PURDUE
UNIVERSITY

NCN

www.nanohub.org

ECE606: Solid State Devices
Lecture 15: Surface Recombination /Generation

Muhammad Ashraful Alam
alam@purdue.edu

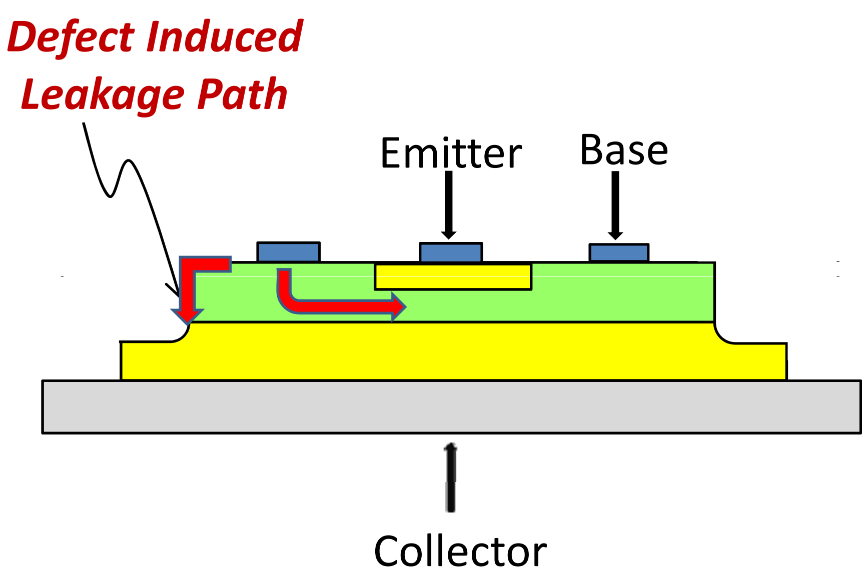
Outline

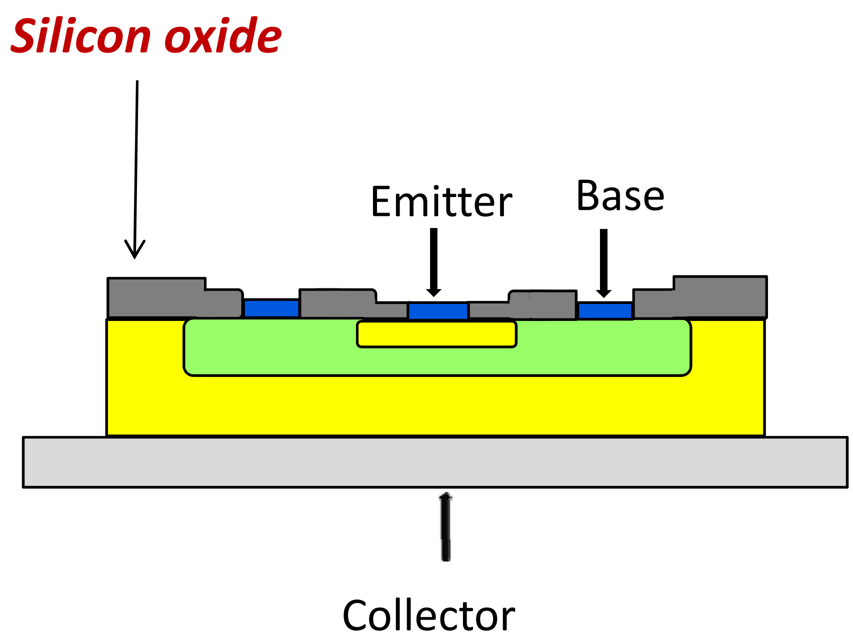
1) **Nature of interface states**
2) SRH formula adapted to interface states
3) Surface recombination in depletion region
4) Conclusion

REF: ADF, Chapter 5, pp. 154-167

Surface states: Little bit of history

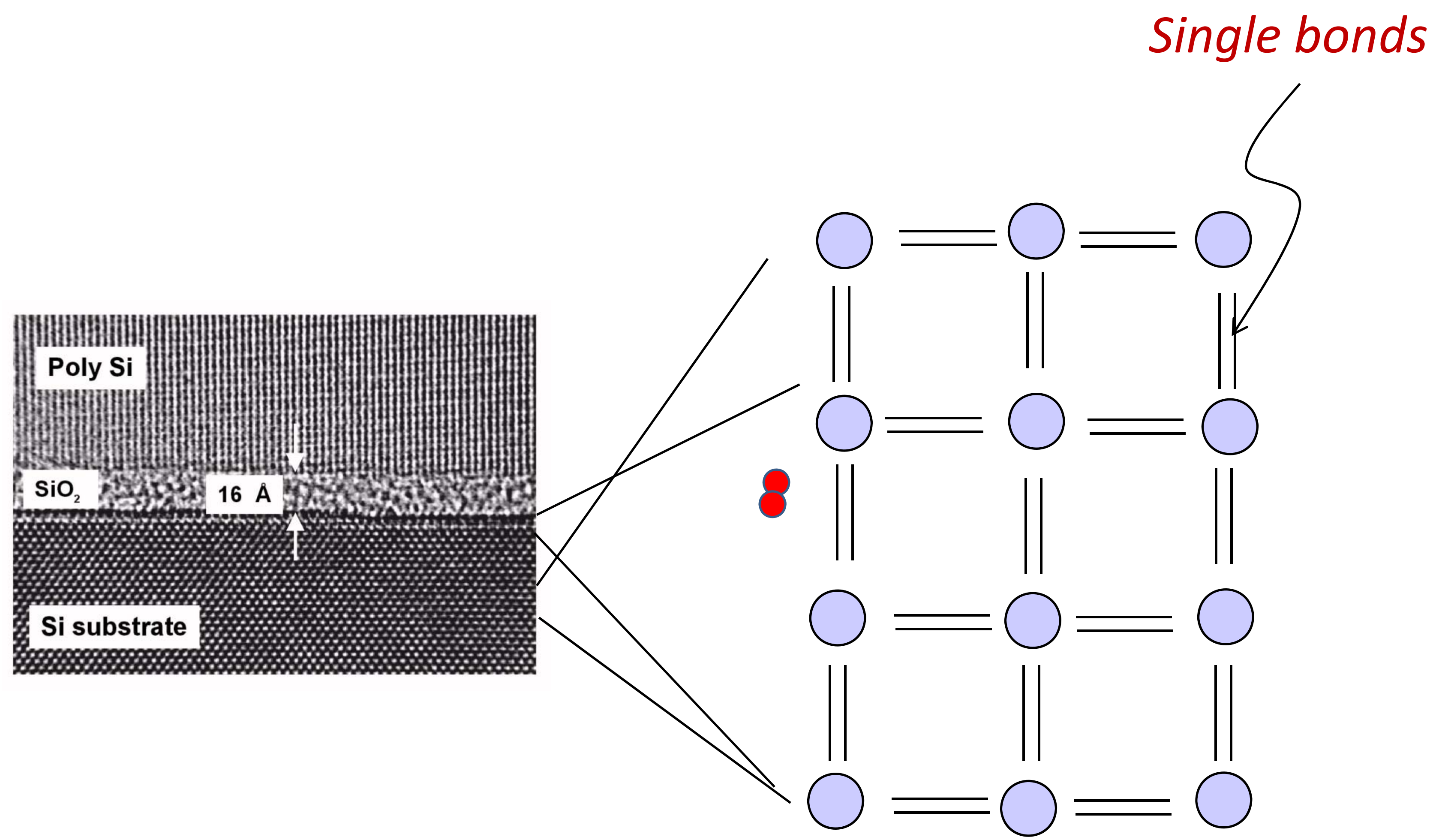
Hoerni's diagram of Mesa and planar transistors



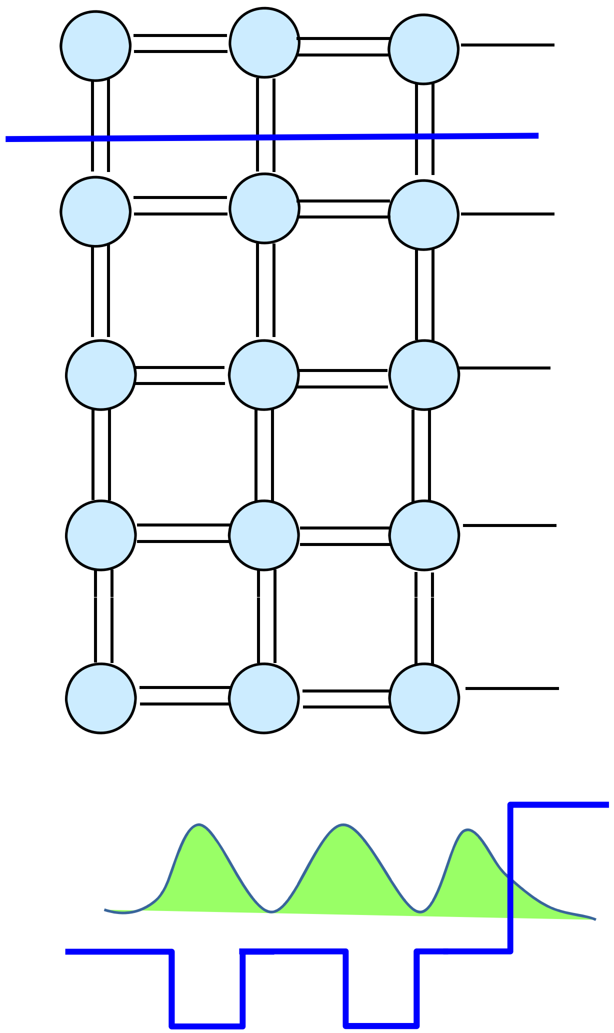


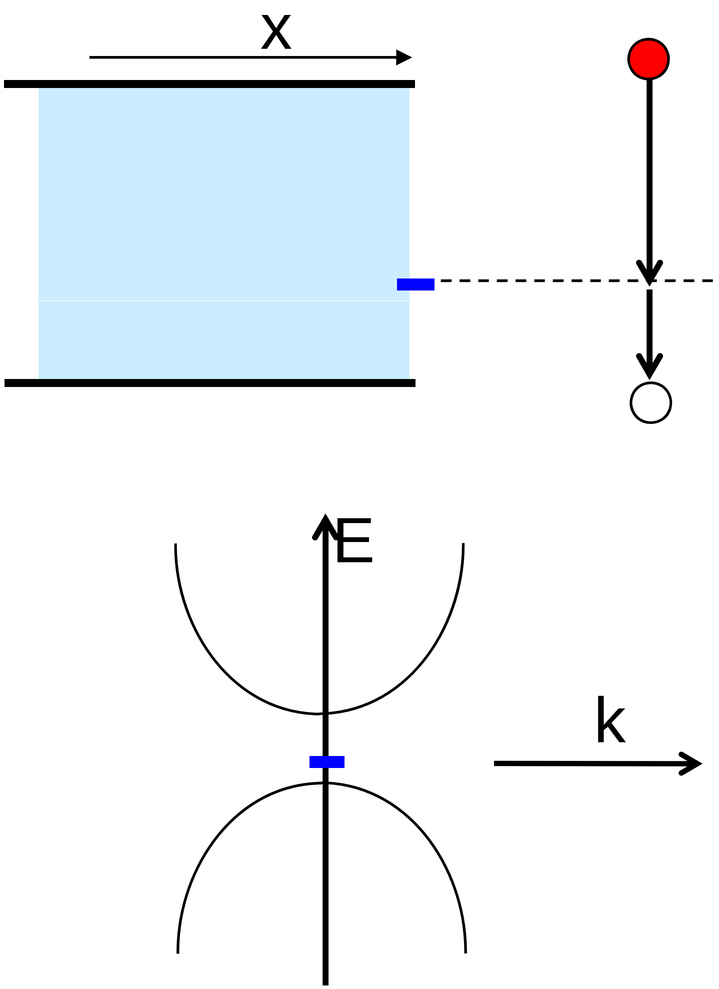
One of the fundamental advances in semiconductor history

Atomic configuration of Surface States

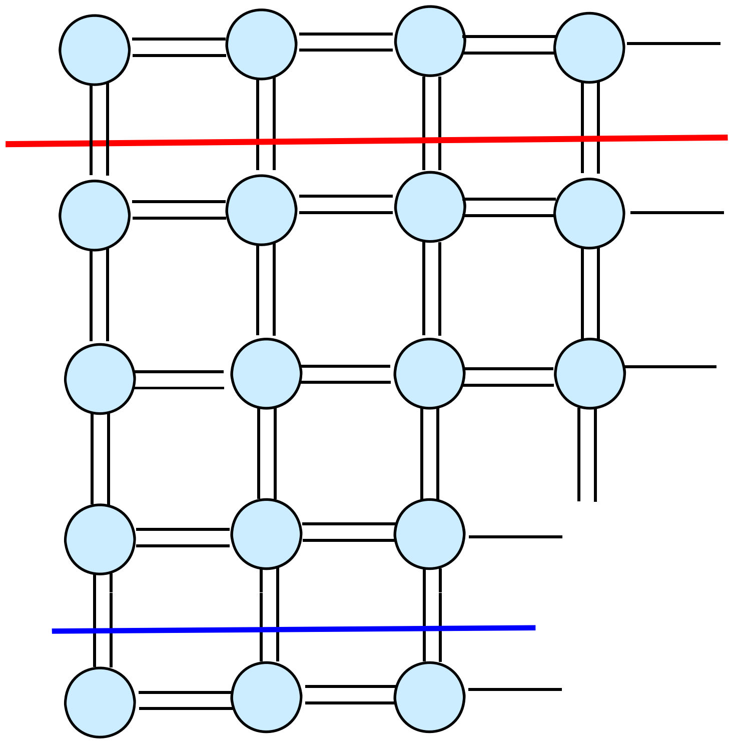


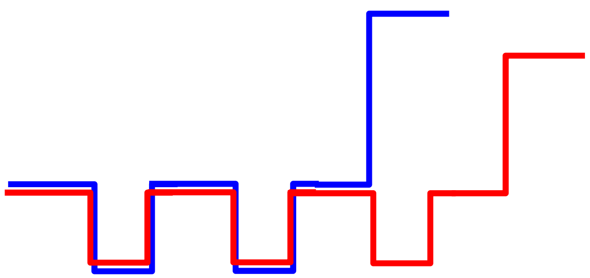
Surface States

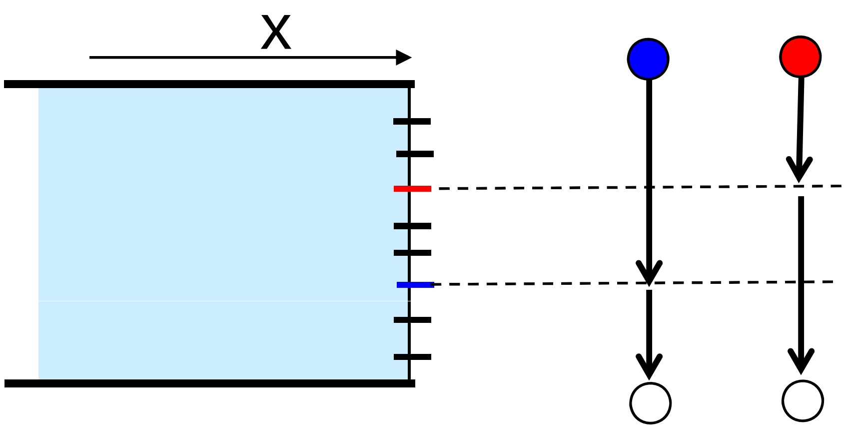


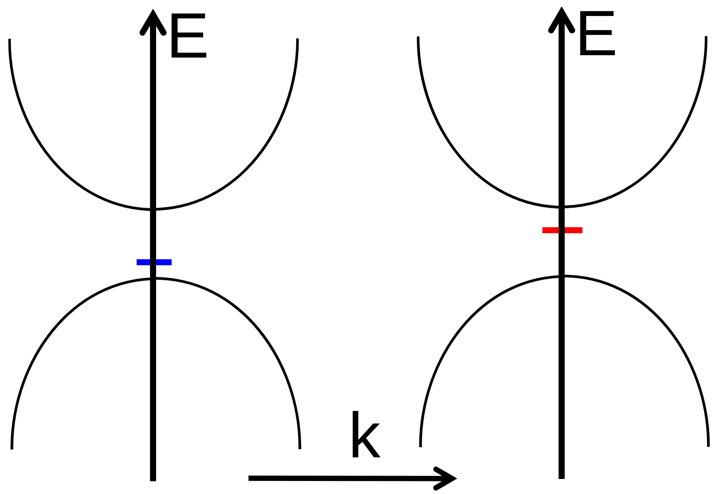


Multiple Levels of Surface States

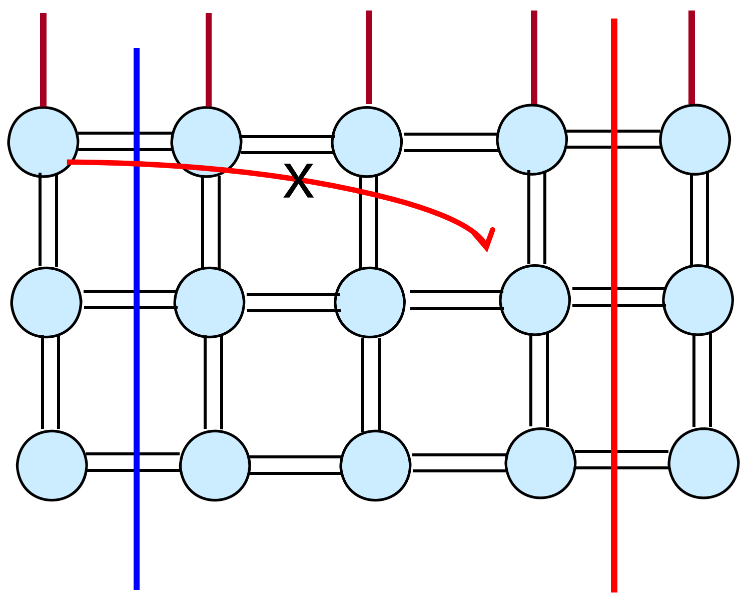


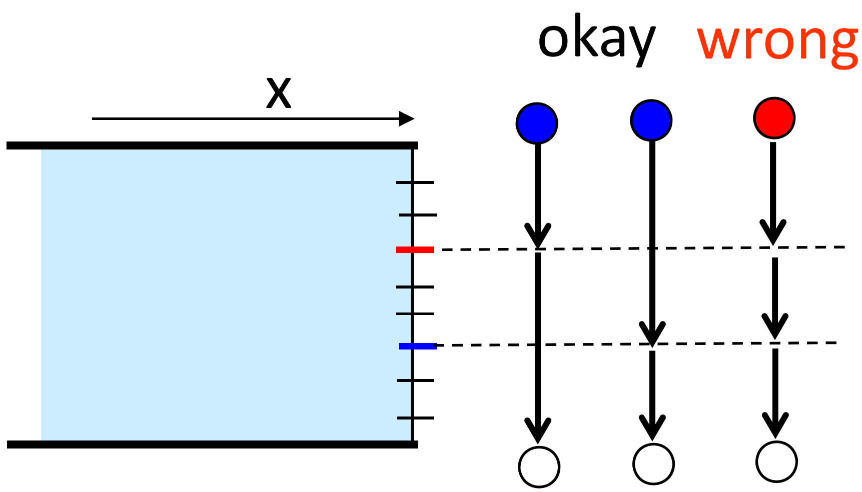






Multiple Levels of Surface States





Outline

1) Nature of interface states
2) **SRH formula adapted to interface states**
3) Surface recombination in depletion region
4) Conclusion

Surface Recombination Current

For single level bulk traps ....

$$R_{bulk}=\frac{np-n_i^2}{\frac{1}{c_pN_T}(n+n_1)+\frac{1}{c_nN_T}(p+p_1)}=\frac{(np-n_i^2)N_T}{\frac{1}{c_p}(n+n_1)+\frac{1}{c_n}(p+p_1)}$$

For single level interface trap at E ...

$$R(E)=\frac{(n_sp_s-n_i^2)D_T(E)dE}{\frac{1}{c_{ps}}(n_s+n_{1s})+\frac{1}{c_{ns}}(p_s+p_{1s})}$$

$$R=\int_{E_V}^{E_C}R(E)dE$$

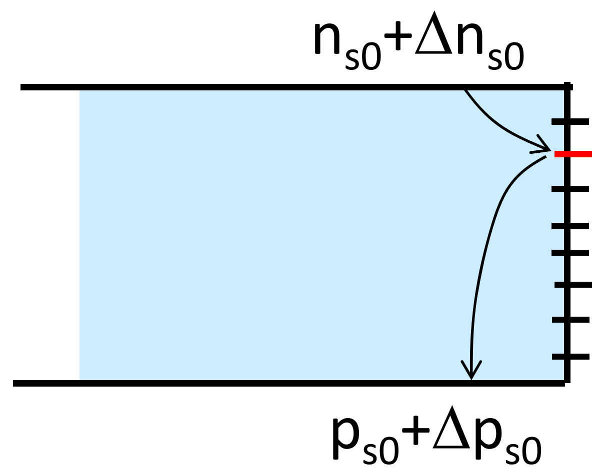
Case 1: Minority Carrier Recombination

$$R(E) = \frac{\left[(n_{s0} + \Delta n_{s0})(p_{s0} + \Delta p_{s0}) - n_i^2\right] D_{IT}(E)\, dE}{\frac{1}{c_{ps}}(n_{s0} + \Delta n_{s0} + n_{1s}) + \frac{1}{c_{ns}}(p_{s0} + \Delta p_{s0} + p_{1s})}$$

$$= \frac{n_{s0} \Delta p_{s0} D_{IT}(E)\, dE}{n_{s0}\left[\frac{1}{c_{ps}} + \frac{n_{1s}}{c_{ps} n_{s0}} + \frac{p_{1s}}{c_{ns} n_{s0}}\right]}$$

$$= \frac{c_{ps} \Delta p_{s0} D_{IT}(E)\, dE}{\left[1 + \frac{n_{1s}}{n_{s0}} + \frac{c_{ps}}{c_{ns}} \frac{p_{1s}}{n_{s0}}\right]}$$

Donor doped



Consider the Denominator …

$$D = 1 + \frac{n_{1s}}{n_{s0}} + \frac{c_{ps}}{c_{ns}} \frac{p_{1s}}{n_{s0}} = 1 + \frac{n_{1s}}{N_D} + \frac{c_{ps}}{c_{ns}} \frac{p_{1s}}{N_D}$$

$$= 1 + \frac{n_i e^{(E-E_i)\beta}}{n_i e^{(E_F-E_i)\beta}} + \frac{c_{ps}}{c_{ns}} \frac{n_i e^{-(E-E_i)\beta}}{n_i e^{(E_F-E_i)\beta}}$$

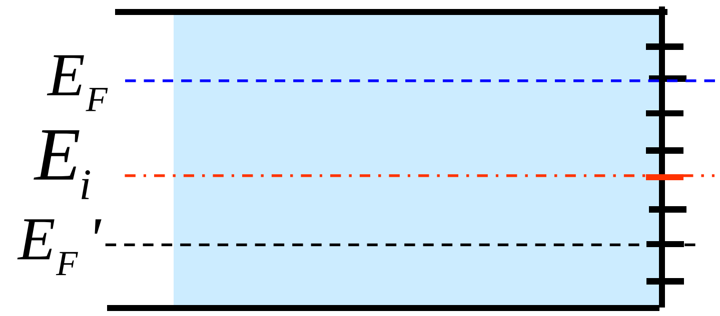
$$= 1 + e^{(E-E_F)\beta} + \frac{c_{ps}}{c_{ns}} e^{(E_F-E\ )\beta}$$

$$= 1 + e^{x} + a e^{-x} \qquad x \equiv \beta\left(E - E_F\right)$$

Consider the Denominator …

$$D = 1 + \frac{n_i e^{(E-E_i)\beta}}{N_D} + \frac{c_{ps}}{c_{ns}} \frac{n_i e^{-(E-E_i)\beta}}{N_D}$$

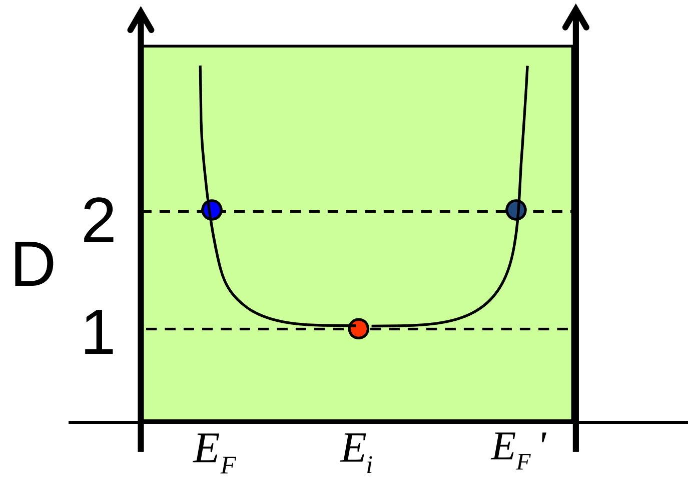
$$= 1 + e^{(E-E_F)\beta} + \frac{c_{ps}}{c_{ns}} e^{(E_F-E\ )\beta}$$



At $E = E_i \Rightarrow \quad D = 1 + \frac{n_i}{N_D} + \frac{c_{ps}}{c_{ns}} \frac{n_i}{N_D} \approx 1$

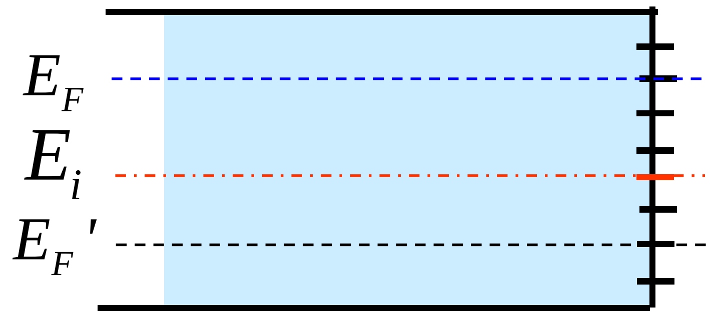
At $E = E_F > E_i, x = 0 \quad D = 1 + 1 + \frac{c_{ps}}{c_{ns}} \times small \approx 2$

At $E = E_F' < E_i, \quad D = 1 + small + 1 = 2$

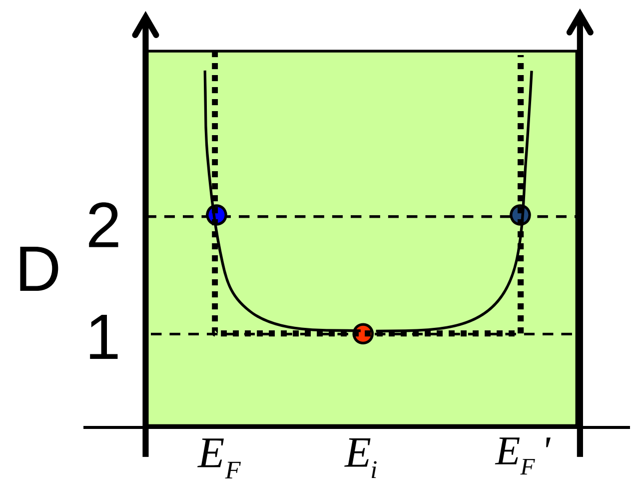


Approximate the Denominator …

$$D = 1 + \frac{n_i e^{(E-E_i)\beta}}{N_D} + \frac{c_{ps}}{c_{ns}} \frac{n_i e^{-(E-E_i)\beta}}{N_D}$$



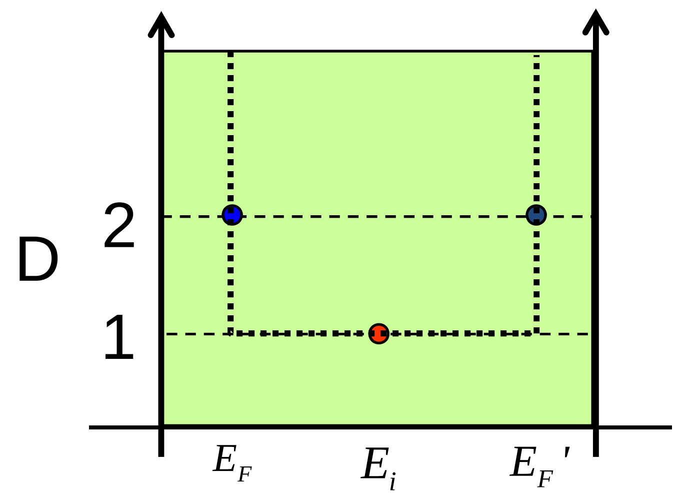
$$D \approx \begin{cases} 1 & \text{for} \quad E_F \le E \le E_F' \\ \infty & \text{otherwise} \end{cases}$$



Integrated Recombination

$$R=\int_{E_V}^{E_C} R(E)=\int_{E_V}^{E_C}\frac{c_{ps}\Delta p_{s0}D_{IT}(E)\,dE}{\left[1+\frac{n_{1s}}{n_{s0}}+\frac{c_{ps}}{c_{ns}}\frac{p_{1s}}{n_{s0}}\right]}$$

$$\approx\int_{E_F'}^{E_F} c_{ps}\Delta p_{s0}D(E)\,dE$$

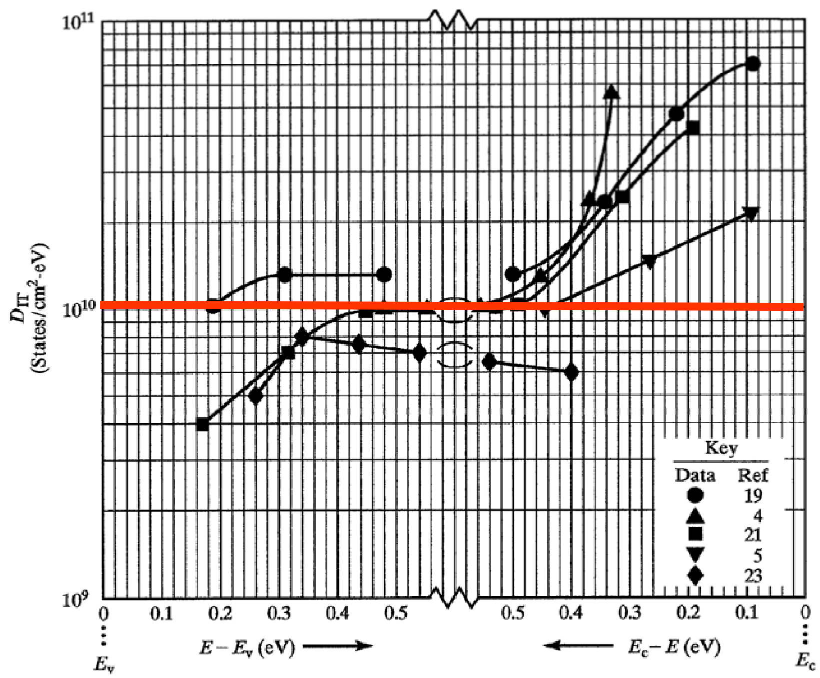


Surface Recombination Velocity

$$R \approx \int_{E_F}^{E_F} c_{ps} \Delta p_{s0} D_{IT}(E)\, dE$$

$$= c_{ps} D_{IT}\left(E_F - E_F^{'}\right) \Delta p_{s0}$$

$$= s_g \Delta p_{s0}$$



Surface recombination velocity

Outline

1) Nature of interface states
2) SRH formula adapted to interface states
3) **Surface recombination in depletion region**
4) Conclusion

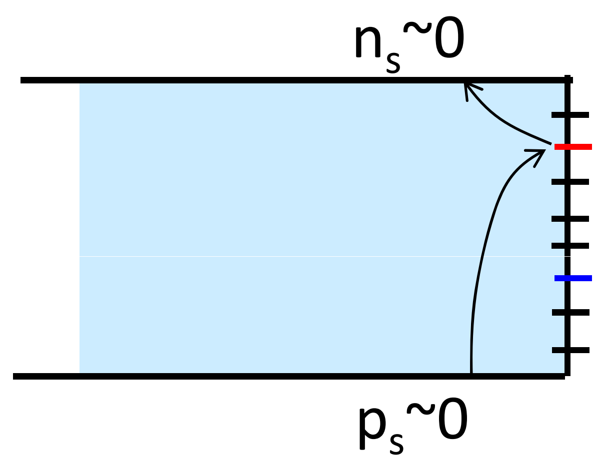
Case 2: Recombination in Depletion

$$R(E) = \frac{\left(n_s p_s - n_i^2\right) D_{IT}(E)\, dE}{\frac{1}{c_{ps}}\left(n_s + n_{1s}\right) + \frac{1}{c_{ns}}\left(p_s + p_{1s}\right)}$$

$$= -\frac{n_i}{\frac{n_i e^{(E-E_i)\beta}}{c_{ps}} + \frac{n_i e^{-(E-E_i)\beta}}{c_{ns}}} n_i D_{IT}(E)\, dE$$

$$= -c_{ns} D_{IT} n_i \frac{e^{(E-E_i)\beta} dE}{\frac{c_{ns}}{c_{ps}} e^{2(E-E_i)\beta} + 1}$$

$$R = -c_{ns} D_{IT} n_i \int_{E_V}^{E_C} \frac{e^{(E-E_i)\beta} dE}{\frac{c_{ns}}{c_{ps}} e^{2(E-E_i)\beta} + 1}$$



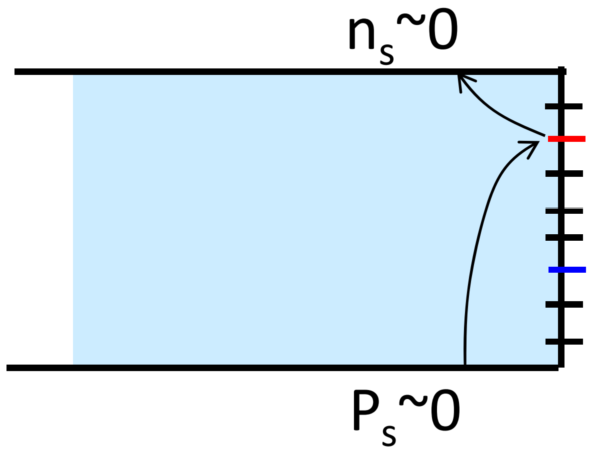
Case 2: Recombination in Depletion

$$R = -c_{ns} D_{IT} n_i \int_{E_V}^{E_C} \frac{e^{(E-E_i)\beta} dE}{\frac{c_{ns}}{c_{ps}} e^{2(E-E_i)\beta} + 1}$$

$$= -c_{ns} D_{IT} n_i \int_{-\infty}^{+\infty} \frac{e^{(E-E_i)\beta} dE}{\frac{c_{ns}}{c_{ps}} e^{2(E-E_i)\beta} + 1}$$

$$= -c_{ns} D_{IT} n_i \phi \sqrt{\frac{c_{ps}}{c_{ns}}} \int_{0}^{+\infty} \frac{dx}{x^2 + 1}$$

$$= -\sqrt{c_{ns} c_{ps}} D_{IT} n_i \beta \frac{\pi}{2}$$



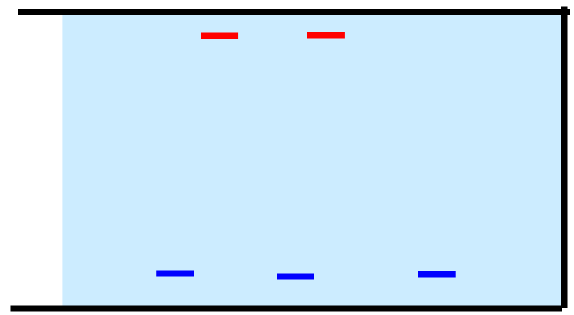
Why do donors/acceptors ***not*** act as R-G Centers?

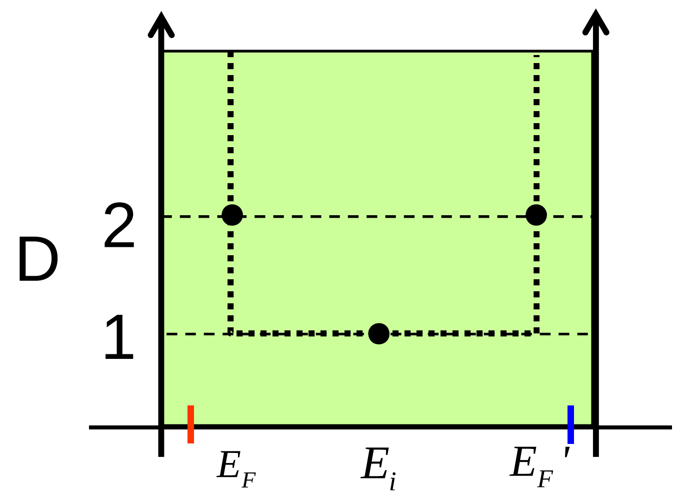
$$R(E_D) = \frac{c_{ps}\Delta p_{s0} D(E)dE}{\left[1 + \frac{n_{1s}}{n_{s0}} + \frac{c_{ps}}{c_{ns}}\frac{p_{1s}}{n_{s0}}\right]}$$

$$= \frac{c_{ps}\Delta p_{s0} N_D}{D(E_D)} \to 0$$

$$R(E_A) = \frac{c_{ps}\Delta p_{s0} D(E)dE}{\left[1 + \frac{n_{1s}}{n_{s0}} + \frac{c_{ps}}{c_{ns}}\frac{p_{1s}}{n_{s0}}\right]}$$

$$= \frac{c_{ps}\Delta p_{s0} N_A}{D(E_A)} \to 0$$





Summary

$$R = -\sqrt{c_{ns} c_{ps}} D_{IT} \beta \frac{\pi}{2} \times n_i$$ Interface (depletion)

$$R = c_{ps} D_{IT} \left(E_F - E_F^{'} \right) \Delta p_s$$ Interface (minority)

$$R = c_p N_T \Delta p$$ Bulk (minority)