<u>pn junctions</u>

Reference: Handout 3; Pierret Ch. 5-6

We will study

- Electrostatics and band structure
- The effect of bias
- The ideal diode equation
- Some examples of diodes

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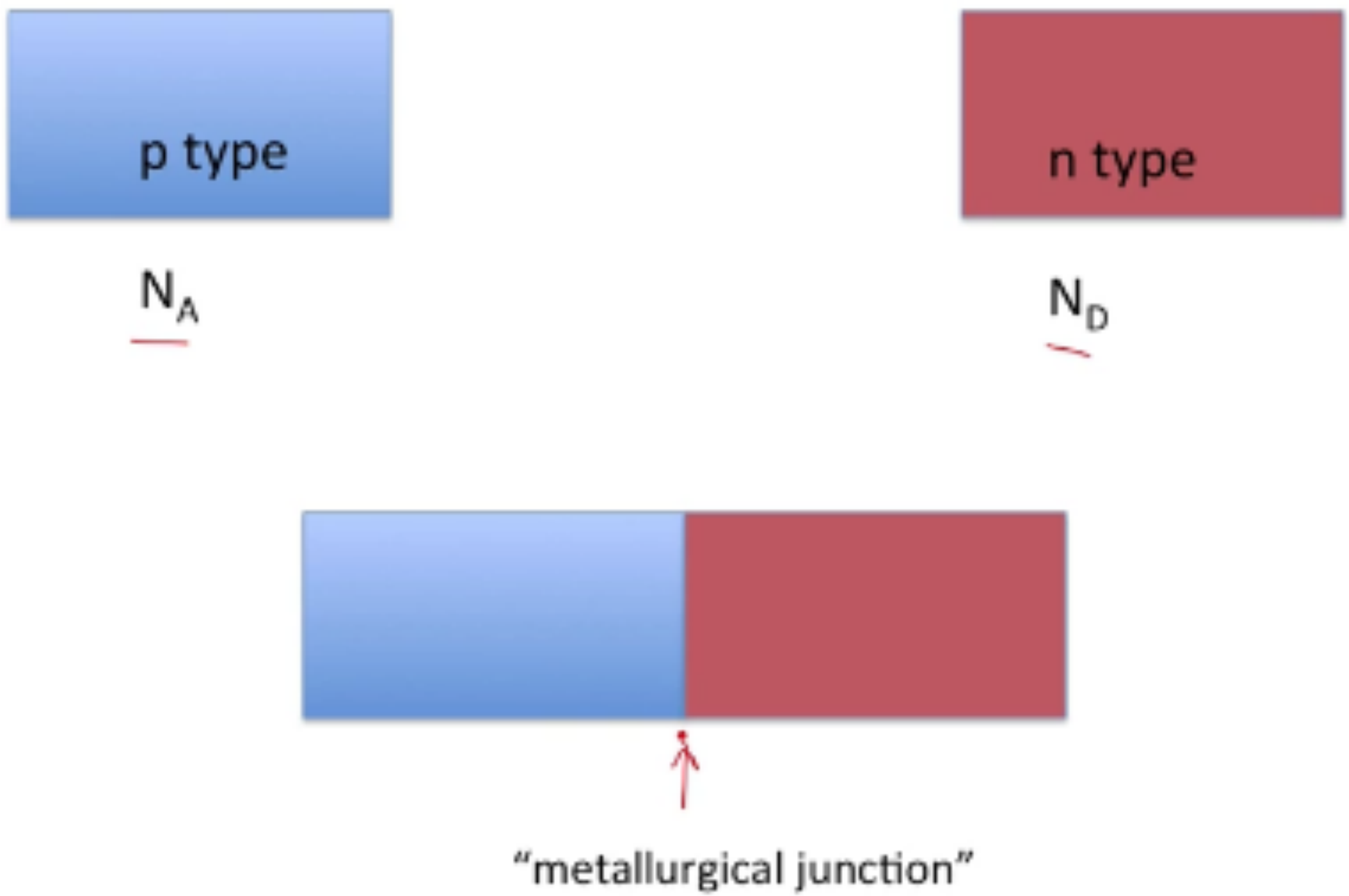
pn electrostatics

What diffusion and drift to you expect at a pn junction?



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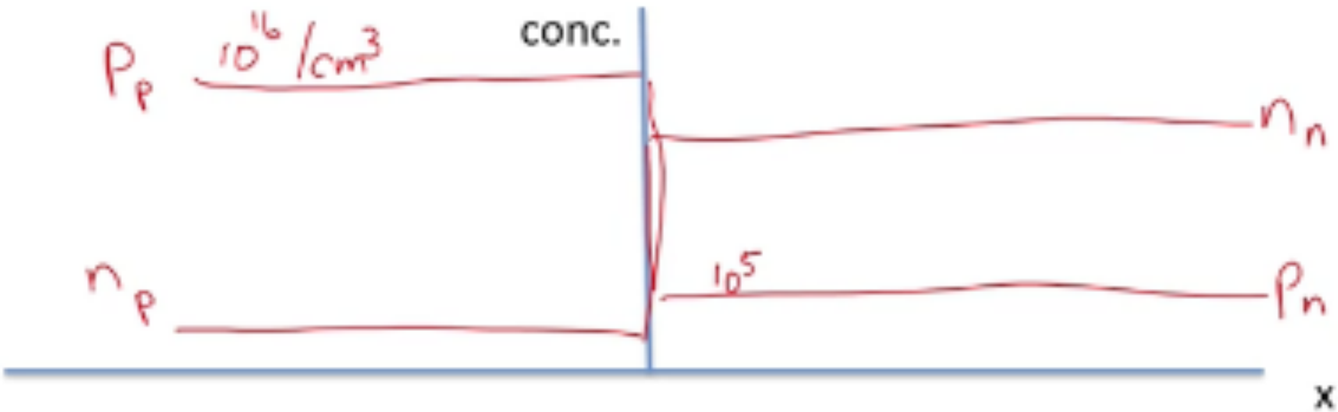
Carrier concentrations



→ holes diffuse

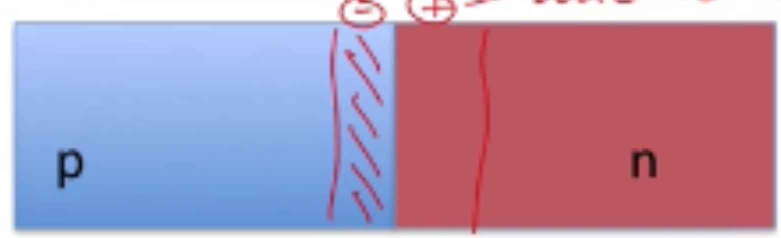
← e diffuse

Eqm.

drift + diffusion = 0

$N_D < N_A$

⊖ ⊕ — due to ionized dopants



depleted electrons

depleted holes

←

Electric field

→ electrons drift

← holes

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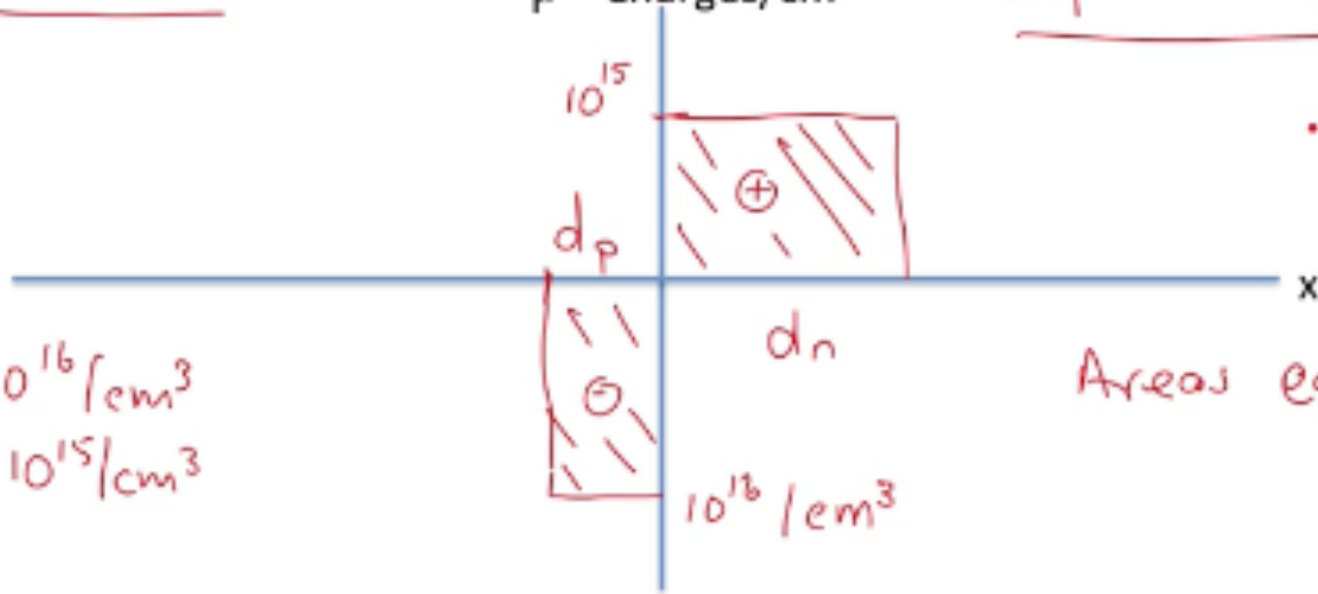
Charge density

Depletion approximation



$N_A = 10^{16}/cm^3$

$N_D = 10^{15}/cm^3$

Areas equal

Electric field: Gauss' law

depletion region → No carriers

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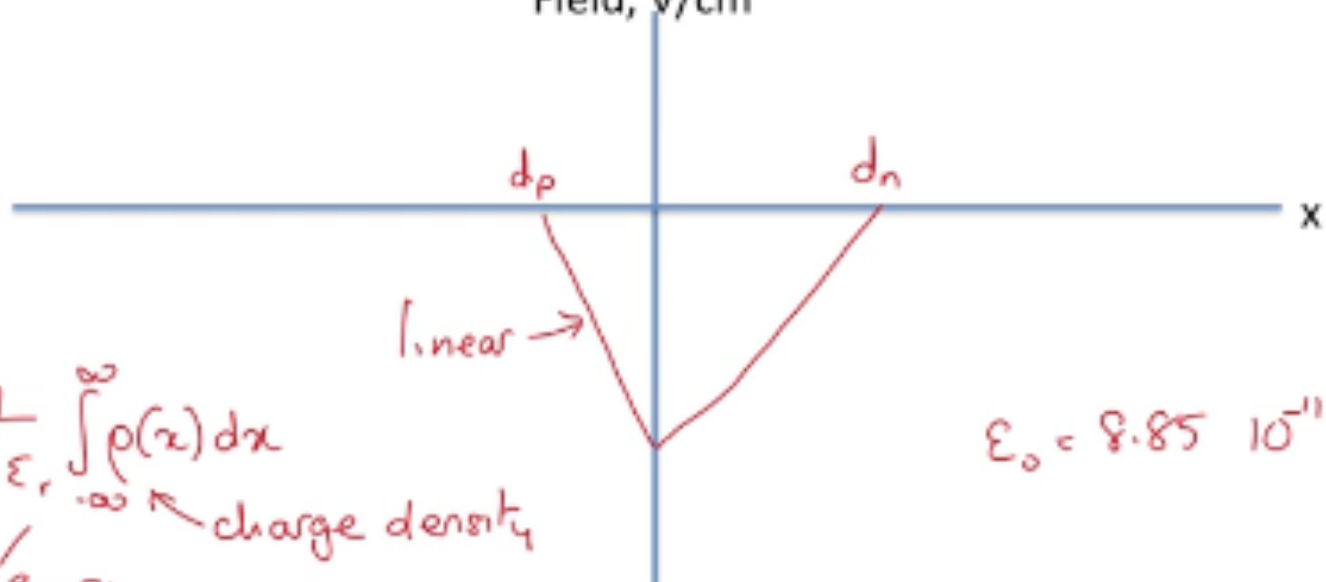
Electric field: Gauss' law



$$\mathcal{E} = \frac{1}{\varepsilon_0 \varepsilon_r} \int_{-\infty}^{\infty} \rho(x)\,dx$$

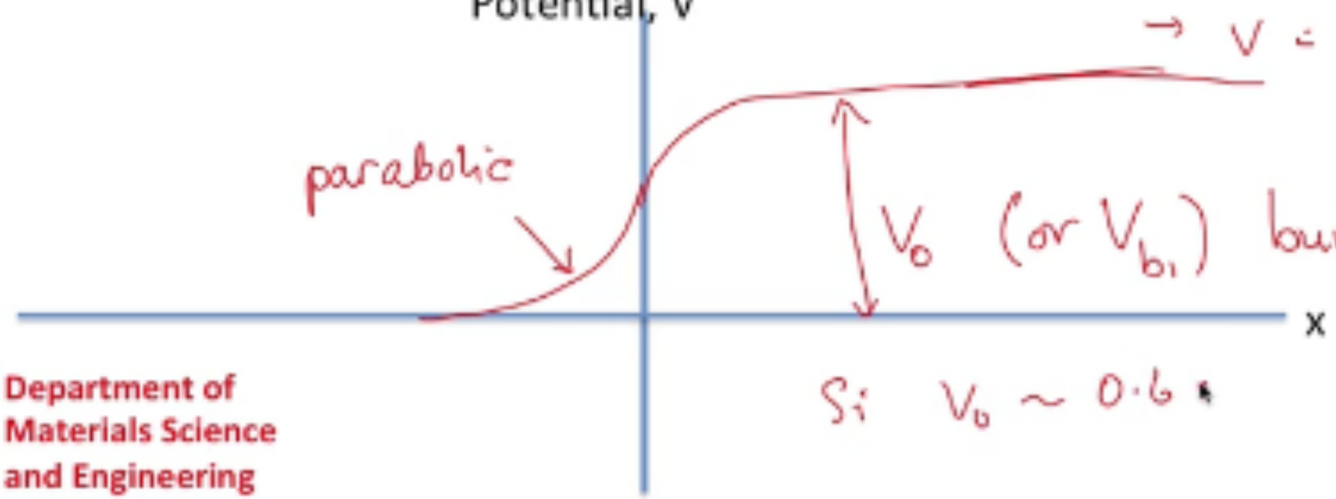
charge density

ε_r: 11.9 for Si.

$\varepsilon_0 = 8.85\ 10^{-11}$ F/cm

$$\mathcal{E} = -\frac{dV}{dx}$$

$\rightarrow V = -\int \mathcal{E}(x)\,dx$



V_0 (or V_{bi}) built-in voltage

Si: $V_0 \sim 0.6$

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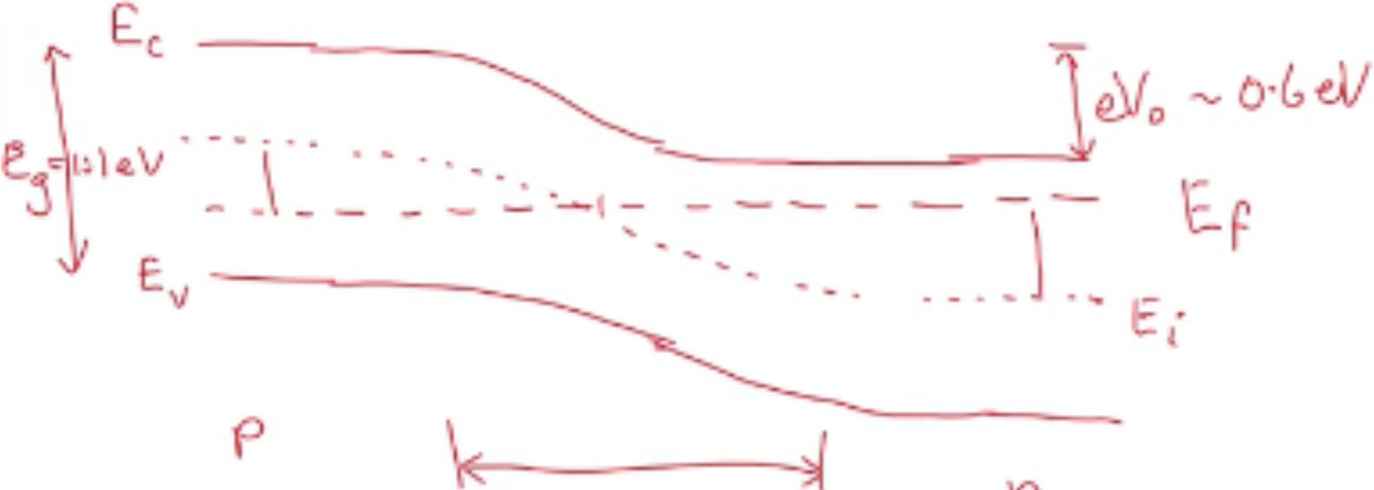
Energy levels ≃ − voltage

Band diagram of a pn junction

at eqm E_f = const



Depletion region ← Have $\mathcal{E}$. Assume $n, p \sim 0$

$n_n = n_i \exp{(E_f - E_i)/kT}$ so $(E_f - E_i) = kT \ln{(n_n/n_i)}$

e in n-type

n_n = number of electrons in n-type

$$e\underline{V}_o = (E_f - E_i)_{n\text{-type}} - (E_f - E_i)_{p\text{-type}}$$
$$= \underline{kT \ln{(n_n p_p / n_i^2)}}$$

10^{16} 10^{15} 10^{20}

$$\Rightarrow \underline{V_o = kT/e \ \ln{(N_A N_D / n_i^2)}}$$

~ 0.6eV at RT in Si

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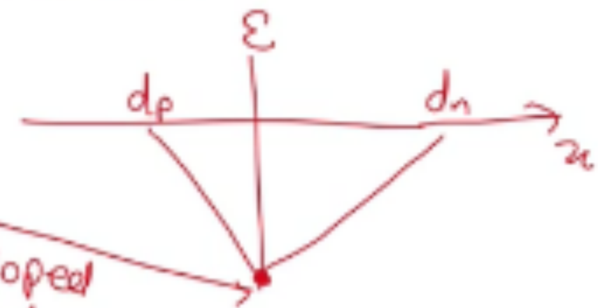
The depletion approximation

If we assume the depletion region really has no electrons or holes, we can derive the depletion width and Vo:

→ $\rho = -N_A e$ on p-side, $+N_D e$ on n-side

$$\mathcal{E} = N_A e\, d_p/\varepsilon_o\varepsilon_r = N_D e\, d_n/\varepsilon_o\varepsilon_r \qquad \text{at } x = 0$$



→ d_p is smaller than d_n when $N_A > N_D$

Depletion width is smaller on more heavily doped side

$$V_o = \frac{e}{2\varepsilon_o\varepsilon_r}(N_D d_n^2 + N_A d_p^2)$$ ~ 0.6 eV

$$d_n = \left\{\frac{2\varepsilon_o\varepsilon_r V_o}{e}\;\frac{N_A}{N_D(N_D + N_A)}\right\}^{0.5}$$

$$\boxed{d = d_p + d_n = \left\{\frac{2\varepsilon_o\varepsilon_r V_o}{e}\;\frac{N_D + N_A}{N_D N_A}\right\}^{0.5}}$$ = total depletion width

~1 – 3 μm

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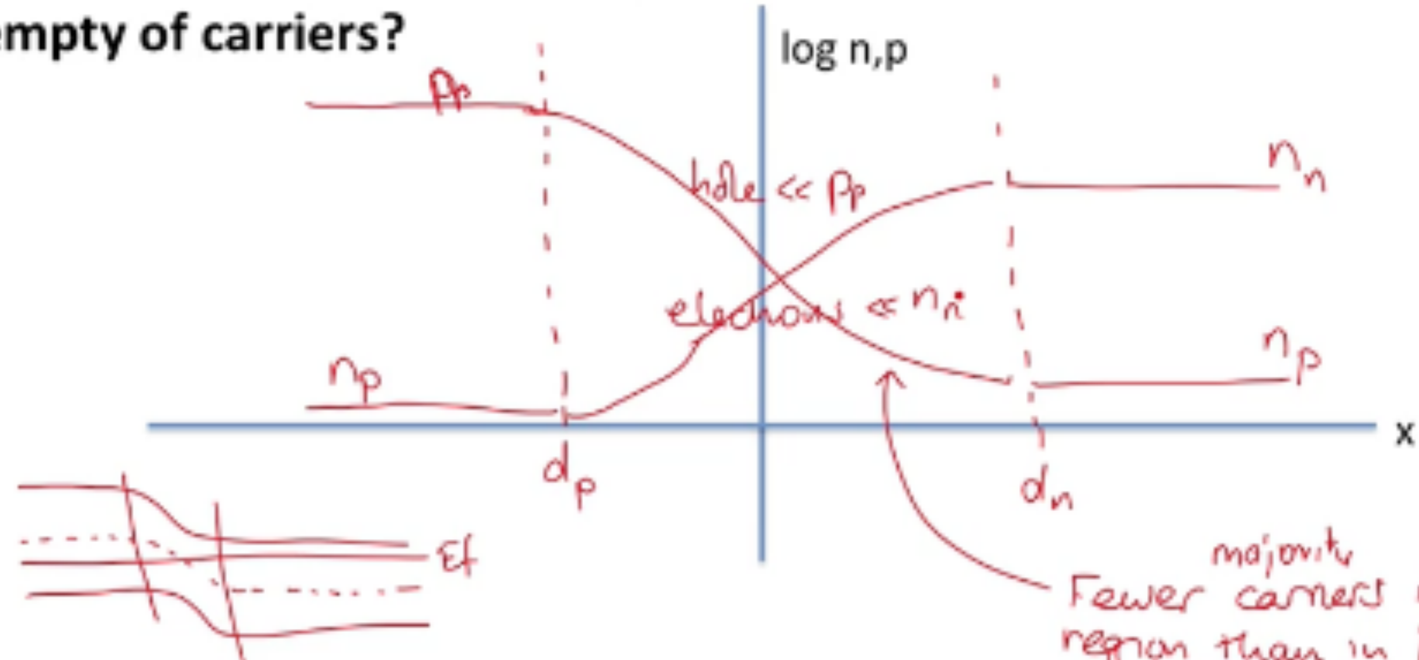
Is the depletion region really empty of carriers?



majority
Fewer carriers in Depl region than in bulk of material

$n_n = n_i \exp (E_f - E_i)/kT$ so $(E_f - E_i) = kT \ln (n_n/n_i)$

n_n = number of electrons in n-type

$$eV_o = (E_f - E_i)_{n\text{-type}} - (E_f - E_i)_{p\text{-type}}$$
$$= kT \ln (n_n p_p/n_i^2)$$

Summary

Put p and n type materials in contact: diffusion of carriers leads to depletion of carriers near the interface and a space charge which causes an electric field.
The electric field causes drift that balances diffusion at equilibrium.

Assuming full depletion of carriers (the depletion approximation), from the space charge we integrate to get electric field, then integrate again to get voltage across the junction. The bands bend in the depletion region, indicating that an electric field is present.

The built-in voltage is $V_o = kT/e \ln (N_D N_A/n_i^2)$

The depletion width is $d = d_p + d_n = \{\frac{2\varepsilon_o \varepsilon_r V_o}{e} \frac{N_D + N_A}{N_D N_A}\}^{0.5}$

Next: What happens when we apply a voltage across the pn junction?