FYS3410 - Vår 2016 (Kondenserte fasers fysikk)

http://www.uio.no/studier/emner/matnat/fys/FYS3410/v16/index.html

Pensum: Introduction to Solid State Physics
by Charles Kittel (Chapters 1-9 and 17, 18, 20)

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2016 FYS3410 Lectures (based on C.Kittel's Introduction to SSP, Chapters 1-9, 17,18,20)

Module I – Periodic Structures and Defects (Chapters 1-3, 20)

M18/1: 9-12 am	**Introduction. Crystal bonding. Periodicity and lattices, Brag diffraction and Laue condition, reciprocal space**	**3h**
W20/1 cancelled		
M25/1: 9-12 am	**Ewald construction, interpretation of a diffraction experiment , Brag planes, and Brillouin zones**	**3h**
W27/1 cancelled		
M01/2: 10-12 am	**Elastic strain and structural defects in crystals**	**2h**
W03/2: 9-10 am	**Atomic diffusion in solids**	**1h**
M08/2: 10-12 am	**Summary of Module I**	**2h**

Module II – Phonons (Chapters 4 and 5)

W10/2: 9-10 am	**Vibrations in monoatomic and diatomic chains of atoms**	**1h**
M15/2: 10-12am	**Periodic boundary conditions, phonons and density of states (DOS)**	**2h**
W17/2: 9-10 am	**Planck distribution**	**1h**
M22/2 : 10-12am	**Lattice heat capacity: Dulong-Petit, Einstein, and Debye models**	**2h**
W24/2 cancelled		
M29/2: 9-12am	**Comparison of different models for lattice heat capacity, thermal conductivity with phonons**	**3h**
W02/3: 9-10 am	**Thermal expansion**	**1h**
M07/3: 10-12am	**Summary of Module II.**	**2h**

Module III – Electrons (Chapters 6, 7, 18 - pp.528-530, and Appendix D)

W09/3: 9-10 am	**Free electron gas (FEG) versus free electron Fermi gas (FEFG)**	**1h**
M14/3: 10-12am	**DOS of FEFG in 3D. Effect of temperature – Fermi-Dirac distribution**	**2h**
W16/3: 9-10 am	**Heat capacity of FEFG in 3D**	**1h**
W30/3: 9-10 am	**DOS in 2D - quantum wells**	**1h**
M04/4: 10-12am	**DOS in 1D and 0D, i.e. quantum wires and quantum dots; transport properties of electrons**	**2h**
W06/4: 9-10 am	**Origin of the energy band gap**	
M11/4: 10-12am	**Nearly free electron model. Kronig-Penney model. Empty lattice approximation.**	**2h**
W13/4: 9-10 am	**Number of orbitals in a band**	**1h**
M18/4: 10-12am	**Summary of Module III.**	**2h**

Module IV – Semiconductors and interfaces (Chapters 8, 9-pp 223-231, 17)

W20/4: 9-10 am	**Metals versus semiconductors. Surfaces and interfaces.**	**1h**
M25/4: 9-12 am	**Effective mass method.**	**3h**
W27/4: 9-10 am	**Intrinsic carrier generation – elctrons and holes.**	**1h**
M02/5: 9-12 am	**Localized levels for hydrogen-like impurities – donors and acceptors. Doping.**	**3h**
W04/5: 9-10 am	**Carrier statistics in semiconductors**	**1h**
M09/5: 9-12 am	**p-n junctions**	**3h**
W11/5: 9-10 am	**Optoelectronic semiconductor properties and devices**	**1h**
M18/5: 9-12 am	**Device demonstrations. Summary of Module IV**	**3h**

Repetition

M23/5 9-12 am	**The course in a nutshell**	**2h**
W25/5, M30/5 and W1/6 cancelled		

Exam during week 22 (tentatively 30-31/5)

Lecture: P-N junction

- **Repetition: intrinsic and extrinsic semiconductors**
- **Charge carrier transport mechanisms – diffusion and drift**
- **Band bending as a function of carrier concentration**
- **P-N junction in equilibrium**
- **Gauss and Poisson equations for the depletion region**
- **P-N junction with applied external bias**

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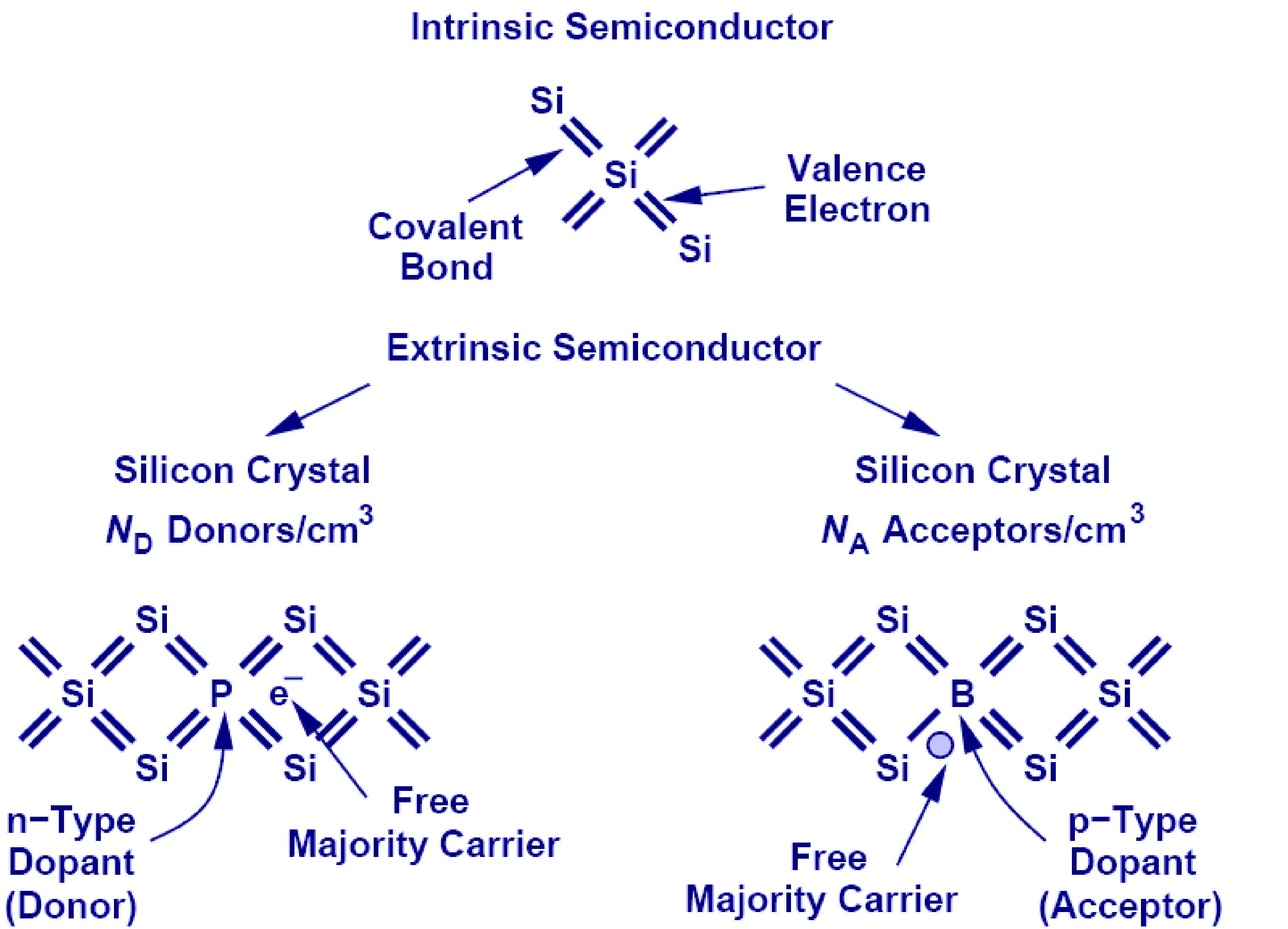
Intrinsic and extrinsic semiconductors

III	IV	V
Boron (B)	Carbon (C)	
Aluminum (Al)	Silicon (Si)	Phosphorous (P)
Galium (Al)	Germanium (Ge)	Arsenic (As)

Intrinsic and extrinsic semiconductors



Lecture: P-N junction

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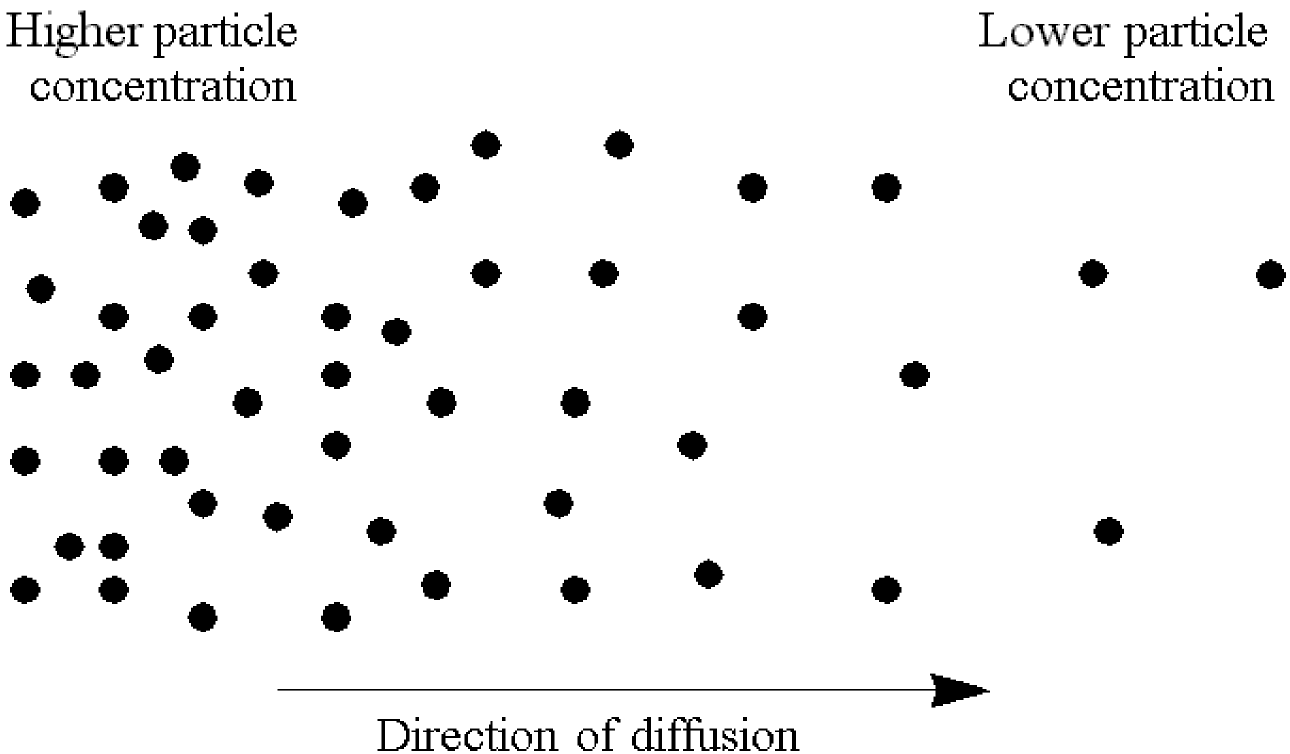
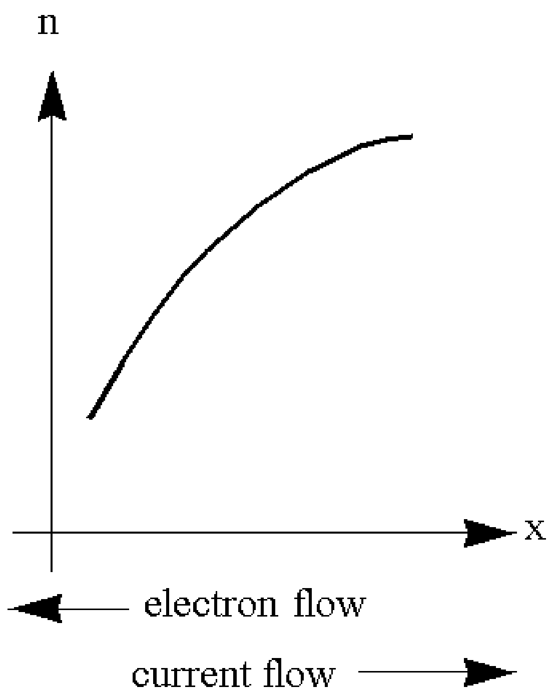
Diffusion of charge carriers

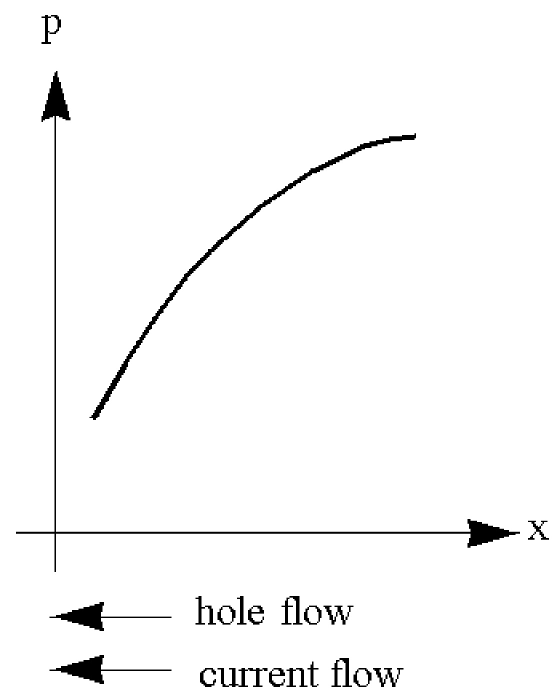
Particles diffuse from regions of higher concentration to regions of lower concentration region, due to random thermal motion.



Diffusion of charge carriers

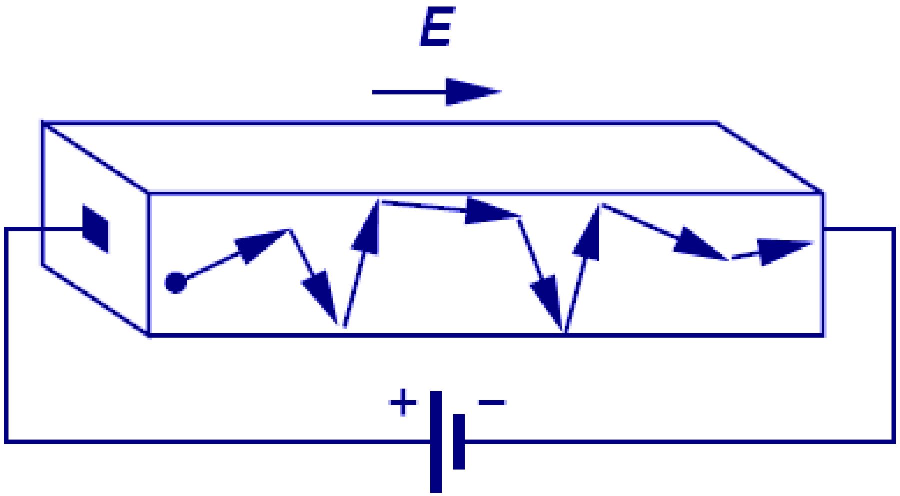
$$J_{\text{n,diff}} = qD_n \frac{dn}{dx} \qquad J_{\text{p,diff}} = -qD_p \frac{dp}{dx}$$





D is the ***diffusion constant***, or ***diffusivity***.

Drift of charge carriers



$$\vec{v}_h = \mu_p \vec{E}$$

$$\vec{v}_e = -\mu_n \vec{E}$$

- The process in which charge particles move because of an electric field is called drift.
- Charge particles will move at a velocity that is proportional to the electric field.

Diffusion + drift of charge carriers

$$\boxed{J = J_n + J_p}$$

$$J_n = J_{n,drift} + J_{n,diff} = qn\mu_n\varepsilon + qD_n\frac{dn}{dx}$$

$$J_p = J_{p,drift} + J_{p,diff} = qp\mu_p\varepsilon - qD_p\frac{dp}{dx}$$

Lecture: P-N junction

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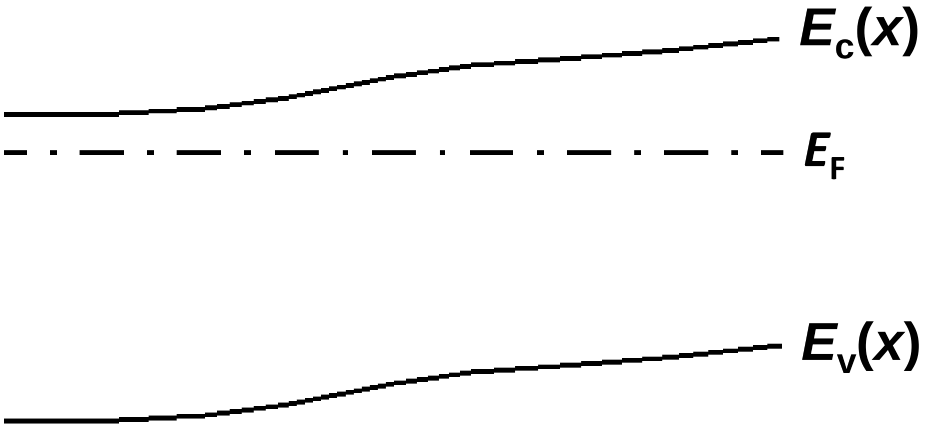
Band bending as a function of carrier concentration

- The position of E_F relative to the band edges is determined by the carrier concentrations, which is determined by the net dopant concentration.
- **In equilibrium $\boldsymbol{E}_{\mathbf{F}}$ is constant**; therefore, the band-edge energies vary with position in a non-uniformly doped semiconductor:



Band bending as a function of carrier concentration

The ratio of carrier densities at two points depends exponentially on the potential difference between these points:

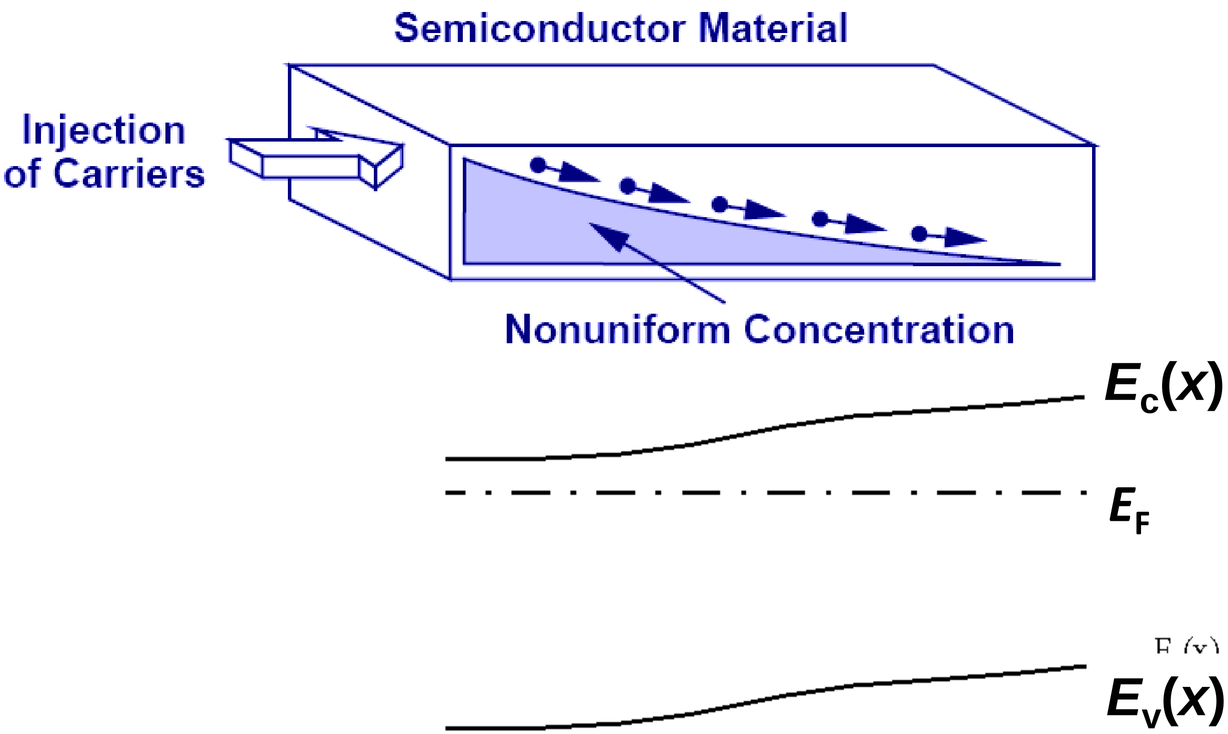
$$E_{\mathrm{F}} - E_{\mathrm{i1}} = kT\ln\left(\frac{n_1}{n_{\mathrm{i}}}\right) \quad => \quad E_{\mathrm{i1}} = E_{\mathrm{F}} - kT\ln\left(\frac{n_1}{n_{\mathrm{i}}}\right)$$

$$\text{Similarly,} \quad E_{\mathrm{i2}} = E_{\mathrm{F}} - kT\ln\left(\frac{n_2}{n_{\mathrm{i}}}\right)$$

$$\text{Therefore} \quad E_{\mathrm{i1}} - E_{\mathrm{i2}} = kT\left[\ln\left(\frac{n_2}{n_{\mathrm{i}}}\right) - \ln\left(\frac{n_1}{n_{\mathrm{i}}}\right)\right] = kT\ln\left(\frac{n_2}{n_1}\right)$$

$$V_2 - V_1 = \frac{1}{q}\left(E_{\mathrm{i1}} - E_{\mathrm{i2}}\right) = \frac{kT}{q}\ln\left(\frac{n_2}{n_1}\right)$$

Band bending as a function of carrier concentration



$$n = N_c e^{-(E_c - E_F)/kT}$$

$$\frac{dn}{dx} = -\frac{N_c}{kT} e^{-(E_c - E_F)/kT} \frac{dE_c}{dx}$$

$$= -\frac{n}{kT}\frac{dE_c}{dx}$$

$$= -\frac{n}{kT} q\varepsilon$$

Lecture: P-N junction

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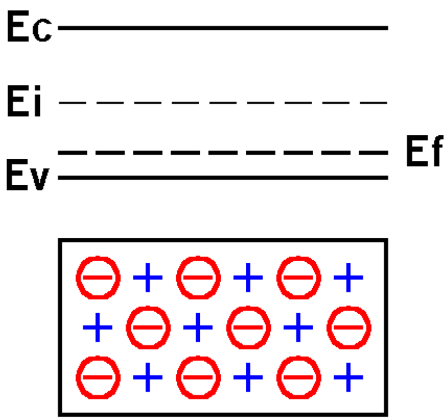
P-N junctions in equilibrium



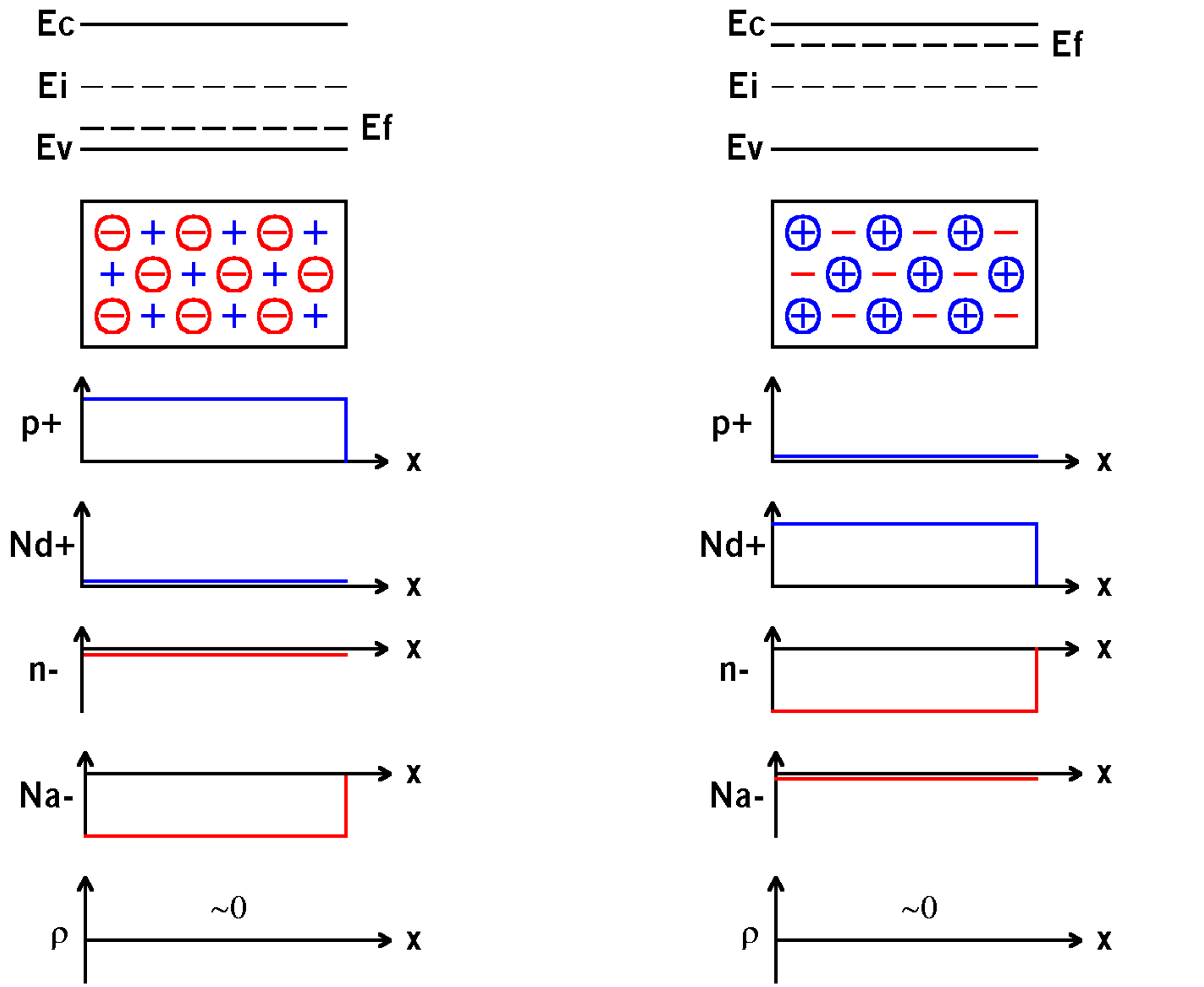
What happens when these bandstructures come into contact?

- Fermi energy must be constant at equilibrium, so bands must bend near the interface
- Far from the interface, bandstructures are conserved

P-N junctions in equilibrium

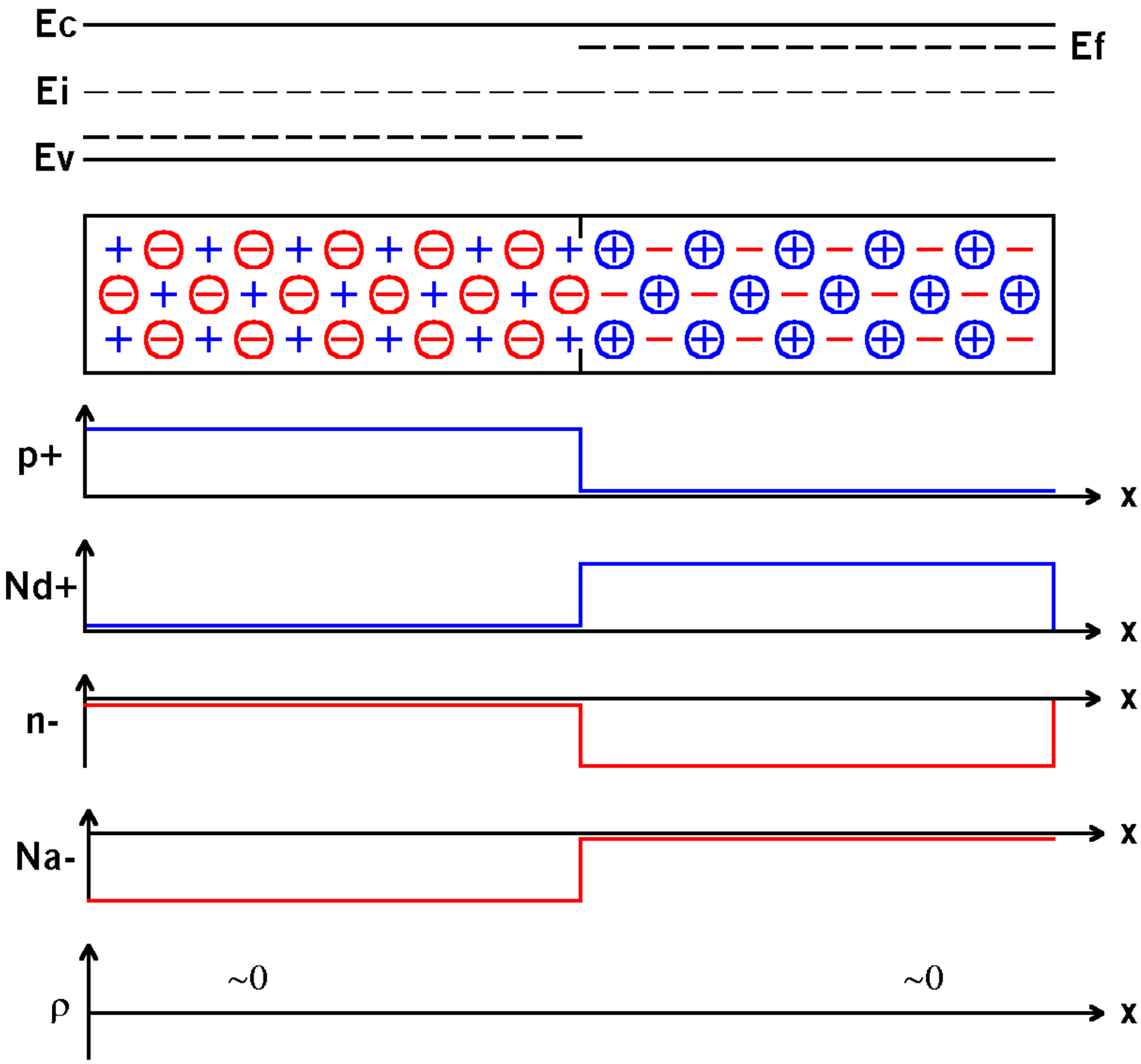
P-type piece N-type piece

Time < 0, i.e. before the contact is established



P-N junctions in equilibrium

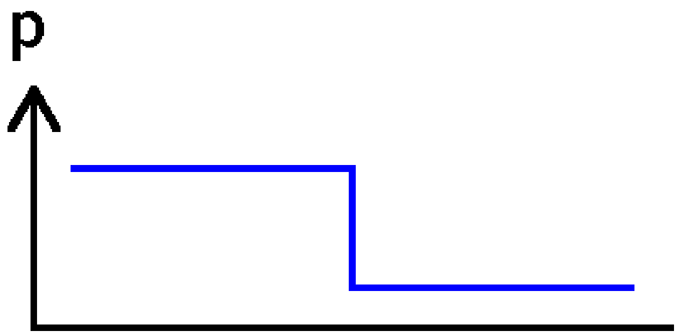
Time =0, the contact is “just” established



P-N junctions in equilibrium

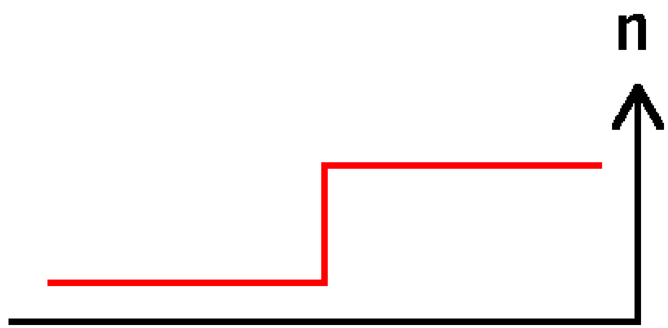
Hole gradient

Question: How



$J_{p,\, diffusion} = -qD_p\, dp/dx$ = current right, holes right

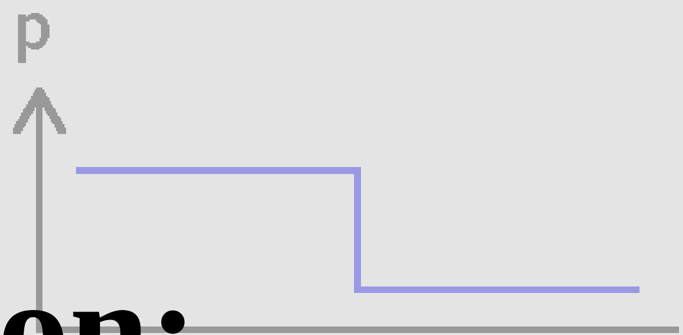
Electron gradient



$J_{n,diffusion} = qD_n\, dn/dx$ = current right, electrons left

P-N junctions in equilibrium

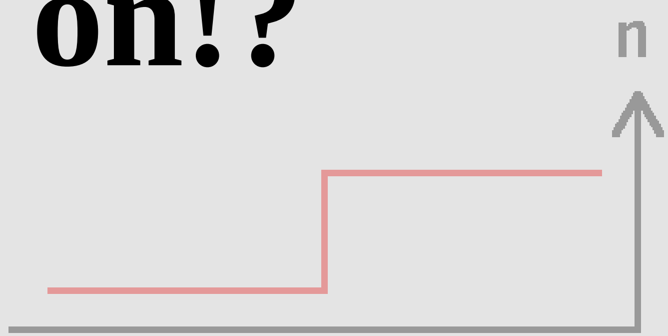
Hole gradient



Question:
How long the diffusion will og on!?

$J_{p,diffusion} = -qD_p\, dp/dx$ = current right, holes right

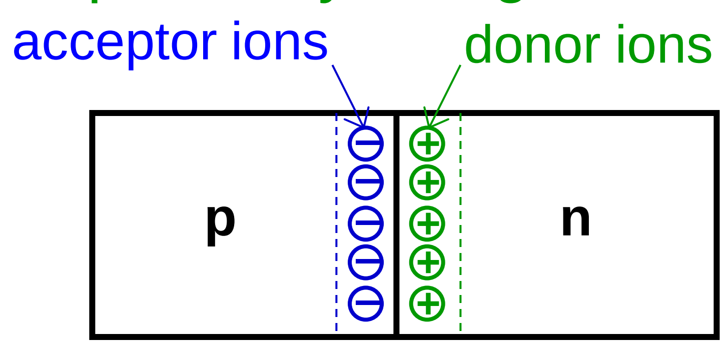
Electron gradient



$J_{n,diffusion} = qD_n\, dn/dx$ = current right, electrons left

P-N junctions in equilibrium

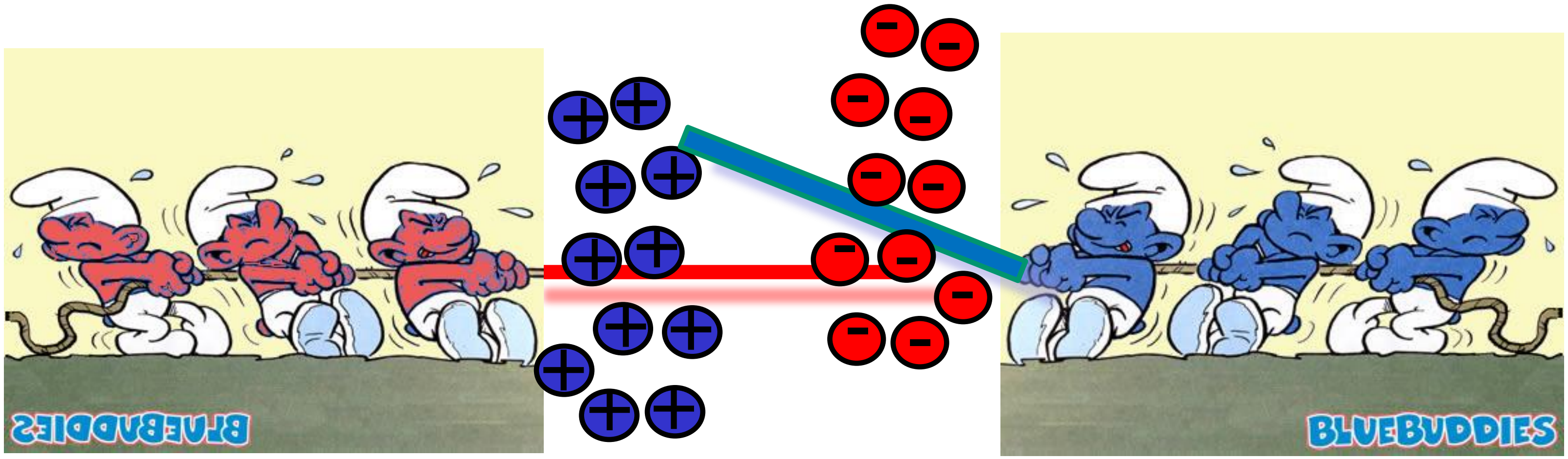
- When the junction is first formed, mobile carriers ***diffuse*** across the junction (due to the concentration gradients)
  - Holes diffuse from the p side to the n side, leaving behind negatively charged immobile acceptor ions
  - Electrons diffuse from the n side to the p side, leaving behind positively charged immobile donor ions



→A region depleted of mobile carriers is formed at the junction.

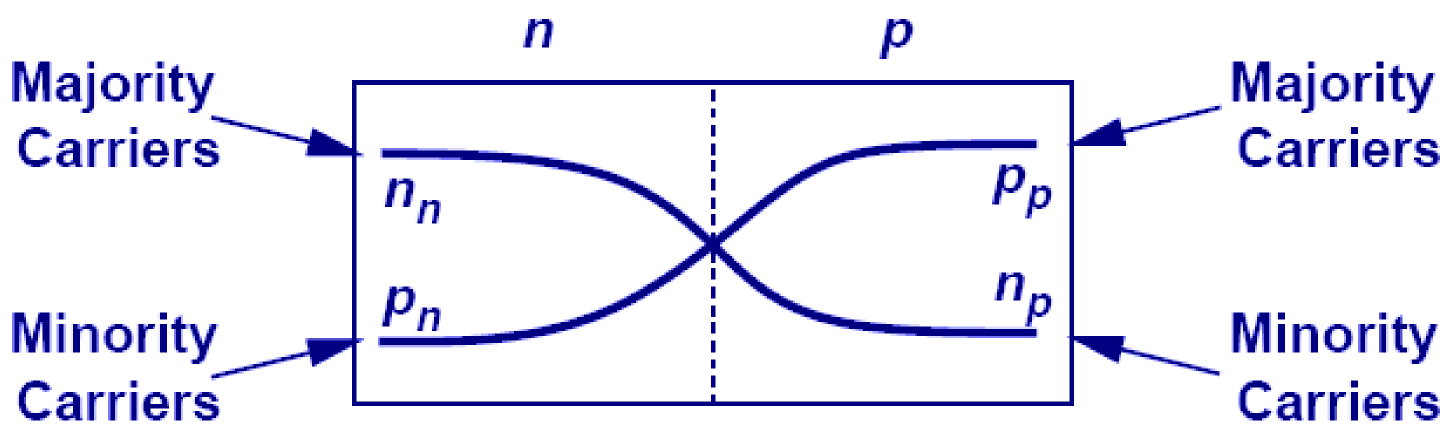
- The space charge due to immobile ions in the depletion region establishes an electric field that opposes carrier diffusion.

P-N junctions in equilibrium



P-N junctions in equilibrium

P-N junctions in equilibrium



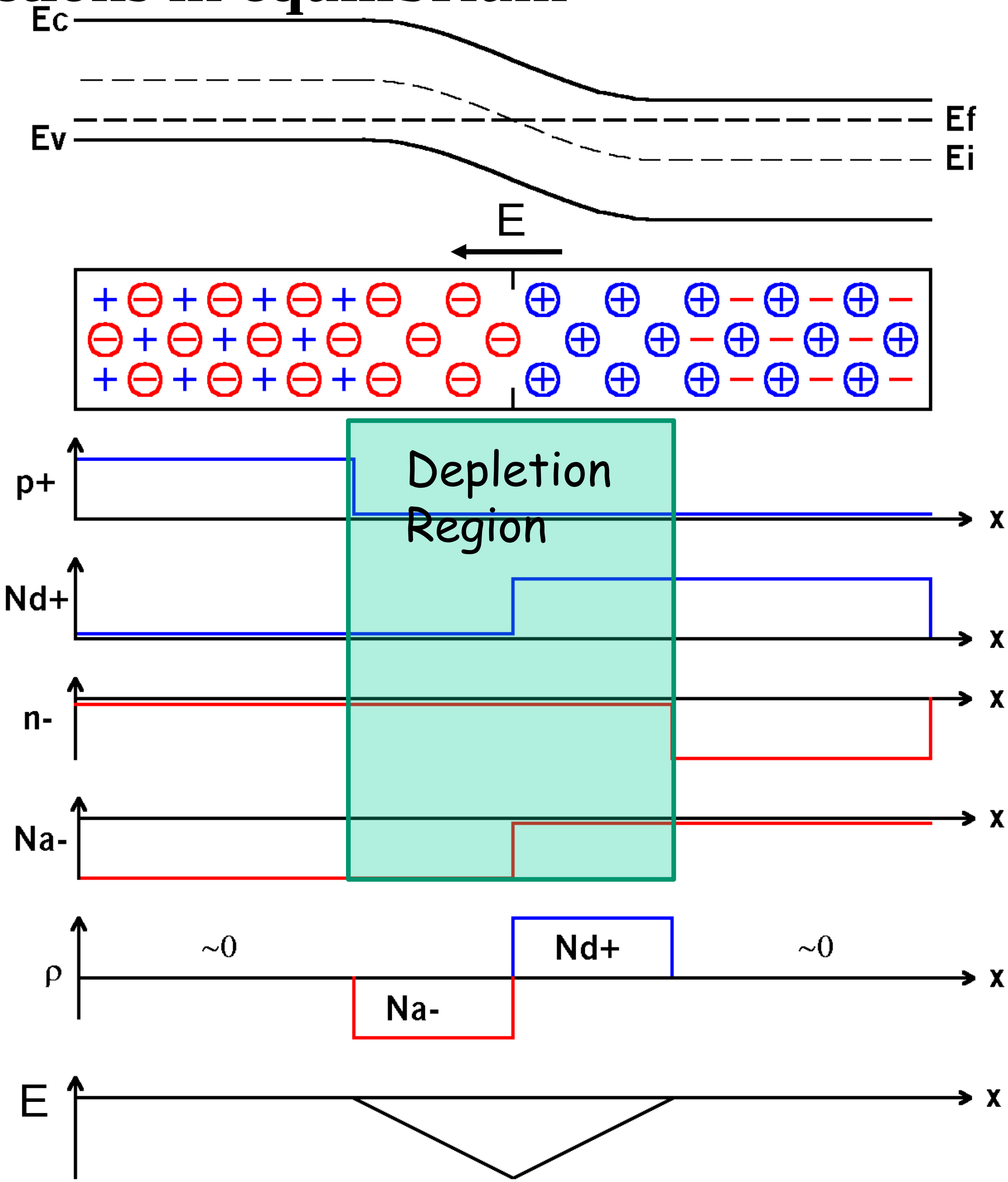
n_n : Concentration of electrons on n side

p_n : Concentration of holes on n side

p_p : Concentration of holes on p side

n_p : Concentration of electrons on p side

P-N junctions in equilibrium

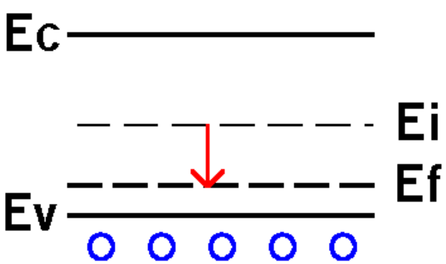


P-N junctions in equilibrium

How big is the built-in voltage?

$$qV_{bi} = (E_i - E_F)_{Left} + (E_F - E_i)_{Right}$$

P side

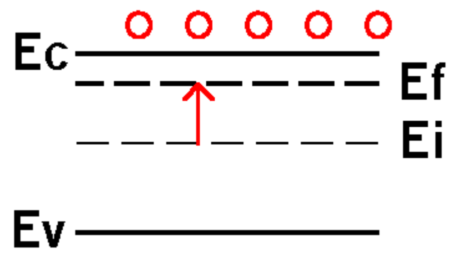


$$p \approx N_a$$

$$N_a = n_i e^{(E_i - E_F)/kT}$$

$$(E_i - E_F)_{Left} = kT \ln\left(\frac{N_a}{n_i}\right)$$

N side



$$n \approx N_d$$

$$N_d = n_i e^{(E_F - E_i)/kT}$$

$$(E_F - E_i)_{Right} = kT \ln\left(\frac{N_d}{n_i}\right)$$

P-N junctions in equilibrium

How big is the built-in voltage?

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_a}{n_i}\right) + \frac{kT}{q}\ln\left(\frac{N_d}{n_i}\right)$$

$$\Rightarrow V_{bi} = \frac{kT}{q}\ln\left(\frac{N_a N_d}{n_i^{\,2}}\right)$$

N_a acceptor level on the p side

N_d donor level on the n side

P-N junctions in equilibrium

- One side of the junction is heavily doped, so that the Fermi level is close to the band edge.
- e.g. p^+-n junction (heavy B implant into lightly doped Si substrate)

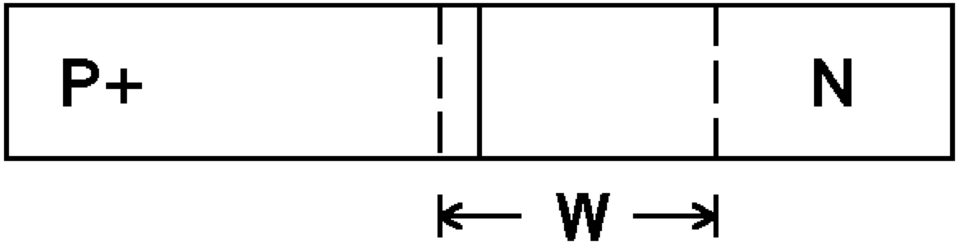
$$(E_i - E_F)_{Left} \approx E_i - E_V = E_G / 2$$

$$(E_F - E_i)_{Right} = kT \ln\left(\frac{N_D}{n_i}\right)$$

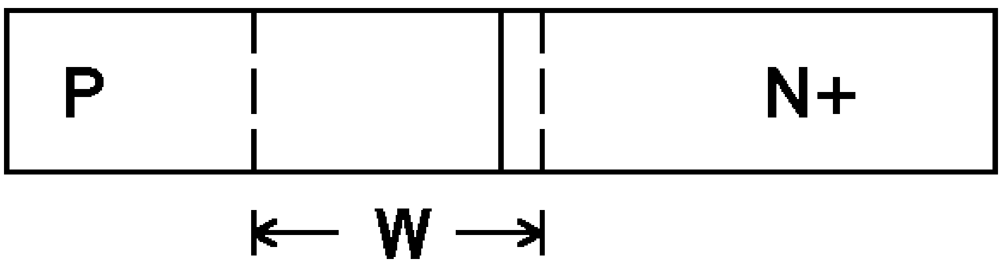
$$\Rightarrow V_{bi} = \frac{E_G}{2q} + \frac{kT}{q} \ln\left(\frac{N_d}{n_i}\right)$$

P-N junctions in equilibrium

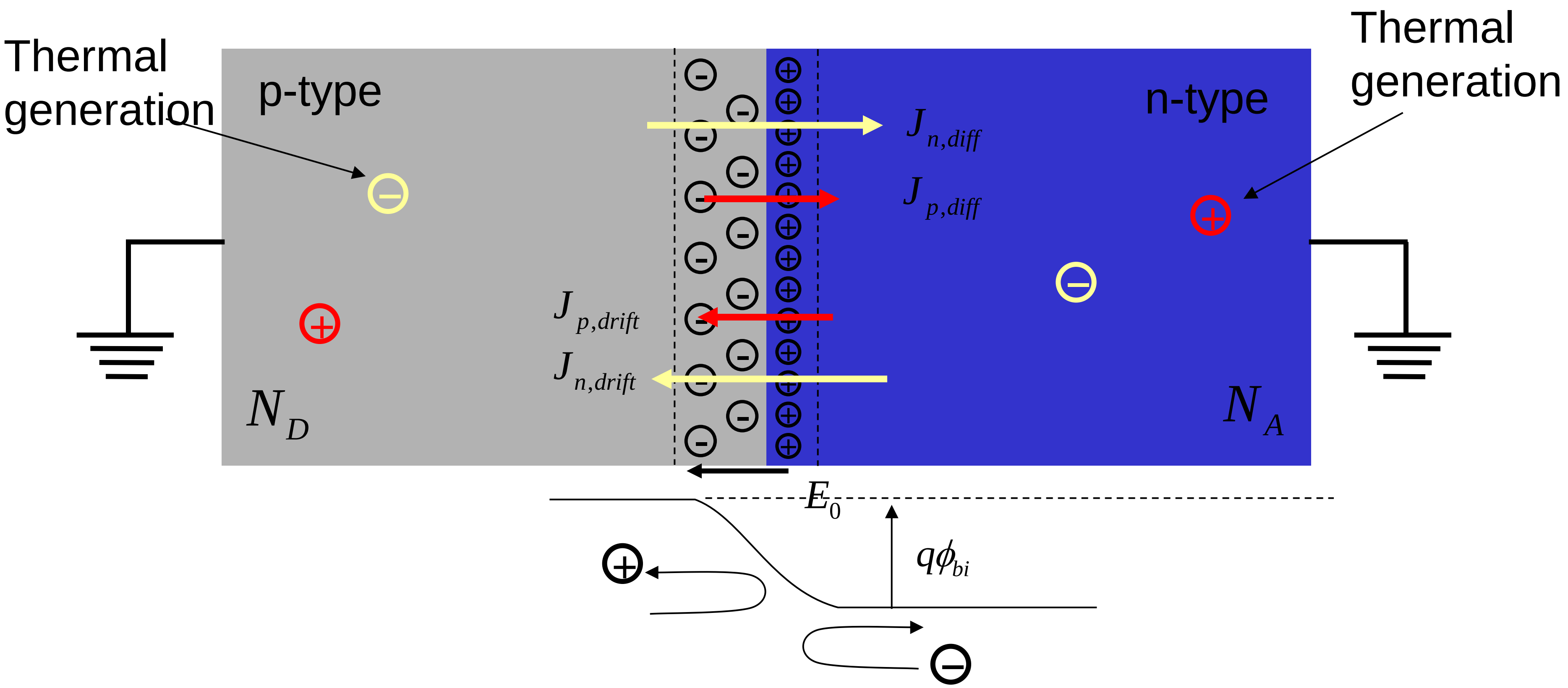
"P^+ - N" => $N_a >> N_d$



"P - N^+" => $N_a << N_d$



P-N junctions in equilibrium



Lecture: P-N junction

- Repetition: intrinsic and extrinsic semiconductors
- Charge carrier transport mechanisms – diffusion and drift
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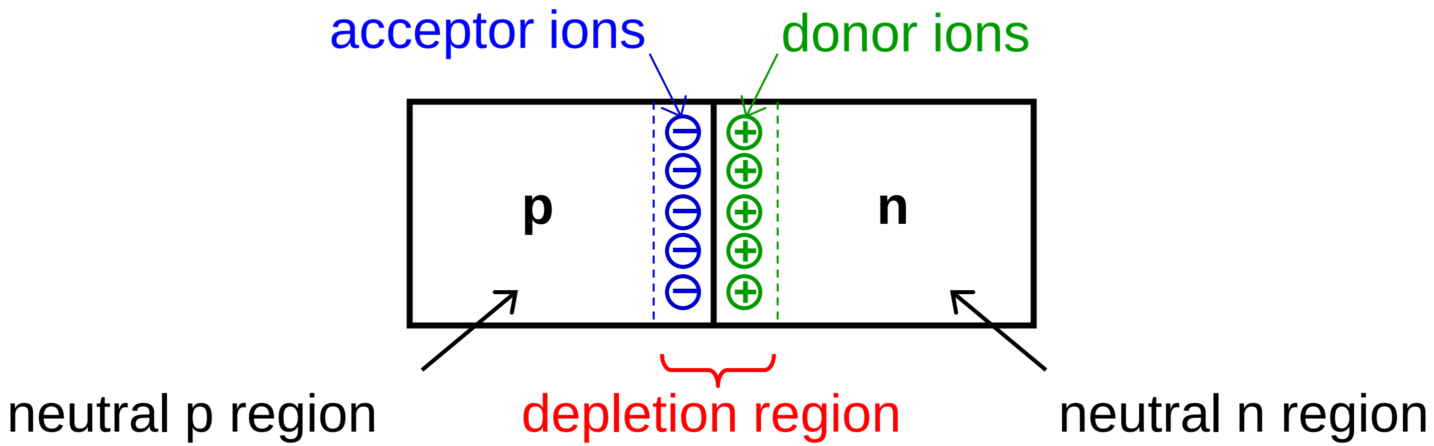
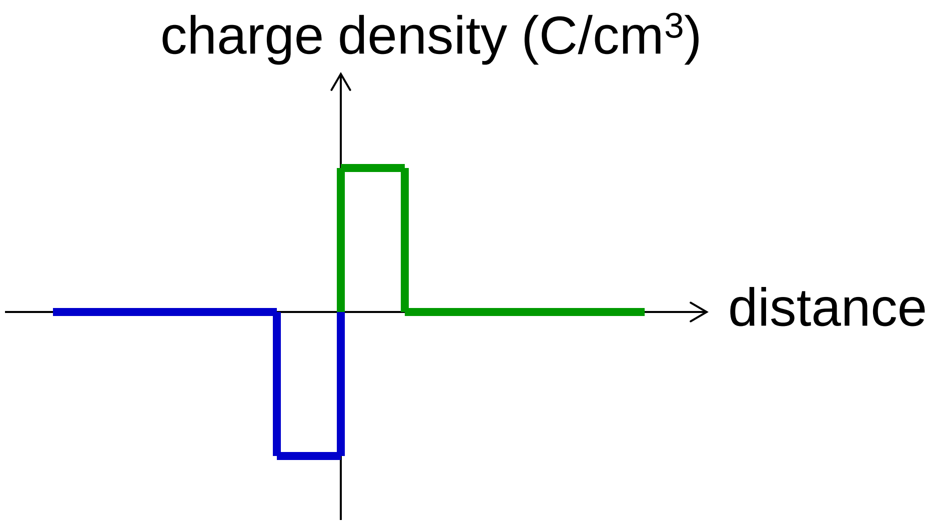
- **Gauss and Poisson equations for the depletion region**
- P-N junction with applied external bias

Gauss and Poisson equations for the depletion region

Charge is stored in the depletion region.





Gauss and Poisson equations for the depletion region

Gauss's law describes the relationship between the charge density and the electric field.

$$\oint_S \vec{E} \cdot d\vec{A} = \frac{1}{\varepsilon} \oint_V \rho \cdot dV = \frac{Q_{encl}}{\varepsilon}$$

$$\boxed{\frac{dE}{dx} = \frac{\rho}{\varepsilon}} \qquad \boxed{E(x) - E(x_0) = \frac{1}{\varepsilon} \int_{x_0}^{x} \rho(x) dx}$$

Poisson's equation describes the relationship between the electric field distribution and the electric potential

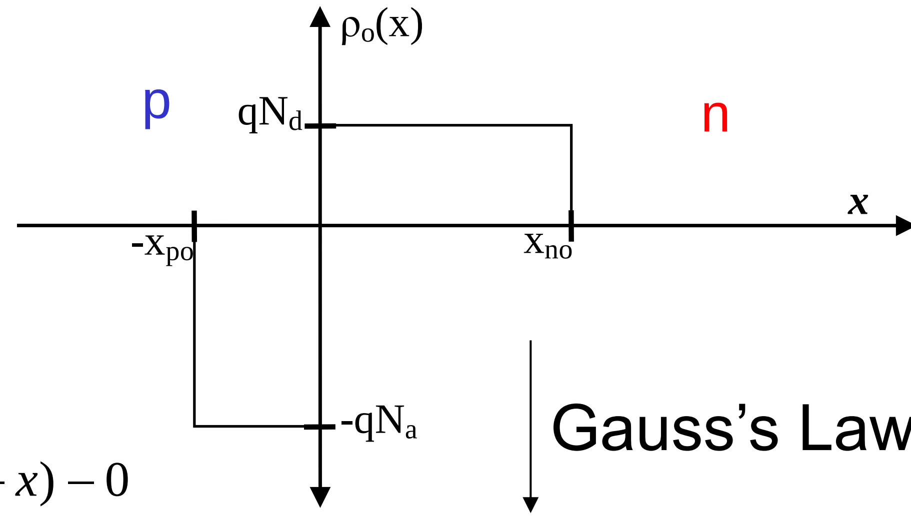
$$\boxed{\phi(x) - \phi(x_0) = \int_{x_0}^{x} -E(x) dx}$$

Gauss and Poisson equations in one dimension

$$\boxed{\frac{d^2\phi(x)}{dx^2} = -\frac{dE(x)}{dx} = -\frac{\rho(x)}{\varepsilon}}$$

Gauss and Poisson equations for the depletion region

$$\rho_0(x) \approx \begin{cases} -qN_a & \left(-x_{p0} \le x \le 0\right) \\ qN_d & \left(0 \le x \le x_{n0}\right) \end{cases} \quad \text{and} \quad \rho_0(x) = 0 \quad \left(x < -x_{p0},\ x > x_{n0}\right)$$

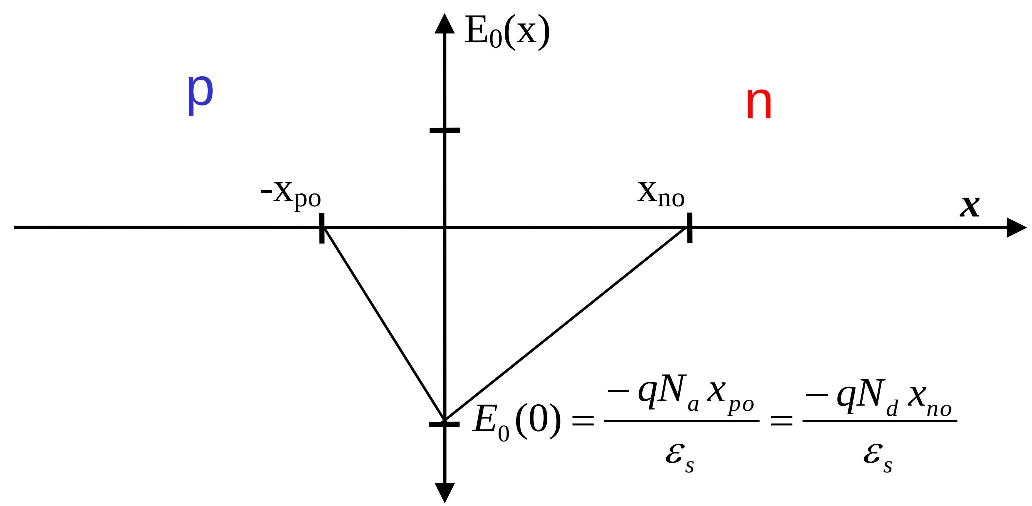


$$E_0(x) = \frac{-qN_a}{\varepsilon_s}(x + x_{po}) \qquad (-x_{po} < x < 0)$$

$$E_0(x) = \int_x^{x_{no}} \frac{\rho_0(x)}{\varepsilon_s} dx \; - E_0(x_{no}) \; = \; \frac{-qN_d}{\varepsilon_s}(x_{no} - x) - 0$$

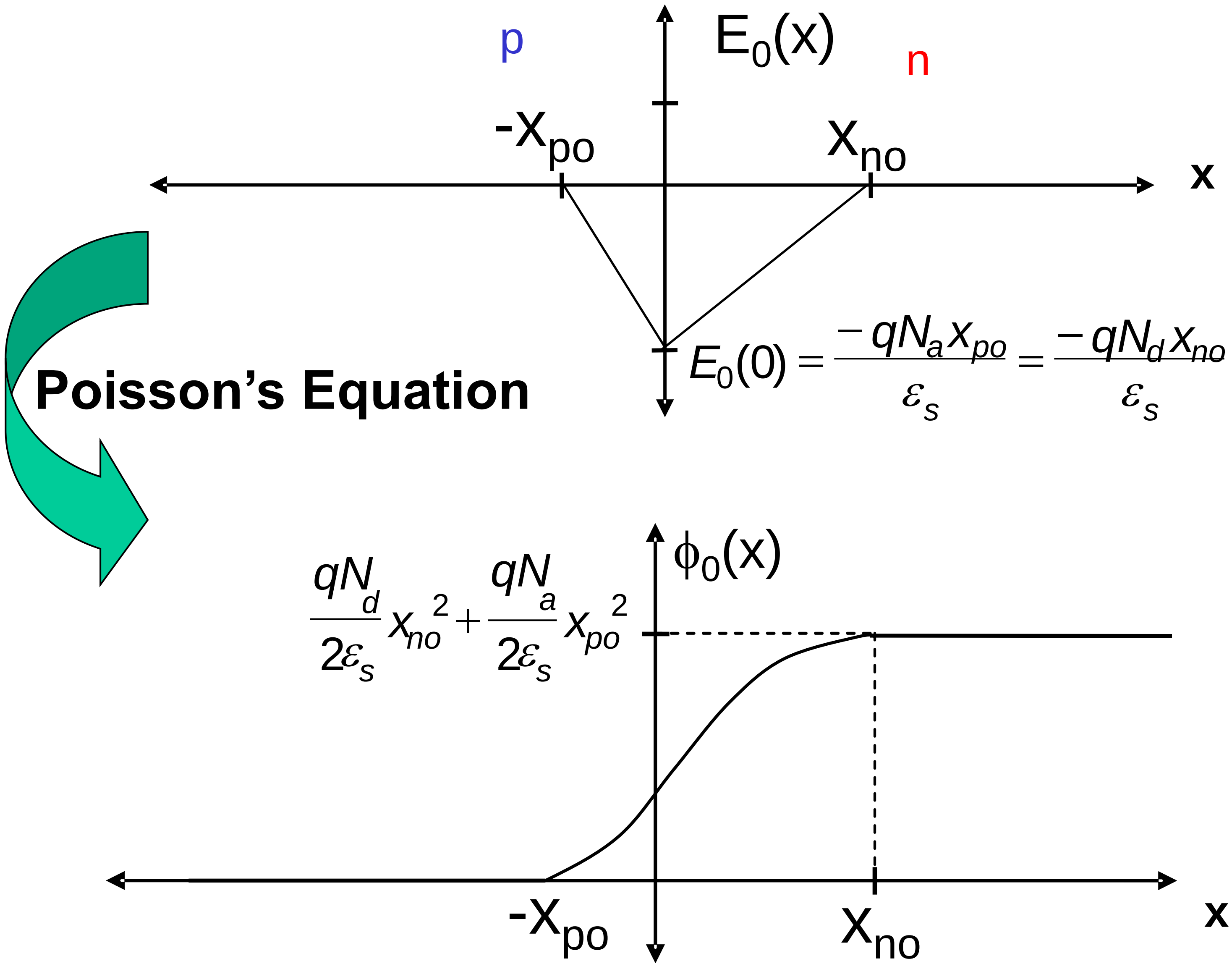
$$E_0(x) \; = \; \frac{qN_d}{\varepsilon_s}(x - x_{no})$$

$$(0 < x < x_{no})$$



$$E_0(0) = \frac{-qN_a x_{po}}{\varepsilon_s} = \frac{-qN_d x_{no}}{\varepsilon_s}$$

Gauss and Poisson equations for the depletion region



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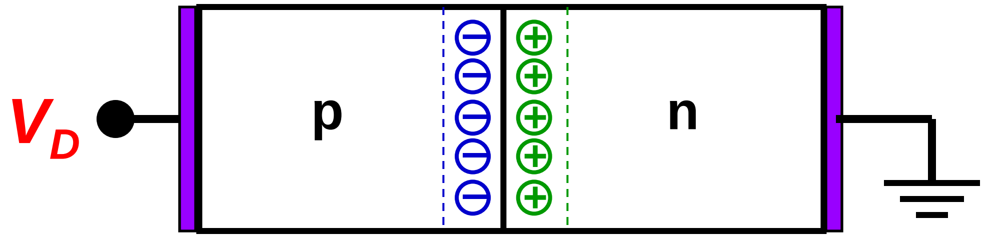
- **P-N junction with applied external bias**

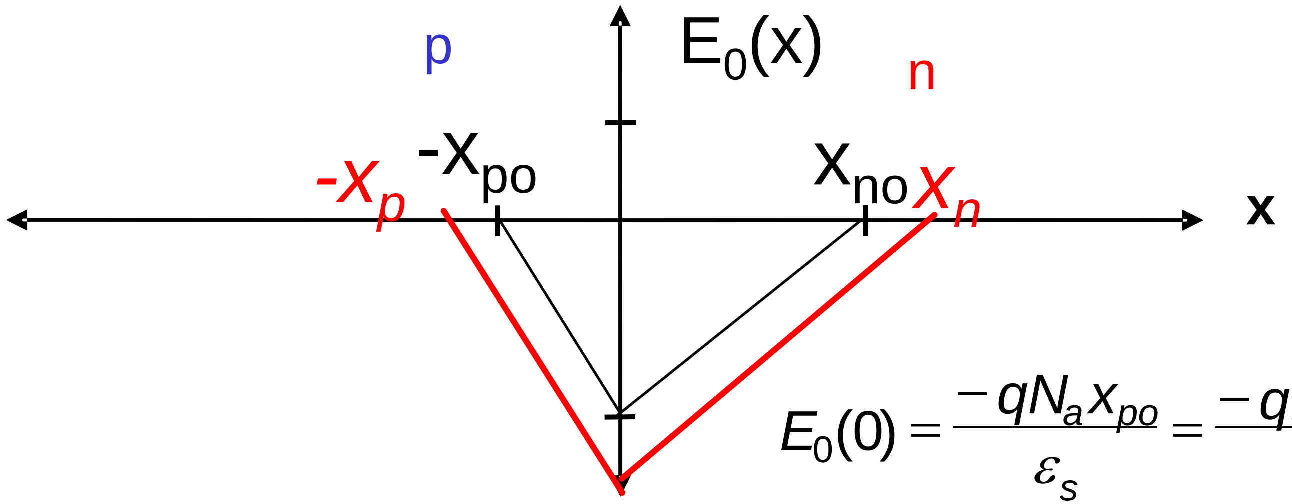
P-N junction with applied external bias



- The quasi-neutral p and n regions have low resistivity, whereas the depletion region has high resistivity. Thus, **when an external voltage V_D is applied across the diode, almost all of this voltage is dropped across the depletion region.**

- If $V_D > 0$ (***forward bias***), the potential barrier to carrier diffusion is reduced by the applied voltage.
- If $V_D < 0$ (***reverse bias***), the potential barrier to carrier diffusion is increased by the applied voltage.

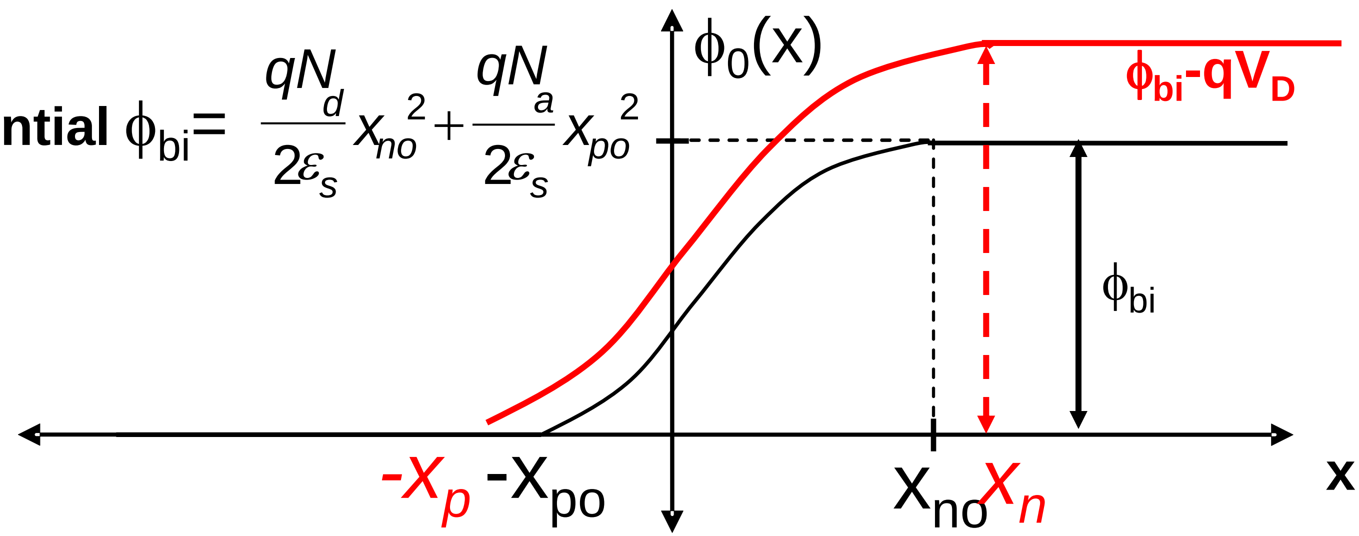
P-N junction with applied external bias



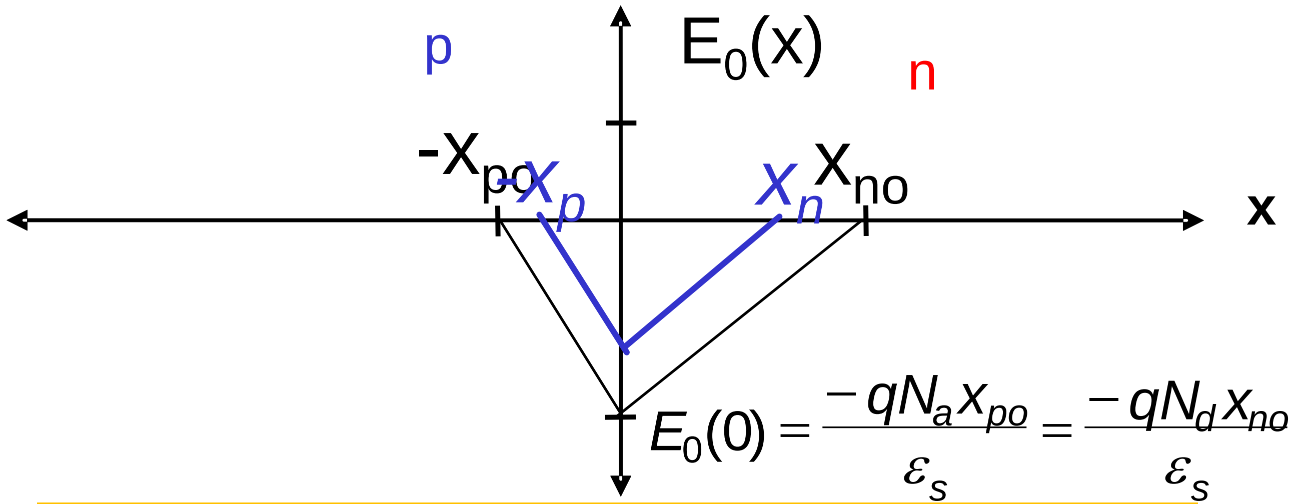
$$E_0(0) = \frac{-qN_a x_{po}}{\varepsilon_s} = \frac{-qN_d x_{no}}{\varepsilon_s}$$

Higher barrier leads to less current!

Built-in potential $\phi_{bi} = \frac{qN_d}{2\varepsilon_s} x_{no}^2 + \frac{qN_a}{2\varepsilon_s} x_{po}^2$



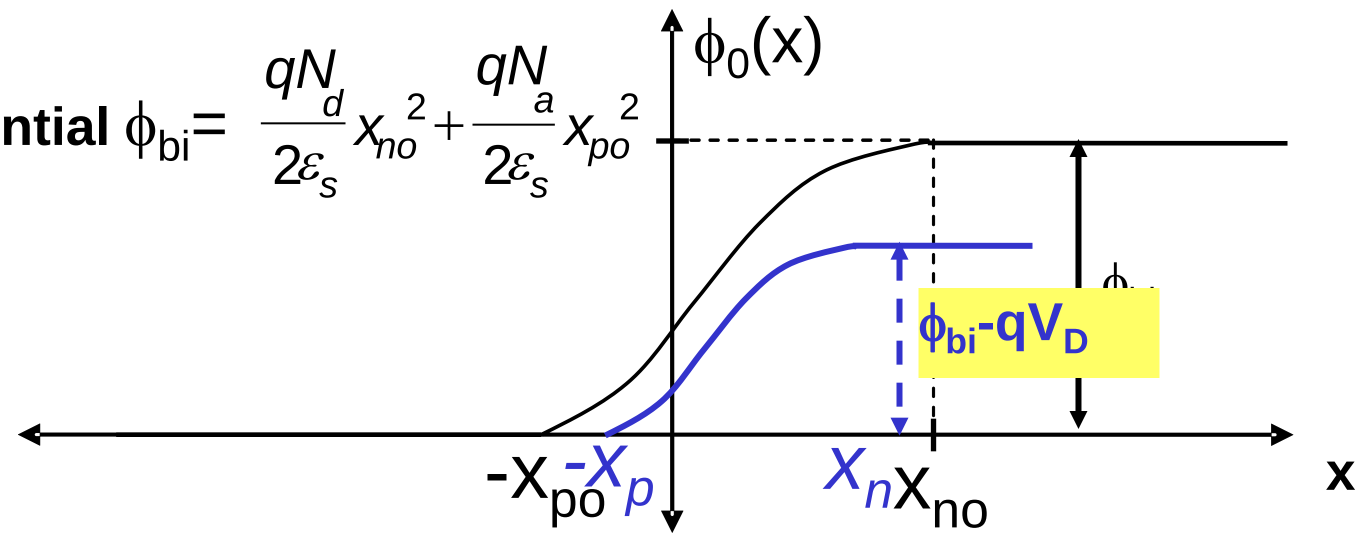
P-N junction with applied external bias



$$E_0(0) = \frac{-qN_a x_{po}}{\varepsilon_s} = \frac{-qN_d x_{no}}{\varepsilon_s}$$

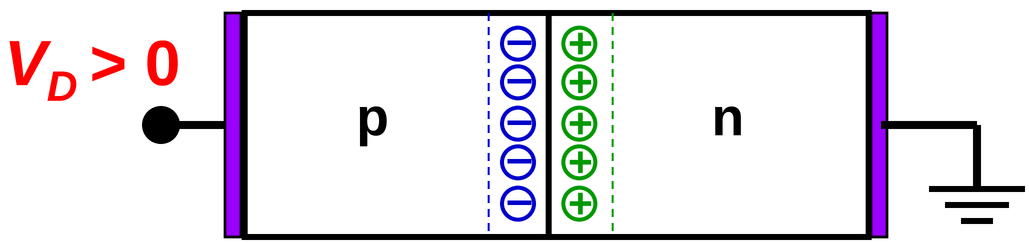
Lower barrier lead to more current!

Built-in potential $\phi_{bi} = \dfrac{qN_d}{2\varepsilon_s} x_{no}^2 + \dfrac{qN_a}{2\varepsilon_s} x_{po}^2$



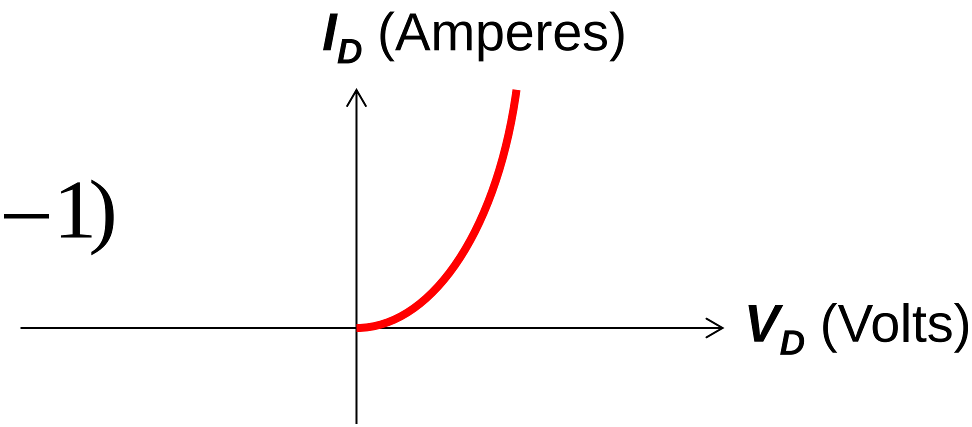
P-N junction with applied external bias

- As V_D increases, the potential barrier to carrier diffusion across the junction decreases*, and current increases exponentially.



The carriers that diffuse across the junction become minority carriers in the quasi-neutral regions; they then recombine with majority carriers, "dying out" with distance.

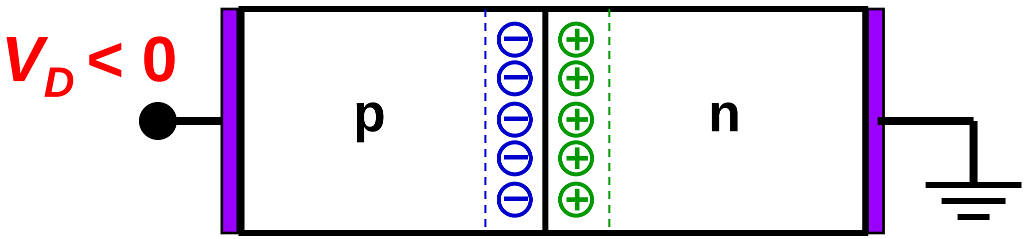
$$I_D = I_S(e^{qV_D/kT} - 1)$$



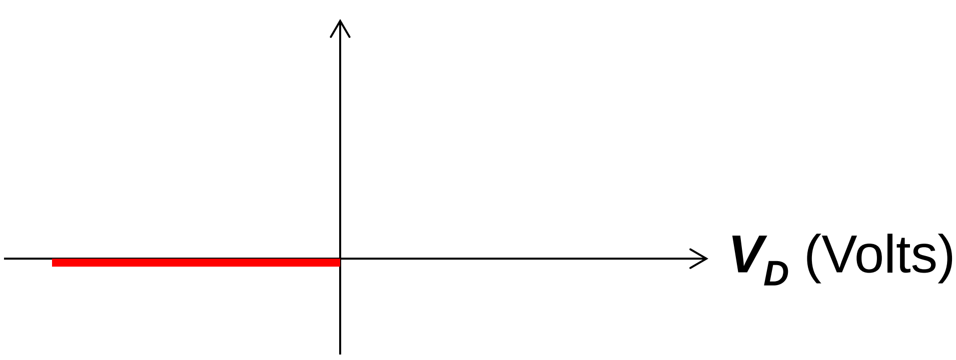
* Hence, the width of the depletion region decreases.

P-N junction with applied external bias

- As $|V_D|$ increases, the potential barrier to carrier diffusion across the junction increases*; thus, no carriers diffuse across the junction.



A very small amount of reverse current ($I_D < 0$) does flow, due to minority carriers diffusing from the quasi-neutral regions into the depletion region and drifting across the junction.

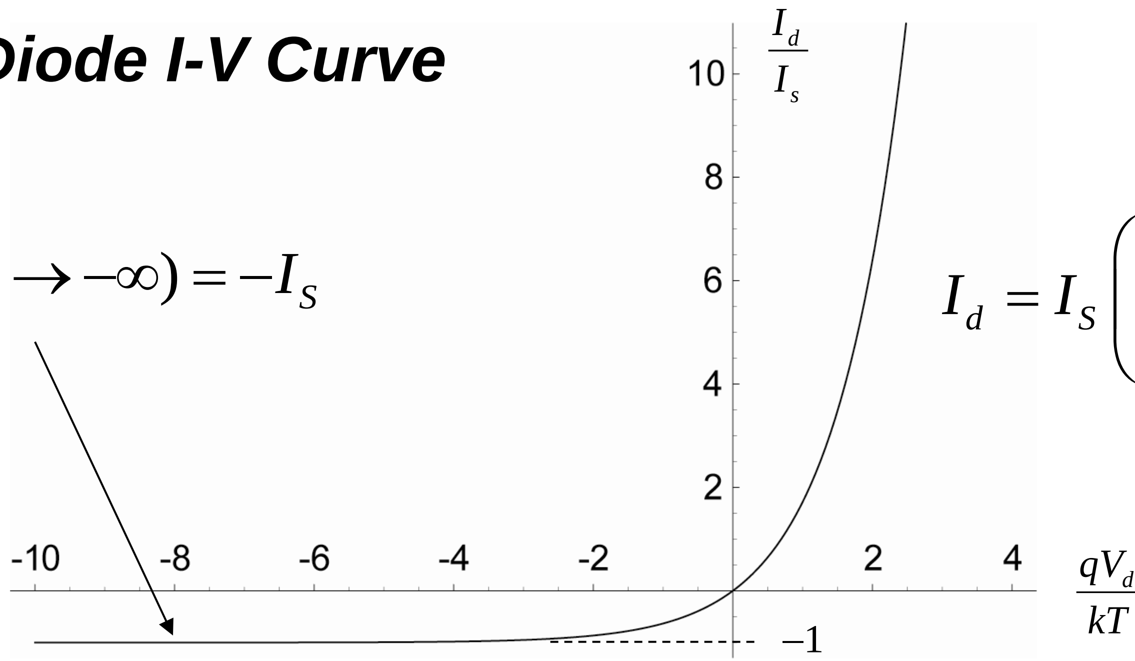


* Hence, the width of the depletion region increases.

P-N junction with applied external bias

Diode I-V Curve

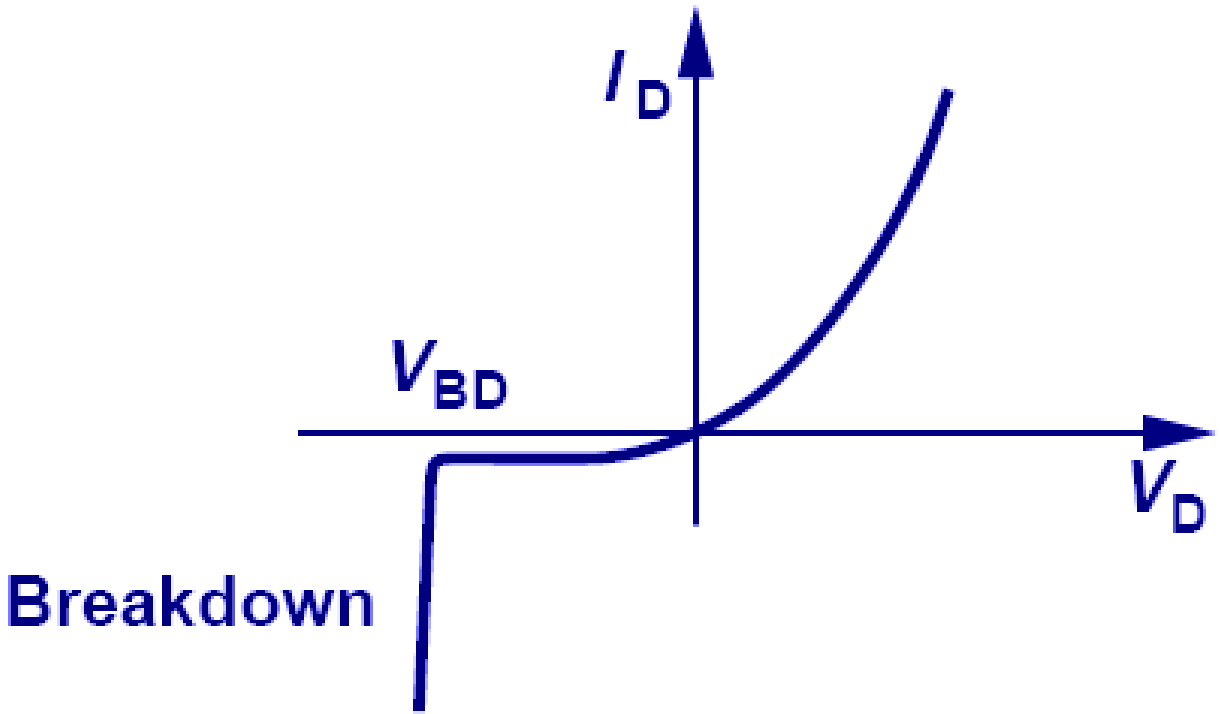
$$I_d(V_d \to -\infty) = -I_S$$



$$I_d = I_S\left(e^{\frac{qV_d}{kT}} - 1\right)$$

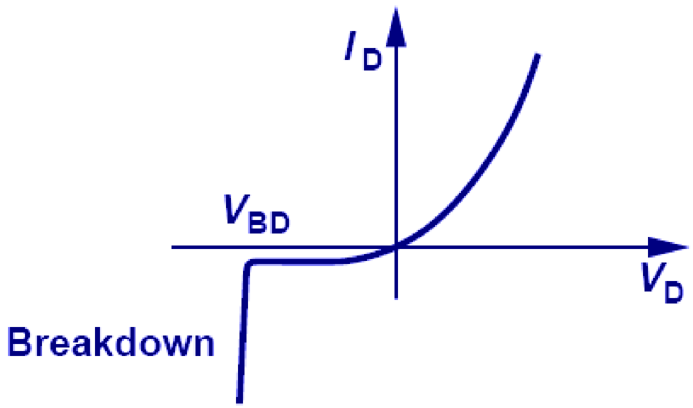
- Diode IV relation is an exponential function
- This exponential is due to the Boltzmann distribution of carriers versus energy
- For reverse bias the current saturations to the drift current due to minority carriers

P-N junction with applied external bias



When a large reverse bias voltage is applied, breakdown occurs and current flows through the diode increases dramatically.

P-N junction with applied external bias



When a large reverse bias voltage is applied, breakdown occurs and current flows through the diode increases dramatically.

- Zener breakdown or tunneling mechanism, occurs in a highly doped p-n junction, while the conduction and valance bands on opposite sides of the junction become so close during the reverse-bias that the electrons on the p-side can tunnel from directly VB into the CB on the n-side.

- Avalanche breakdown mechanism occurs when electrons and holes moving through the depletion region and acquire sufficient energy from the electric field to break a bond i.e. create electron-hole pairs by colliding with atomic electrons within the depletion region. These newly created electrons and holes move in opposite directions due to the electric field and thereby add to the existing reverse bias current.