Section 19
Introduction to PN Junctions

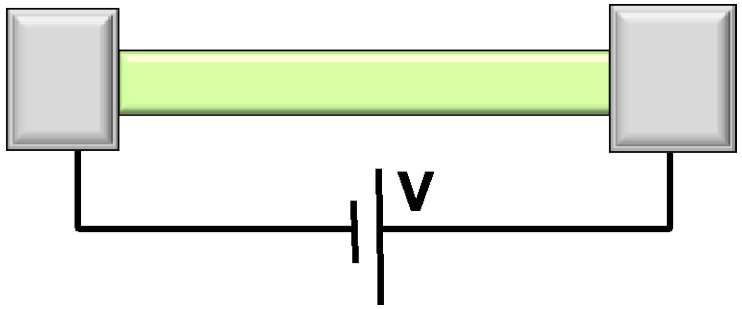
Gerhard Klimeck

gekco@purdue.edu

PURDUE UNIVERSITY

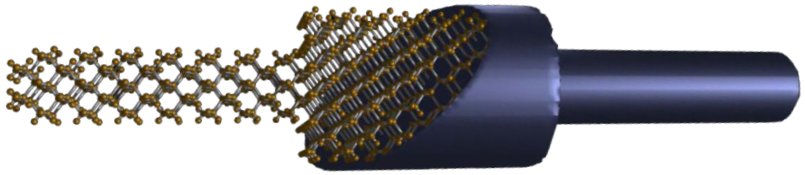
School of Electrical and Computer Engineering

Current Flow Through Semiconductors



$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area



- **Materials, composition, crystals**
- Tabulated for **"known" bulk materials**
- At nm-scale properties change with geometry => theory

⇒ Quantum Mechanics Mechanics

- Concepts of **density of states and masses**

⇒ Equilibrium Statistical Mechanics

- **Occupation factors**

Transport with scattering, non-equil. Stat. Mech.

- Drift-diffusion Eq. with recombination-generation

Understanding transport in concrete devices

PN Diode Schottky Diode

BJT/ HBT MOS

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

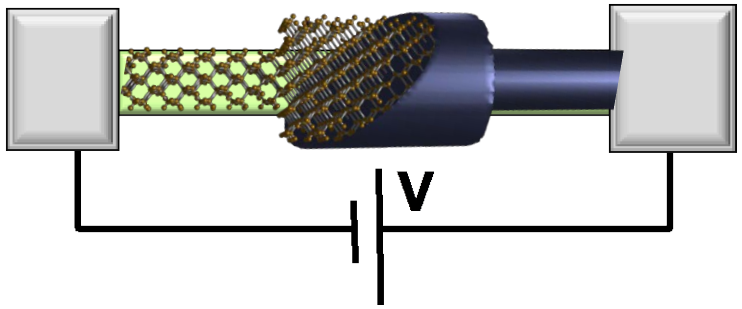
$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{-1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

Topic Map



$I = G \times V$

$= q \times n \times v \times A$

charge density velocity area

	Equilibrium				
PN Diode					
Schottky Diode					
BJT/ HBT					
MOS					

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

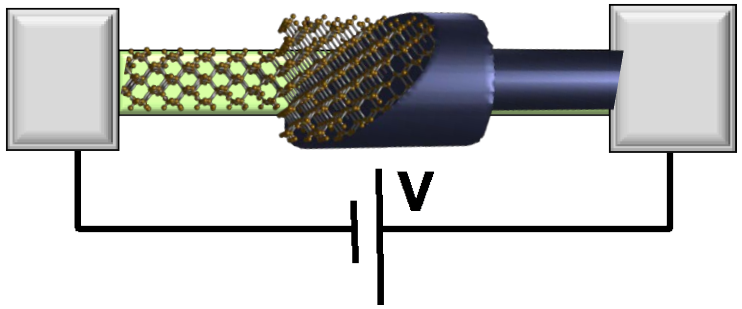
$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{-1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

Topic Map



$I = G \times V$

$= q \times n \times v \times A$

charge density velocity area

	Equilibrium	DC			
PN Diode					
Schottky Diode					
BJT/ HBT					
MOS					

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

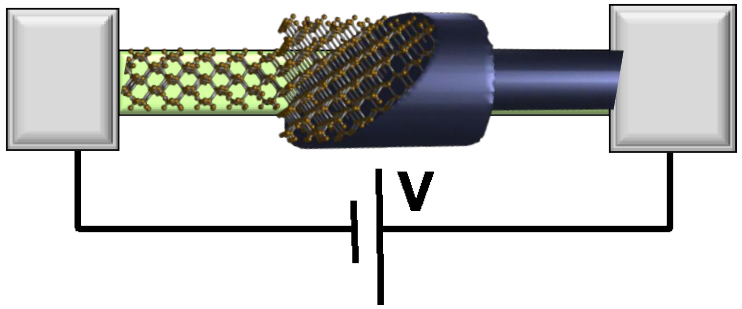
$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{-1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

Topic Map



$I = G \times V$

$= q \times n \times v \times A$

charge density velocity area

	Equilibrium	DC	Small signal	Large Signal	Circuits
PN Diode					
Schottky Diode					
BJT/ HBT					
MOS					

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

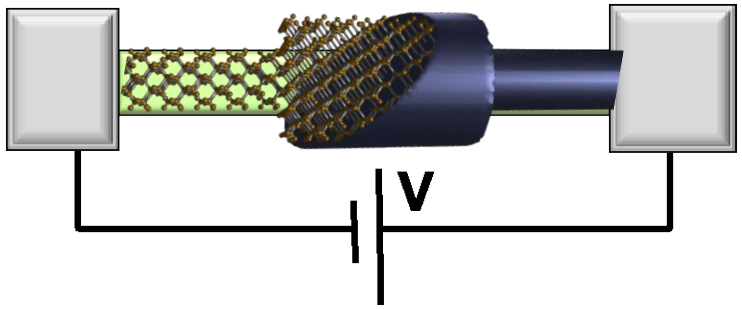
$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{-1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

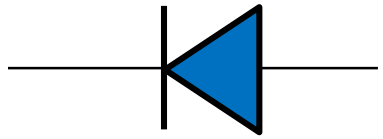
$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

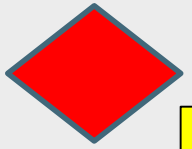
Section 19
Introduction to PN Junctions



$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density, velocity, area



	Equilibrium	DC	Small signal	Large Signal	Circuits
PN Diode					
Schottky Diode					
BJT/ HBT					
MOS					

Diode in Equilibrium.
(No external voltage applied)

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

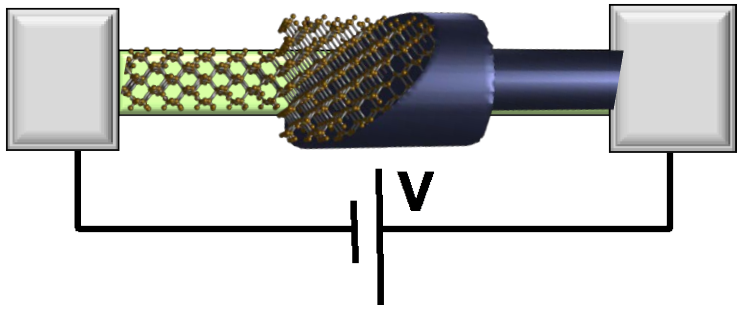
$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{-1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

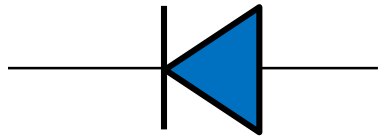
$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

Section 19
Introduction to PN Junctions



$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area



Vid

Vid

- 19.1 Structure and Depletion Region
- 19.2 Drawing band-diagrams in equilibrium

$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{-1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

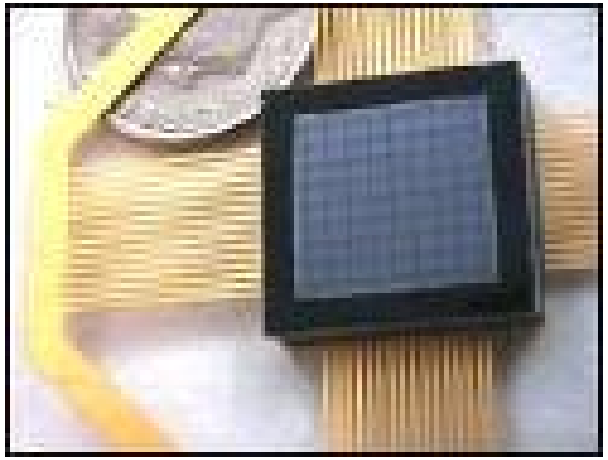
What is a Diode good for ….

solar cells

GaAs lasers

Organic LED

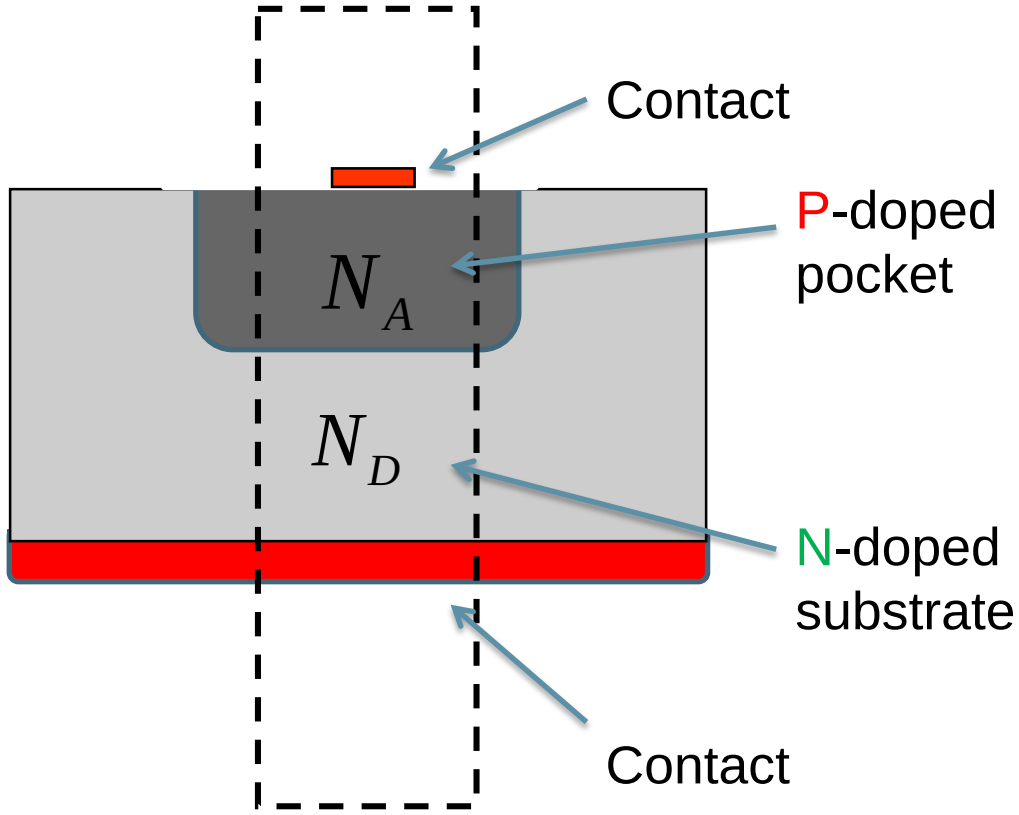
Avalanche Photodiode



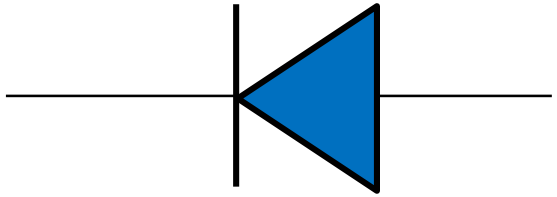
GaN lasers

p-n Junction Devices …

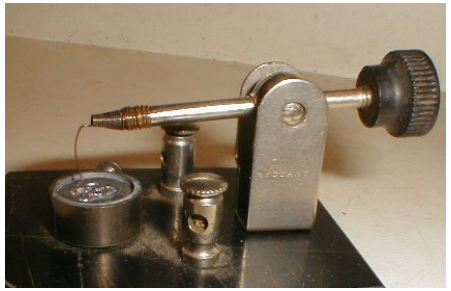
Schematic of a p-n Diode



Symbol

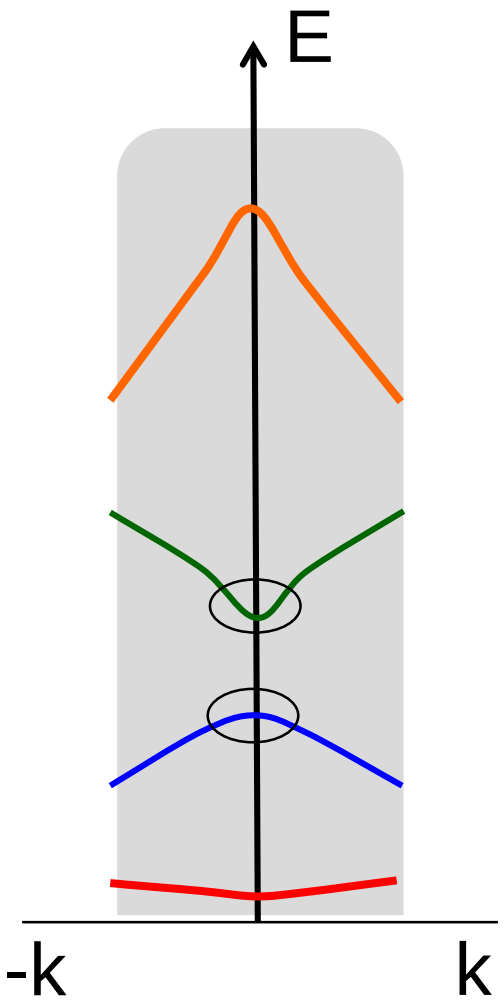


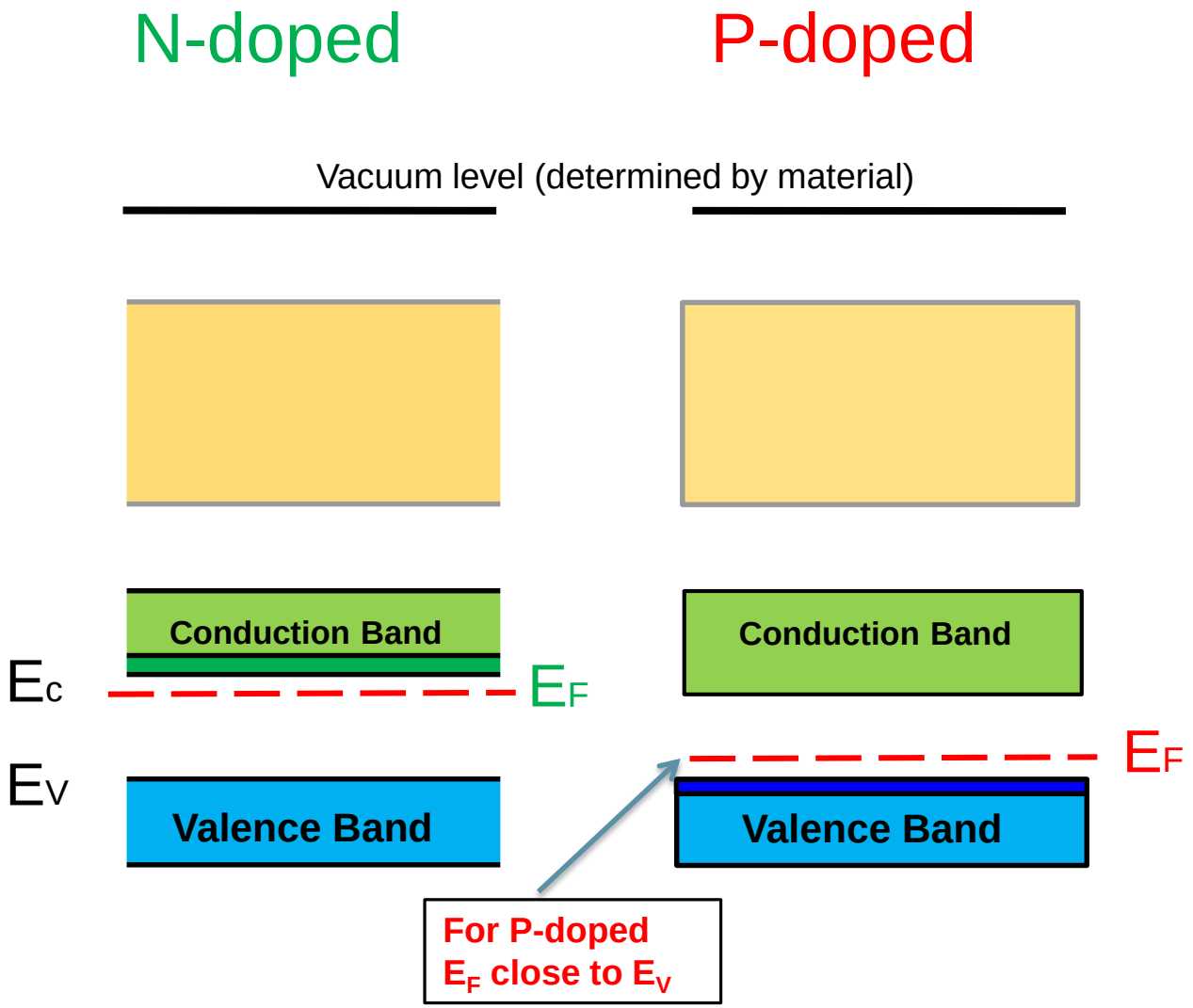
Point-contact diode



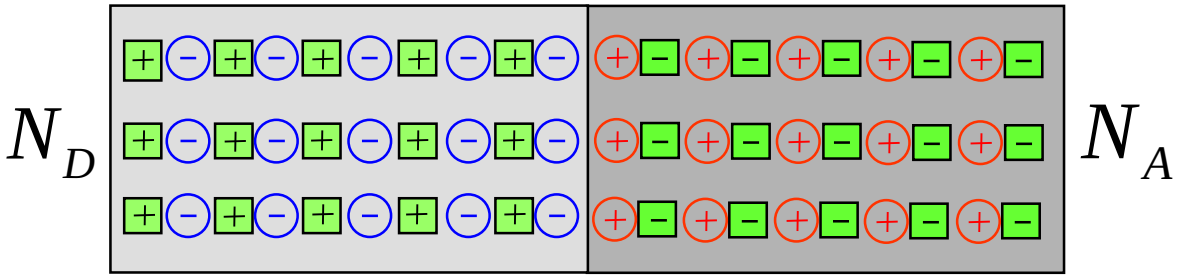
https://upload.wikimedia.org/wikipedia/commons/8/8c/CatWhisker.jpg

P and N doped Material Side by Side …





Forming a Junction

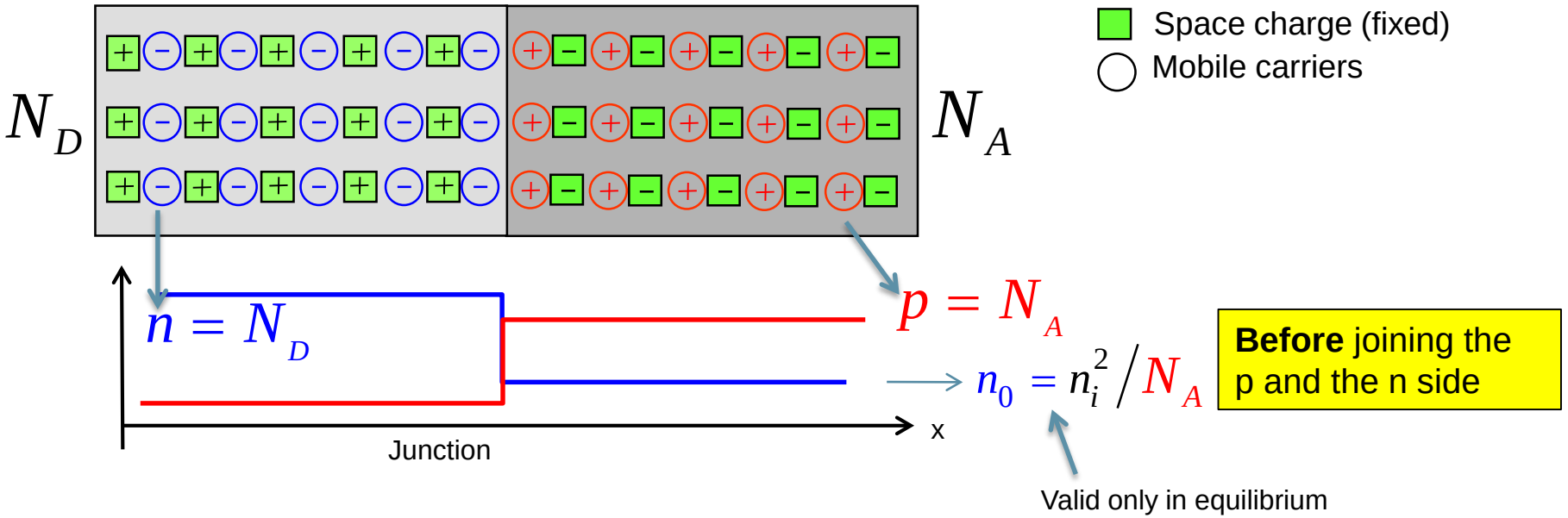


Space charge (fixed)
Mobile carriers

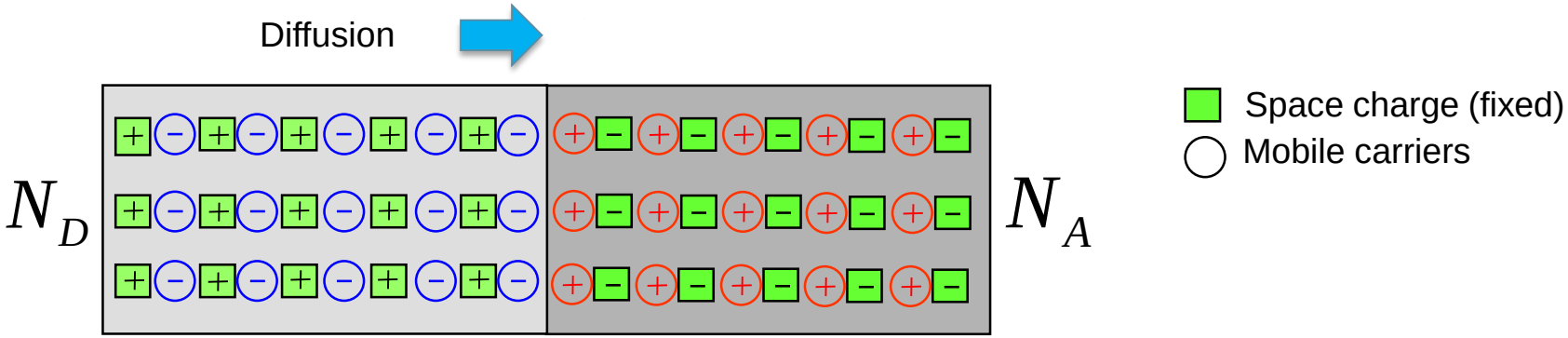
Donor-side (N-side)
Squares are fixed **donor atoms**.
Every donor atom has given away one **electron** (blue **circle**)

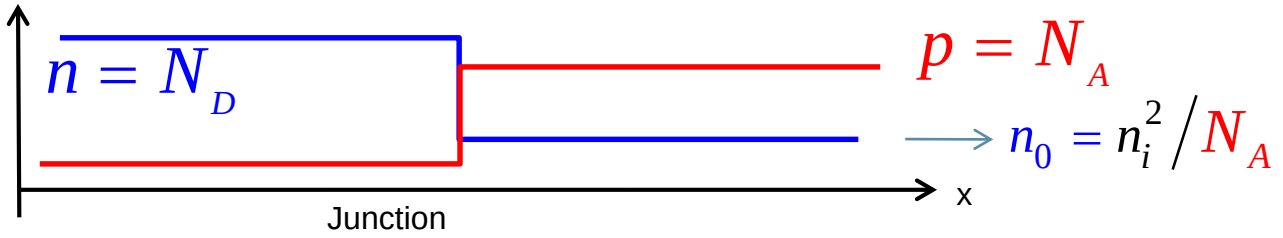
Acceptor-side (P-side)
Squares are fixed **acceptor atoms**.
Every acceptor atom has captured one **electron** (from the valence band).
Every acceptor atom leaves behind one **hole** in the valence band. (red **circle**)

Forming a Junction

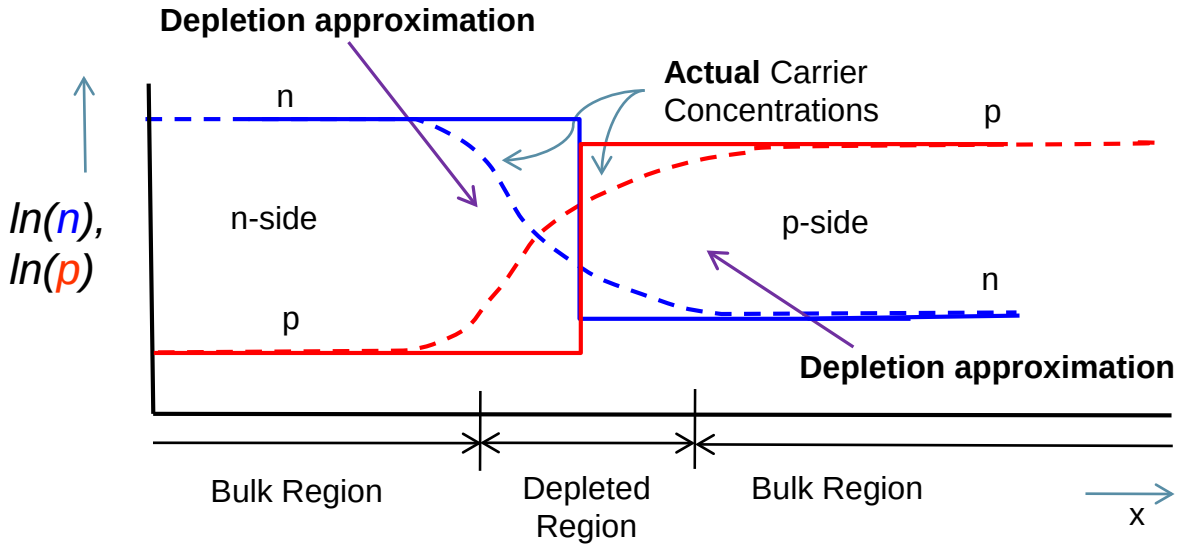


Forming a Junction



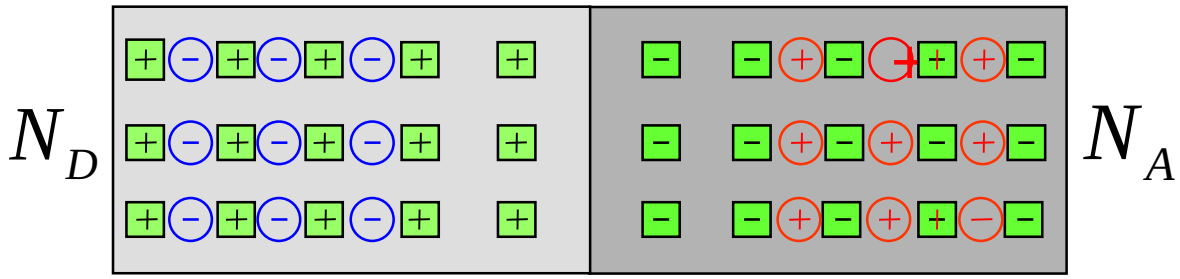


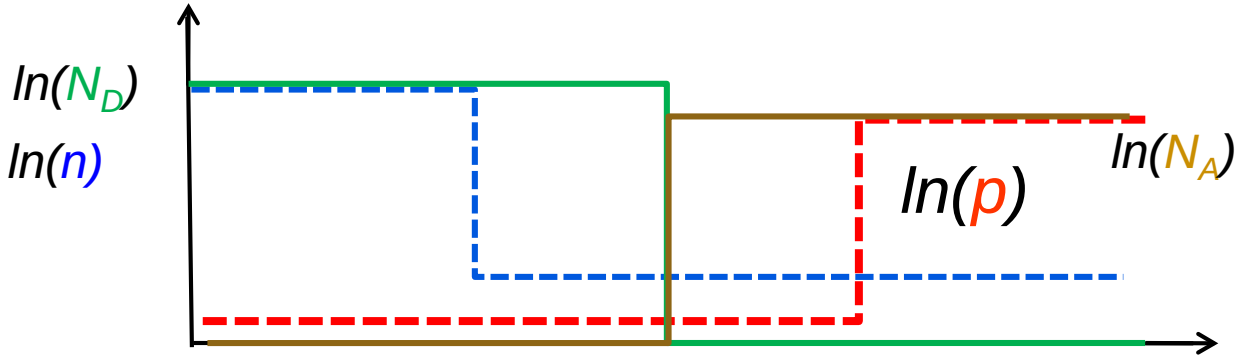
Before joining the p and the n side



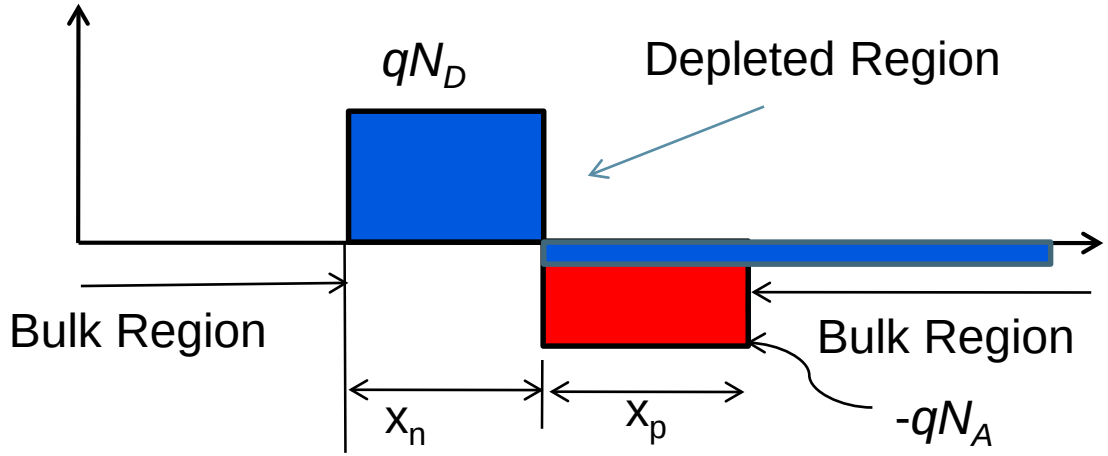
After joining the p and the n side

Formation of a Junction





Q=p-n+N_D-N_A



Net charge on **N-side**: qN_D
(subtract green from blue line)
Space charge region: fixed donor atoms
Neglect electrons in p-side
X_n: depletion region in N-side

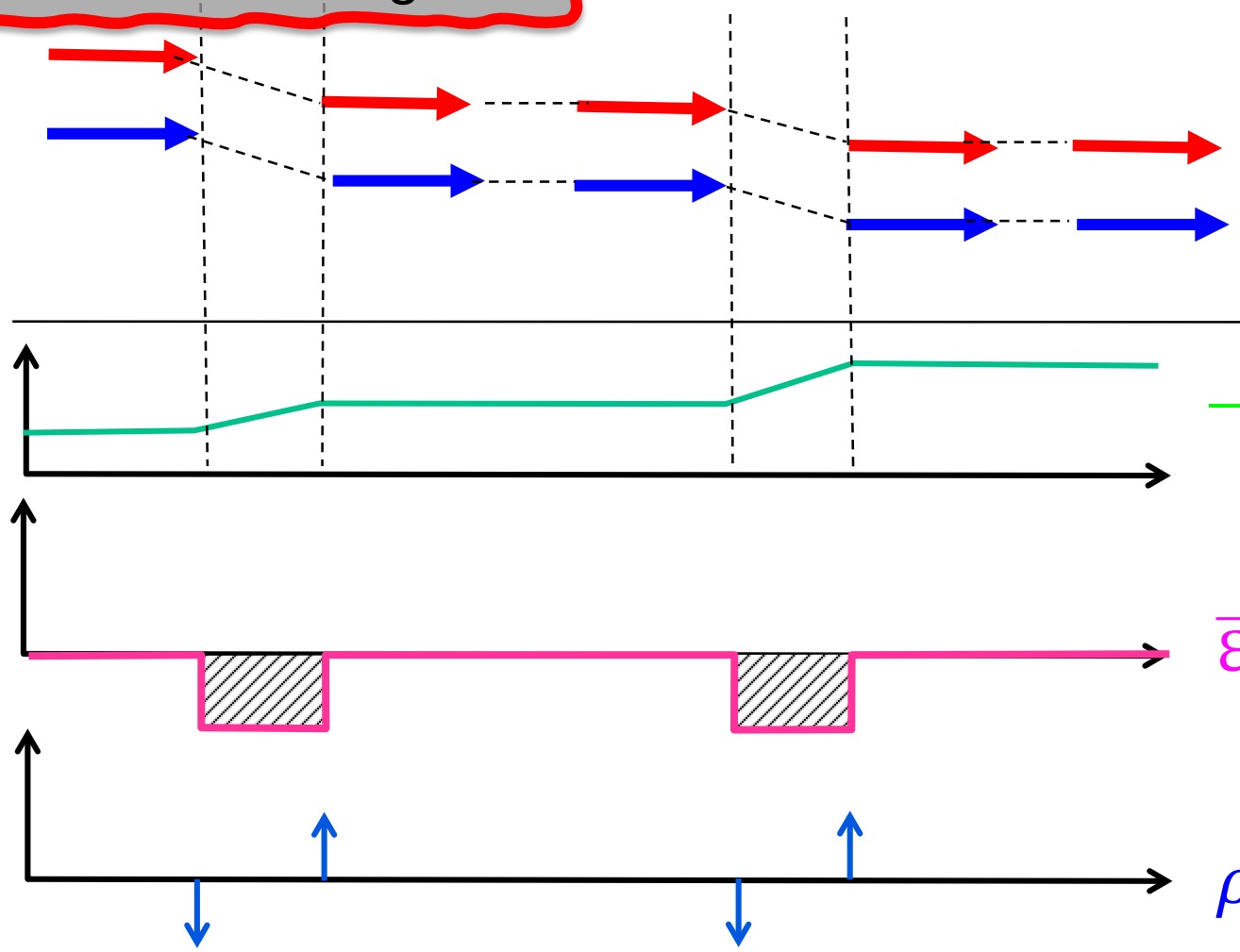
Net charge on **P-side**: $-qN_A$
(subtract brown from red line)
Space charge region: fixed acceptor atoms
X_p: depletion region in P-side

red and blue are of equal size
→ **charge balance**

Depletion Region means depleted of "mobile" charges

Potential, Field and Charge

From Section 13 – Band Diagrams



$$P.E. = E_c - E_{ref}$$

$$E_{ref}$$

$$-qV = E_c - E_{ref}$$

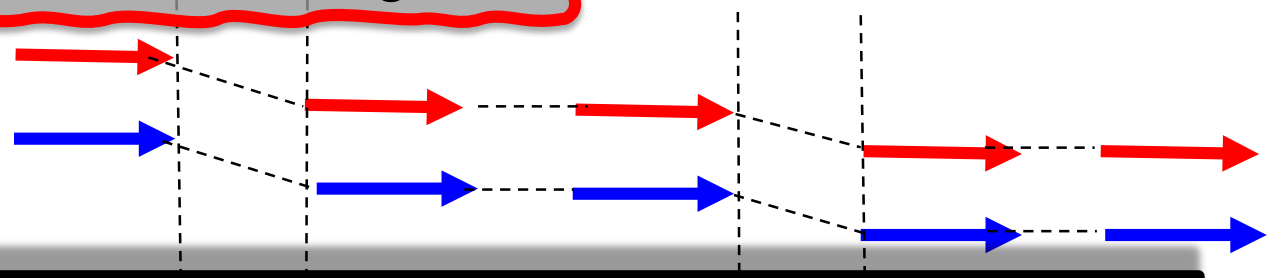
$$\vec{\varepsilon} = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_c}{dx}$$

$$\rho \propto \frac{d\vec{\varepsilon}}{dx} = -\frac{d^2V}{dx^2}$$

In most practical cases start from charge and derive potentials!
=> Useful to learn “graphical” integration

Potential, Field and Charge

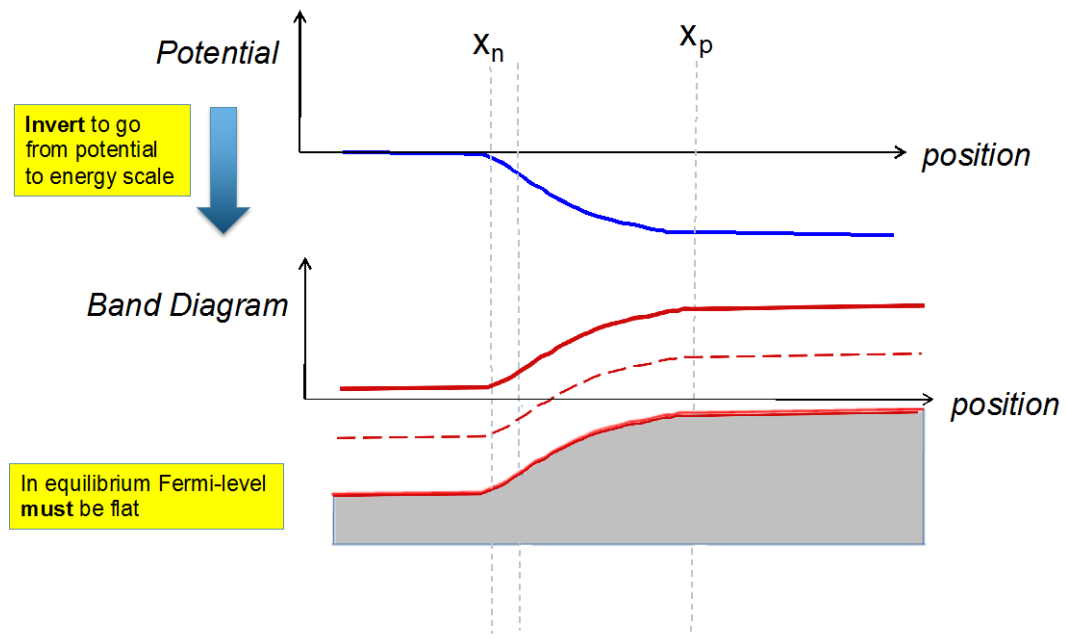
From Section 13 – Band Diagrams



$$P.E. = E_c - E_{ref}$$

$$E_{ref}$$

Sketch of Electrostatics



$$-qV = E_c - E_{ref}$$

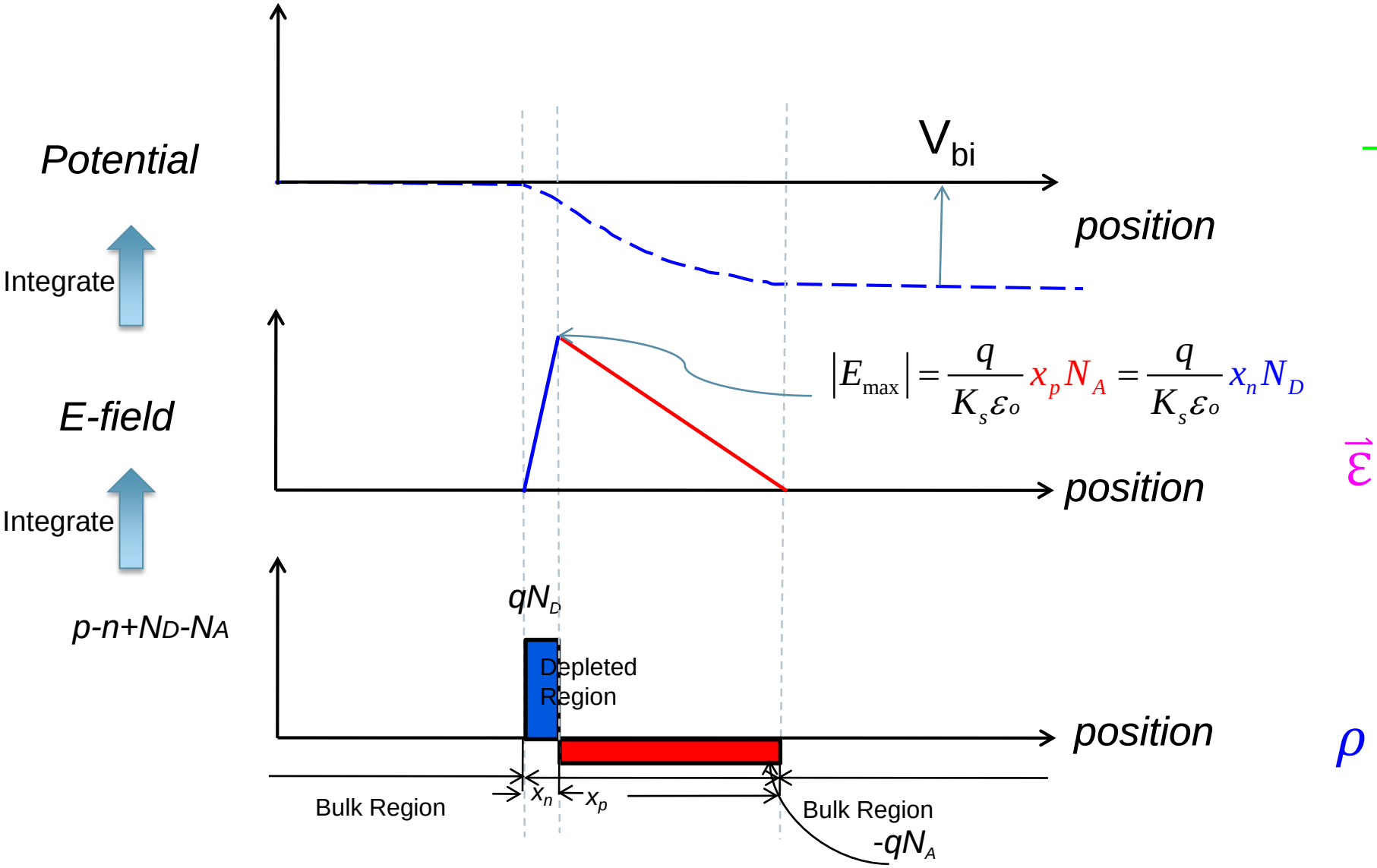
$$\vec{\mathcal{E}} = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_c}{dx}$$

$$\rho \propto \frac{d\vec{\mathcal{E}}}{dx} = -\frac{d^2V}{dx^2}$$

In most practical cases start from charge and derive potentials!

=> Useful to learn "graphical" integration

Sketch of Electrostatics



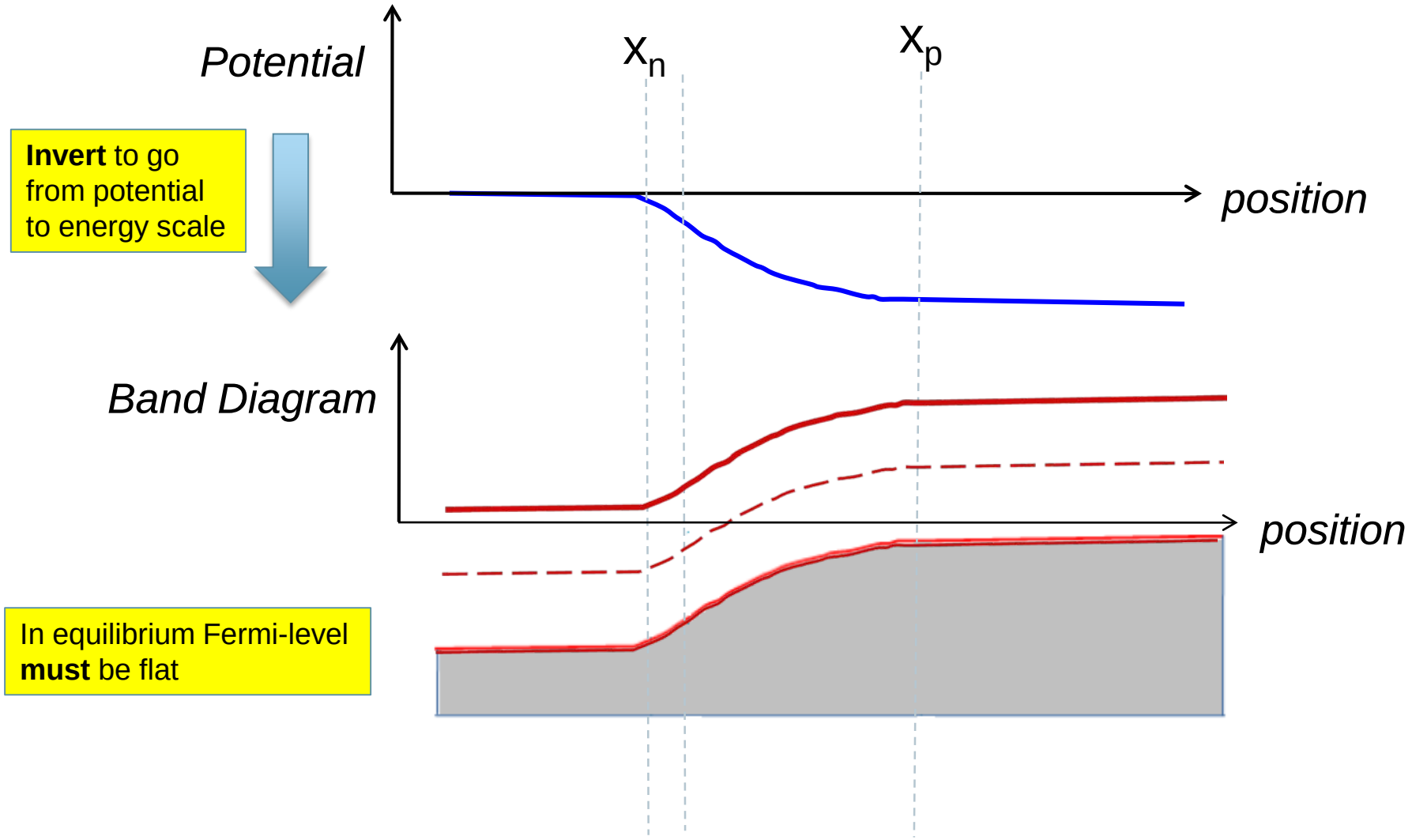
$$-qV = E_c - E_{ref}$$

$$\left|E_{\max}\right| = \frac{q}{K_s \varepsilon_o} x_p N_A = \frac{q}{K_s \varepsilon_o} x_n N_D$$

$$\vec{\varepsilon} = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_c}{dx}$$

$$\rho \propto \frac{d\vec{\varepsilon}}{dx} = -\frac{d^2V}{dx^2}$$

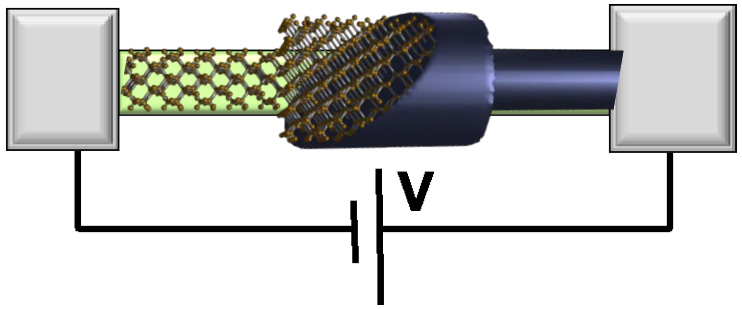
Sketch of Electrostatics



Invert to go from potential to energy scale

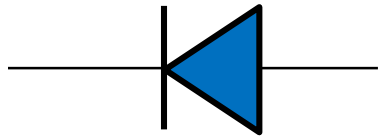
In equilibrium Fermi-level **must** be flat

Section 19
Introduction to PN Junctions



$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area

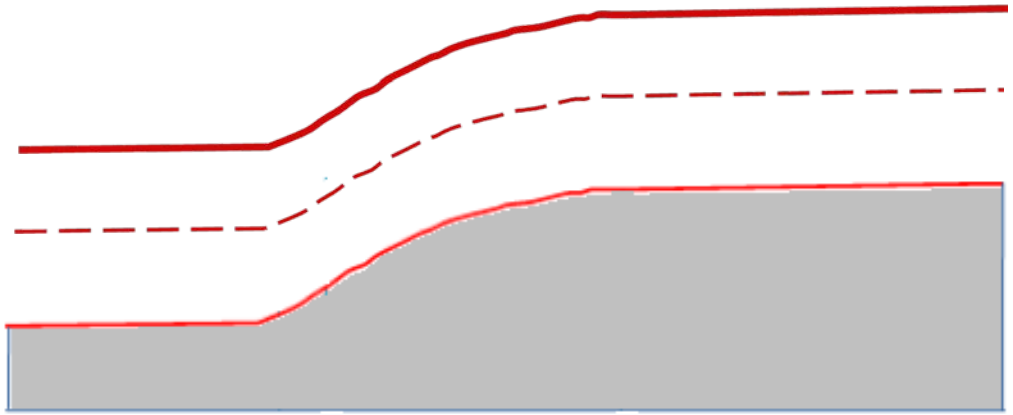


Vi

Vid

- 19.1 Structure and Depletion Region
- 19.2 Drawing band-diagrams in equilibrium

status



$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

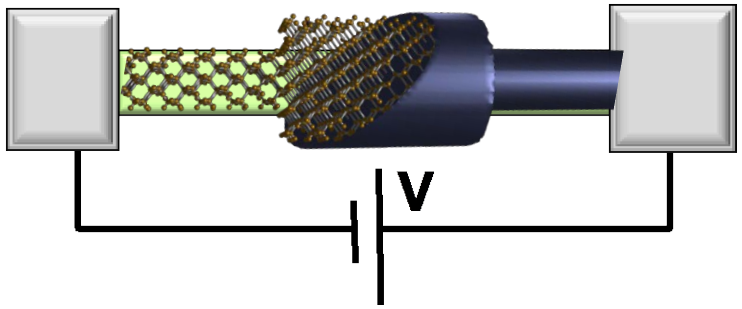
$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{-1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

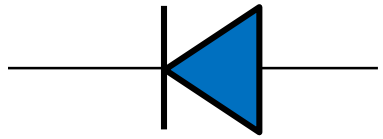
$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

Section 19
Introduction to PN Junctions

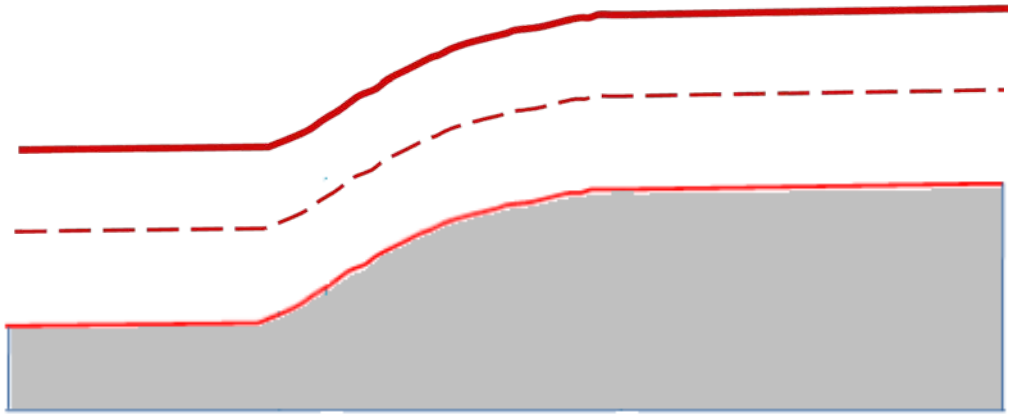


$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area



- 19.1 Structure and Depletion Region
- 19.2 Drawing band-diagrams in equilibrium



$$\nabla \bullet D = q\left(p - n + N_D^+ - N_A^-\right)$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \mathbf{J}_N - r_N + g_N$$

$$\mathbf{J}_N = qn\mu_N E + qD_N \nabla n$$

$$\frac{\partial p}{\partial t} = \frac{-1}{q}\nabla \bullet \mathbf{J}_P - r_P + g_P$$

$$\mathbf{J}_P = qp\mu_P E - qD_P \nabla p$$

Vi

Vid