ELEC2104 – Week 3

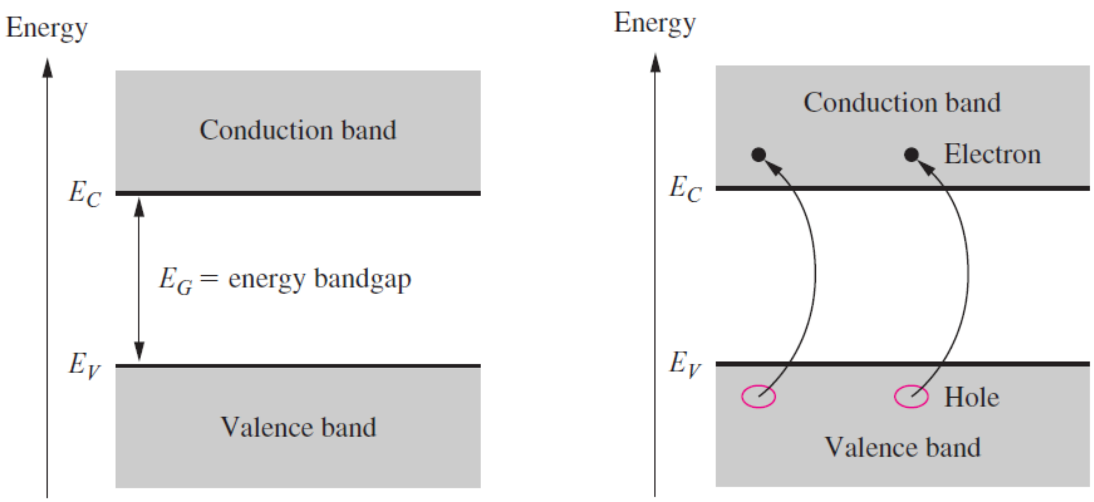
Schottky contact, PN Junctions

Reference for Fermi levels, Schottky contact:
Device Electronics for Integrated Circuits by Richard S. Muller, Theodore I. Kamins, Mansun Chan

THE UNIVERSITY OF SYDNEY

What have we learnt so far?

- Silicon is a semiconductor with
  - n is the number of (free) electrons in the conduction band
  - p is the number of holes in the valence band



- For both intrinsic and extrinsic semiconductor

$$pn = n_i^2$$

What have we learnt so far?

- Doping produces free electrons or holes in a semiconductor
- In n-type semiconductor $N_D >> N_A$ and $n>>p$, so:

$$n \approx N_D \text{ and } p \approx n_i^2/N_D$$

- In p-type semiconductor $N_A>>N_D$ and $p>>n$, so

$$p \approx N_A \text{ and } n \approx n_i^2/N_A$$

- The sum of all charges is zero

$$p + N_D = n + N_A$$

What have we learnt so far?

- An electric field or a concentration gradient leads to the movement of these charge carriers
- Drift current

$$j_n^{drift} = Q_n \mathbf{v}_n = (\text{-qn})(\text{-}\mu_n \mathbf{E}) = qn\mu_n \mathbf{E} \quad \text{A/cm}^2$$

$$j_p^{drift} = Q_p \mathbf{v}_p = (+\text{qp})(+\mu_p \mathbf{E}) = qp\mu_p \mathbf{E} \quad \text{A/cm}^2$$

- Diffusion current

$$j_p^{diff} = (+q)D_p\left(-\frac{dp}{dx}\right) = -qD_p\frac{dp}{dx} \quad \text{A/cm}^2$$

$$j_n^{diff} = (-q)D_n\left(-\frac{dn}{dx}\right) = +qD_n\frac{dn}{dx} \quad \text{A/cm}^2$$

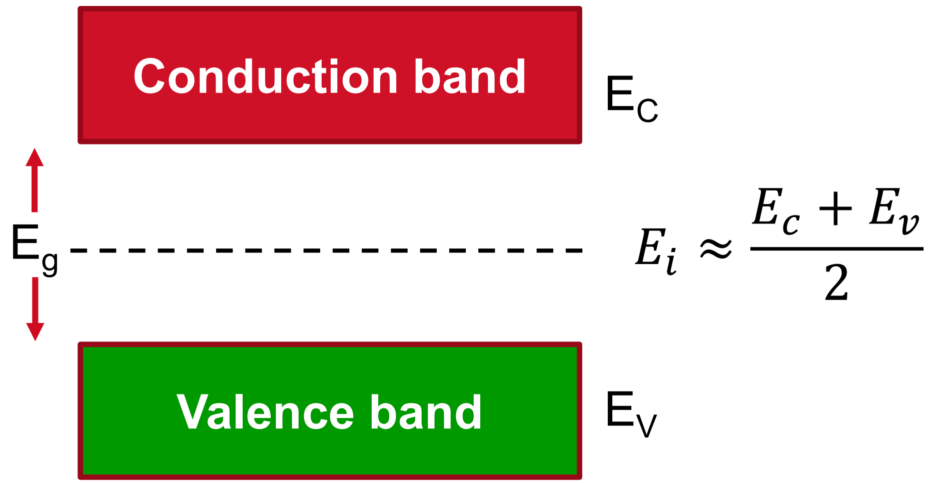
- Total current

$$j^T = j^{drift} + j^{diff}$$

Fermi level

Fermi energy level

- Fermi level
  - The energy level where the probability of finding a (free) electron is one-half
- Intrinsic semiconductor
  - E_i is the undoped or intrinsic Fermi level (for semiconductors without doping)
    - $E_i = \frac{E_c+E_v}{2}$ (mid-gap)
  - Generally, the Fermi level is denoted E_f



$n_i = p_i =$ intrinsic carrier density

Fermi level

- Definition of the Fermi level E_f in the general case

Fermi-Dirac distribution

$$f = \frac{1}{1 + e^{(E-E_f)/k_BT}}$$

Possibility of a state with energy E being occupied by an electron

$$E = E_f: f = \frac{1}{2}$$

$$n = N_C \boxed{\frac{1}{1 + e^{(E_C-E_f)/k_BT}}} \approx N_C e^{-(E_C-E_f)/k_BT}$$

$$p = N_V \left(1 - \boxed{\frac{1}{1 + e^{(E_V-E_f)/k_BT}}}\right) \approx N_V e^{-(E_f-E_V)/k_BT}$$

n, p: electron and hole concentration
N_C, N_V: effective density of states for the Conduction band and the Valance band
k_B: Boltzmann constant
n_i: intrinsic carrier concentration

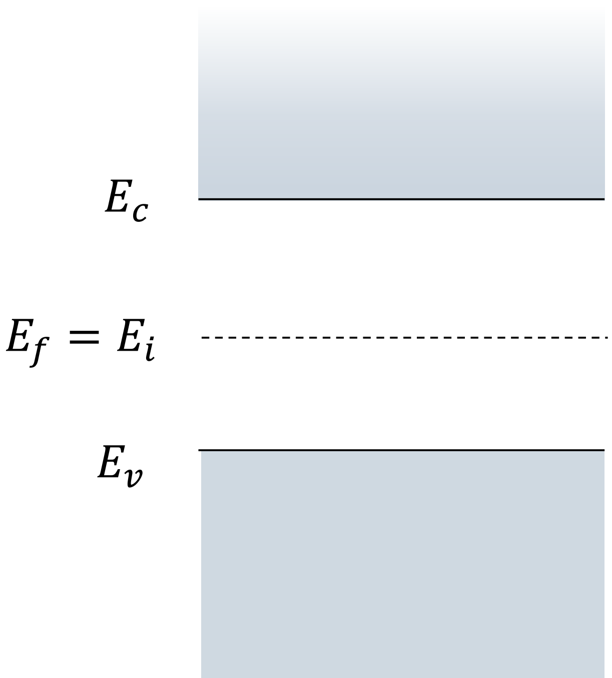
since $$n_i = N_C e^{-(E_C-E_i)/k_BT} = N_V e^{-(E_i-E_V)/k_BT}$$

We have $$n = n_i e^{(E_f-E_i)/k_BT} \qquad p = n_i e^{(E_i-E_f)/k_BT}$$

$$\left(np = n_i^2\right)$$

Fermi level and carrier concentration

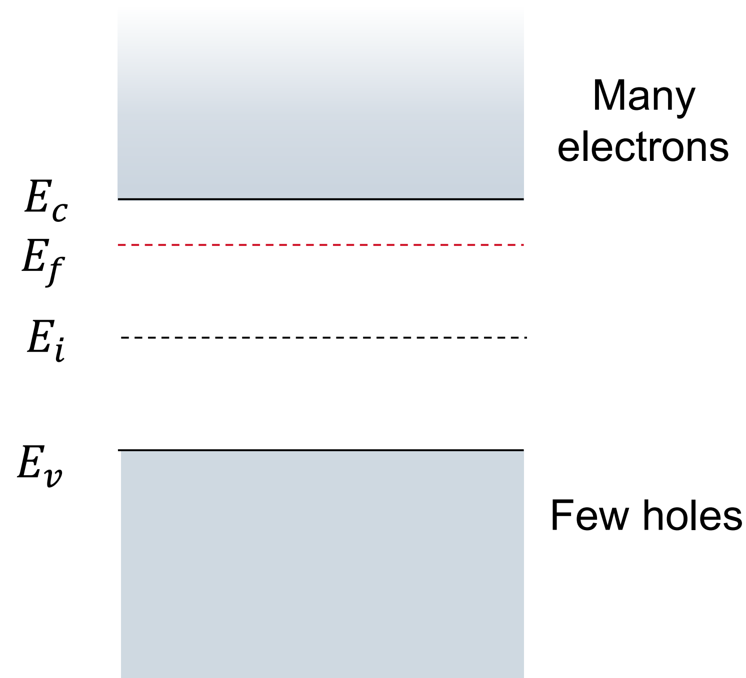
Intrinsic



$$n = n_i e^{(E_f - E_i)/k_B T}$$

$$p = n_i e^{(E_i - E_f)/k_B T}$$

N-doped

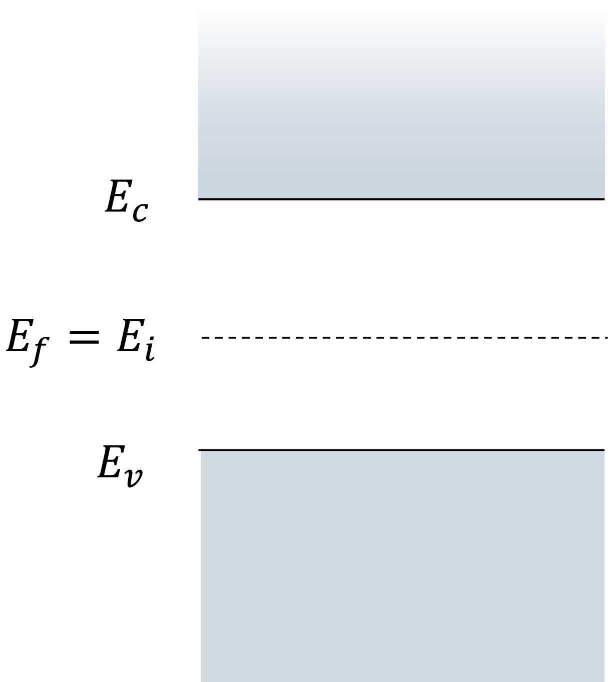


$$N_D \approx n = n_i e^{(E_f - E_i)/k_B T}$$

$$p = n_i e^{(E_i - E_f)/k_B T}$$

Fermi level and Carrier concentration

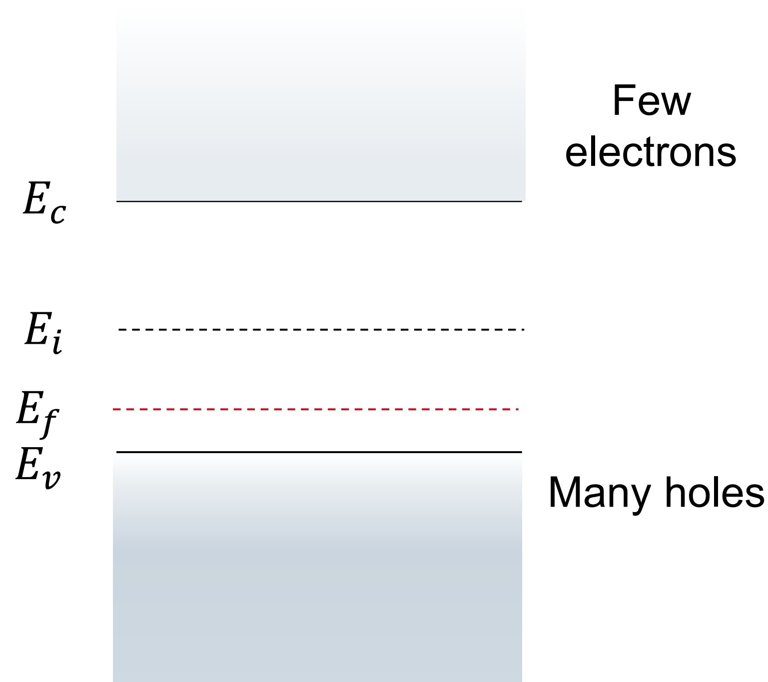
Intrinsic



$$n = n_i e^{(E_f - E_i)/k_B T}$$

$$p = n_i e^{(E_i - E_f)/k_B T}$$

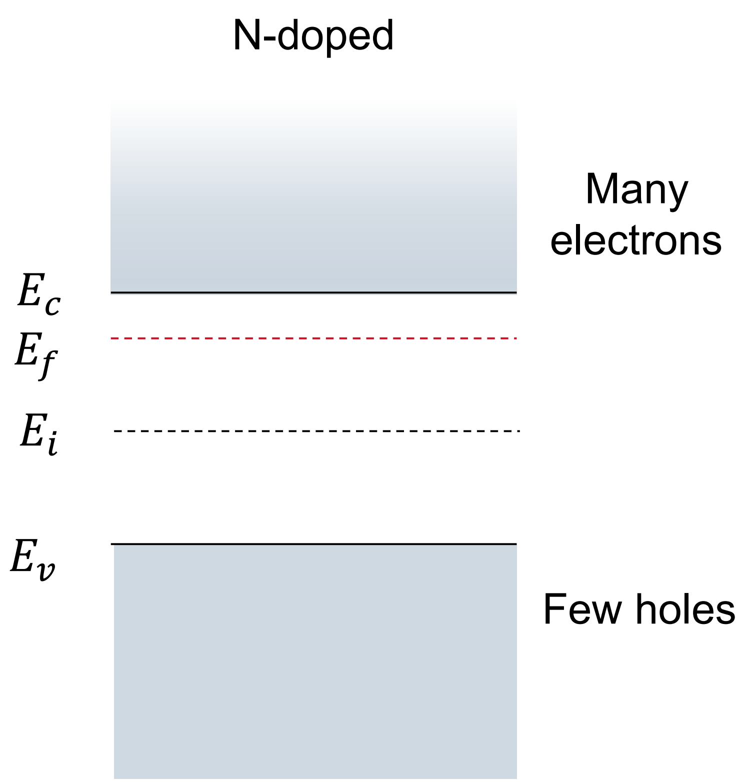
P-doped

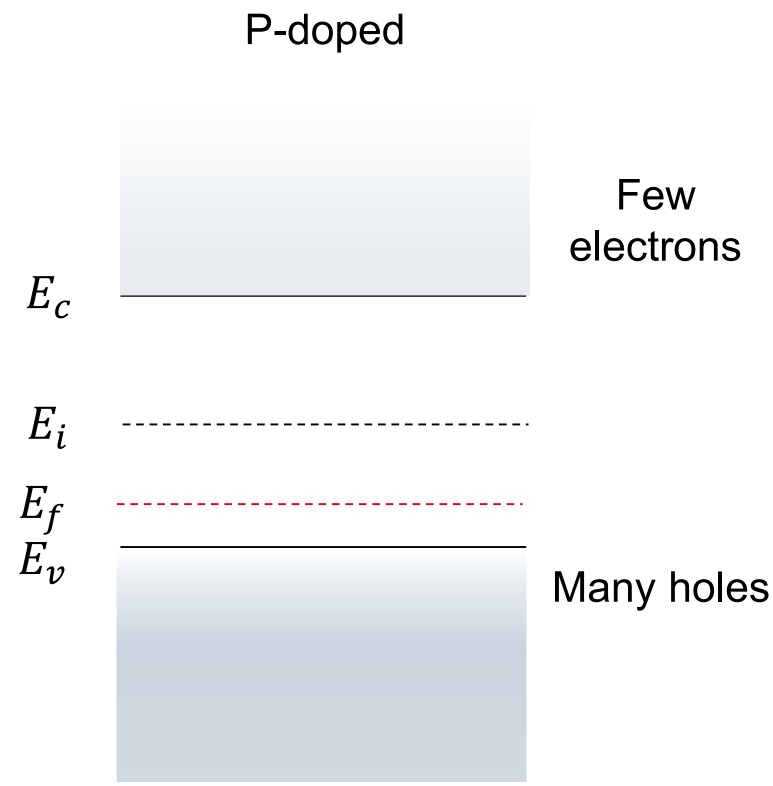


$$n = n_i e^{(E_f - E_i)/k_B T}$$

$$N_A \approx p = n_i e^{(E_i - E_f)/k_B T}$$

Fermi level and Carrier concentration





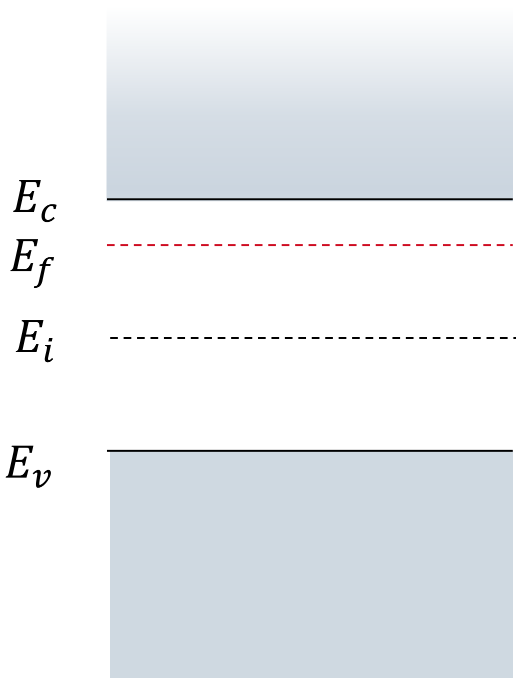
$$n = n_i e^{(E_f - E_i)/k_B T}$$

$$p = n_i e^{(E_i - E_f)/k_B T}$$

$$E_f \nearrow, n \nearrow, p \searrow$$

Remember this

Fermi level and Carrier concentration



$$N_D \approx n = n_i e^{(E_f - E_i)/k_B T}$$

Given N_D, ask E_f?

since $\quad n = n_i e^{(E_f - E_i)/k_B T} \approx N_D$

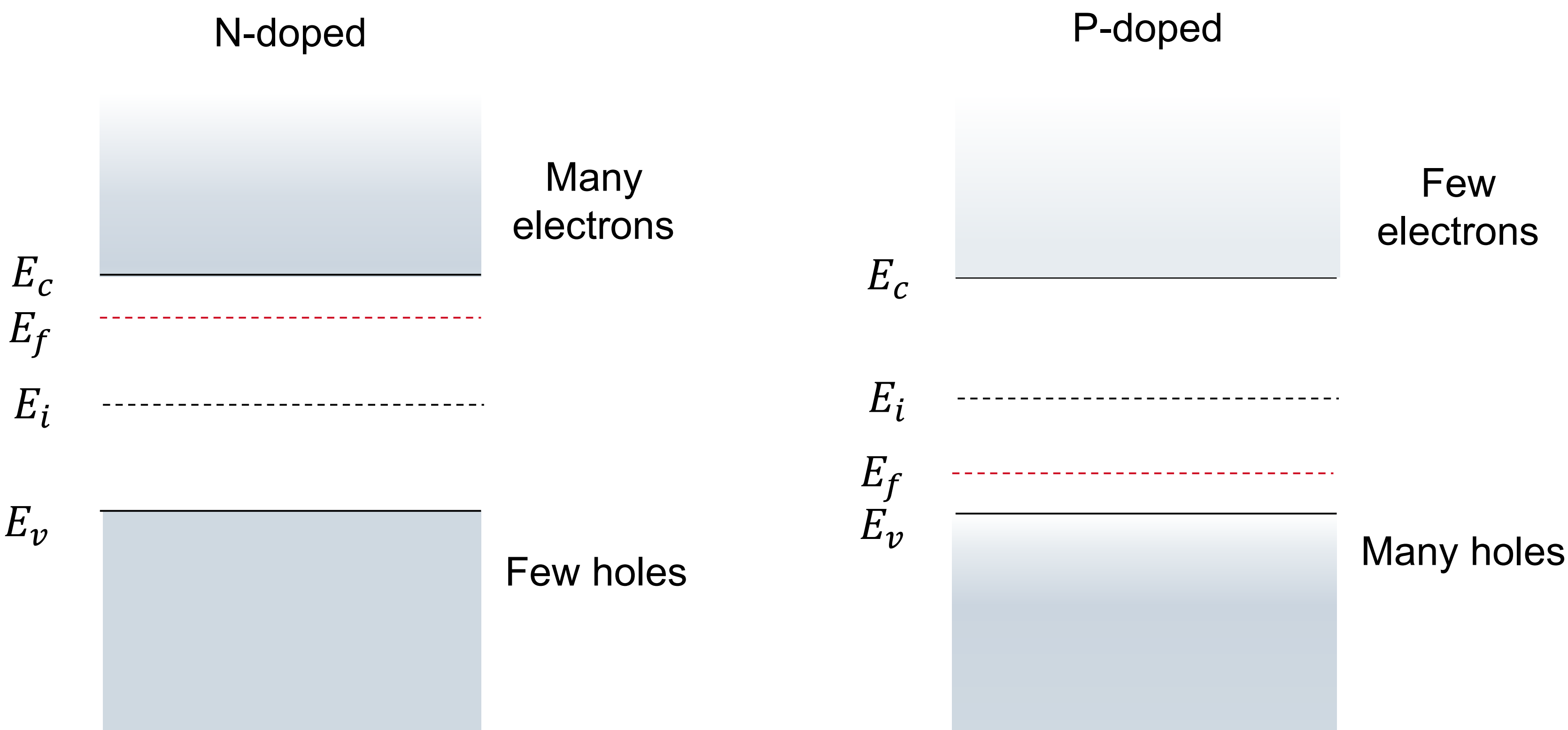
We have $\quad (E_f - E_i) = k_B T \ln \dfrac{N_D}{n_i}$

Example:

$N_D = 10^{16}\mathrm{cm}^{-3}$, $n_i = 10^{10}$ cm^{-3}, $k_B T = 26\mathrm{meV}$

$$(E_f - E_i) = 0.026\mathrm{eV} \times \ln \frac{10^{16}}{10^{10}}$$
$$= 0.36\mathrm{eV}$$

Fermi level



Fermi level is a token for carrier concentration.

It is where the electron filling probability *would be* $\frac{1}{2}$.

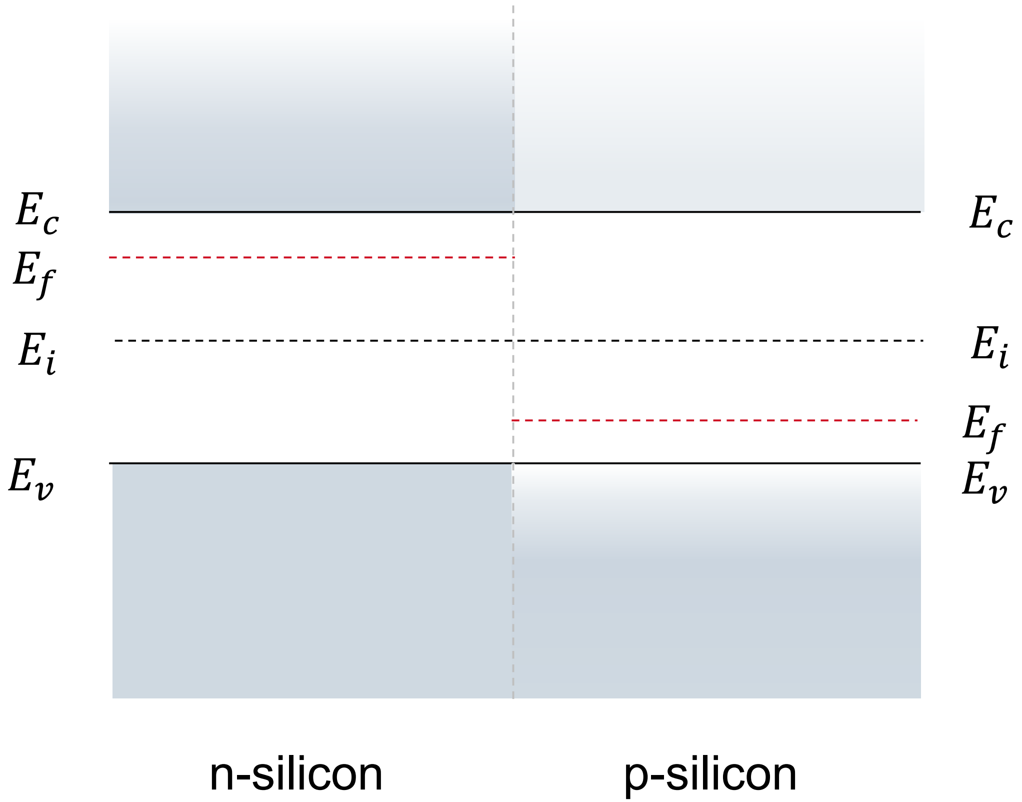
The higher E_f, the more electrons, less holes. Vice versa.

Fermi level must levels

In a piece of any material in equilibrium, the Fermi level must

levels

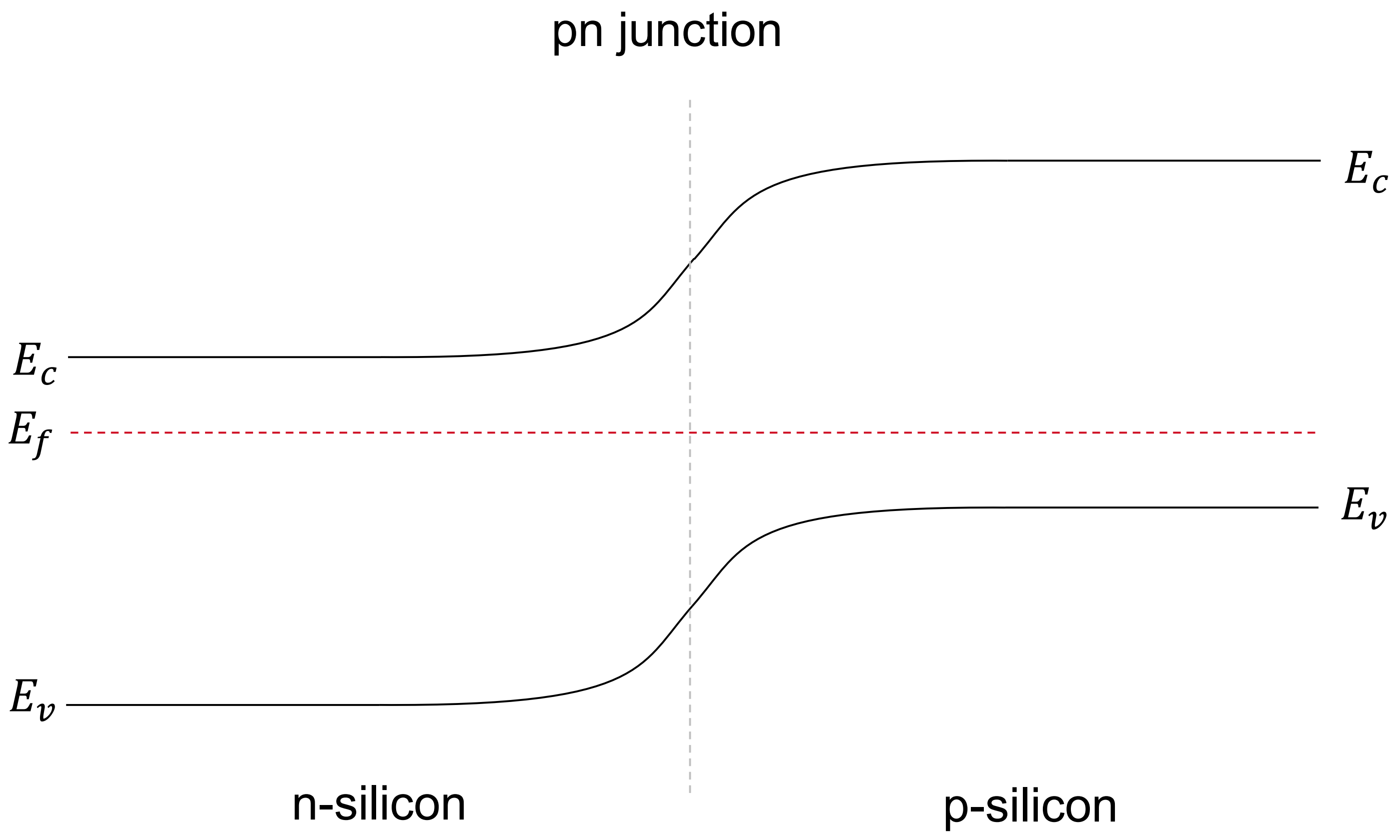
through out the structure.



What happens now?

How does the Fermi level LEVEL?

pn junction



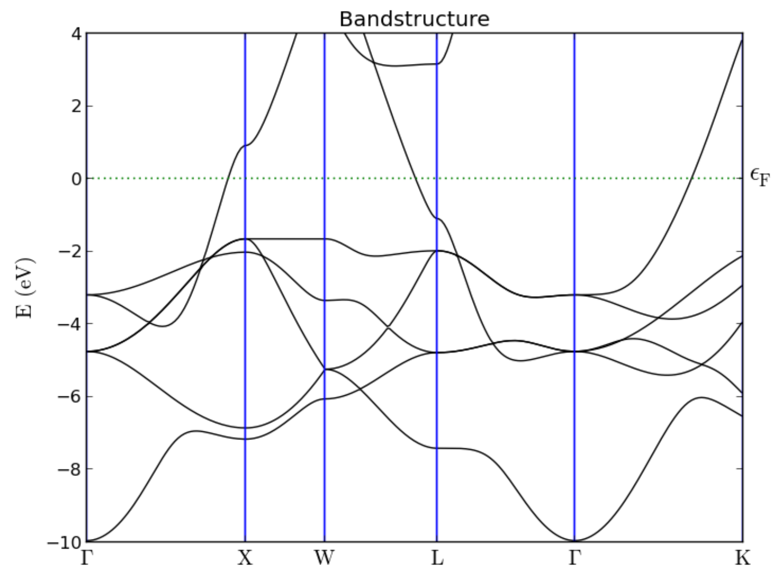
Note: E_c, E_v can move up and down together (with $E_c - E_v = E_g$ fixed), just like the voltage at a node in a circuit. If there are electric fields in the space, these "voltage levels" can shift up and down.

Metal-semiconductor contact (Schottky diode)

Metal

› Band structure and Fermi level of metal
  - No bandgap, Fermi level crosses some bands
  - Many carriers $10^{23}\mathrm{cm}^{-3}$
  - Fermi level won't move with respect to the bands
    - Even if you could "dope" it, the extra carriers are negligible compared to intrinsic

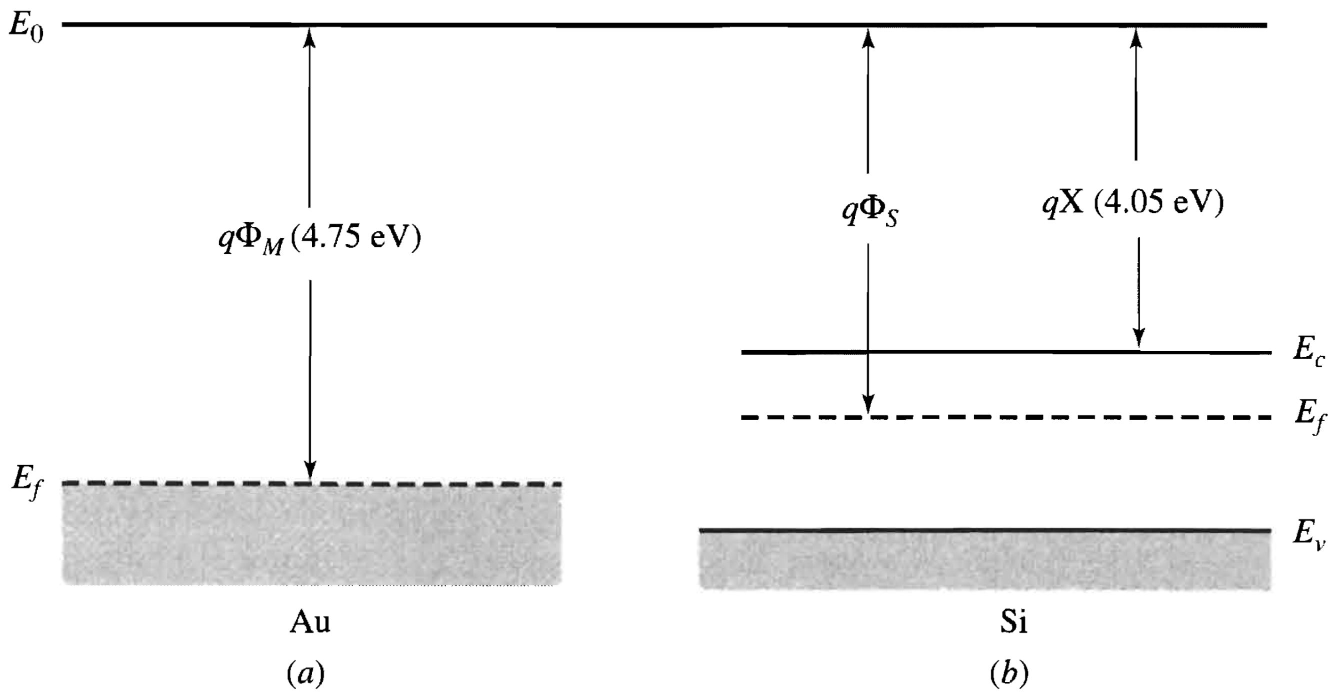
Gold



Metal vs Semiconductor

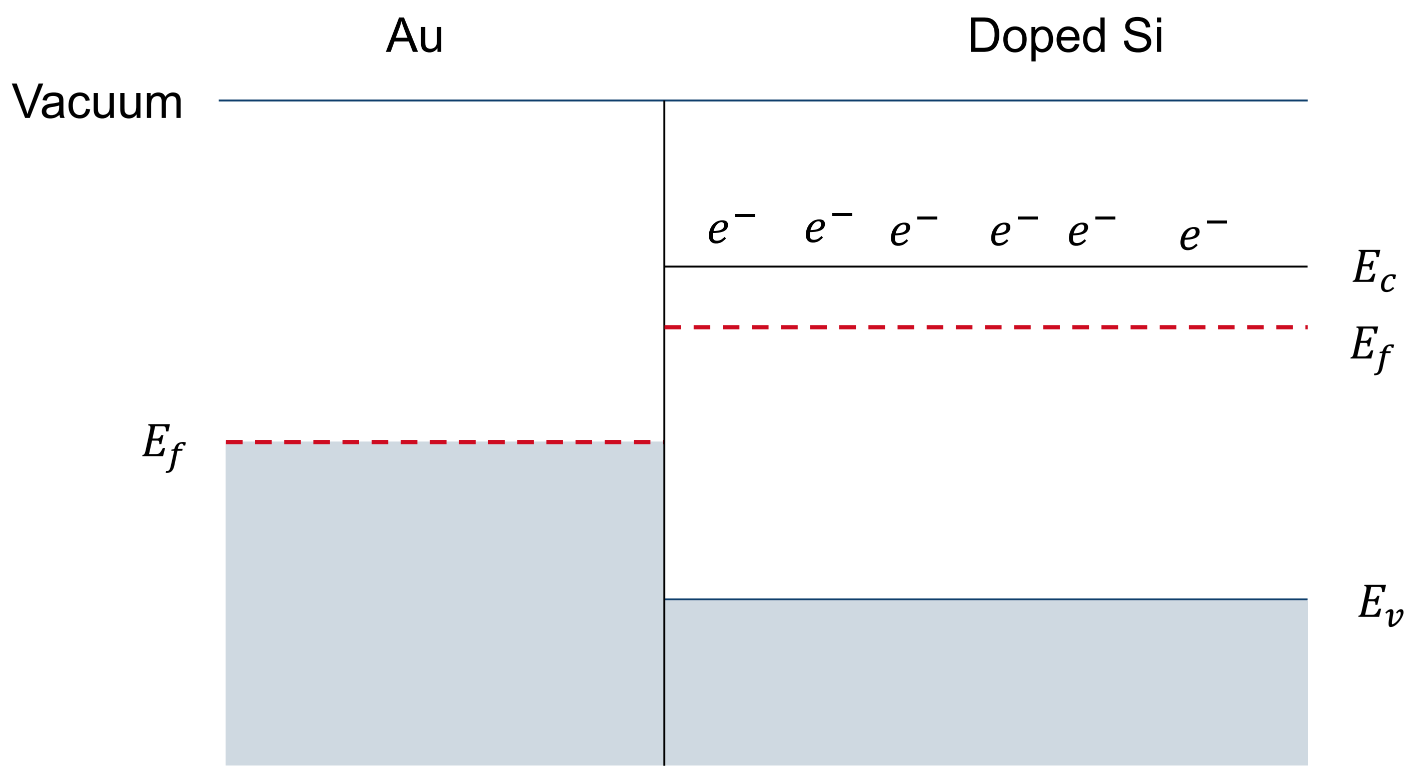
- ϕ: work function (energy needed to kick electrons out to vacuum)

Without electric field, the energy levels are flat over space



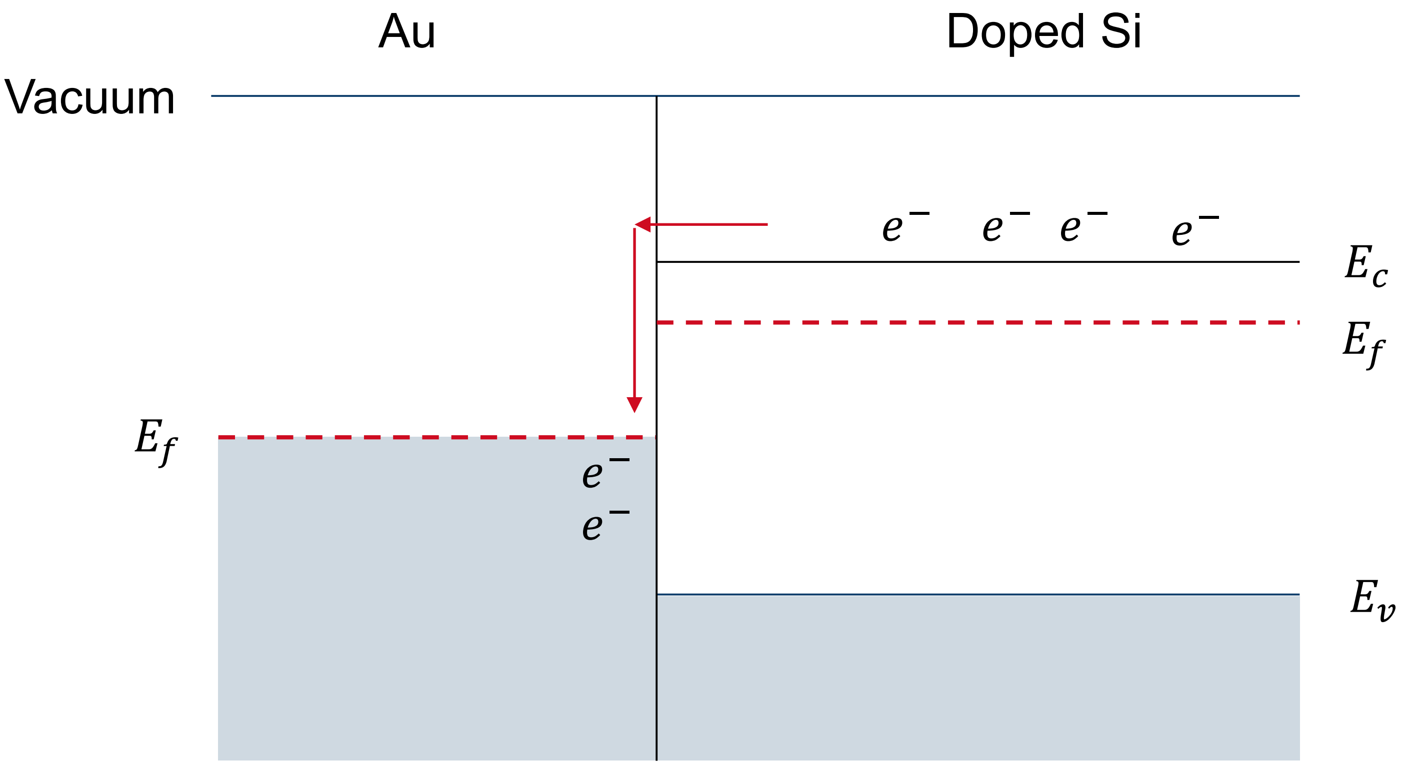
ϕ_m metal work function
ϕ_s semiconductor work function
χ electron affinity

Metal-Semiconductor contact

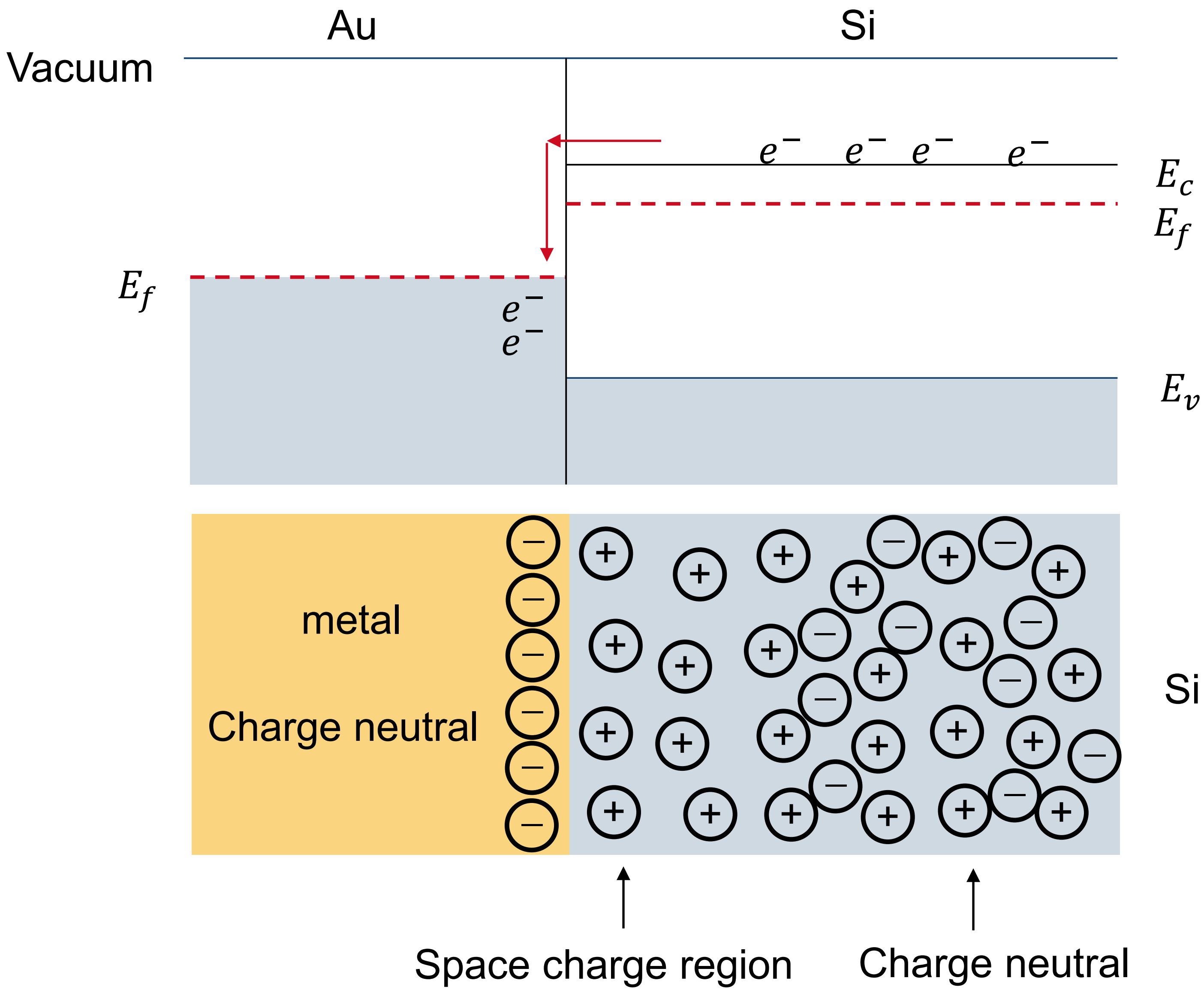


Fermi level: Si>Au
“water level”

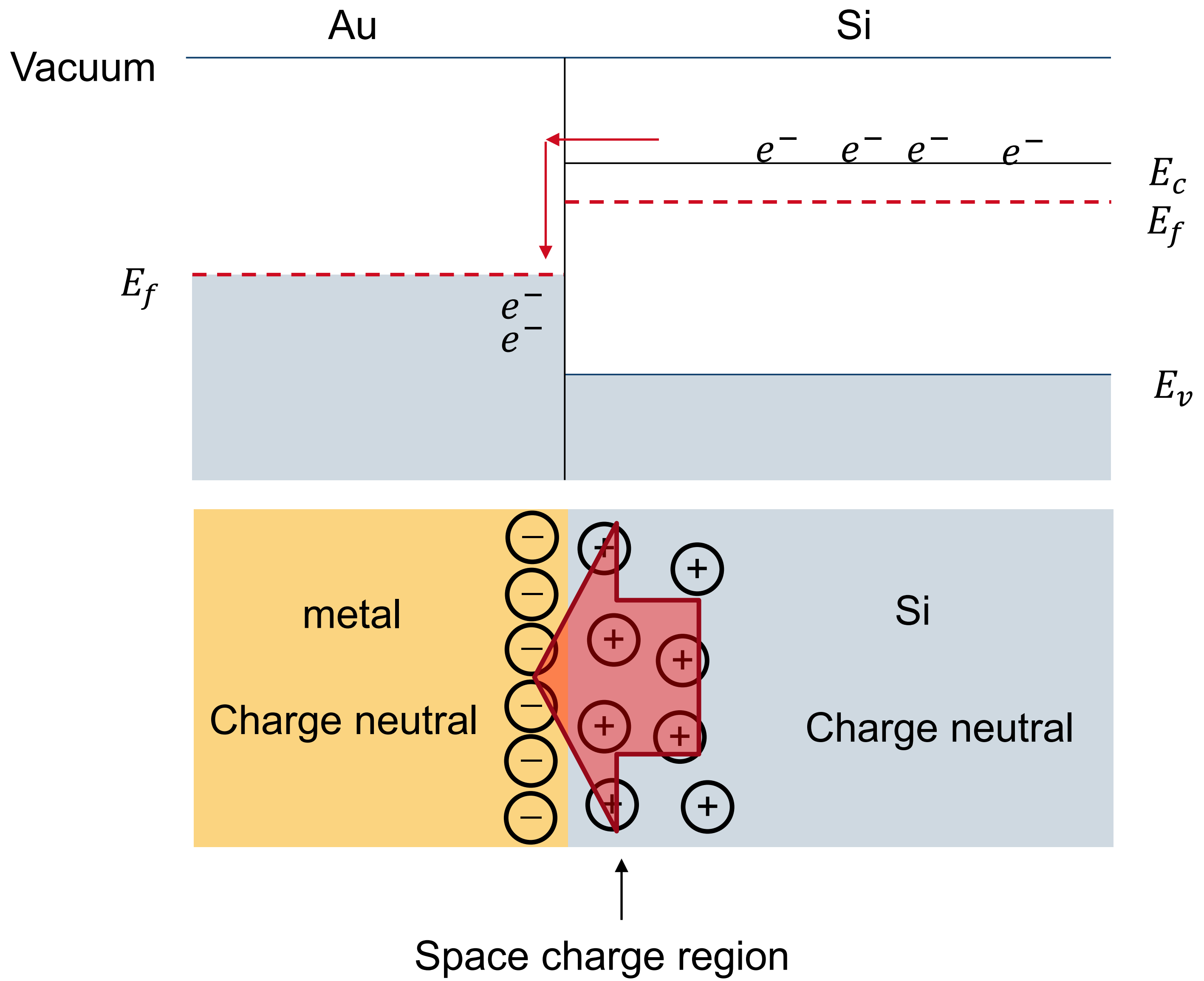
Metal-Semiconductor contact



Electrons move from semiconductor to metal surface
Leaving behind positively charged region (positively charged ion lattice)
Electric field is created

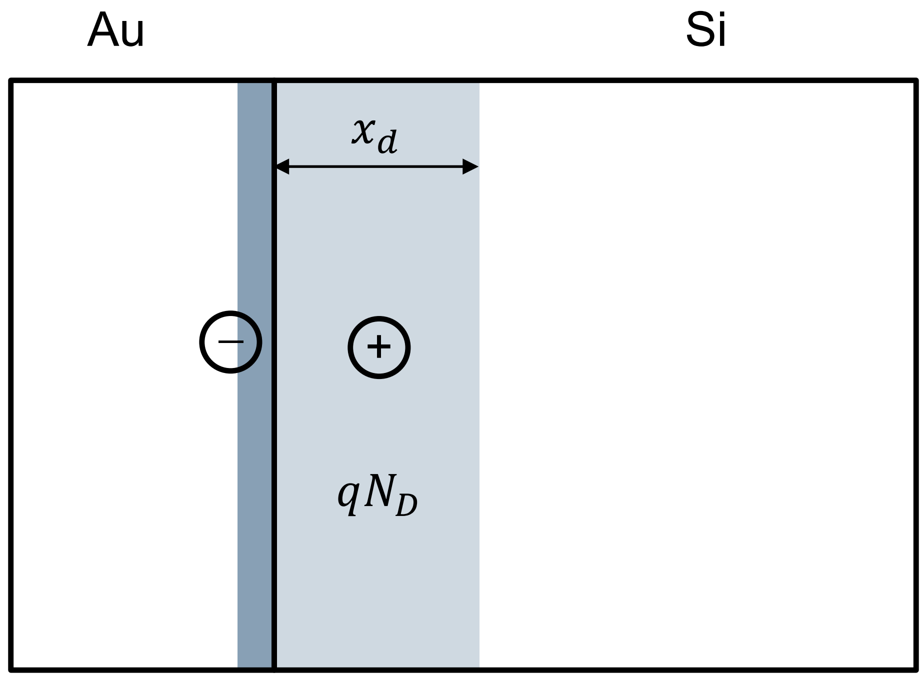


The charge can't flow forever. What stops them eventually?



Electric field established

Charge in depletion region

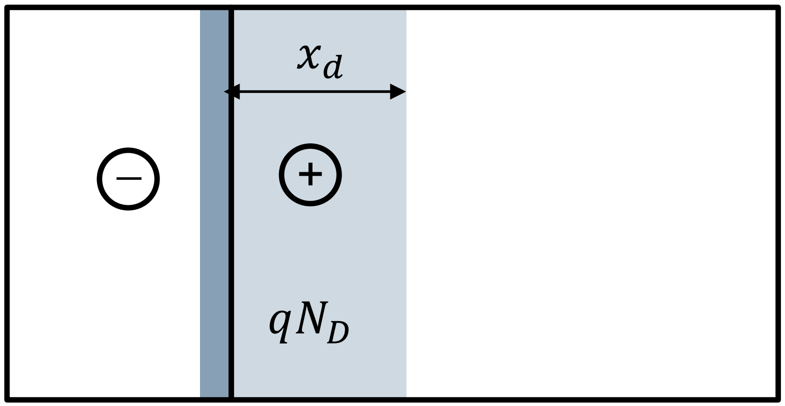


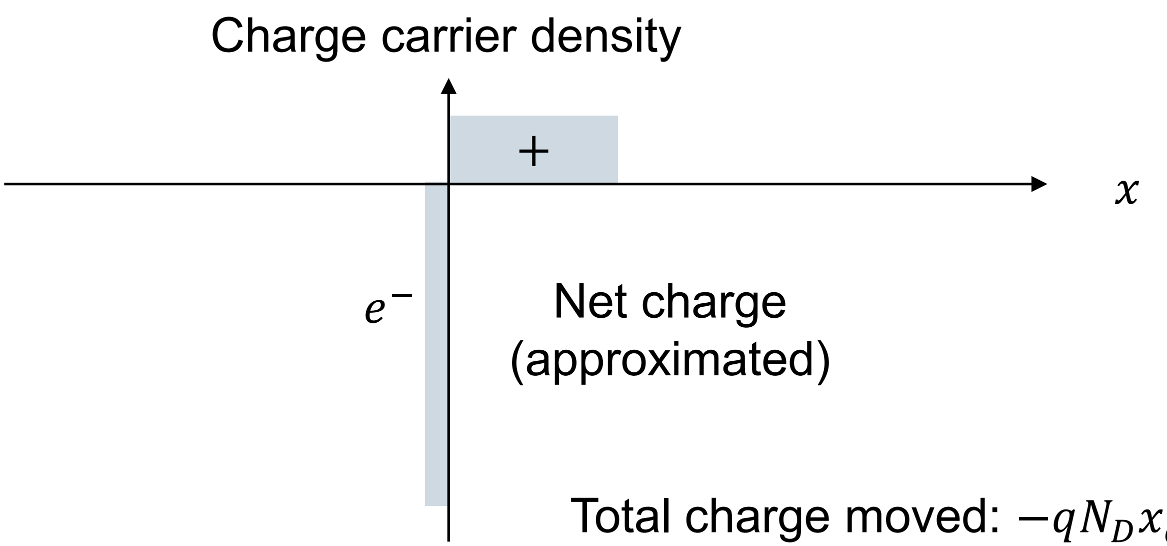
For simplicity, assume the depletion region has no free carriers (the free carrier density is orders of magnitude smaller than original)

Hence, the space charge region has a uniform charge density: qN_D

Total charge moved: $-qN_Dx_d$

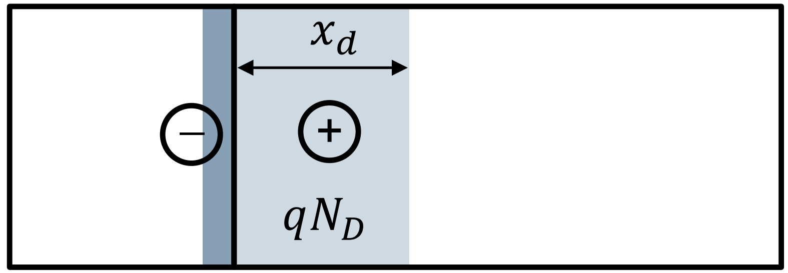
Charge in depletion region

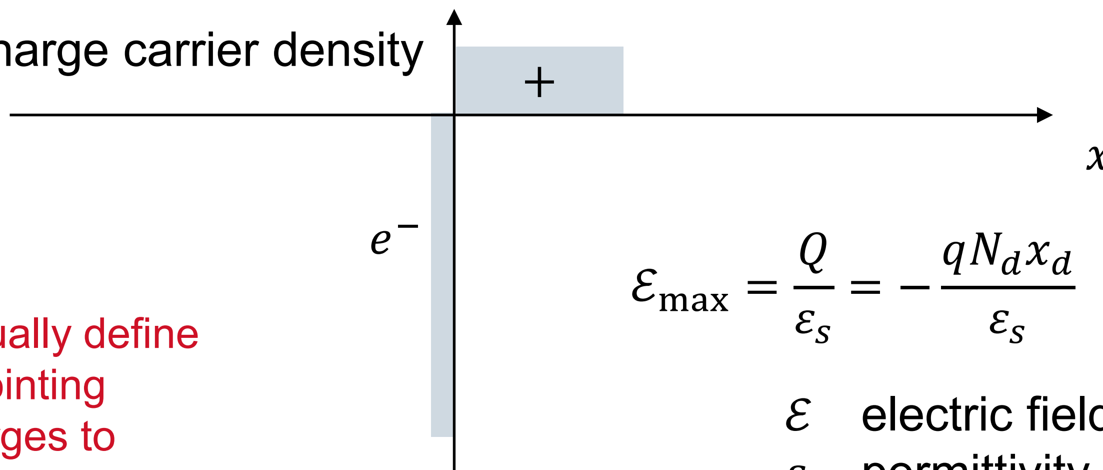




Total charge moved: $-qN_Dx_d$

Electric field in depletion region





Gauss' law:

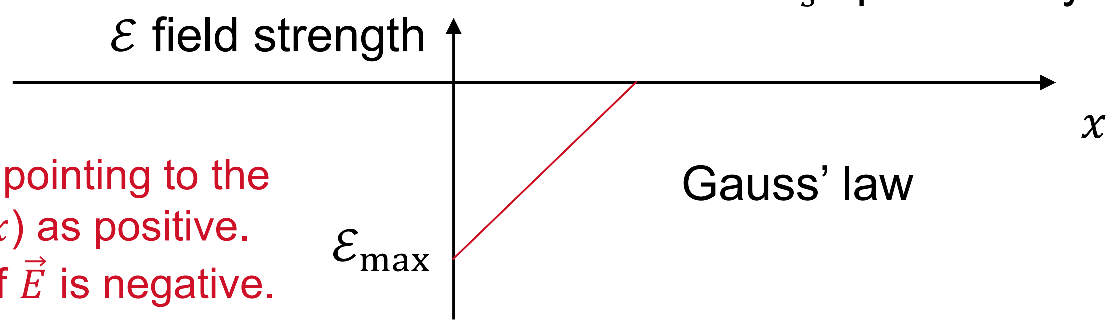
$$\mathcal{E} = \frac{1}{\varepsilon_s}\int \rho dx$$

$$\mathcal{E}_{\max} = \frac{Q}{\varepsilon_s} = -\frac{qN_d x_d}{\varepsilon_s}$$

$\mathcal{E}$ electric field strength

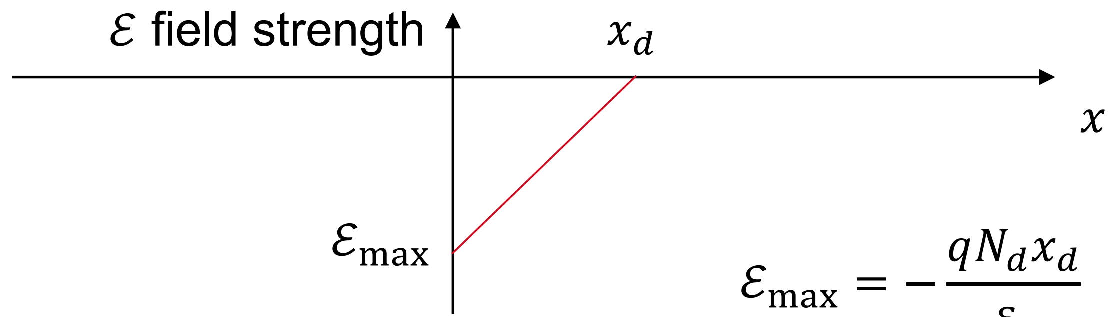
ε_s permittivity of semiconductor

Physically, we usually define electric field as pointing from positive charges to negative charges



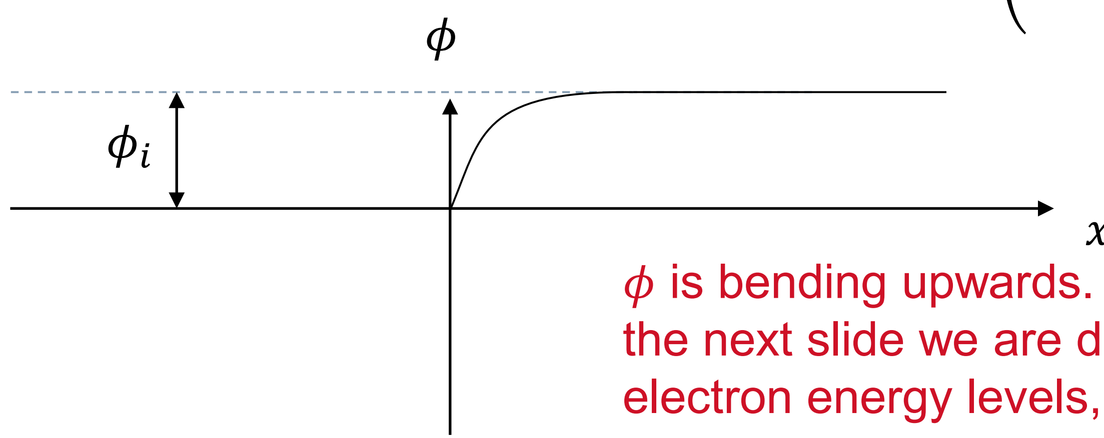
Here, we define $\vec{E}$ pointing to the right (i.e. positive x) as positive. Hence the value of $\vec{E}$ is negative.

Electric field and potential



$$\mathcal{E}_{\max} = -\frac{qN_d x_d}{\varepsilon_s}$$

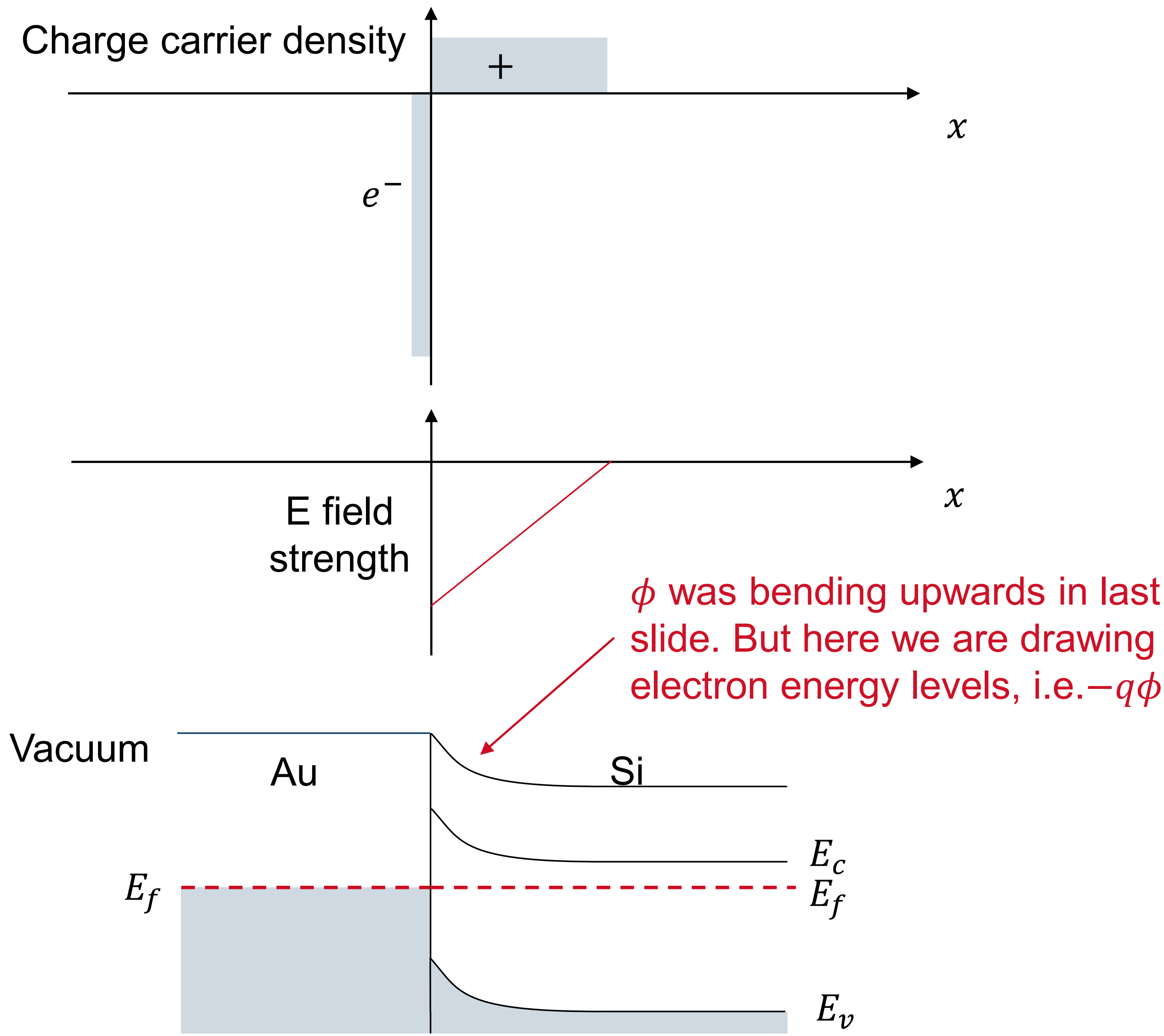
$$\mathcal{E} = \mathcal{E}_{max}\left(1 - \frac{x}{x_d}\right)$$



ϕ is bending upwards. But in the next slide we are drawing electron energy levels, i.e. $-q\phi$

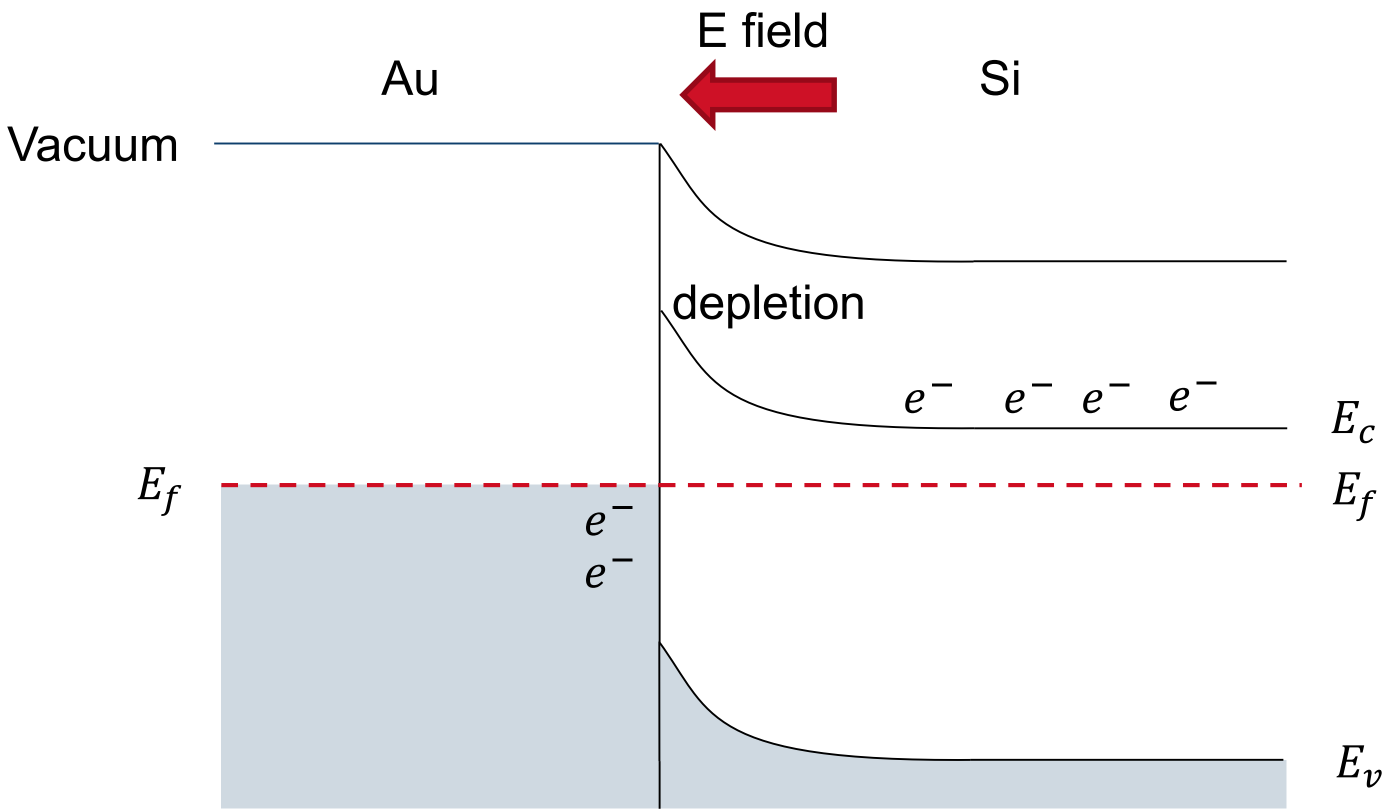
$$\phi(x) = -\int \mathcal{E}dx = \frac{qN_d}{2\varepsilon_s}\left(x_d^2 - (x_d - x)^2\right), \qquad (x < x_d)$$

potential difference: $$\phi_i = -\frac{1}{2}\mathcal{E}_{max}x_d = \frac{1}{2\varepsilon_s}qN_d x_d^2$$



When does charge stop moving?

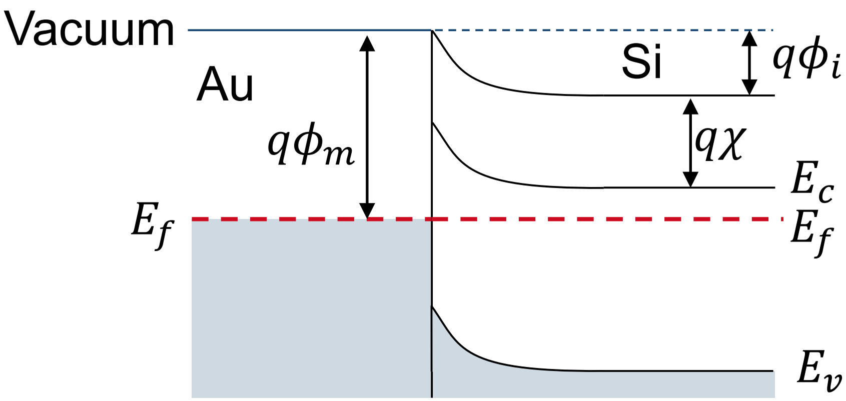
Metal-Semiconductor contact

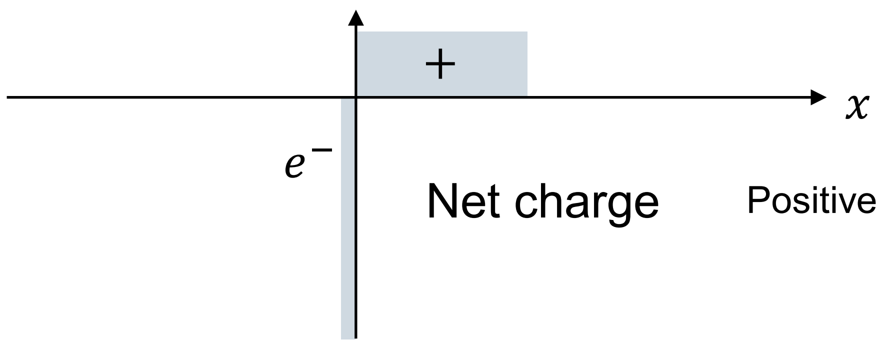


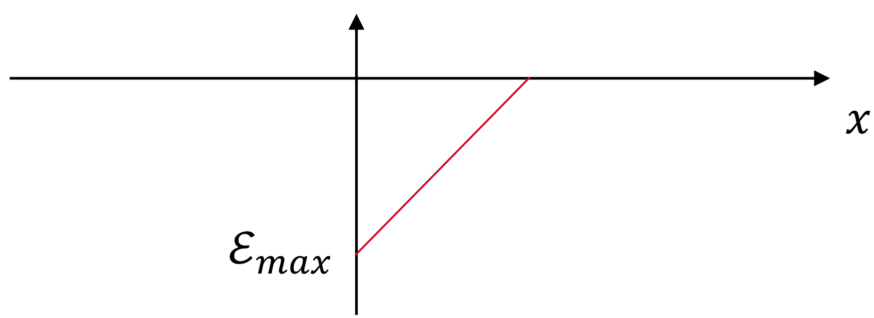
Principle: Fermi level is horizontal throughout

Note: E_c, E_v can move together (with $E_c - E_v = E_g$ fixed). Just like voltage at a node in a circuit, if there are electric fields in the space, these "voltage levels" can shift up and down.

Depletion region length







$$Q = qN_d x_d$$

Q total transferred charge
x_d depletion region length
N_d electron density in Si

$$\mathcal{E}_{max} = -\frac{Q}{\varepsilon_s} = -\frac{qN_d x_d}{\varepsilon_s} \qquad \text{(Gauss')}$$

$\mathcal{E}$ electric field strength
ε_s permittivity of semiconductor

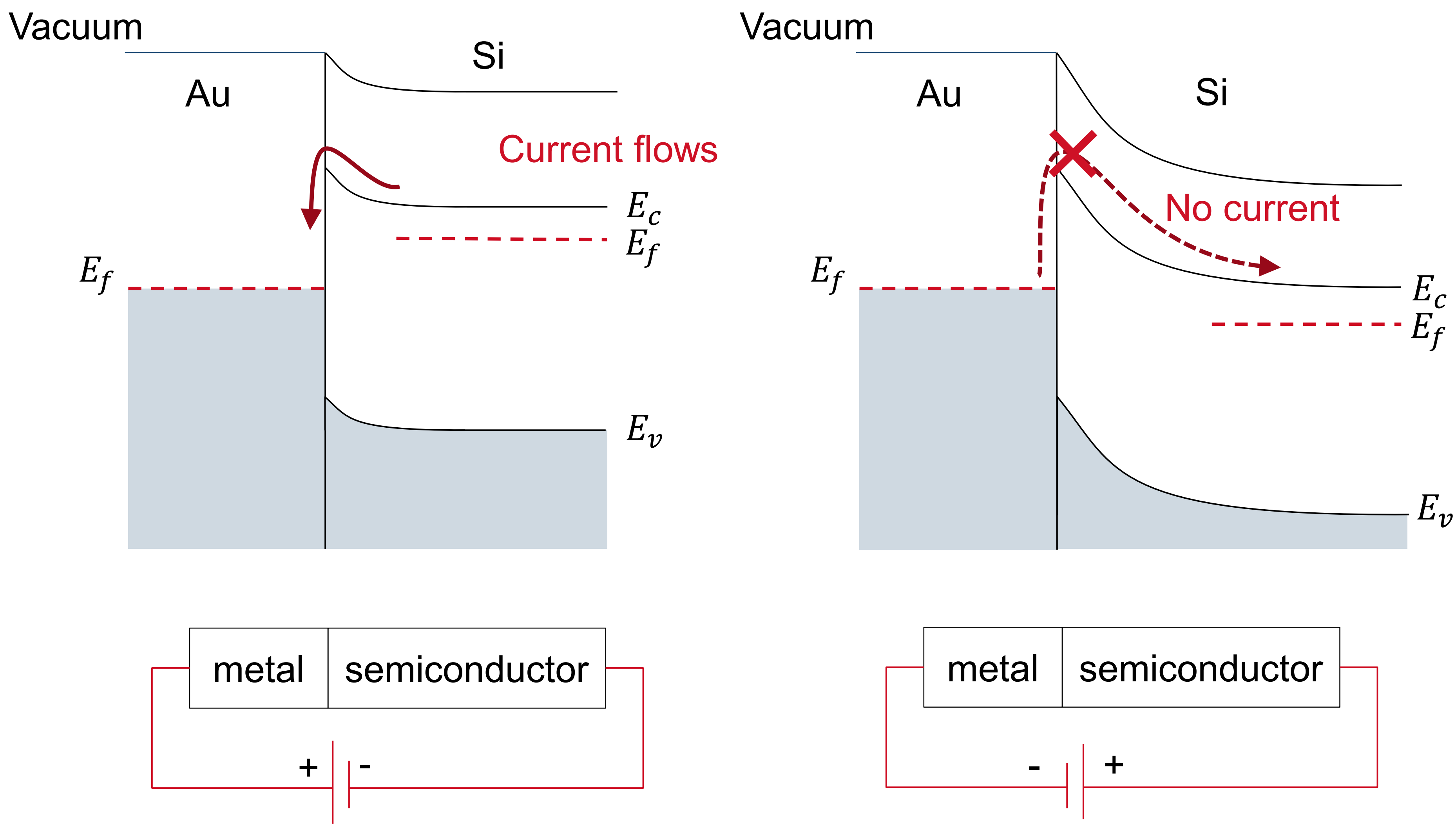
Positive →

$$\left.\begin{array}{l} \phi_i = -\dfrac{1}{2}\mathcal{E}_{max} x_d = \dfrac{1}{2}\dfrac{qN_d x_d^2}{\varepsilon_s} \\[2ex] q\phi_i = q\phi_m - q\chi - (E_c - E_f) \end{array}\right\} x_d$$

ϕ_i voltage drop over depletion
ϕ_m metal work function
χ electron affinity

Will have an example calculation of x_d in tutorial

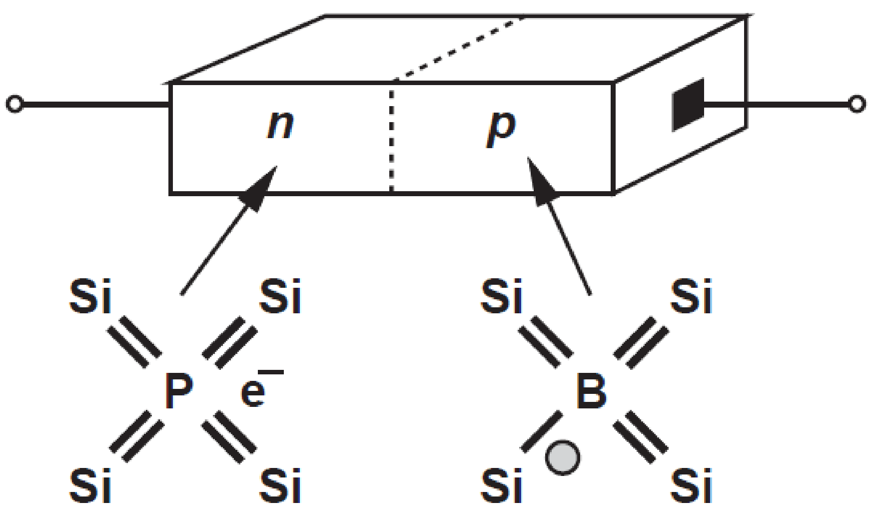
Schottky contact (Schottky diode)

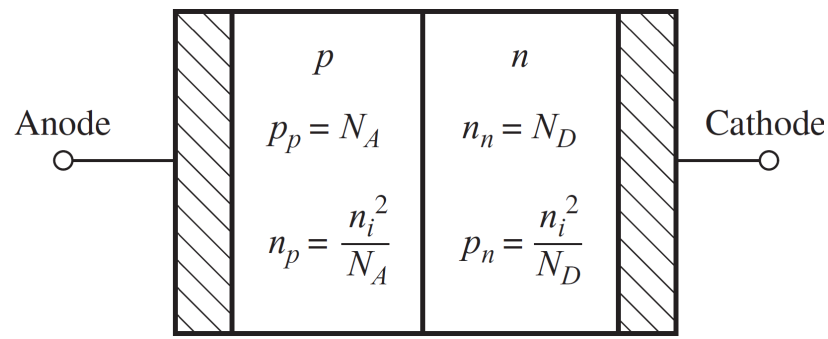


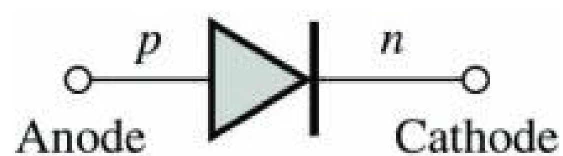
pn junctions

PN Junctions

- If we join a *p*-type semiconductor to a *n*-type semiconductor, we can create a PN junction
- This is a semiconductor diode
- The *p*-side is called the "anode" and the *n*-side is called the "cathode"





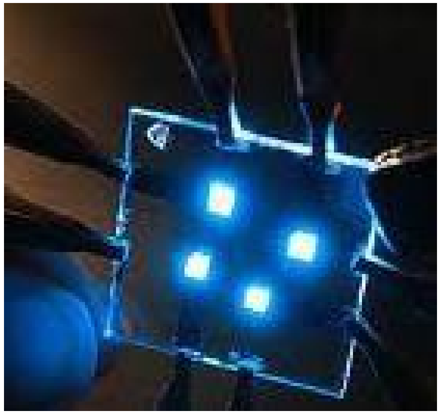


Diode symbol

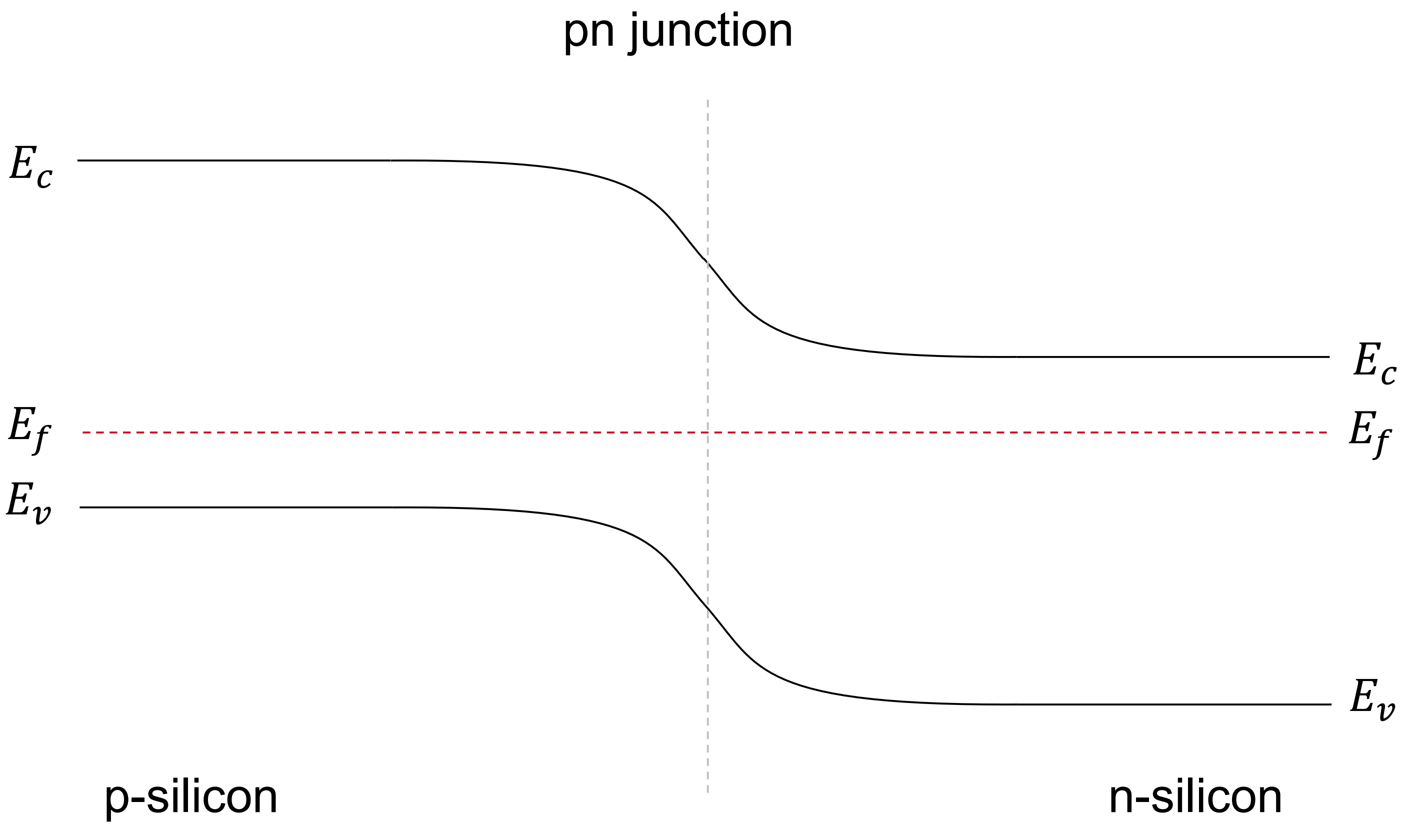
PN Junction Diodes

› Diode Uses

- PN junctions are the fundamental building blocks of almost all semiconductor devices
- It is critical to understand how these junctions work if you want to understand anything about transistors
- Diodes are used for rectifiers, voltage protectors, lasers, radiation detectors

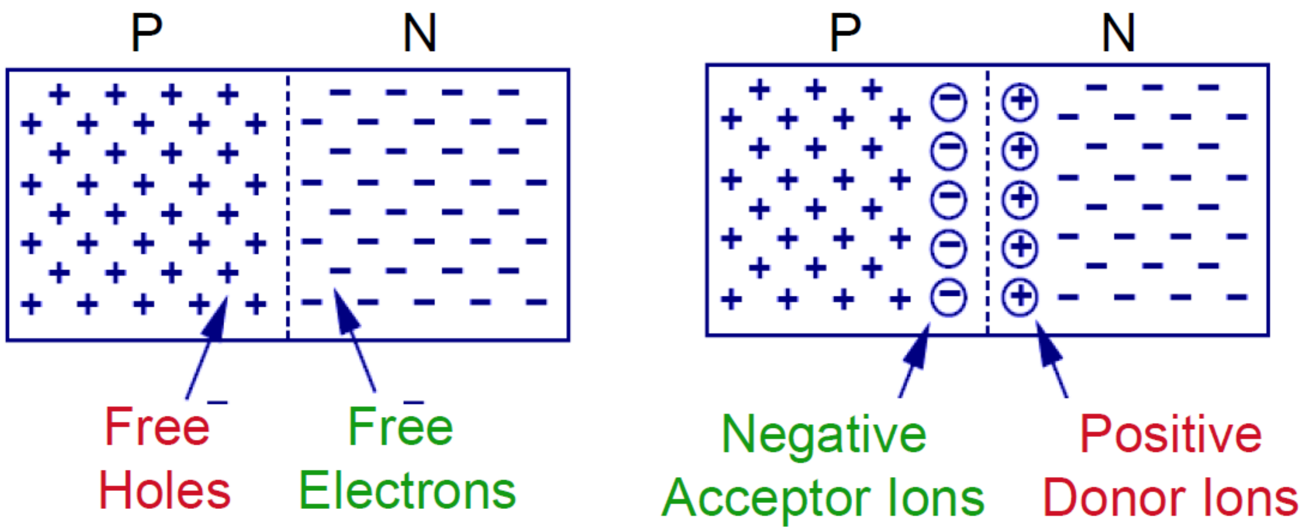


PN junction in equilibrium



This is the only way the Fermi level can level

PN junction in equilibrium

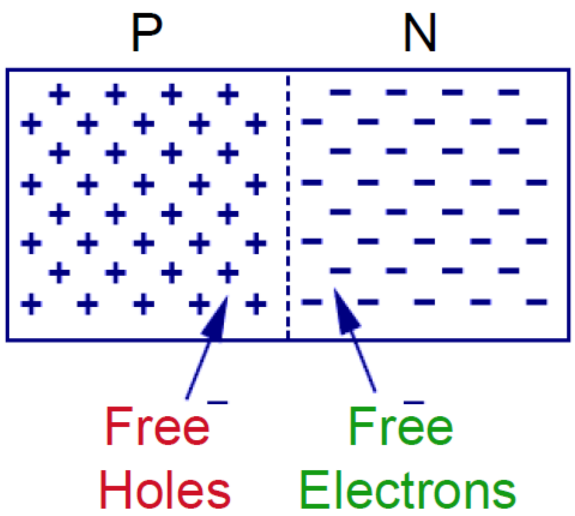


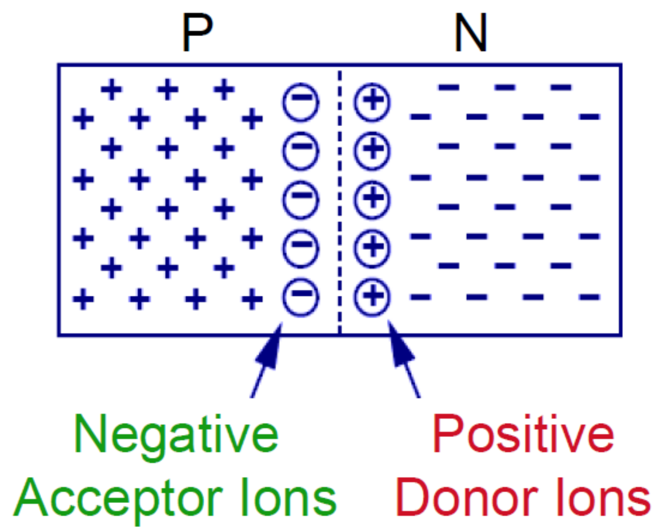
Electron diffuse from n to p
Holes diffuse from p to n

Electrons from the n region recombine with holes in the p region
Holes from the p region recombine with electrons in the n region

What stops them from flowing indefinitely?

PN junction in equilibrium



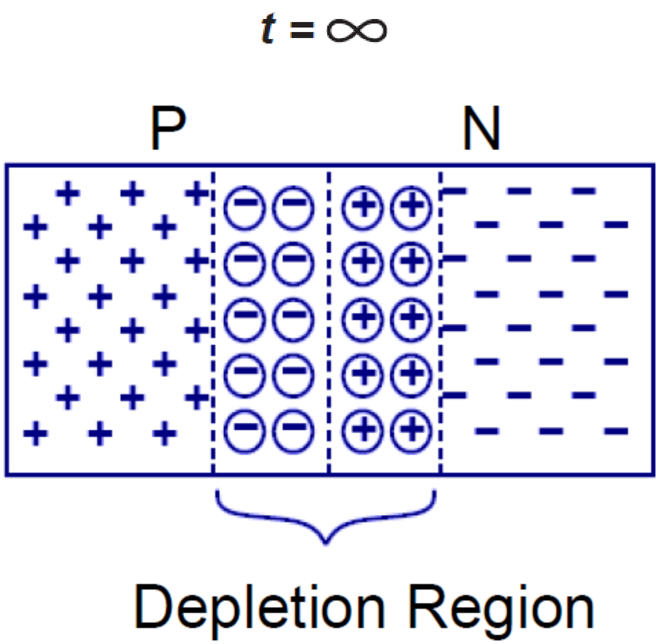


When an electron is taken from the n region or a hole is taken from the p region, a charged donor or acceptor is left behind.

The fixed charged ions create electric fields

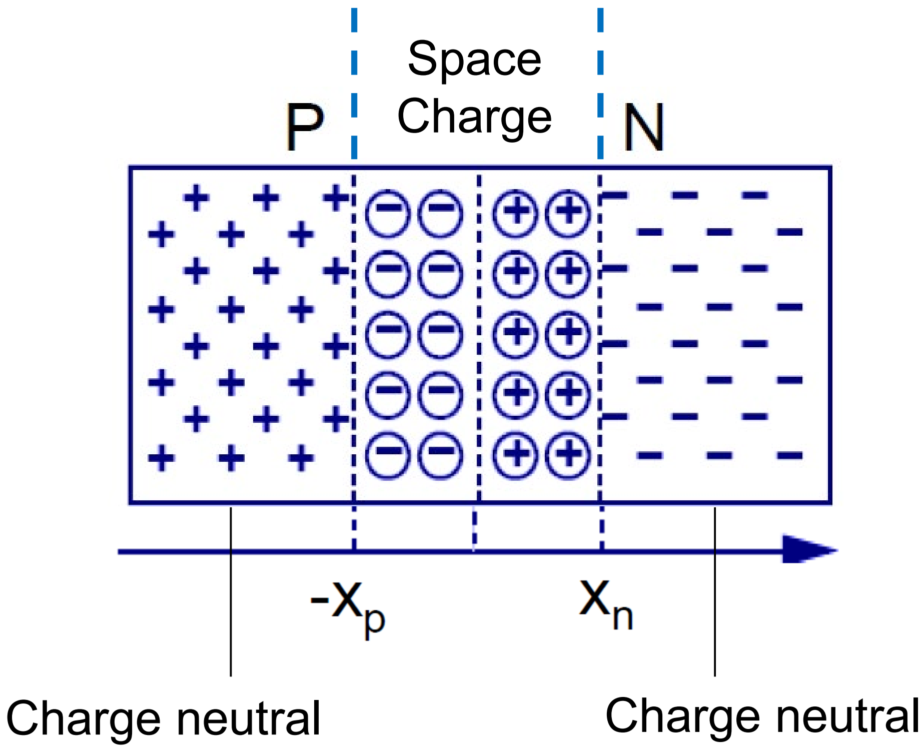
Depletion Region

- As free electrons and holes diffuse across the junction, a region of fixed ions is left behind
- This region is known as the “depletion region” because it is 'depleted' of charge carriers



Depletion Region

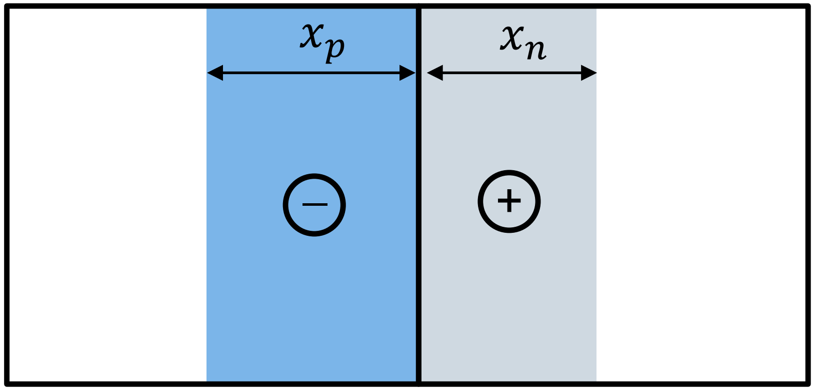
- The depletion region is made up of fixed ions due to diffusion of carrier to opposite sides of the junction
  - also known as space-charge region



- Depletion region is not charge-neutral
  - Creates a built-in voltage
- The regions outside of the depletion region are *still charge-neutral*

Electric field in depletion region

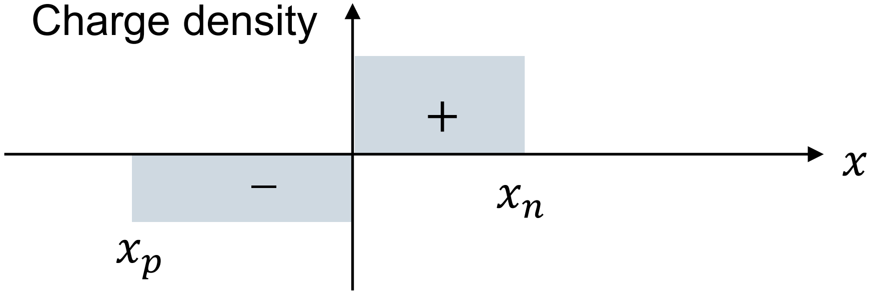
p-silicon n-silicon



For simplicity, assume the depletion region has no free carriers (the free carrier density is orders of magnitude smaller than original)

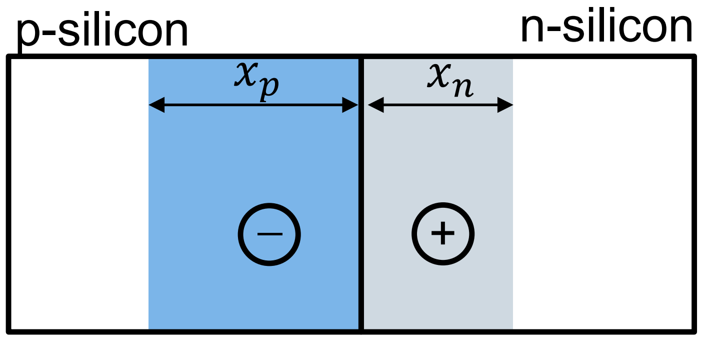
Hence, the space charge region has a uniform charge density

p-side: qN_A n-side: qN_D

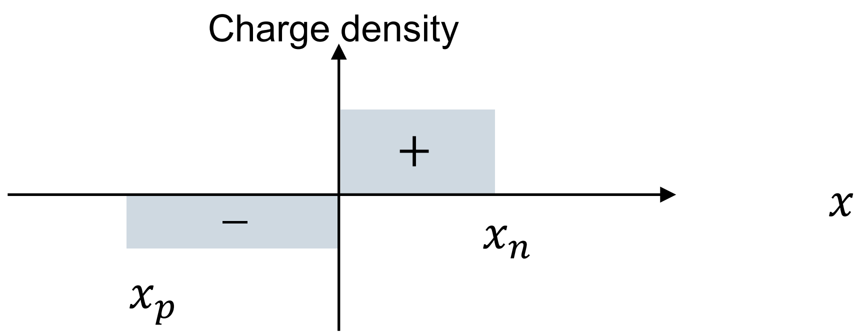


Charge neutral condition $$qN_A x_p = qN_D x_n \Rightarrow \frac{x_p}{x_n} = \frac{N_D}{N_A}$$

Electric field in pn juinction

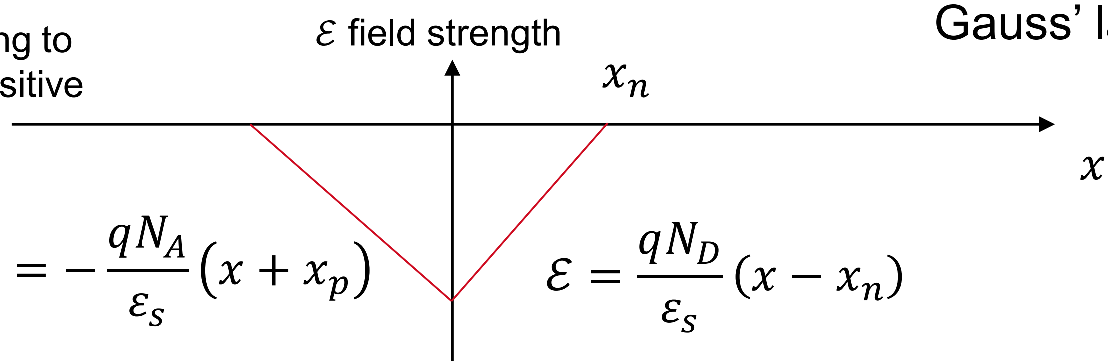


$$\frac{x_p}{x_n} = \frac{N_D}{N_A}$$



Define $\mathcal{E}$ pointing to $+x$ as being positive

Gauss' law: $\mathcal{E} = \frac{1}{\varepsilon_s}\int \rho dx$

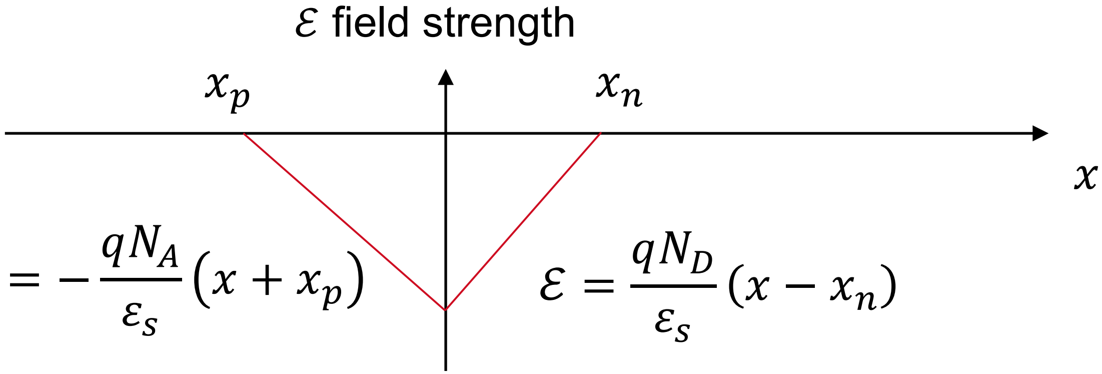


$$\mathcal{E} = -\frac{qN_A}{\varepsilon_s}(x + x_p)$$

$$\mathcal{E} = \frac{qN_D}{\varepsilon_s}(x - x_n)$$

$$\mathcal{E}_{\max} = -\frac{qN_A}{\varepsilon_s}x_p = -\frac{qN_D}{\varepsilon_s}x_n$$

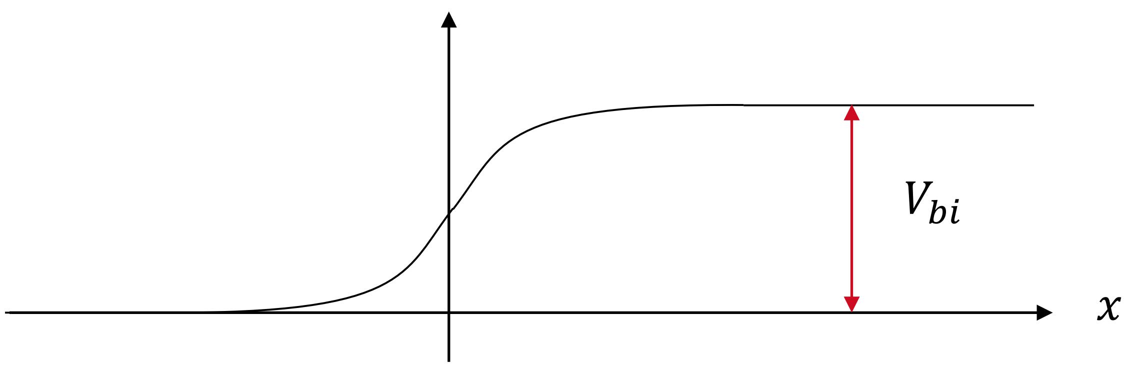
Build-in Potential in pn-junction



$$\mathcal{E} = -\frac{qN_A}{\varepsilon_s}\left(x + x_p\right) \qquad \mathcal{E} = \frac{qN_D}{\varepsilon_s}(x - x_n)$$

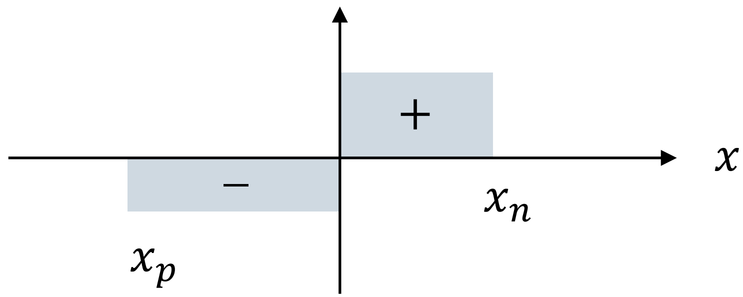
$$\mathcal{E}_{\max} = -\frac{qN_A}{\varepsilon_s}x_p = -\frac{qN_D}{\varepsilon_s}x_n$$

Build-in Potential $V = -\int \mathcal{E} dx$

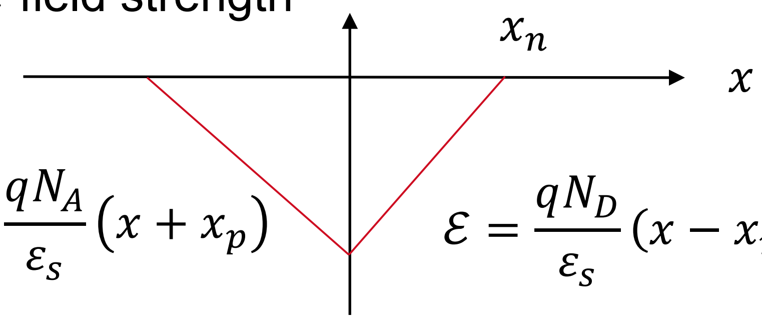


$$V_{bi} = \frac{1}{2}\frac{qN_A}{\varepsilon_s}x_p^2 + \frac{1}{2}\frac{qN_D}{\varepsilon_s}x_n^2 = \frac{1}{2}\mathcal{E}_{max}w \qquad w = x_p + x_n$$

Depletion region width w



$\mathcal{E}$ field strength

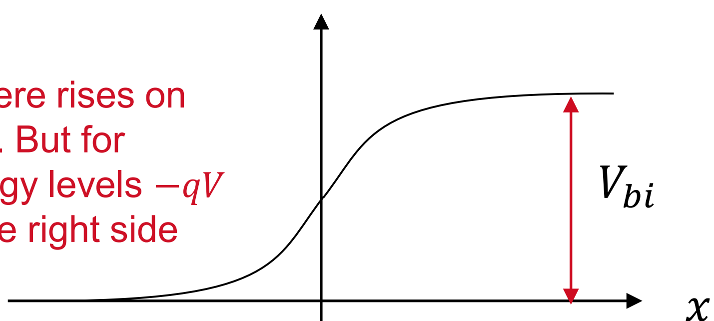


$$\mathcal{E} = -\frac{qN_A}{\varepsilon_s}(x + x_p)$$

$$\mathcal{E} = \frac{qN_D}{\varepsilon_s}(x - x_n)$$

$$\mathcal{E}_{\max} = -\frac{qN_A}{\varepsilon_s}x_p = -\frac{qN_D}{\varepsilon_s}x_n$$

Potential V here rises on the right side. But for electron energy levels $-qV$ it drops on the right side



$$V_{bi} = \frac{1}{2}\frac{qN_A}{\varepsilon_s}x_p^2 + \frac{1}{2}\frac{qN_D}{\varepsilon_s}x_n^2$$

Let $w = x_p + x_n$

$$\frac{x_p}{x_n} = \frac{N_D}{N_A}$$

Hence:

$$x_p = \frac{N_D w}{N_A + N_D}$$

$$x_n = \frac{N_A w}{N_A + N_D}$$

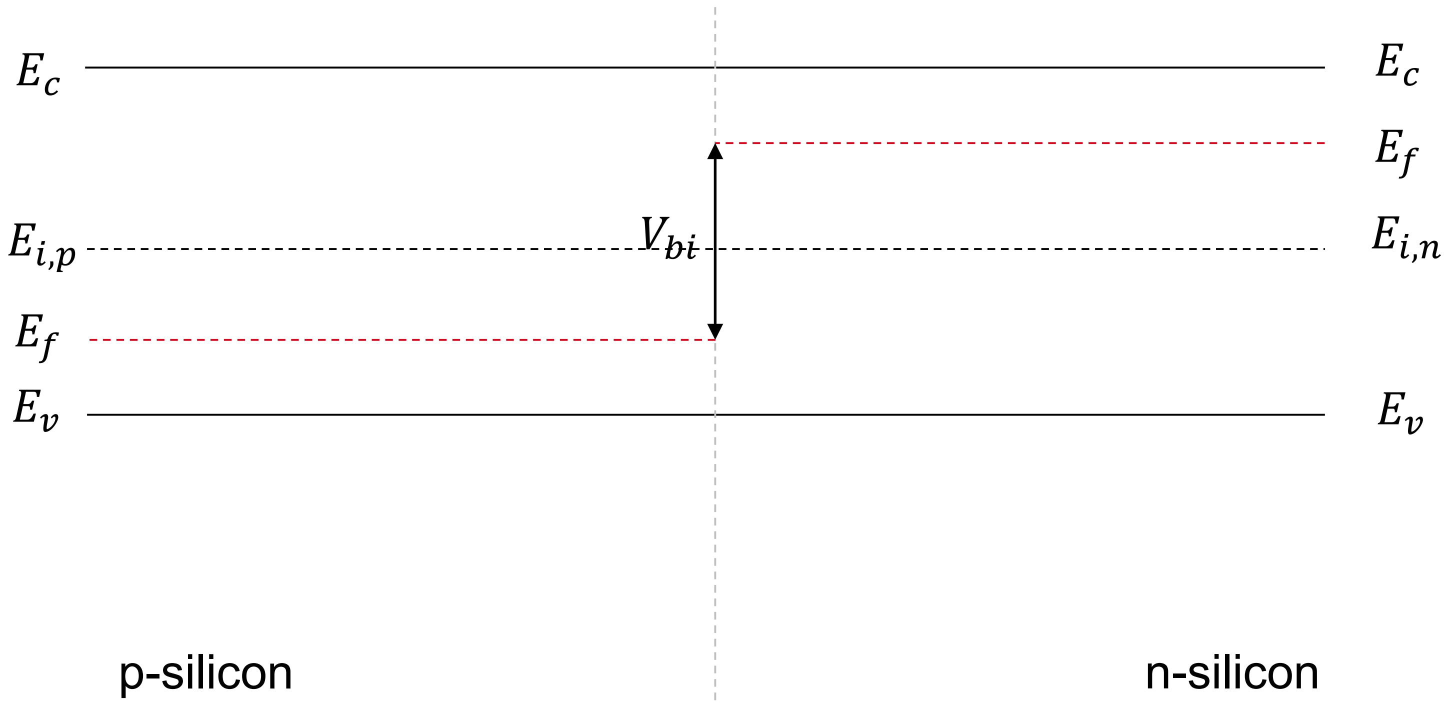
$$V_{bi} = \frac{1}{2}\frac{qN_A}{\varepsilon_s}x_p^2 + \frac{1}{2}\frac{qN_D}{\varepsilon_s}x_n^2$$

$$= \frac{1q}{2\varepsilon_s}\frac{N_A N_D}{N_A + N_D}w^2$$

i.e. $w = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_{bi}}$

How to calculate V_{bi}? Fermi level have to LEVEL

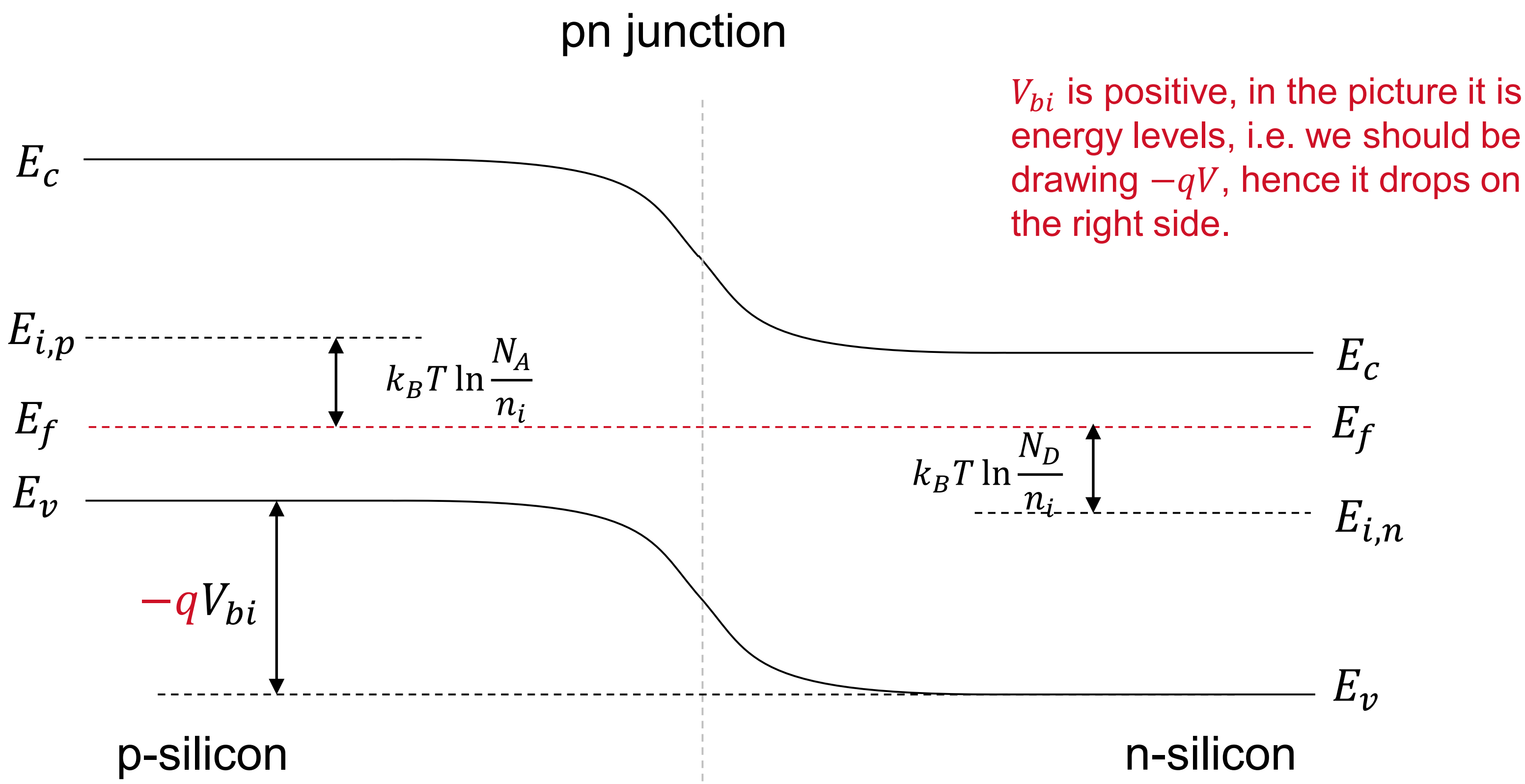
pn junction



$$E_{i,p} - E_f = k_B T \ln \frac{N_A}{n_i}$$

$$E_f - E_{i,n} = k_B T \ln \frac{N_D}{n_i}$$

How to calculate V_{bi}? Fermi level have to LEVEL



$$E_{i,p} - E_f = k_B T \ln \frac{N_A}{n_i} \qquad E_f - E_{i,n} = k_B T \ln \frac{N_D}{n_i}$$

$$V_{bi} = \frac{1}{q}\left(E_{c,p} - E_{c,n}\right) = \frac{1}{q}\left(E_{v,p} - E_{v,n}\right) = \frac{1}{q}\left(E_{i,p} - E_{i,n}\right) = \frac{k_B T}{q} \ln \frac{N_A N_D}{n_i^2}$$

Depletion width in pn-junctions

$$w = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_{bi}}$$

$$V_{bi} = \frac{k_B T}{q} \ln \frac{N_A N_D}{n_i^2}$$

Example

Find built-in potential and depletion-region width for a diode with the following charge densities.

$$N_A = 10^{17}\text{cm}^{-3} \qquad N_D = 10^{20}\text{cm}^{-3} \qquad k_B T = 0.025eV$$

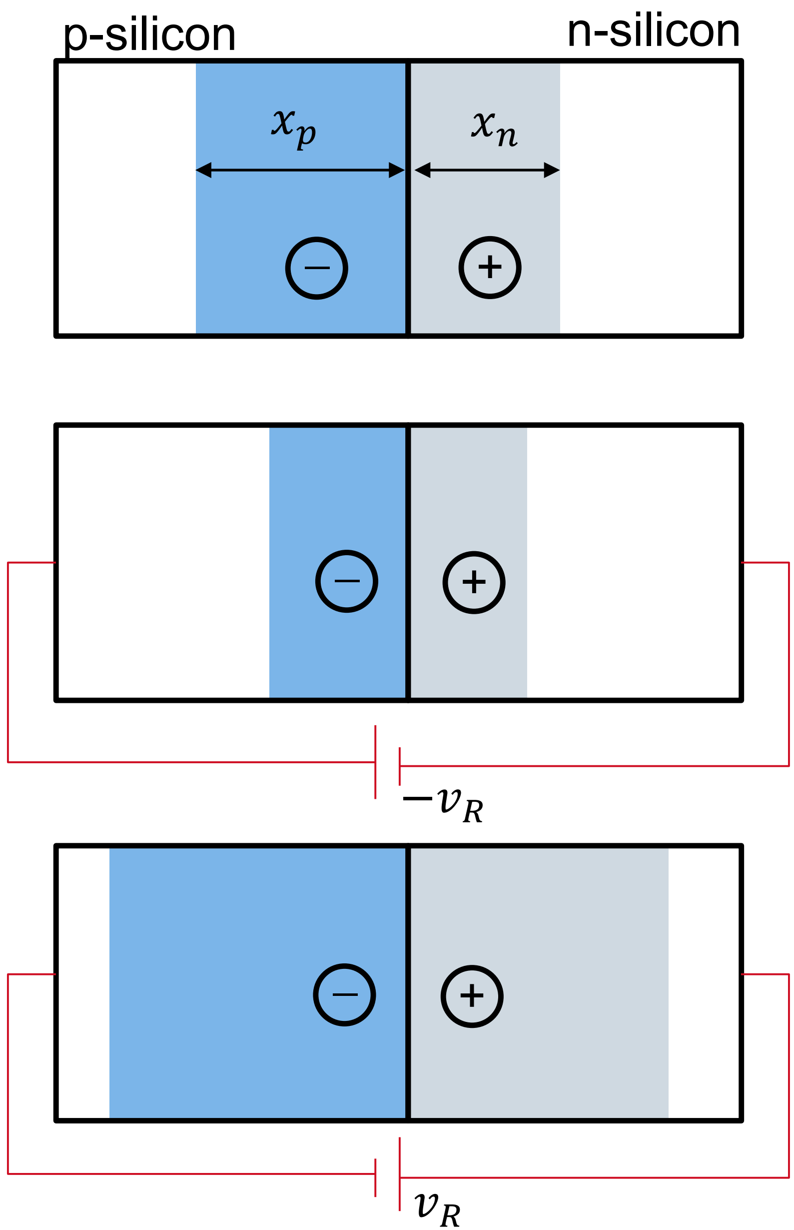
$$V_{bi} = \frac{kT}{q} ln \frac{N_A N_D}{{n^i}^2}$$

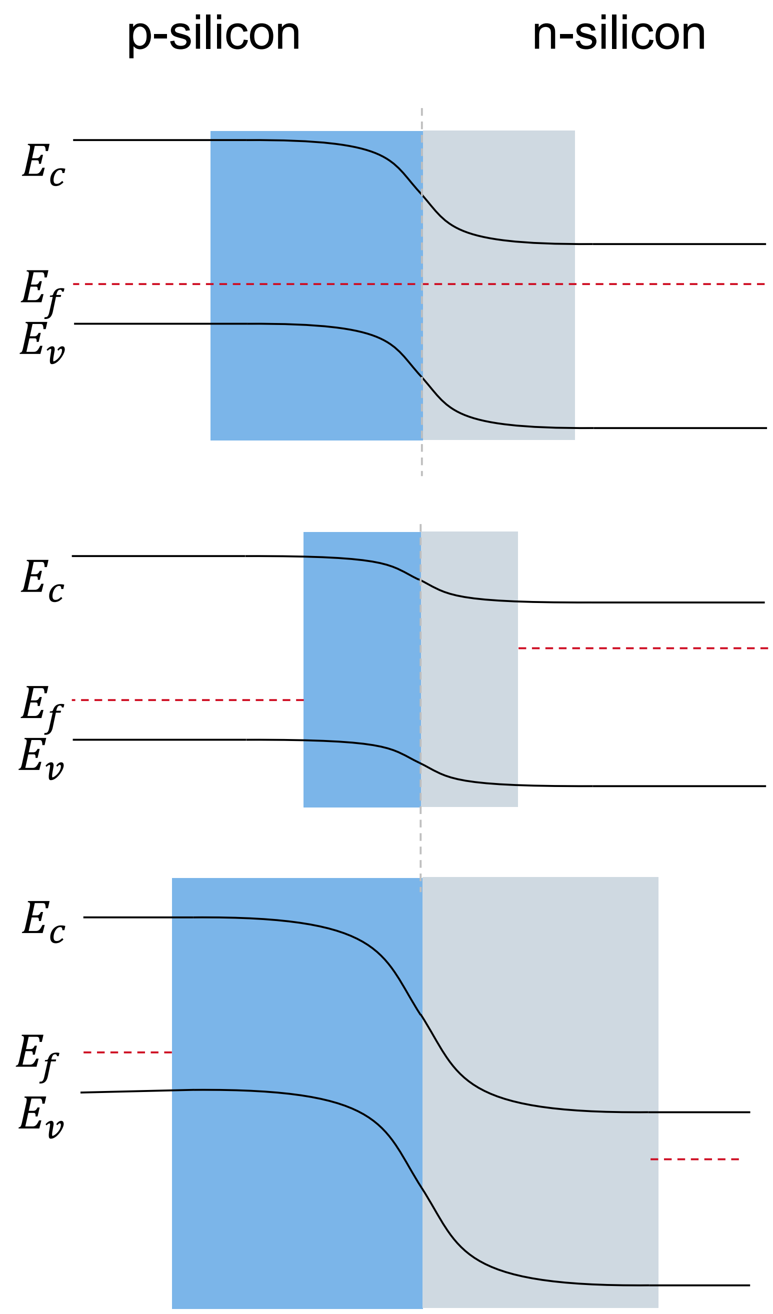
$$= 0.025 \; ln \frac{10^{17} 10^{20}}{10^{20}} = 0.979 \; V$$

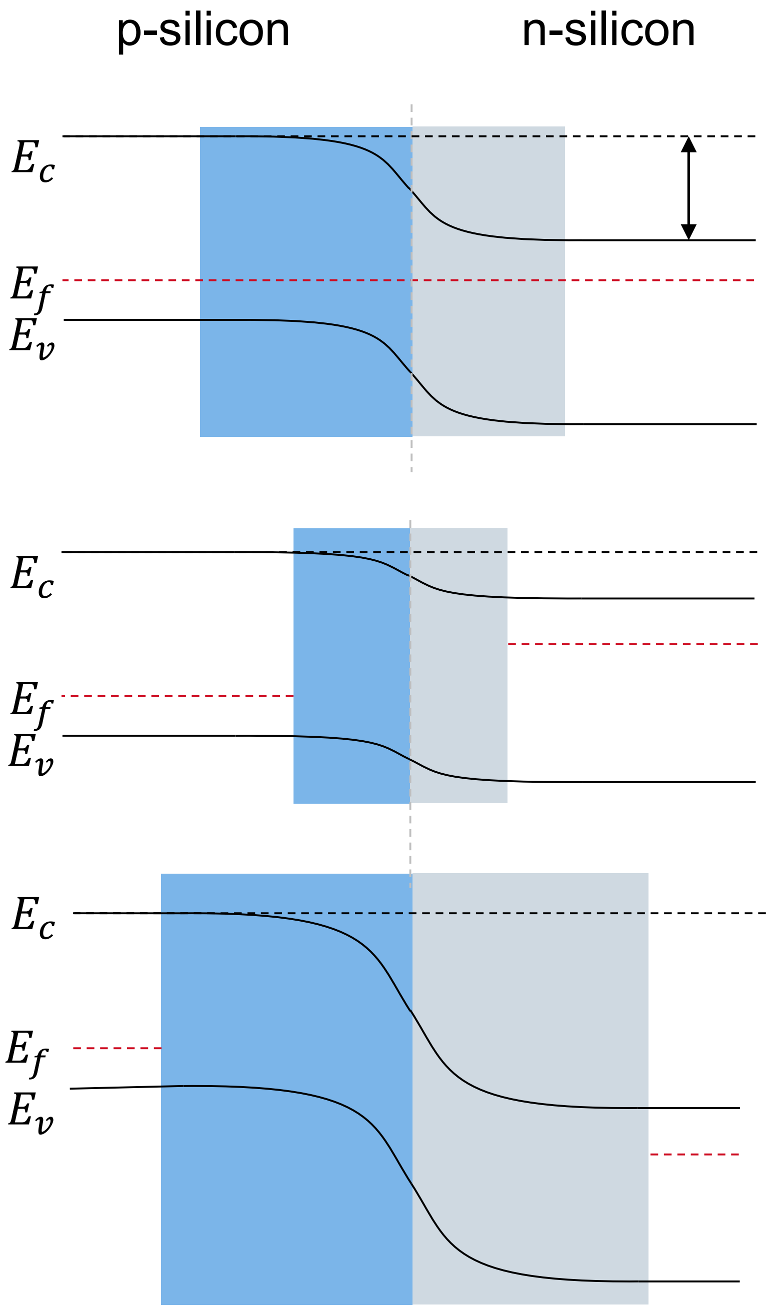
$$w = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right) V_{bi}} = 0.113 \mu m$$

$$\mathcal{E}_{max} = \frac{2V_{bi}}{w} = 173 kV/cm$$

pn-junction with bias







Depletion region charge

Electric field

potential difference

$$V_{bi} = -\frac{1q}{2\varepsilon_s}\frac{N_A N_D}{N_A + N_D}w^2$$

$$V_{bi} + v_R = -\frac{1q}{2\varepsilon_s}\frac{N_A N_D}{N_A + N_D}w^2$$

v_R: external applied voltage

$$w = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_{bi} + v_R)}$$

Batteries actually move Fermi levels!