Junction Diode Under Applied Bias



J-*V* characteristic of a *p*-*n* junction; (a) linear plot; and (b) semi-logarithmic plot.

Source: textbook

p–n Junction Diodes



Source: http://www.pveducation.org/pvcdrom/pn-junction/bias-of-pn-junction

Outline

- RECAP: Charge concentration, doped semiconductor
- Part I: pn-junction in thermal equilibrium
- Part II: pn-junction under applied bias
- **Part III: pn-junction under light**
- Part IV: Heterojunctions (extra materials)

p–n Junction Diode Under Light

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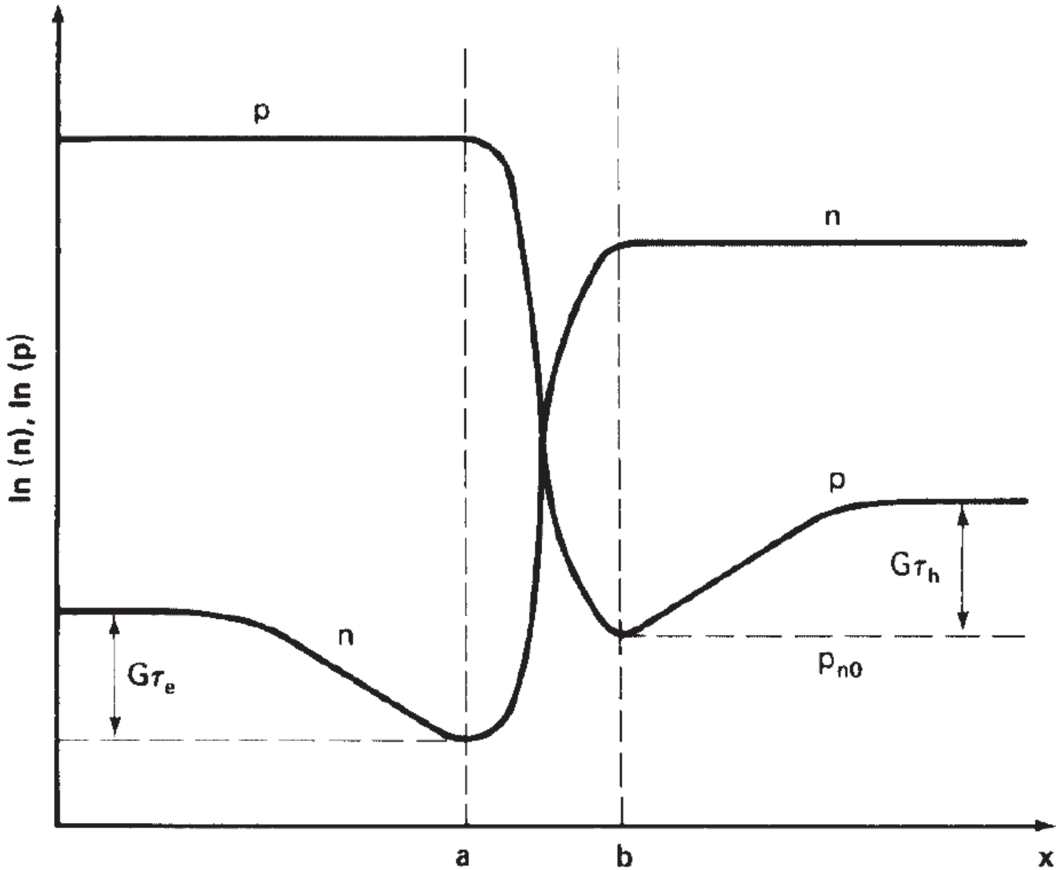
When the p-n junction is illuminated, additional electron hole pairs are generated => concentration of minority charge carriers strongly increases.

= > Flow of the minority carriers across the depletion region into the quasi-neutral regions. (Photogeneration current)

Here the generation of rate of e^{-}-h^{+} pairs via illumination is assumed to be constant throughout the device

Increase in minority carrier concentrations looks like this:



p–n Junction Diode Under Light

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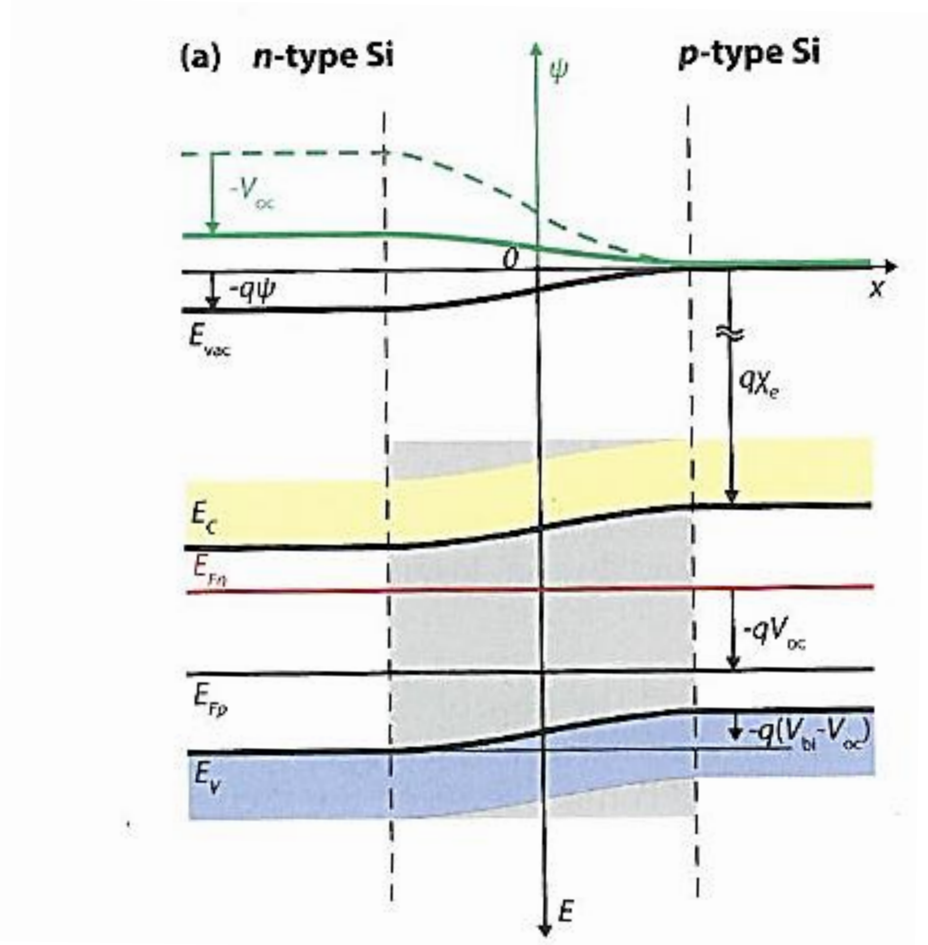
When no external electrical contact between the *n*-type and the *p*-type regions is established, the junction is in *open circuit condition*.

⇒ current resulting from the flux of photogenerated and thermally-generated carriers has to be balanced by the opposite recombination current.

$$J_{\text{gen}} + J_{\text{ph}} = J_{\text{rec}}$$

- The recombination current will increase through lowering of the electrostatic potential barrier across the depletion region.



p–n Junction Diode Under Light

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At *open circuit condition* the quasi-Fermi level of the electrons ($E_{F,n}$) is higher than the quasi-Fermi level of the holes ($E_{F,p}$) by the *open-circuit voltage* V_{OC}. => One will measure this voltage across the device.

- There is no external current:

$$J = J_n + Jp = \mu_n n \frac{dE_{Fn}}{dx} + \mu_n n \frac{dE_{Fp}}{dx} = 0$$

The current density can only be zero if which implies that the quasi-Fermi levels are horizontal in the entire band diagram of the solar cell.

<u>Derivation for J_n (J_p similar):</u>

$$J_n = J_{n,\,drift} + Jn_{,\,diff} = q\mu_n nE + qD_n \frac{d\,n}{dx} = q\mu_n n\left(\frac{1}{q}\frac{dE_C}{dx}\right) + k_B T\mu_n \frac{d\,n}{dx}$$

with $$n = N_C\,exp\left(-\frac{E_C - E_{Fn}}{k_B T}\right) \qquad \frac{d\,n}{dx} = -\frac{n}{k_B T}\left(\frac{dE_C}{dx} - \frac{dE_{Fn}}{dx}\right)$$

=> $$J_n = q\mu_n n\left(\frac{1}{q}\frac{d\,E_C}{dx}\right) + k_B T\mu_n \frac{d\,n}{dx} = \mu_n n\frac{dE_{Fn}}{dx}$$

p–n Junction Diode Under Light

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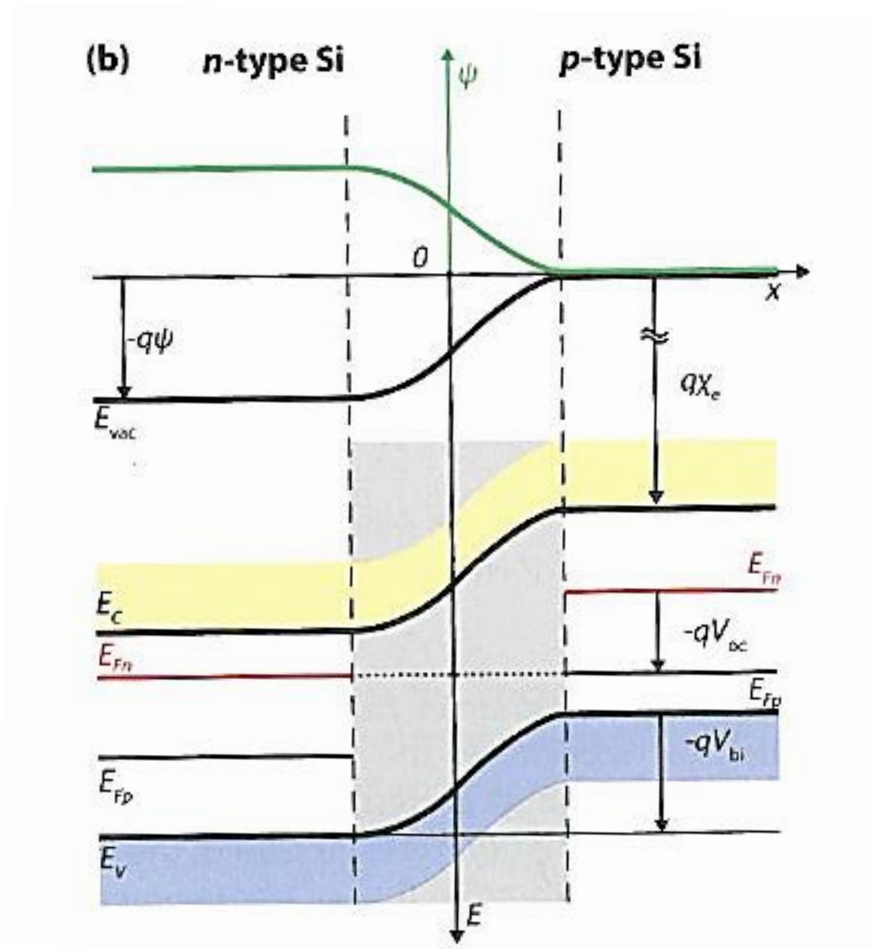
At *short-circuit condition* the photogenerated current will also flow through the external circuit.

- In the short circuit condition the electrostatic-potential barrier is not changed.
- But from a strong variation of the quasi-Fermi levels inside the depletion region, one can determine that the current is flowing inside the semiconductor.



p–n Junction Diode Under Light

In between *open circuit condition* and short-circuit conditions

- If a load is connected between the electrodes of the illuminated *p-n* junction, only a fraction of the photogenerated charge carriers collected at open circuit conditions will flow through the external circuit.

- The electrochemical potential difference between the *n*-type and *p*-type regions will be lowered by a voltage drop over the load. This in turn lowers the electrostatic potential over the depletion region which results in an increase of the recombination current.

=> The device generates a voltage and a current.

=> This implies it generates power!

p–n Junction Diode Under Light

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In the *superposition approximation*, the net current flowing through the load is determined as the sum of the photo- and thermal-generation currents and the recombination current.

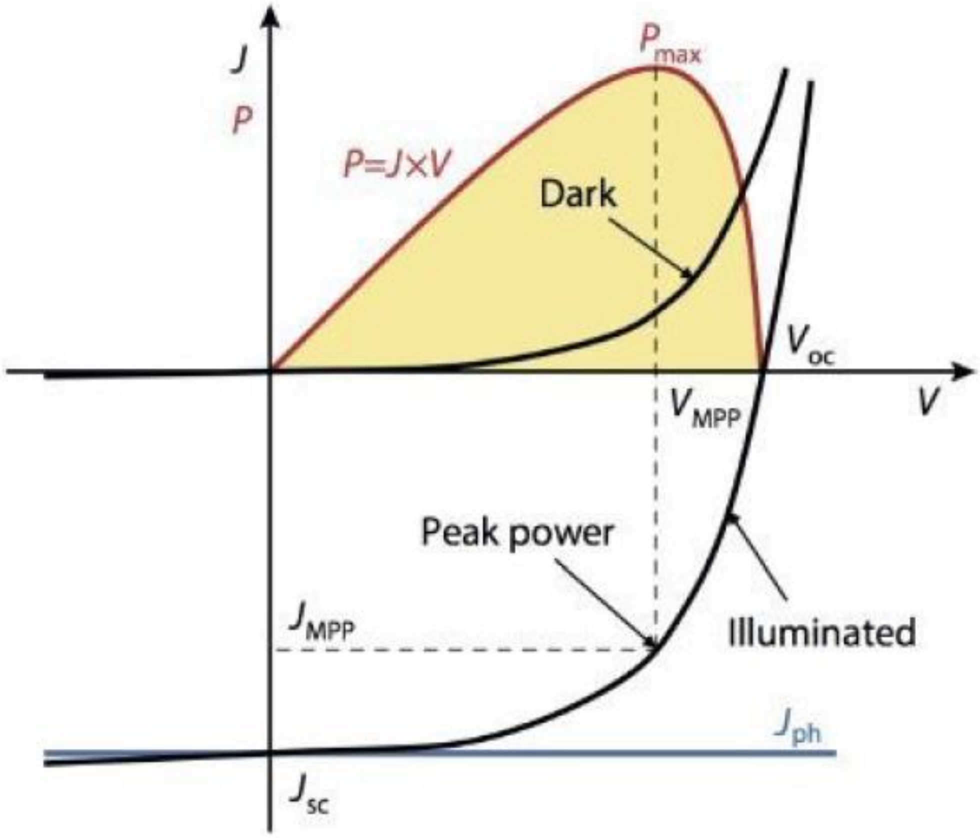
$$J(V_a) = \underbrace{J_{rec}(V_a) - J_{gen}(V_a)}_{\text{dark current}} - J_{ph}(V_a)$$

$$J(V_a) = J_0\left(exp\left(\frac{qV_a}{k_B T}\right) - 1\right) - J_{ph}(V_a)$$

Note, the detailed derivation of the photogenerated current density of the *p-n* junction is carried in the textbook (appendix B.2.) under a uniform generation rate, *G*, its value is $J_{\mathrm{ph}} = \mathrm{qG}\,(\mathrm{L_n} + \mathrm{W} + \mathrm{L_p})$

Only carriers generated in the depletion region and in the regions up to the minority-carrier diffusion length can contribute to photogenerated current.

p–n Junction Diode Under Light

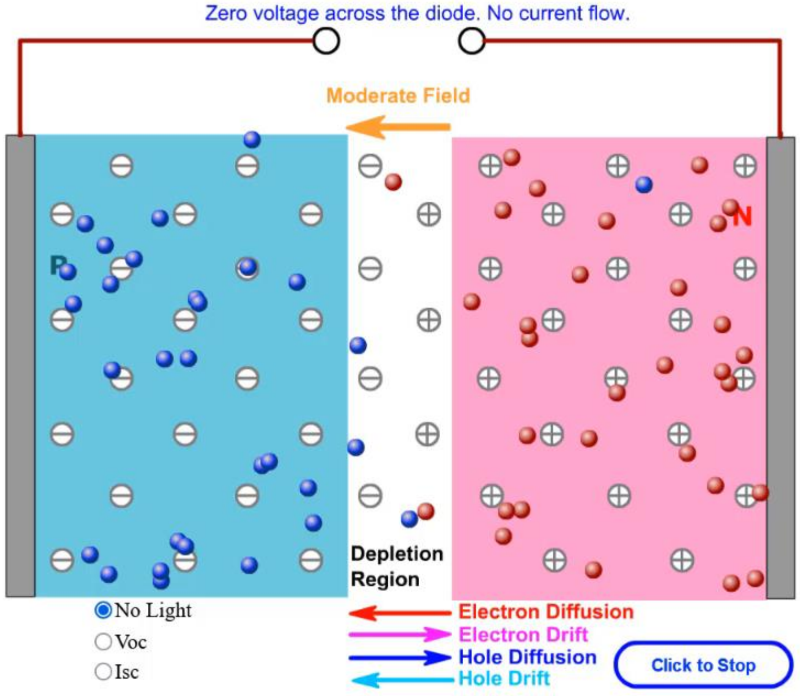


<ins>Detailed discussion of the IV-characteristic of a solar cell in the next lecture.</ins>

p–n Junction Diode Under Light

Remember:

- Minority carriers are metastable and only exist, on average, for time = τ before recombining. If carrier recombines, then light-generated e^{-}-h^{+} pair is lost and no current or power can be generated
- Collection of these carriers facilitated by *p-n* junction, $\Rightarrow$ spatial separation of e^{-} and h^{+}. Carriers separated electric field existing at the *p-n* junction



Simulation of carrier flows in a solar cell under equilibrium, short-circuit current and open-circuit voltage conditions. Note the different magnitudes of currents crossing the junction. In equilibrium (i.e. in the dark) both the diffusion and drift current are small. Under short circuit conditions, the minority carrier concentration on either side of the junction is increased and the drift current, which depends on the number of minority carriers, is increased. Under open circuit conditions, the light-generated carriers forward bias the junction, thus increasing the diffusion current. Since the drift and diffusion current are in opposite direction, there is no net current from the solar cell at open circuit.

Source: https://www.pveducation.org/pvcdrom/solar-cell-operation/the-photovoltaic-effect

Outline

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Heterojunctions

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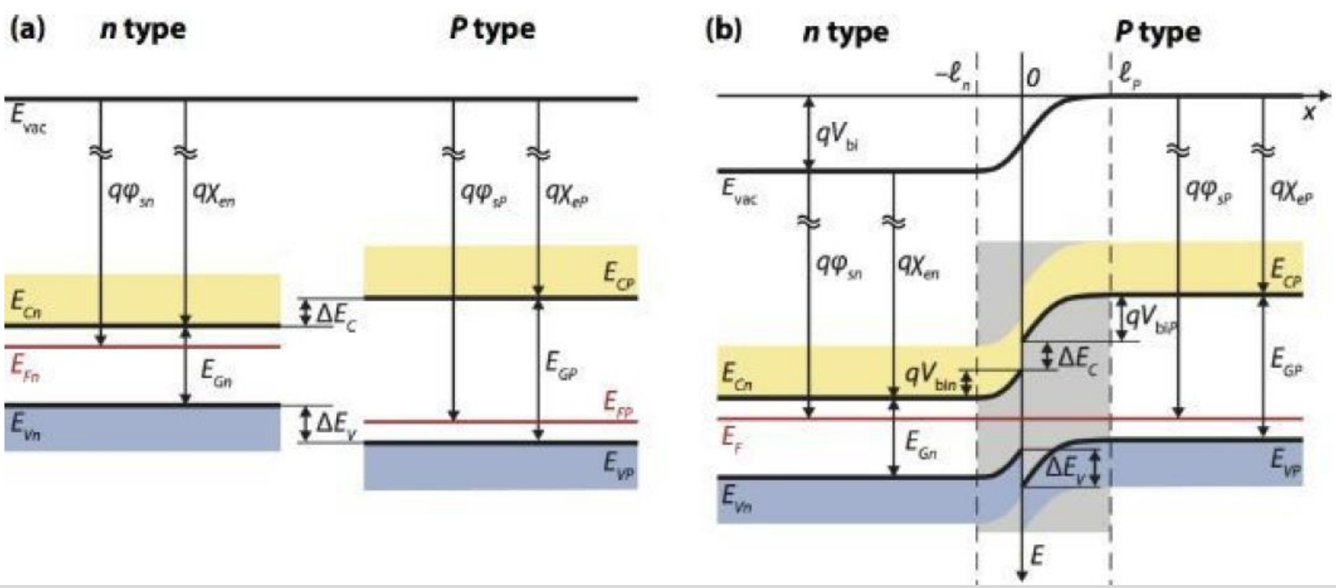
- So far, we discussed the physics of *homojunctions* between an *n*-doped and a *p*-doped semiconductor of the same material.
- **BUT a pn-junction is only one out of many way to create selective contacts! Alternative route is to make use of** junctions between different materials are called *heterojunctions* (E_G and electron affinity is different on both sides of the junction).
- One distinguishes between *n-P*, *p-N*, *n-N*, and *p-P* (lower case: low E_G, upper-case: larger E_G
- *For n-P* heterojunctions, the band diagram:

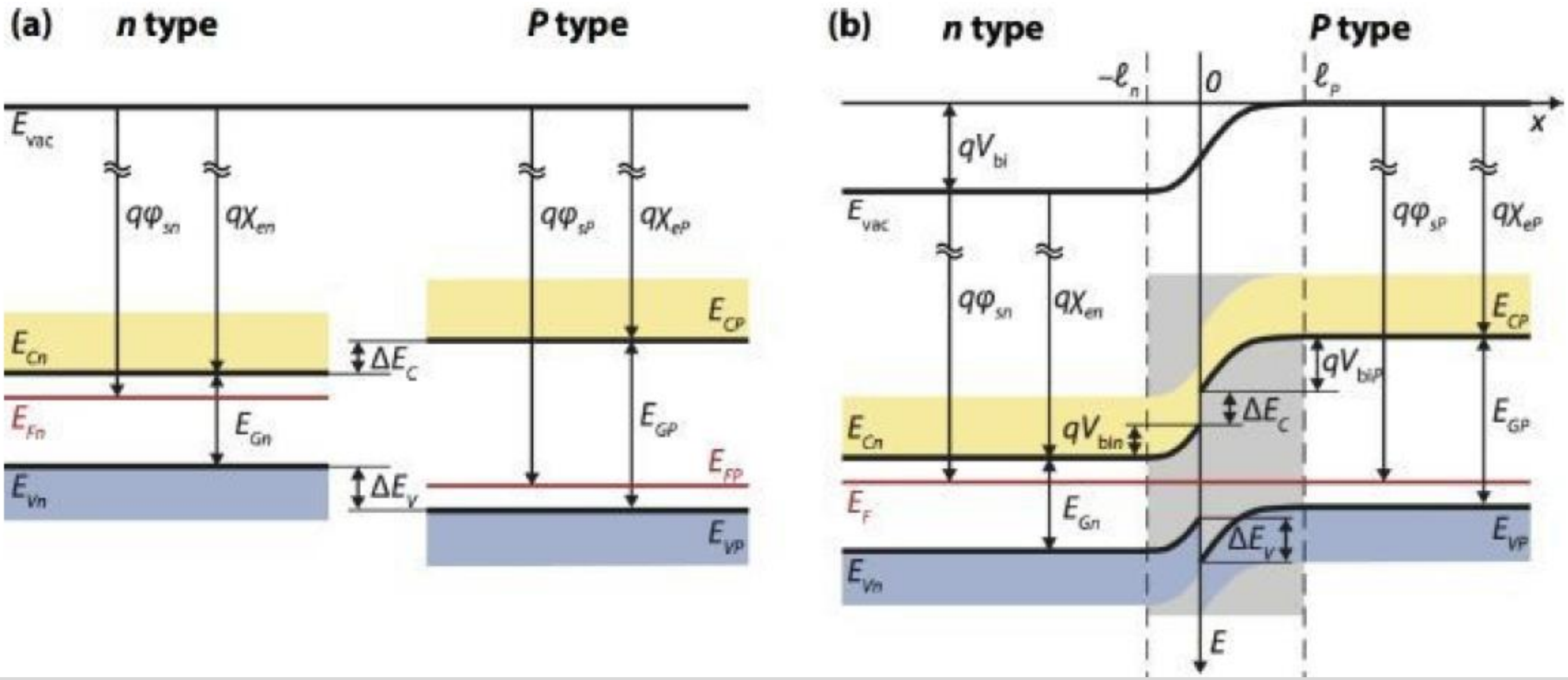


Heterojunctions

- The built-in voltage of the heterojunction is given by the difference of the work functions,

$$V_{\mathrm{bi}} = \phi_{sP} - \phi_{sn}.$$

$$qV_{\mathrm{bi}} = -\Delta E_C + \Delta E_g + k_B T \ln\left(\frac{N_{Vn}}{p_{n0}}\right) - k_B T \ln\left(\frac{N_{VP}}{p_{P0}}\right),$$



Heterojunctions

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- For the n- and P-type depletion regions the electric field is given by

$$\xi_n(x) = \frac{qN_{dn}}{\epsilon_0\epsilon_n}(\ell_n + x) \qquad (-\ell_n \leq x < 0),$$

$$\xi_P(x) = \frac{qN_{aP}}{\epsilon_0\epsilon_P}(\ell_P - x) \qquad (0 < x < \ell \leq \ell_P),$$

with the doping concentrations N_{dn} and N_{aP}, the dielectric constants ϵ_n and ϵ_P, and the depletion widths ℓ_n and ℓ_P for the *n*- and *P*-type materials, respectively. The net charge in the *n*-type region is equivalent to the net charge in the *P*-type region,

$$N_{dn}\ell_n = N_{aP}\ell_P.$$

Heterojunctions

- The widths of the depletion regions in the *n*- and *P*-type zones are given by:

$$\ell_n = \sqrt{\frac{2\epsilon_0\epsilon_n\epsilon_P N_{aP} V_{\mathrm{bi}}}{qN_{dn}(\epsilon_n N_{dn} + \epsilon_P N_{aP})}},$$

$$\ell_P = \sqrt{\frac{2\epsilon_0\epsilon_n\epsilon_P N_{dn} V_{\mathrm{bi}}}{qN_{aP}(\epsilon_n N_{dn} + \epsilon_P N_{aP})}}.$$

- Many similarities between a p-n junction and a heterojunction. <u>But</u> the band diagrams of heterojunctions are much more complex than that of homojunctions due to the different bandgaps and electron affinities.
- Discontinuities at the edges of the valence and conduction bands can lead to the formation of barriers for the electrons, the holes, or both.
- Depending on the barrier heights and the applied voltage, different transport mechanisms might be dominant (diffusion, tunnelling, and thermionic emission,

Metal-semiconductor junctions

- The widths of the depletion regions in the *n*- and *P*-type zones are given by:

$$\ell_n = \sqrt{\frac{2\epsilon_0 \epsilon_n \epsilon_P N_{aP} V_{\rm bi}}{q N_{dn} (\epsilon_n N_{dn} + \epsilon_P N_{aP})}},$$

$$\ell_P = \sqrt{\frac{2\epsilon_0 \epsilon_n \epsilon_P N_{dn} V_{\rm bi}}{q N_{aP} (\epsilon_n N_{dn} + \epsilon_P N_{aP})}}.$$

- Many similarities between a p-n junction and a heterojunction. But the band diagrams of heterojunctions are much more complex than that of homojunctions due to the different bandgaps and electron affinities.
- Discontinuities at the edges of the valence and conduction bands can lead to the formation of barriers for the electrons, the holes, or both.
- Depending on the barrier heights and the applied voltage, different transport mechanisms might be dominant (diffusion, tunnelling, and thermionic emission,

APPENDIX

Quick Test

- Explain the origin of the depletion region in a p-n diode.
- Why do the bands (E_C, E_V, E_{vac}) bend in a p-n junction?
- What is the origin of the built-in voltage? What are the key proportionalities? What does the built-in voltage converge to with increasing doping concentration?
- In the abrupt junction limit:
    - How does the electric field look like?
    - How does the potential look like?
    - How would you derive the electric field and the potential?
    - What is the width of the space charge region? What are the key dependencies? How does it change with the doping concentration?
- Look at the p-n junction as a capacitor

Quick Test

- Look at the p-n junction under applied bias. What happens with the charge carriers for
  - forward bias
  - reverse bias
- How does the band structure change under reverse and forward bias?
- Derivation of IV-characteristic for the p-n junction in the dark
  - Explain the concept/origin of minority charge carrier injection
  - How to derive (a) density of minority charge carrier injection ?
  - How to further derive the total current density?
- What is the saturation current?
- How does the IV-characteristic of a diode behave in (i) forward bias and (ii) reverse bias?
- Know the IV-characteristic of a diode in the dark !!!

Quick Test

- p-n junction diode under light
  - Open circuit: How does the band structure look like? What happens to the quasi-Fermi levels? Why is there no current?
  - Short circuit: How does the band structure look like? What happens to the quasi-Fermi levels? Why is there no voltage?
  - Why does the diode under light generate power for voltages in between the open-circuit and short-circuit voltage?
  - Which is the underlying balance of currents?
  - Know the IV-characteristic!

- Heterojunctions:
  - Explain the difference between a homojunction and a heterojunction.
  - Draw a schematic band diagram.