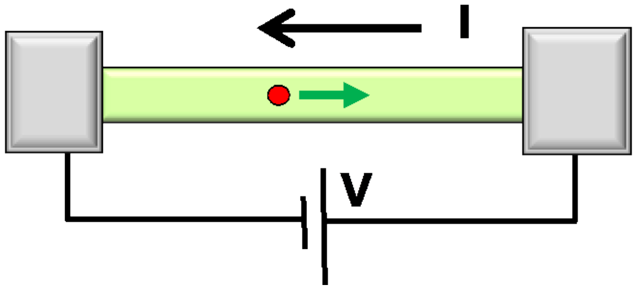
Section 14
Doping

14.3 Temperature dependence of carrier concentration

Gerhard Klimeck
gekco@purdue.edu

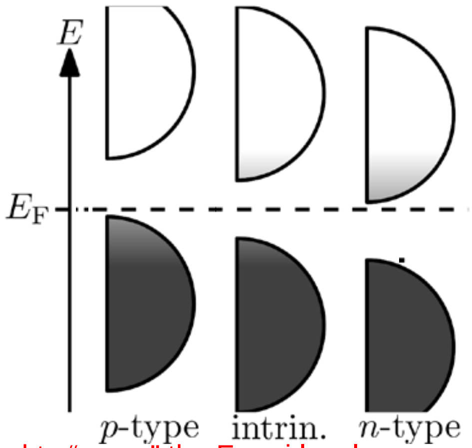
PURDUE UNIVERSITY

School of Electrical and Computer Engineering



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

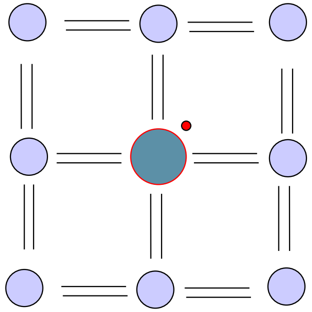
charge density velocity area

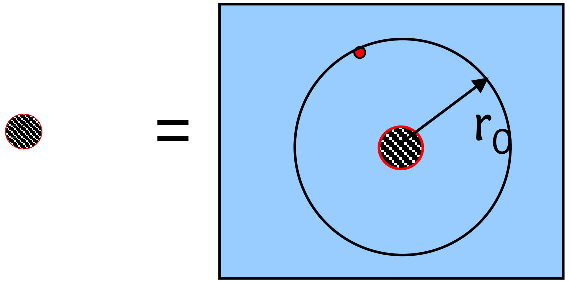


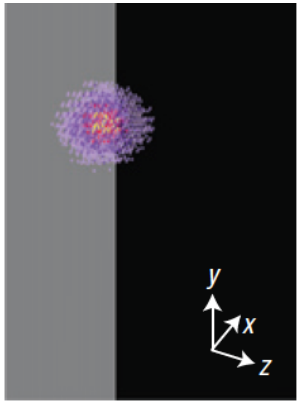
- Need to "move" the Fermi level
- "add" electrons – n-type doping – E_F close to E_c
- "add" holes – p-type doping – E_F close to E_v

Video

- 14.1 Basic concepts of donors and acceptors

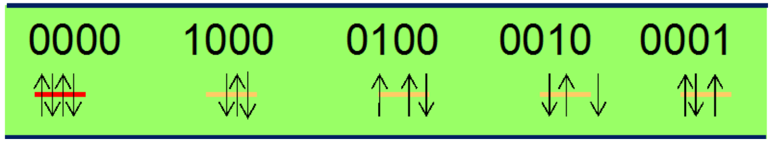






Video

- 14.2 Statistics of donor and acceptor levels



$$N_V e^{-(E_F - E_V)/k_BT} - N_C e^{-(E_C - E_F)/k_BT} + \frac{N_D}{1+2e^{(E_F - E_D)/k_BT}} - \frac{N_A}{1+4e^{(E_A - E_F)/k_BT}} = 0$$

Video

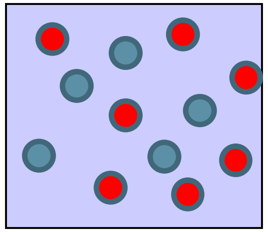
- 14.3 Temperature dependence of carrier concentration

Video

- 14.4

Carrier Density with Donors

In spatially homogenous field-free region …



Assume
N-type doping …

$$p - n + N_D^+ + N_A^- = 0$$

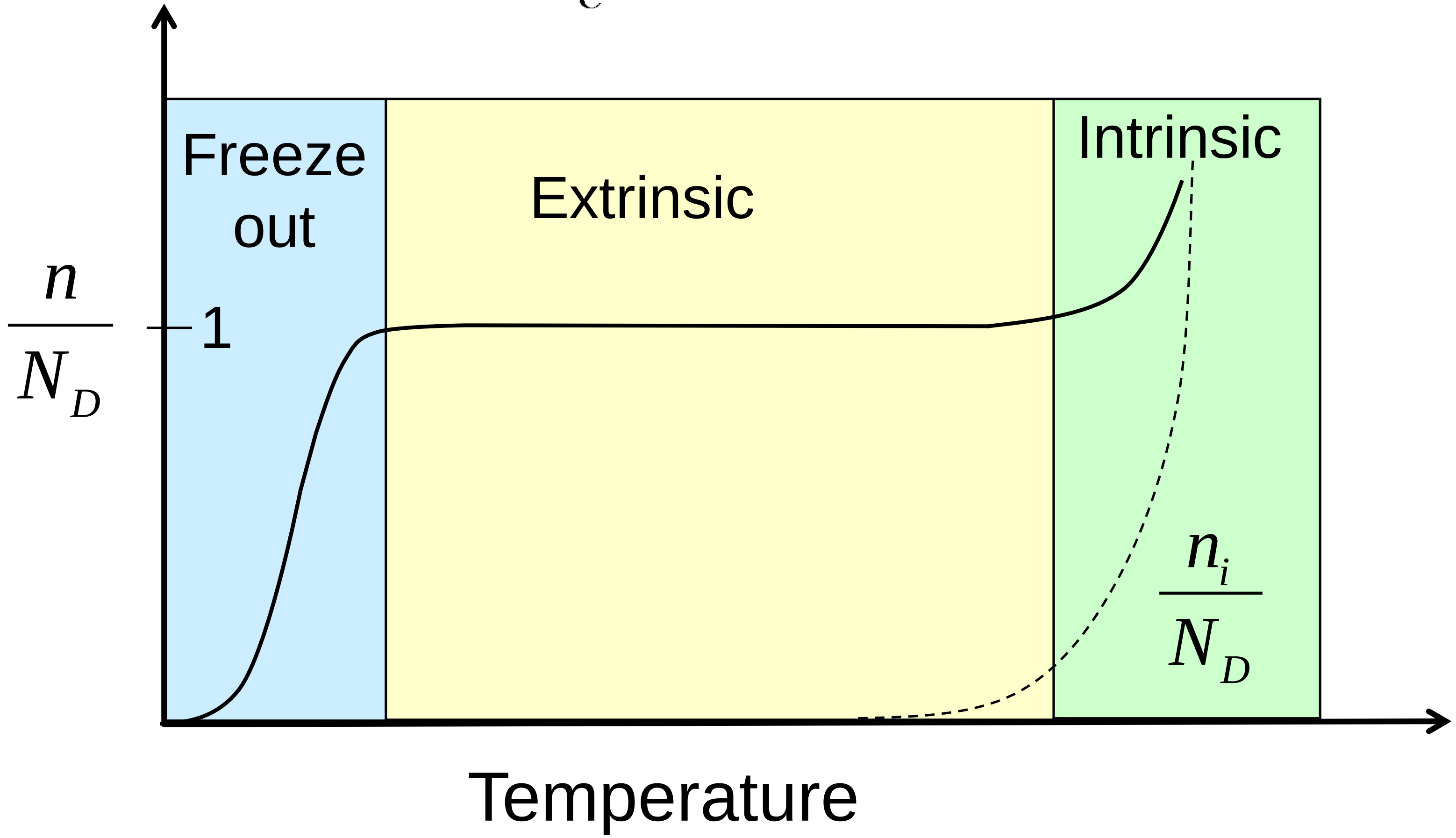
$$N_V e^{-(E_F-E_V)/k_BT} - N_C e^{-(E_C-E_F)/k_BT} + \frac{N_D}{1+2e^{(E_F-E_D)/k_BT}} - \cancel{\frac{N_A}{1+4e^{(E_A-E_F)/k_BT}}} = 0$$

n

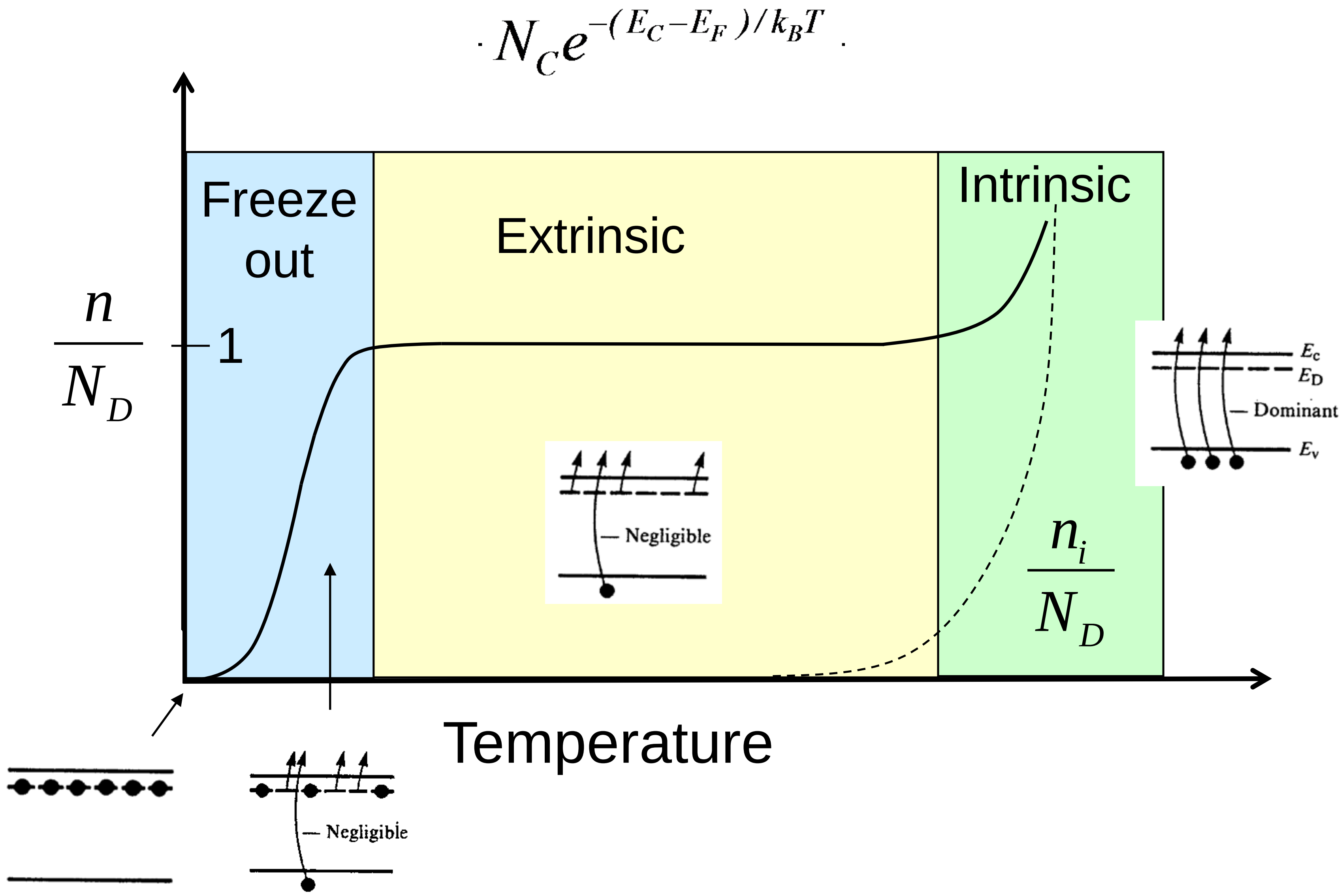
(will plot in next slide)

Temperature-dependent Concentration

$$N_C e^{-(E_C - E_F)/k_B T}$$



Physical Interpretation



Electron Concentration with Donors

$$n = N_C e^{-\beta(E_C - E_F)} \Rightarrow \frac{n}{N_C} e^{\beta E_C} = e^{\beta E_F}$$

$$N_D^+ = \frac{N_D}{1 + 2e^{\beta(E_F - E_D)}} = \frac{N_D}{1 + 2\left[\frac{n}{N_C} e^{\beta(E_c - E_D)}\right]} \equiv \frac{N_D}{1 + \frac{n}{N_\xi}}$$

$$N_\xi = \frac{1}{2} N_C e^{-\beta(E_c - E_D)}$$

Electron concentration with Donors

$$p - n + N_D^+ = 0$$

$$N_V e^{-(E_F - E_V)/k_BT} - N_C e^{-(E_C - E_F)/k_BT} + \frac{N_D}{1 + 2e^{(E_F - E_D)/k_BT}} = 0$$

$$p \times n = n_i^2$$

$$\frac{n_i^2}{n} - n + \frac{N_D}{1 + \frac{n}{N_\xi}} = 0$$

$$N_D^+ = \frac{N_D}{1 + 2e^{\beta(E_F - E_D)}} \equiv \frac{N_D}{1 + \frac{n}{N_\xi}}$$

$$N_\xi = \frac{1}{2} N_C e^{-\beta(E_c - E_D)}$$

No approximation so far ....

High Donor Density / Freeze out T

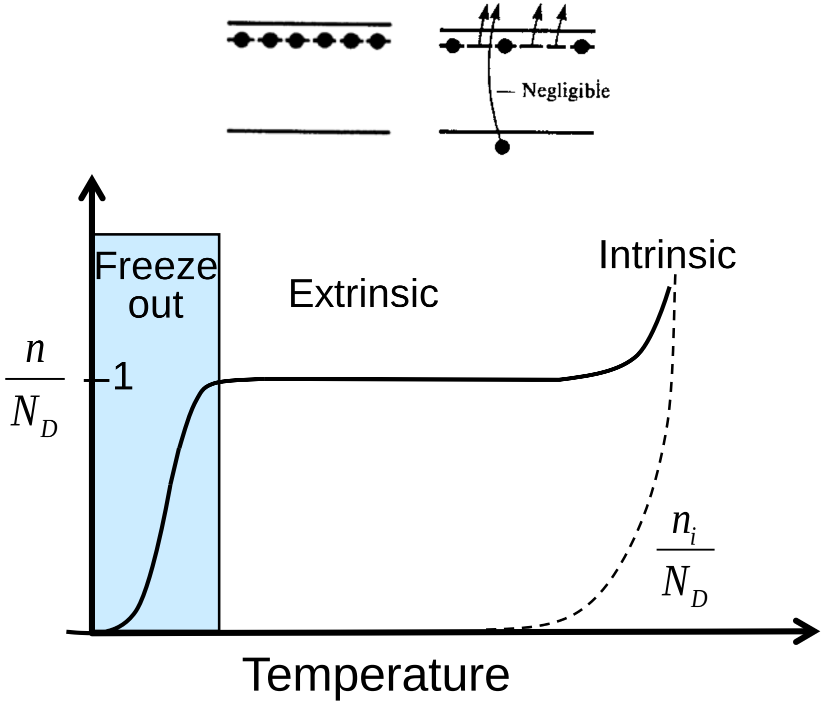
$$\frac{n_i^2}{n} - n + \frac{N_D}{1+\frac{n}{N_\xi}} = 0$$

$$N_D \approx n \gg n_i$$

$$\Rightarrow -n + \frac{N_D}{1+\frac{n}{N_\xi}} \approx 0$$

$$\Rightarrow n^2 + N_\xi n - N_\xi N_D = 0$$

$$n = \frac{N_\xi}{2}\left[\left(1+\frac{4N_D}{N_\xi}\right)^{1/2} - 1\right]$$



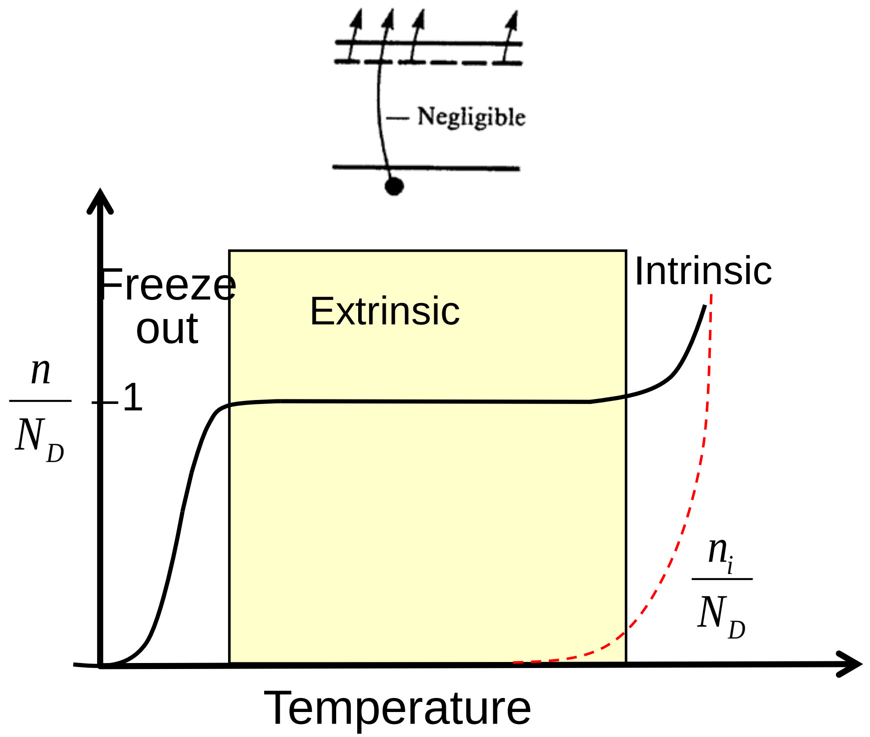
$$N_\xi = \frac{1}{2} N_C e^{-\beta(E_C - E_D)}$$

$$n = \frac{N_\xi}{2}\left[\left(1+\frac{4N_D}{N_\xi}\right)^{1/2} - 1\right] \qquad N_\xi = \frac{1}{2} N_C e^{-\beta(E_C - E_D)}$$

$$Assume:\ N_\xi \gg N_D$$

$$\approx \frac{\cancel{N_\xi}}{2}\left[\left(\cancel{1}+\frac{1}{2}\frac{4N_D}{\cancel{N_\xi}}\right)-\cancel{1}\right]$$

$$\approx N_D$$



Electron concentration equals donor density
hole concentration by $n \times p = n_i^2$

Intrinsic T

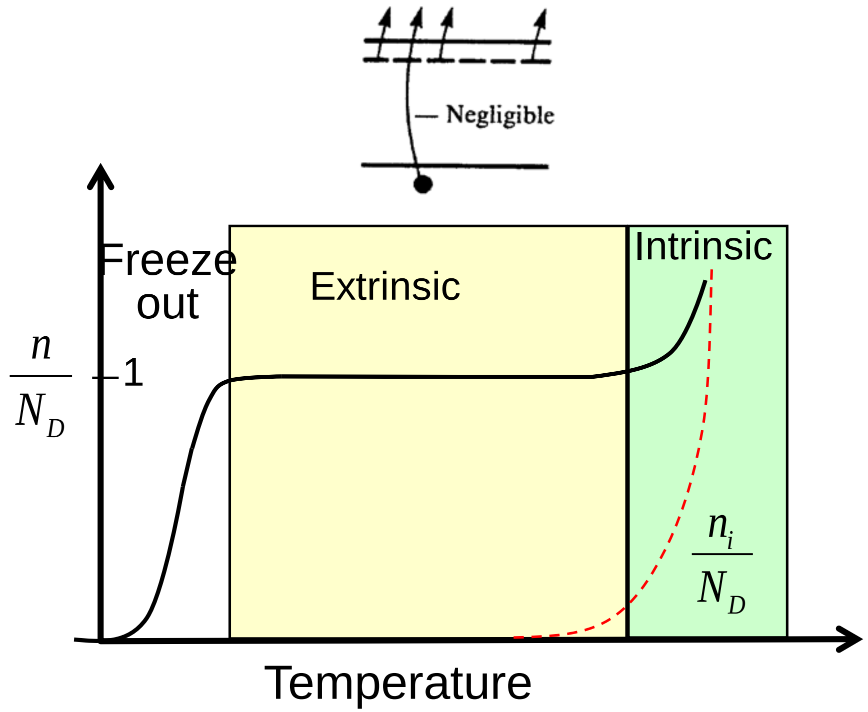
$$N_D^+ = \frac{N_D}{1 + 2e^{(E_F - E_D)/k_B T}} \approx N_D \quad \text{for } E_F < E_D$$

0

$$\frac{n_i^2}{n} - n + \frac{N_D}{1 + \frac{n}{N_\xi}} = 0$$

$$\frac{n_i^2}{n} - n + N_D \approx 0$$

$$\Rightarrow -n_i^2 + n^2 - N_D n = 0$$



$$n = \frac{N_D}{2} + \left[\frac{N_D^{\,2}}{4} + n_i^2\right]^{1/2}$$

Extrinsic/Intrinsic T

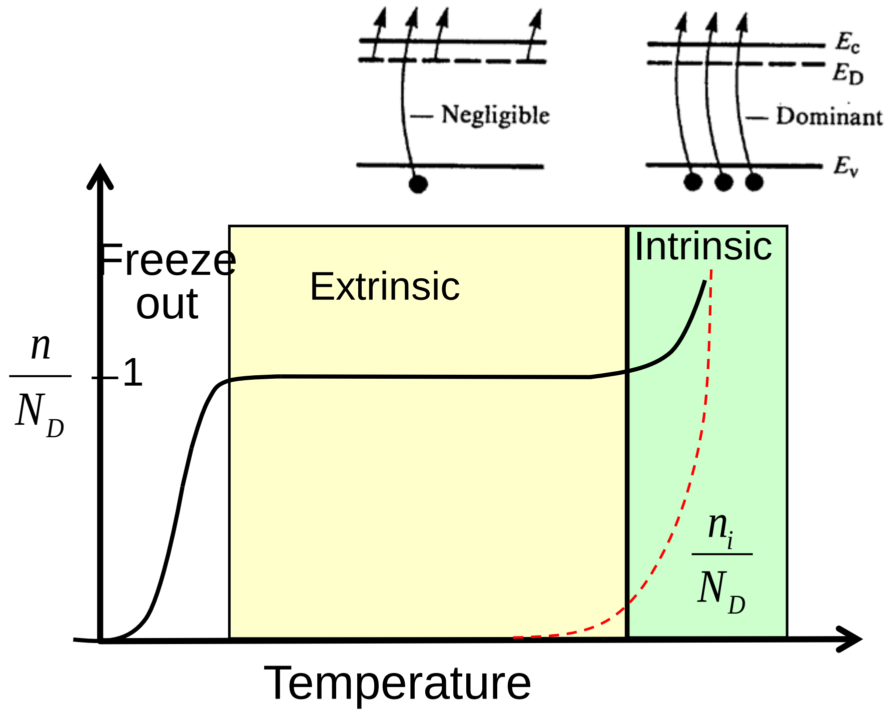
$$n = \frac{N_D}{2} + \left[\frac{N_D^{\,2}}{4} + n_i^2\right]^{1/2}$$

$$Assume:\ N_D \gg n_i$$

$$n = \frac{N_D}{2} + \left[\frac{N_D^{\,2}}{4} + n_i^2\right]^{1/2} \approx N_D$$

$$Assume:\ N_D \ll n_i$$

$$n = \frac{N_D}{2} + \left[\frac{N_D^{\,2}}{4} + n_i^2\right]^{1/2} \approx n_i$$



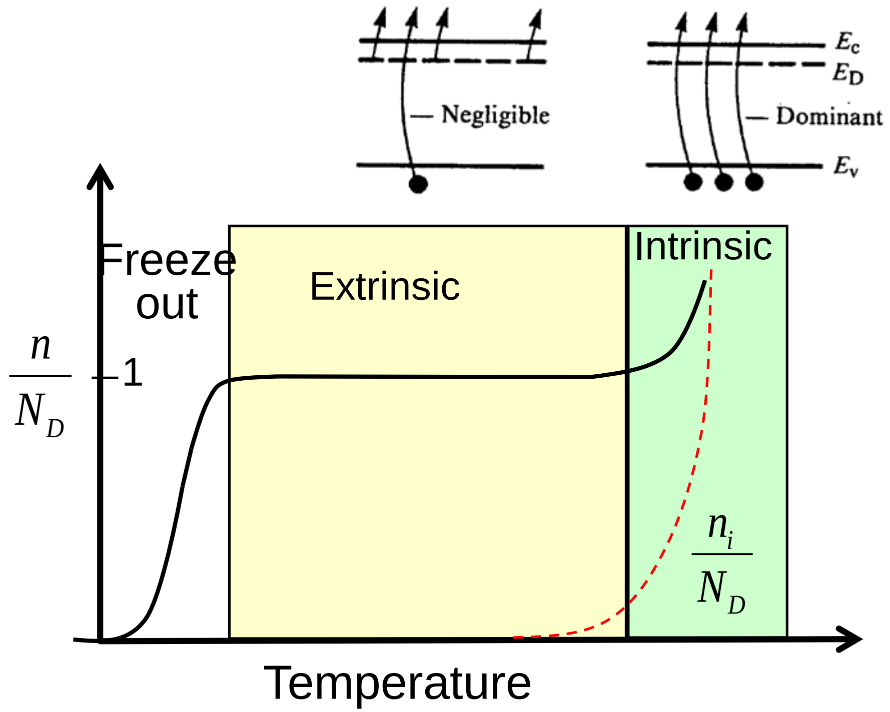
What will happen if you use silicon circuits at very high temperatures ?
Bandgap determines the intrinsic carrier density.

Determination of Fermi-level

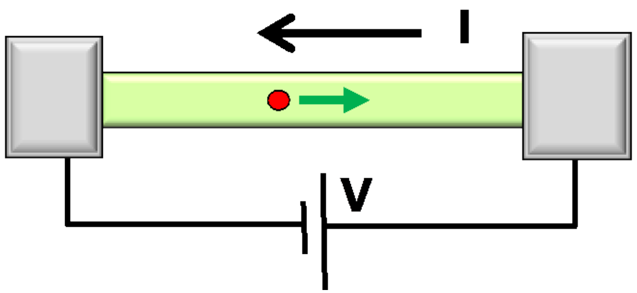
$$n = N_C e^{-\beta(E_c - E_F)} \Rightarrow E_F = E_C + \frac{1}{\beta} ln\left(\frac{n}{N_C}\right)$$

$$p - n + N_D^+ = 0$$

$$N_V e^{-(E_F - E_V)/k_B T} - N_C e^{-(E_C - E_F)/k_B T} + \frac{N_D}{1 + 2e^{(E_F - E_D)/k_B T}} = 0$$

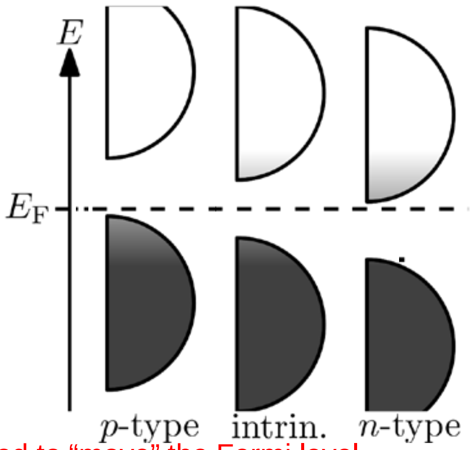


Section 14
Doping



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

charge density velocity area



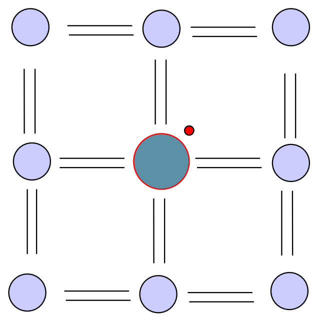
» Need to "move" the Fermi level

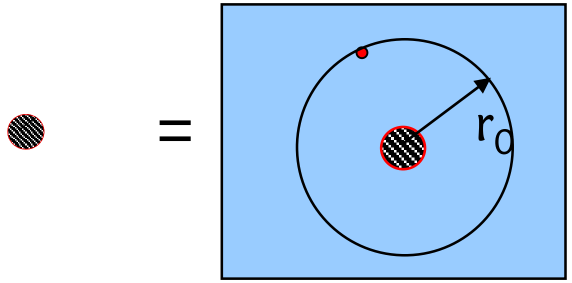
» "add" electrons – n-type doping – E_F close to E_c

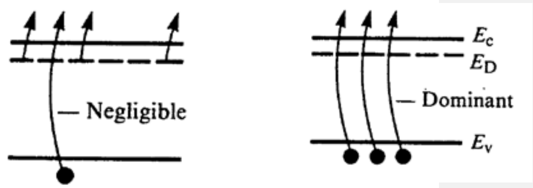
» "add" holes – p-type doping – E_F close to E_v

Video

- 14.1 Basic concepts of donors and acceptors

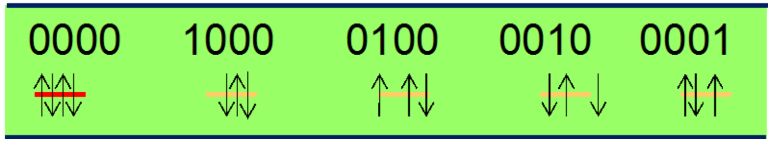


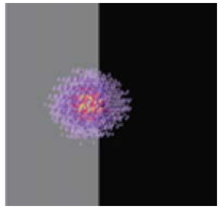




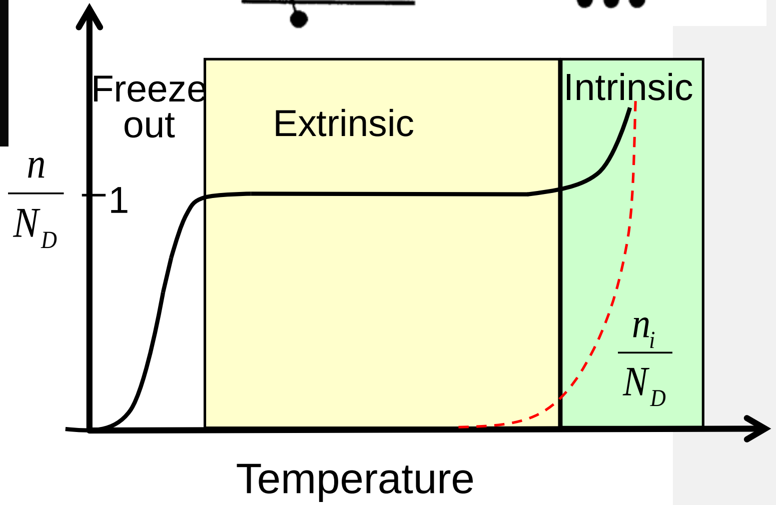
Video

- 14.2 Statistics of donor and acceptor levels





$$N_V e^{-(E_F - E_V)/k_B T} - N_A e^{-(E_C - E_F)/k_B T} + \frac{N_D}{1 + 2e^{(E_F - E_D)/k_B T}} - \frac{N_A}{1 + 4e^{(E_A - E_F)/k_B T}} = 0$$



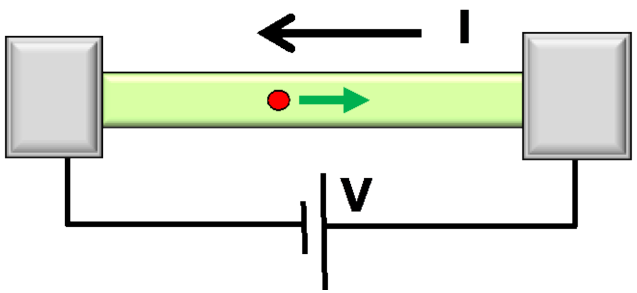
Video

- 14.3 Temperature dependence of carrier concentration

Video

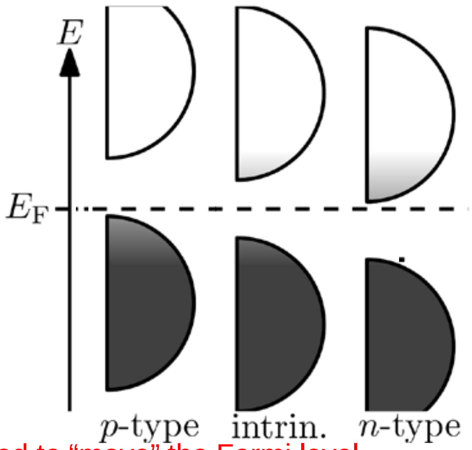
- 14.4

Section 14
Doping



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

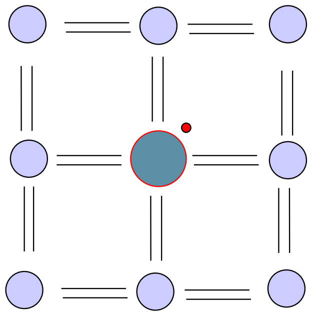
charge density velocity area

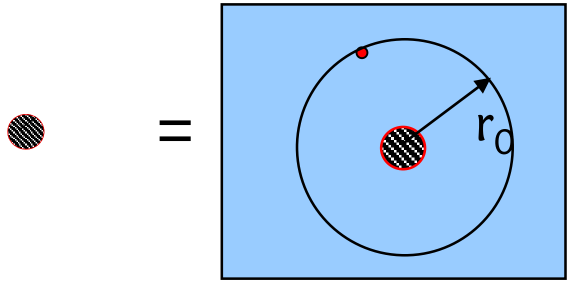


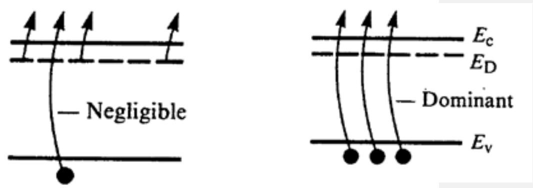
» Need to “move” the Fermi level
» ”add” electrons – n-type doping – E_F close to E_c
» “add” holes – p-type doping – E_F close to E_v

Video

- 14.1 Basic concepts of donors and acceptors

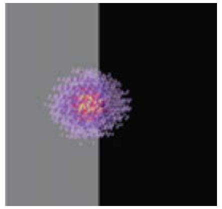


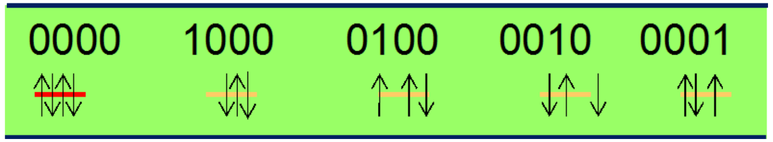




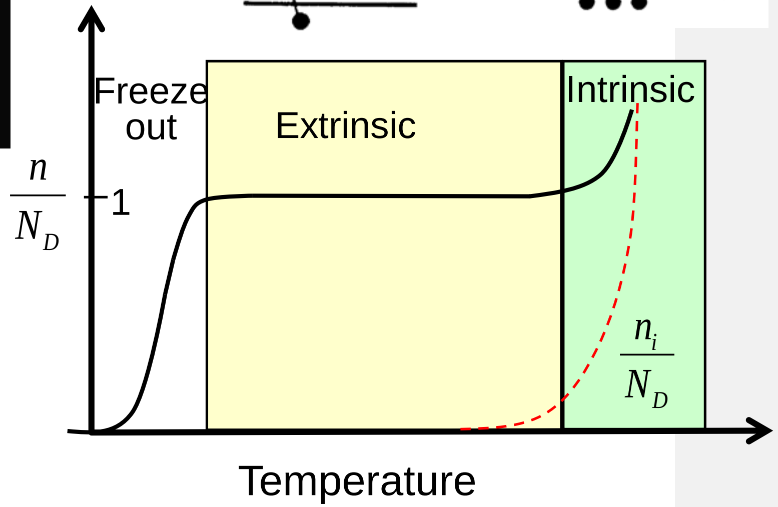
Video

- 14.2 Statistics of donor and acceptor levels





$$N_V e^{-(E_F-E_V)/k_BT} - N_A e^{-(E_C-E_F)/k_BT} + \frac{N_D}{1+2e^{(E_F-E_D)/k_BT}} - \frac{N_A}{1+4e^{(E_A-E_F)/k_BT}} = 0$$



Video

- 14.3 Temperature dependence of carrier concentration

Video

- 14.4 Multiple doping, co-doping, and heavy-doping