Section 16
Recombination & Generation

16.6 SRH formula adapted to interface states

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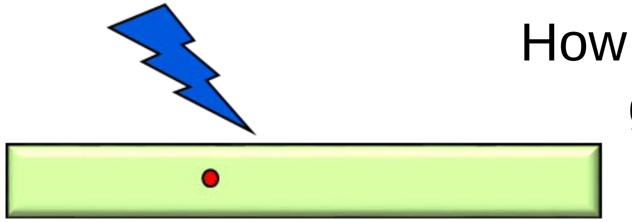
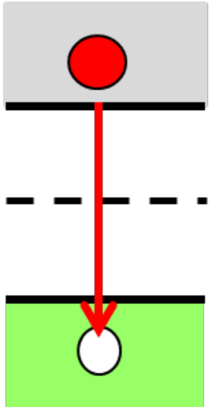


How does the system go BACK to equilibrium?

- 16.1 Capture coefficient & Capture Cross Section
- 16.2 Derivation of SRH formula (Shockley, Reed, Hall)
  - » 16.2.1 Trap Assisted Recombination Rates
  - » 16.2.2 Capture and emission relationship (n_1 and p_1)
  - » 16.2.3 Steady State Trap Population
  - » 16.2.4 Recombination-Generation Rate
- 16.3 Application of SRH formula for special cases
  - » Low level, high-level injection, depletion region
- 16.4 Direct and Auger recombination
- 16.5 Nature of interface states
- 16.6 SRH formula adapted to interface state
- 16.7



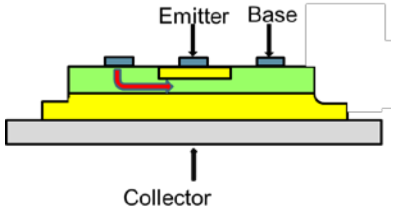
$$\tau_n = \frac{1}{c_n N_T} \qquad \tau_p = \frac{1}{c_p N_T}$$

$$n_1 = n_i g_D e^{\beta(E_T - E_i)}$$

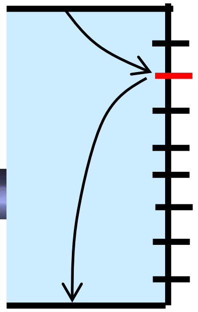
$$p_1 = n_i g_D^{-1} e^{\beta(E_i - E_T)}$$

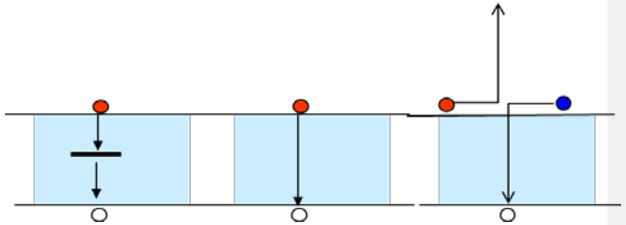
$$R = \frac{pn - n_i^2}{\tau_p(n + n_1) + \tau_n(p + p_1)}$$

$$R = \frac{\Delta n}{\tau_n}$$



$$R = \frac{\Delta n}{(\tau_n + \tau_p)}$$





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For single level bulk traps ….

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

For single level interface trap at E …

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

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

All surface recombination goes through one step => single integral

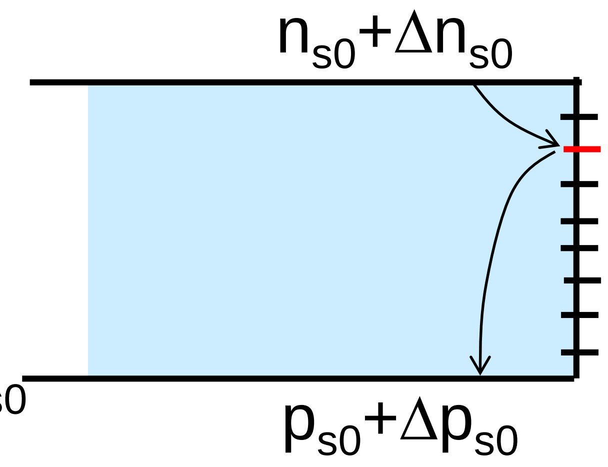
Case 1: Minority Carrier Recombination

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

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

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

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



Donor doped

$n_{s0} \gg \Delta n_{s0} \gg p_{s0}$

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

Consider the Denominator … $n_{s0}=N_D$

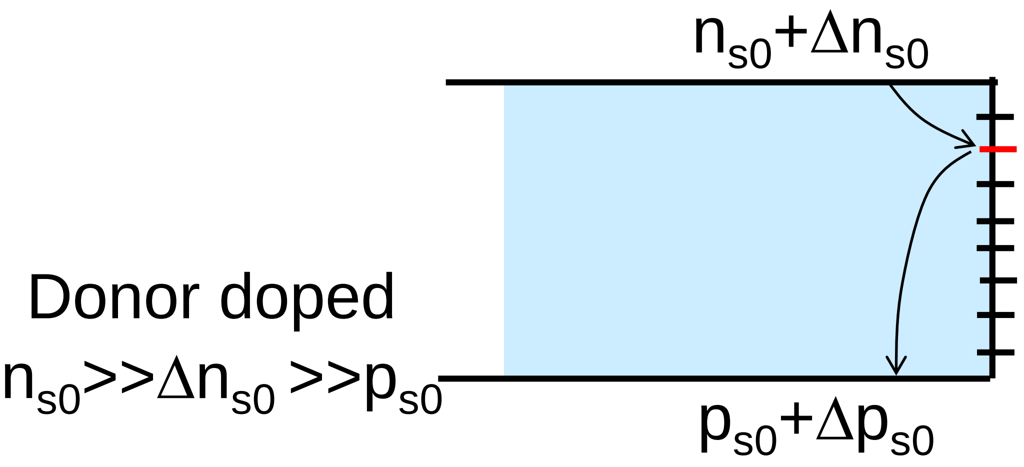
$$W=1+\frac{n_{1s}}{n_{s0}}+\frac{c_{ps}}{c_{ns}}\frac{p_{1s}}{n_{s0}} \qquad W=1+\frac{n_{1s}}{N_D}+\frac{c_{ps}}{c_{ns}}\frac{p_{1s}}{N_D}$$

Case 1: Minority Carrier Recombination

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

$$R(E) = \frac{c_{ps}\Delta p_{s0} D_{IT}(E)dE}{W(E)}$$

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



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

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

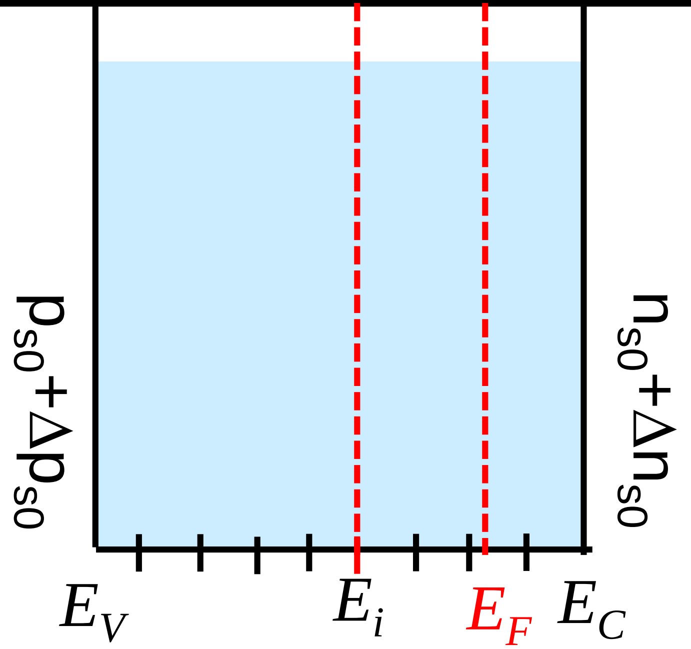
Case 1: Minority Carrier Recombination

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

$$R(E) = \frac{c_{ps}\Delta p_{s0} D_{IT}(E)dE}{W(E)}$$

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

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

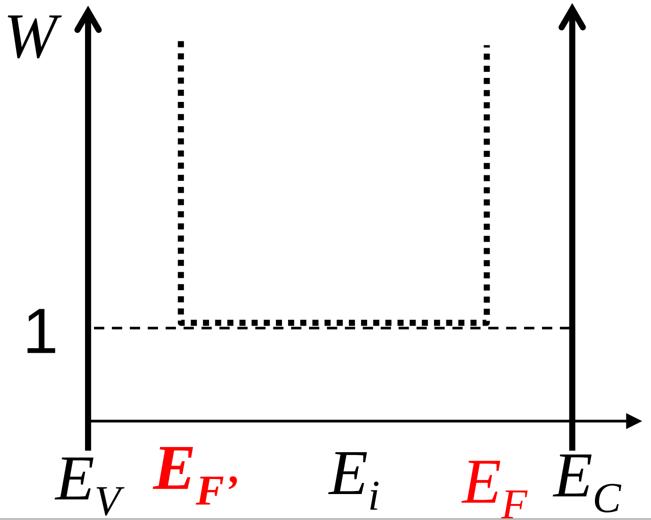


Will derive an approximate Window Function

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

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

$$\widetilde{W}(E) = \begin{cases} 1 & for\ E_{F'} \le E \le E_F \\ \infty & otherwise \end{cases}$$



Consider the Denominator … at E_i

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

$$n_{1s} = n_i e^{(E-E_i)\beta}$$

$$p_{1s} = n_i e^{-(E-E_i)\beta}$$

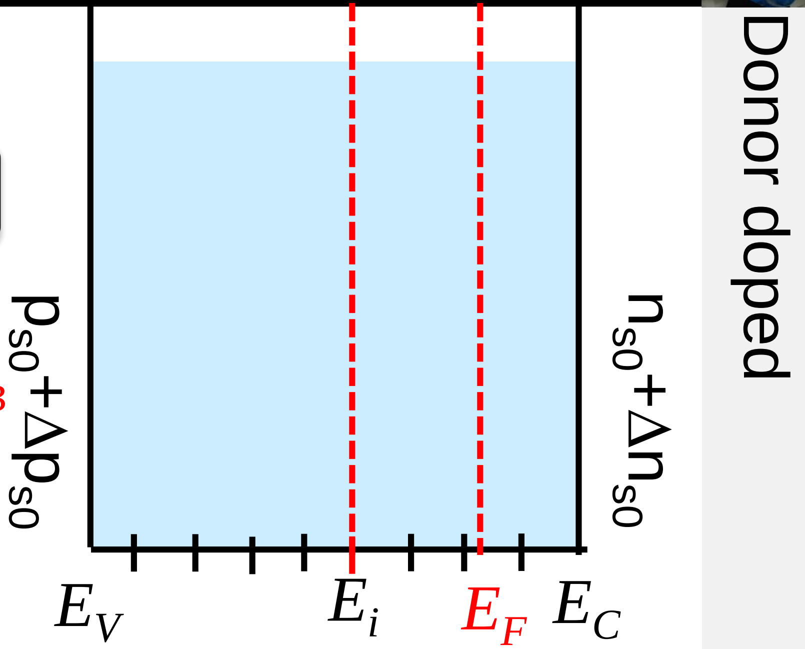
$$W(E_i) = 1 + \frac{n_i e^{0}}{N_D} + \frac{c_{ps}}{c_{ns}}\frac{n_i e^{-0}}{N_D}$$

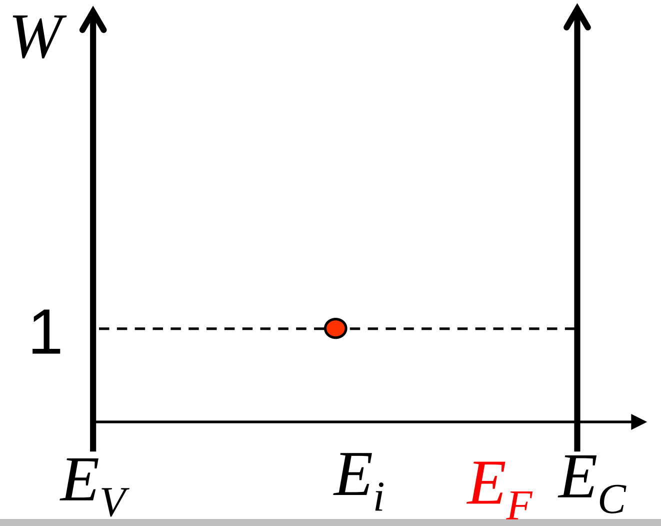
$$= 1 + \frac{10^{10}}{10^{18}} + \frac{c_{ps}}{c_{ns}}\frac{10^{10}}{10^{18}} \approx 1$$

$$n_{s0} = n_i e^{(E_F-E_i)\beta}$$

$$n_{s0} = N_D \approx 10^{18}\ cm^{-3}$$

$$n_i \approx 10^{10} cm^{-3}$$





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

Consider the Denominator … at E_F

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

$$W(E_i) \approx 1$$

$$n_{1s}(E_F) = n_i e^{(E_F - E_i)\beta} = n_{s0} = N_D \approx 10^{18}\ cm^{-3}$$

$$p_{1s} n_{1s} = n_i^2$$

$$p_{1s}(E_F) = \frac{n_i^2}{n_{1s}} = \frac{10^{20}}{10^{18}} cm^{-3} = 100 cm^{-3}$$

$$W(E_F) = 1 + \frac{10^{18}}{10^{18}} + \frac{c_{ps}}{c_{ns}}\frac{100}{10^{18}} \approx 2$$

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

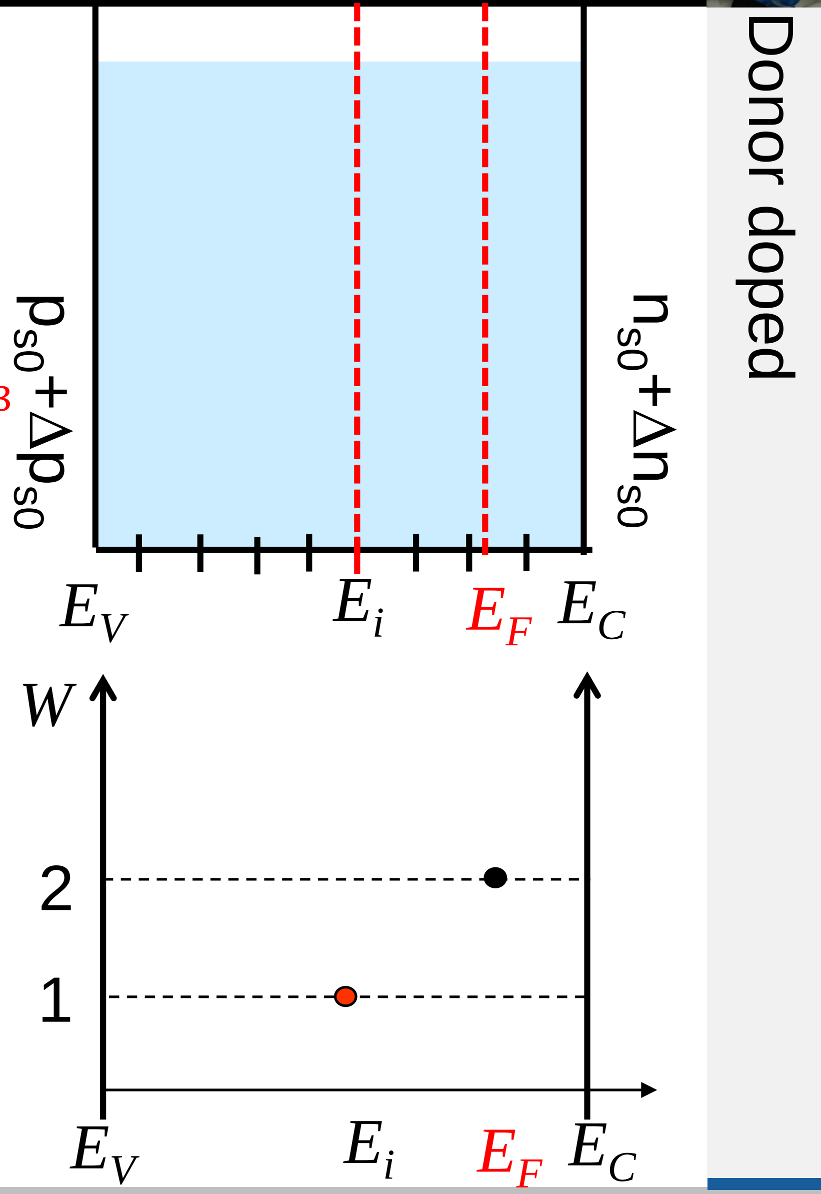
$$n_{1s} = n_i e^{(E - E_i)\beta}$$

$$p_{1s} = n_i e^{-(E - E_i)\beta}$$

$$n_{s0} = n_i e^{(E_F - E_i)\beta}$$

$$n_{s0} = N_D \approx 10^{18}\ cm^{-3}$$

$$n_i \approx 10^{10} cm^{-3}$$



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

$$n_{1s} = n_i e^{(E-E_i)\beta}$$

$$p_{1s} = n_i e^{-(E-E_i)\beta}$$

$$n_{s0} = n_i e^{(E_F-E_i)\beta}$$

$$n_{s0} = N_D \approx 10^{18}\ cm^{-3}$$

$$n_i \approx 10^{10} cm^{-3}$$

$$W(E_i) \approx 1$$

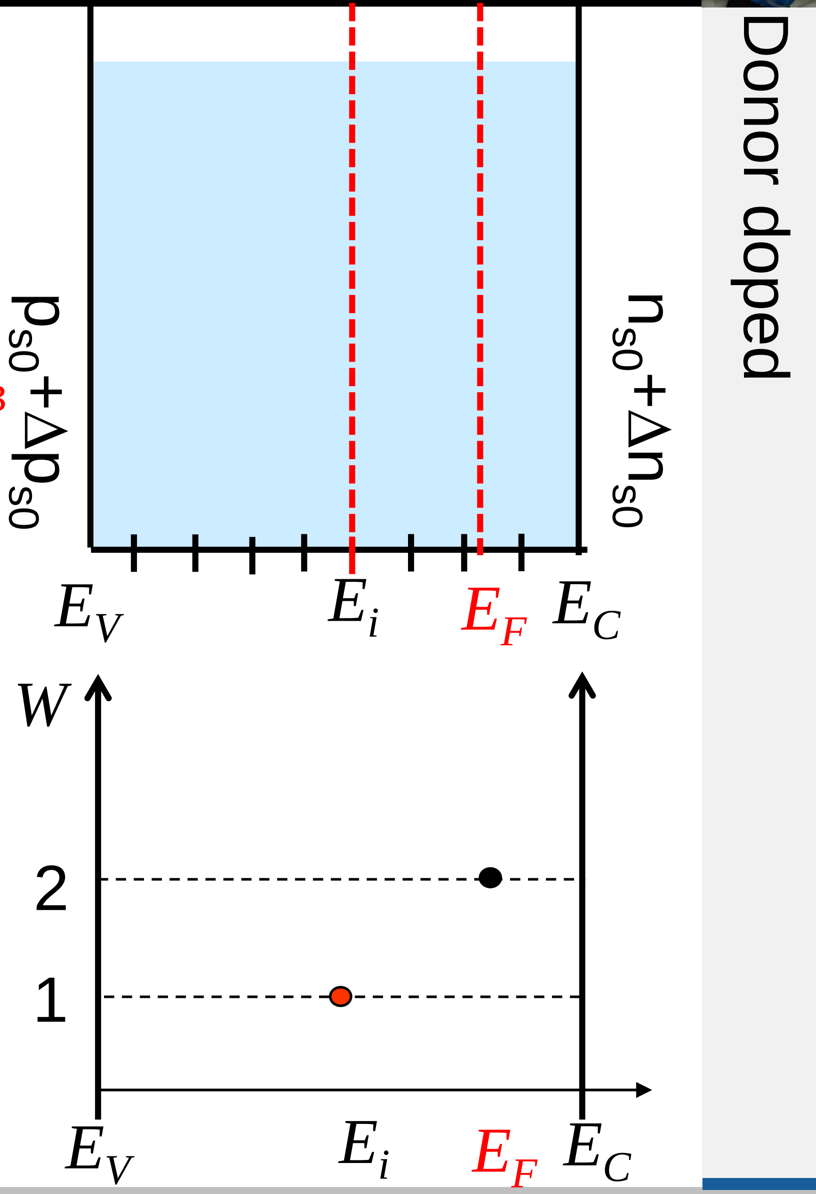
$$W(E_F) \approx 2$$

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

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

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

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



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

$$W(E_i) \approx 1$$

$$W(E_F) \approx 2$$

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

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

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

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

$$W(E_i < E < E_F) \approx 1 + e^{x}$$

$$n_{1s} = n_i e^{(E-E_i)\beta}$$

$$p_{1s} = n_i e^{-(E-E_i)\beta}$$

$$n_{s0} = n_i e^{(E_F-E_i)\beta}$$

$$n_{s0} = N_D \approx 10^{18}\ cm^{-3}$$

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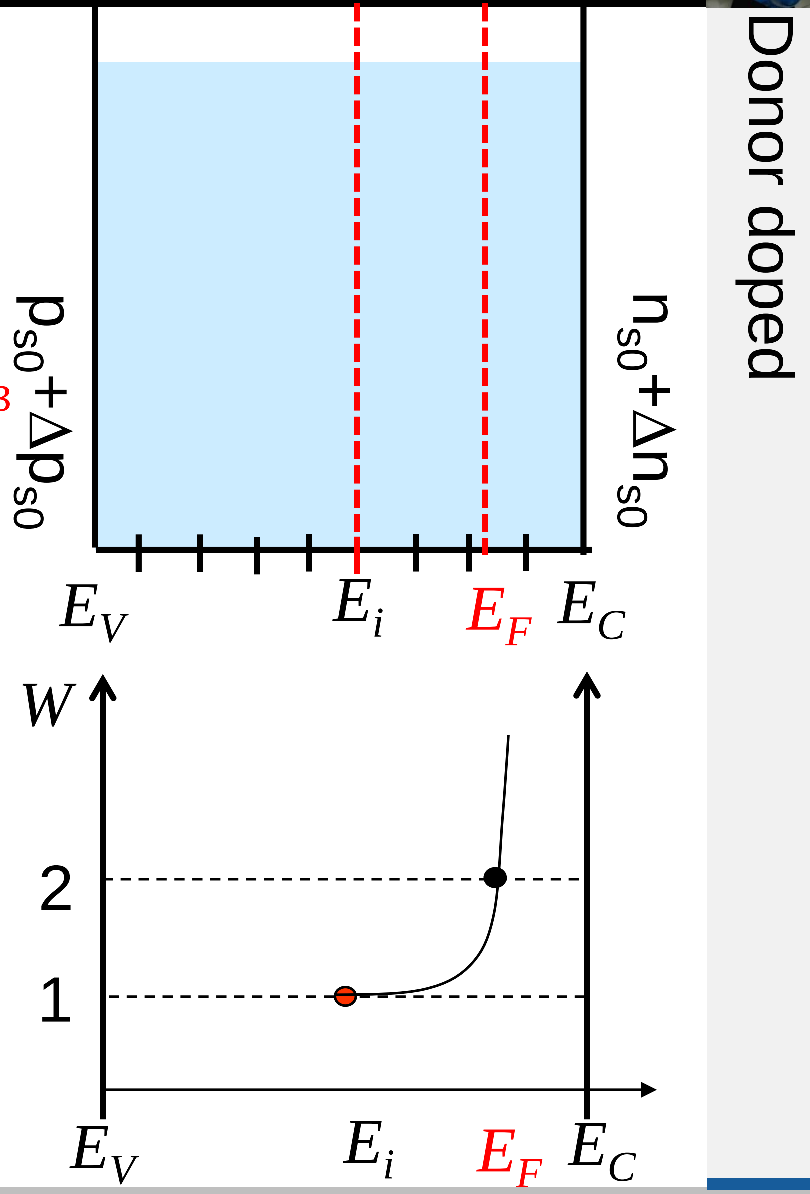

By Symmetry … below E_i

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

$$W(E_i) \approx 1$$

$$W(E_F) \approx 2$$

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

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

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

$$W(E) = 1 + e^{x} + a e^{-x}$$

$$x(E) \equiv \beta(E - E_F)$$

$$W(E_i < E < E_F) \approx 1 + e^{x}$$

$$W(E_{F'} < E < E_i) \approx 1 + a e^{-x}$$

$$n_{1s} = n_i e^{(E-E_i)\beta}$$

$$p_{1s} = n_i e^{-(E-E_i)\beta}$$

$$n_{s0} = n_i e^{(E_F-E_i)\beta}$$

$$n_{s0} = N_D \approx 10^{18}\ cm^{-3}$$

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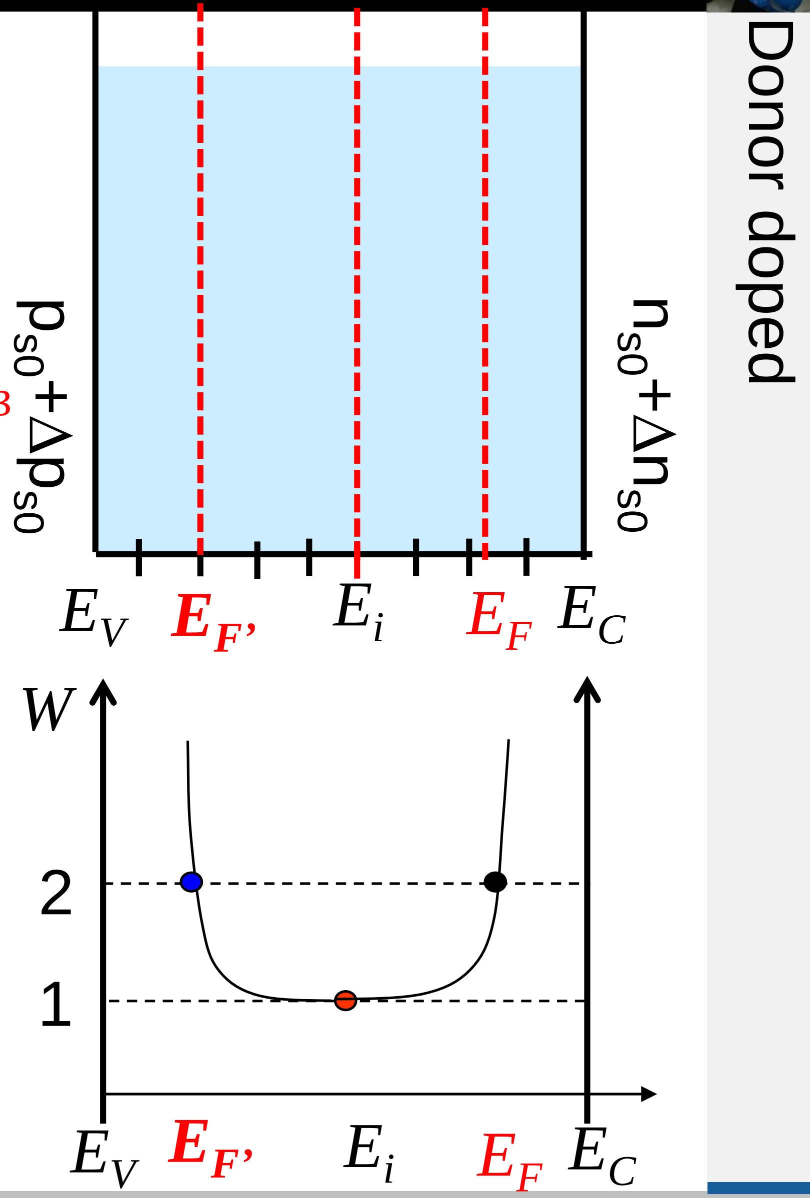

By Symmetry … below E_i

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

$$W(E_i) \approx 1$$

$$W(E_F) \approx 2$$

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

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

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

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

$$\equiv 1$$

$$W(E_{F'}) \equiv 2 \qquad W(E_{F'} < E < E_i) \approx 1 + a e^{-x}$$

$$n_{1s} = n_i e^{(E-E_i)\beta}$$

$$p_{1s} = n_i e^{-(E-E_i)\beta}$$

$$n_{s0} = n_i e^{(E_F-E_i)\beta}$$

$$n_{s0} = N_D \approx 10^{18}\ cm^{-3}$$

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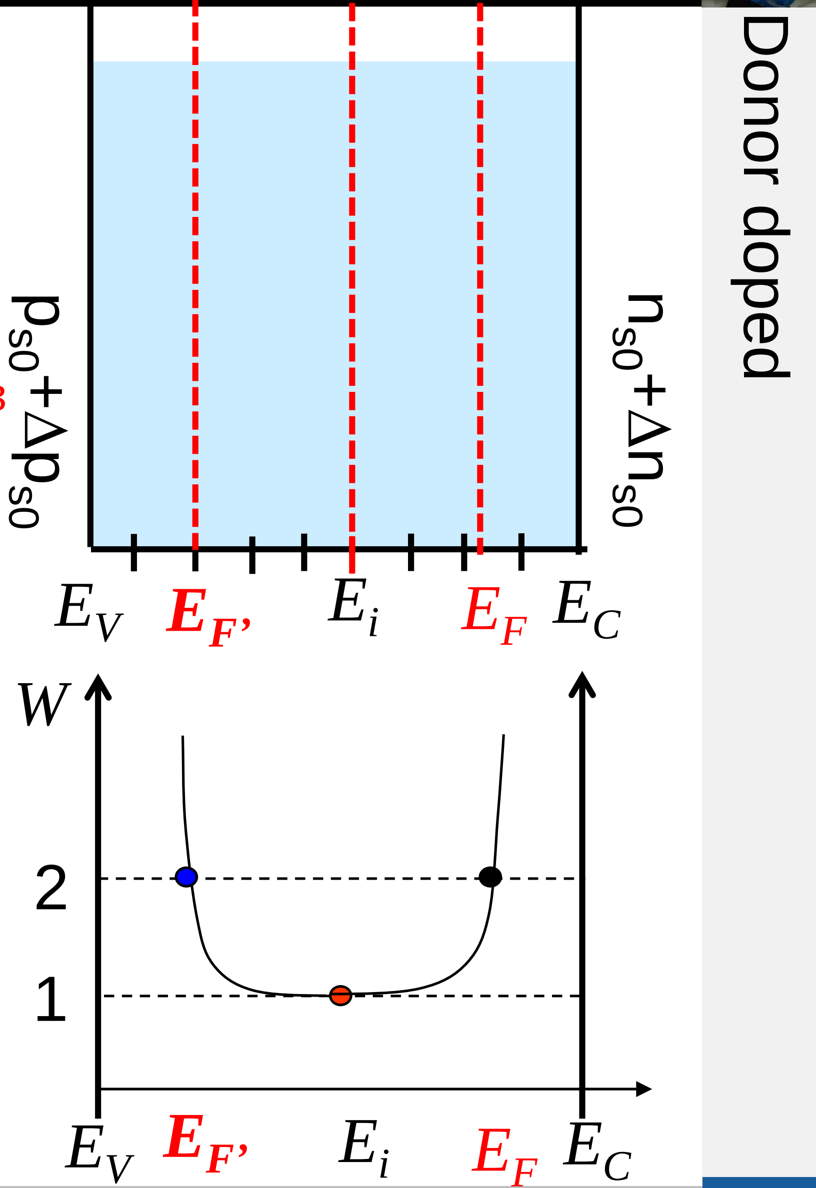

By Symmetry … below E_i

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

$$W(E_i) \approx 1$$

$$W(E_F) \approx 2$$

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$$p_{1s} = n_i e^{-(E-E_i)\beta}$$

$$n_{s0} = n_i e^{(E_F-E_i)\beta}$$

$$n_{s0} = N_D \approx 10^{18}\ cm^{-3}$$

$$n_i \approx 10^{10} cm^{-3}$$

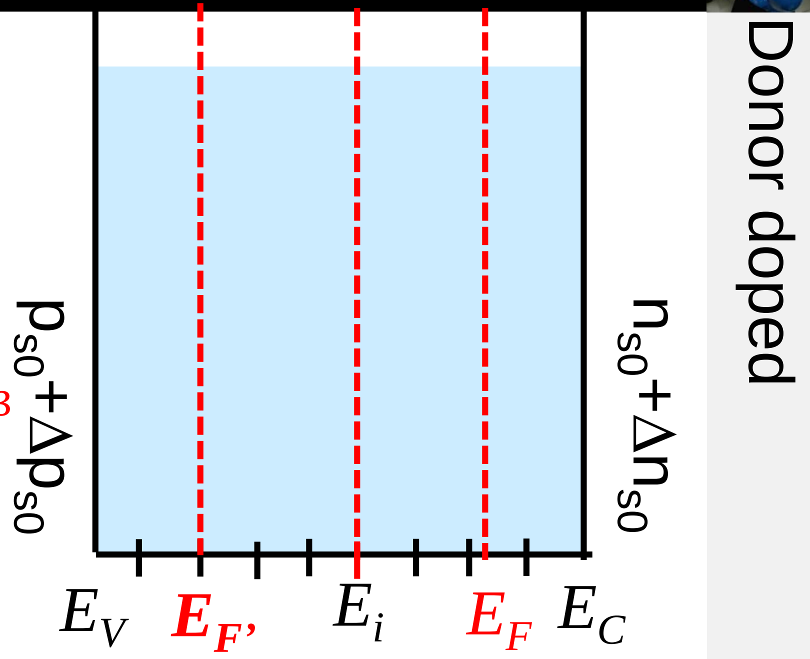
$$1 \equiv \frac{c_{ps}}{c_{ns}}\frac{p_{1s}}{n_{s0}}$$

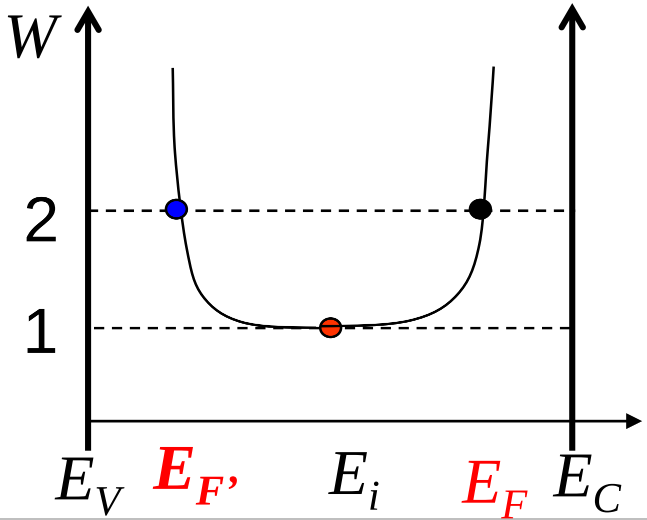
$$= \frac{c_{ps}}{c_{ns}}\frac{n_i e^{-(E_{F'}-E_i)\beta}}{N_D}$$

$$1 = \frac{c_{ps}}{c_{ns}}\frac{n_i}{N_D} e^{-(E_{F'}-E_i)\beta}$$

$$W(E_{F'}) \equiv 2$$

$$W(E_{F'} < E < E_i) \approx 1 + ae^{-x}$$





By Symmetry … below E_i

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

$$W(E_i) \approx 1$$

$$W(E_F) \approx 2$$

$$W(E_{F'}) \equiv 2$$

$$1 \equiv \frac{c_{ps}}{c_{ns}}\frac{p_{1s}}{n_{s0}}$$

$$n_{1s} = n_i e^{(E-E_i)\beta}$$

$$p_{1s} = n_i e^{-(E-E_i)\beta}$$

$$n_{s0} = n_i e^{(E_F-E_i)\beta}$$

$$n_{s0} = N_D \approx 10^{18}\ cm^{-3}$$

$$n_i \approx 10^{10} cm^{-3}$$

$$1 = \frac{c_{ps}}{c_{ns}}\frac{n_i}{N_D}\, e^{-(E_{F'}-E_i)\beta}$$

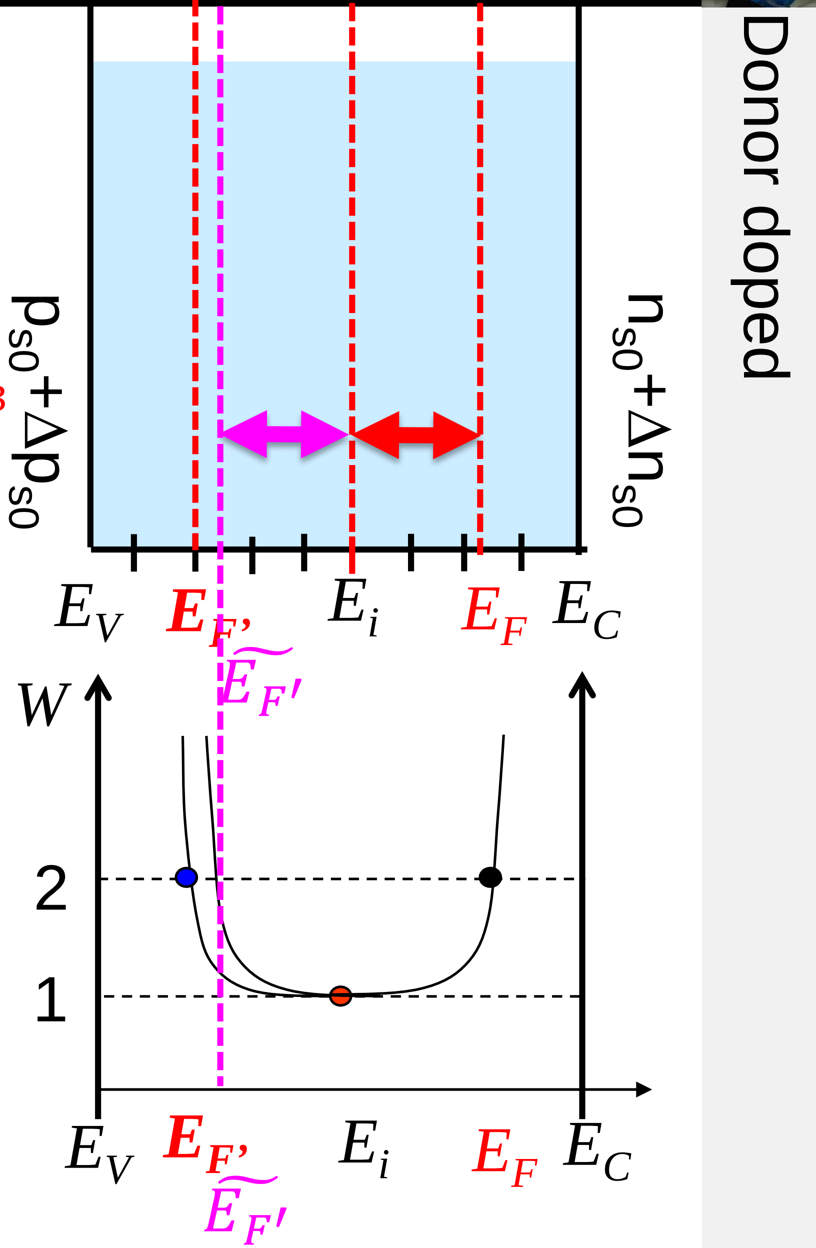
Unsatisfying - complex

Let's assume $\frac{c_{ps}}{c_{ns}}$=1

$$p_{1s}(\widetilde{E_{F'}}) = n_i e^{-(\widetilde{E_{F'}}-E_i)\beta}$$
$$= n_{s0} = n_i e^{(E_F-E_i)\beta}$$

$$(E_i - \widetilde{E_{F'}}) = (E_F - E_i)$$

Symmetric to E_i



How Different is $E_{F\prime}$ from $\widetilde{E_{F'}}$?

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

$$n_{1s} = n_i e^{(E-E_i)\beta}$$

$$p_{1s} = n_i e^{-(E-E_i)\beta}$$

$$W(E_i) \approx 1$$

$$W(E_F) \approx 2$$

$$W(E_{F'}) \equiv 2$$

$$E_{F\prime} = \widetilde{E_{F'}} + \Delta E$$

$$\ldots n_i e^{(E_F-E_i)\beta}$$

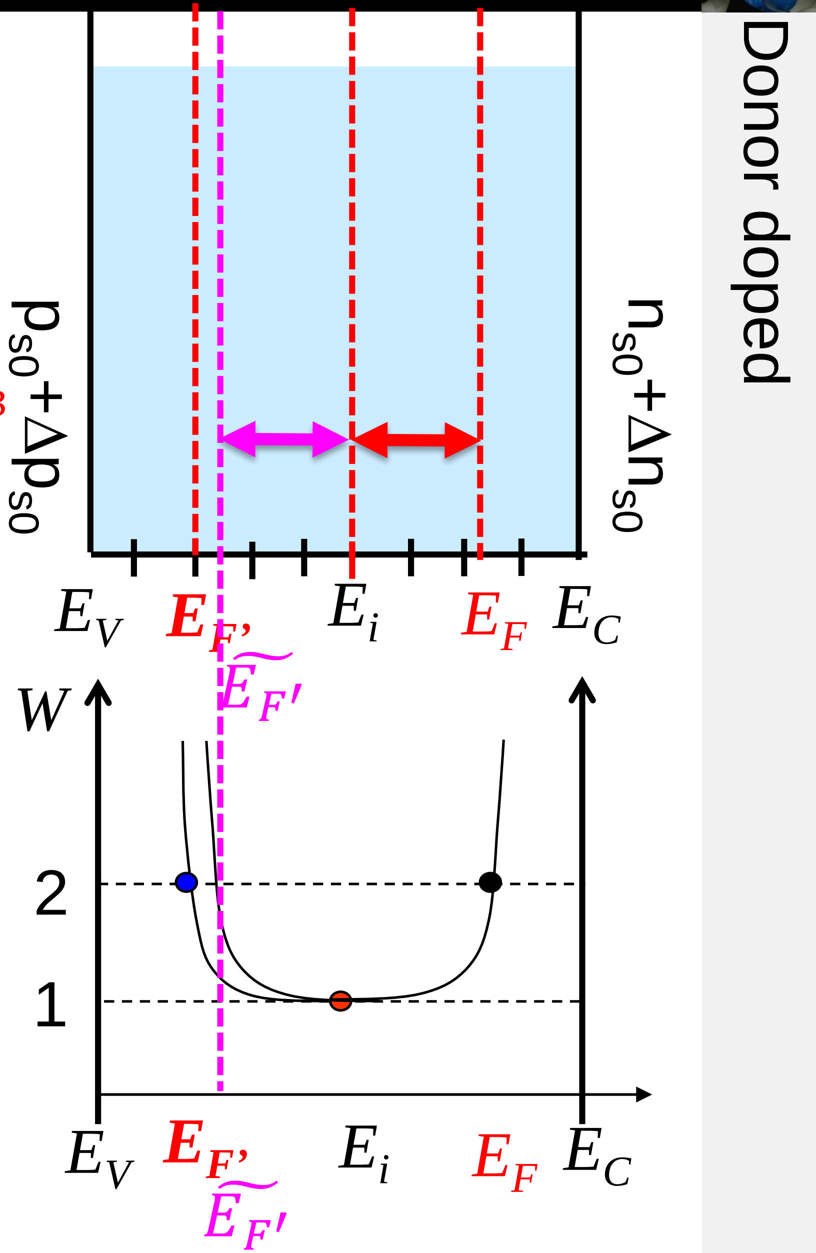
$$\ldots_D \approx 10^{18}\ cm^{-3}$$

$$n_i \approx 10^{10} cm^{-3}$$

$$1 \equiv 1 \equiv \frac{c_{ps}}{c_{ns}}\frac{p_{1s}}{n_{s0}}$$

$$1 = \frac{c_{ps}}{c_{ns}}\frac{n_i}{N_D} e^{-(E_{F\prime}-E_i)\beta}$$

$$(E_i - \widetilde{E_{F'}}) = (E_F - E_i)$$



How Different is $E_{F'}$ from $\widetilde{E_{F'}}$?

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

$$W(E_i) \approx 1$$

$$W(E_F) \approx 2$$

$$W(E_{F'}) \equiv 2$$

$$E_{F'} = \widetilde{E_{F'}} + \Delta E$$

$$n_{1s} = n_i e^{(E-E_i)\beta}$$

$$p_{1s} = n_i e^{-(E-E_i)\beta}$$

$$n_{s0} = n_i e^{(E_F-E_i)\beta}$$

$$n_{s0} = N_D \approx 10^{18}\ cm^{-3}$$

$$n_i \approx 10^{10} cm^{-3}$$

$$1 \equiv \frac{c_{ps}}{c_{ns}}\frac{p_{1s}}{n_{s0}}$$

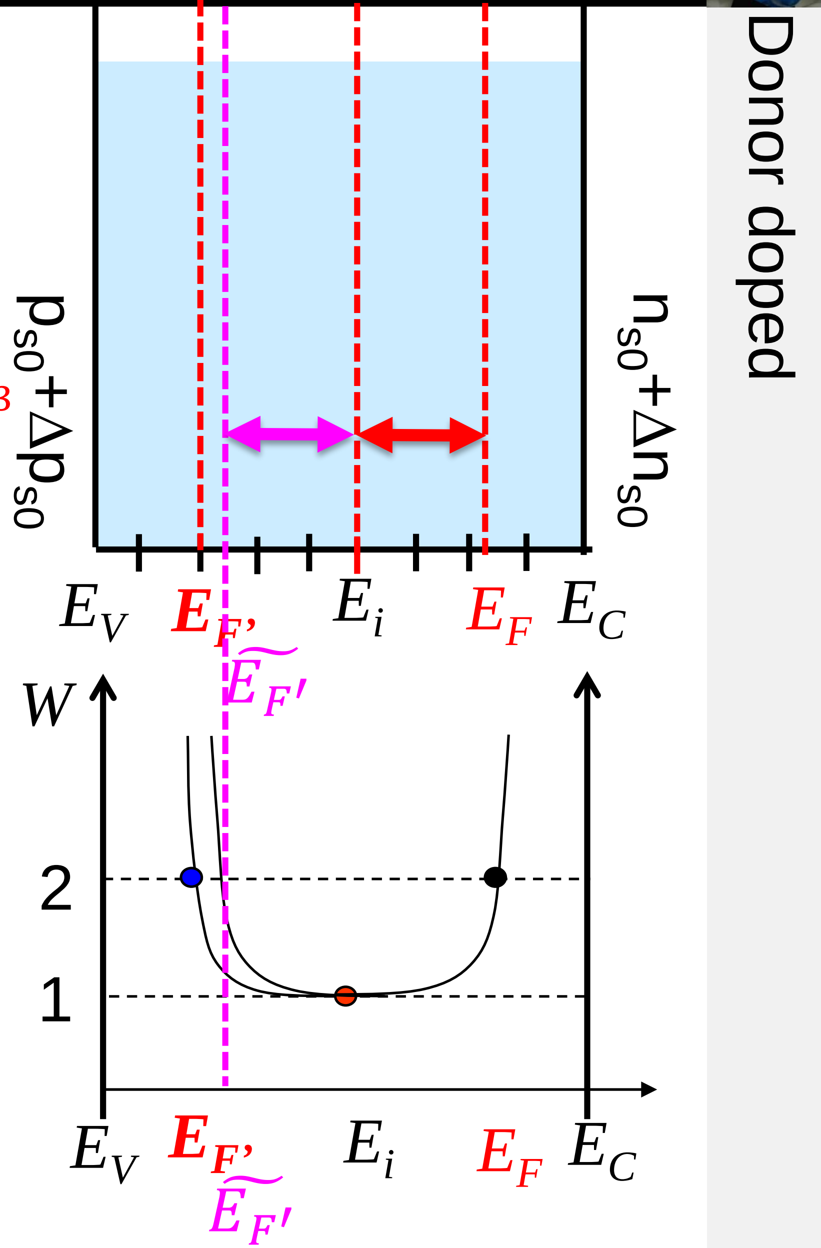
$$1 = \frac{c_{ps}}{c_{ns}}\frac{n_i}{N_D} e^{-(E_{F'}-E_i)\beta}$$

$$(E_i - \widetilde{E_{F'}}) = (E_F - E_i)$$

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

$$1 = \frac{c_{ps}}{c_{ns}}\frac{n_i e^{-\Delta E\beta} e^{-(\widetilde{E_{F'}}-E_i)\beta}}{n_i e^{(E_F-E_i)\beta}}$$

$$e^{\Delta E\beta} = \frac{c_{ps}}{c_{ns}} \qquad \Delta E = k_B T \ln\left(\frac{c_{ps}}{c_{ns}}\right)$$



How Different is $E_{F\prime}$ from $\widetilde{E_{F'}}$?

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

$$W(E_i) \approx 1$$

$$W(E_F) \approx 2$$

$$W(E_{F'}) \equiv 2$$

$$E_{F\prime} = \widetilde{E_{F'}} + \Delta E$$

$$1 \equiv \frac{c_{ps}}{c_{ns}}\frac{p_{1s}}{n_{s0}}$$

$$\Delta E = k_B T \ln\left(\frac{c_{ps}}{c_{ns}}\right)$$

How big is ΔE?

Assume $\frac{c_{ps}}{c_{ns}}$=10 or 0.1 : $\Delta E \approx \pm 2.3 k_B T \approx 0.060 eV$

Small (<6%) correction $\mathrm{E_c} - \mathrm{E_v} \approx 1.100 eV$

$$n_{1s} = n_i e^{(E-E_i)\beta}$$

$$p_{1s} = n_i e^{-(E-E_i)\beta}$$

$$n_{s0} = n_i e^{(E_F-E_i)\beta}$$

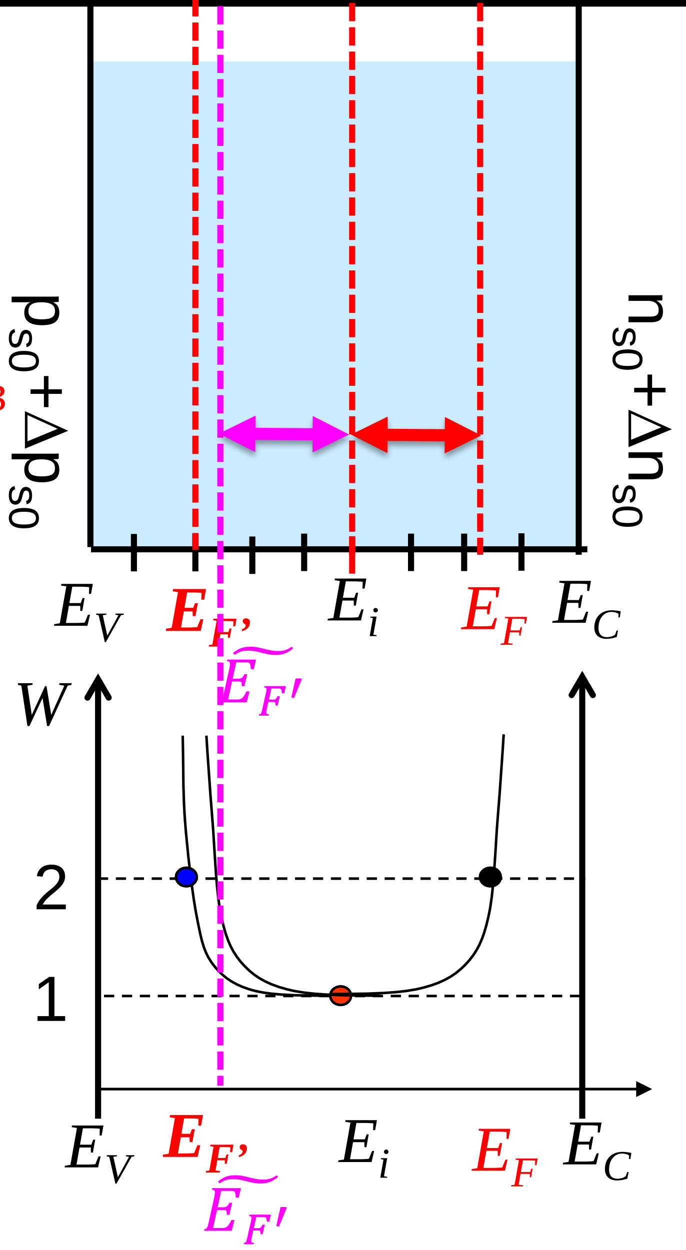
$$n_{s0} = N_D \approx 10^{18}\ cm^{-3}$$

$$n_i \approx 10^{10} cm^{-3}$$

$$1 = \frac{c_{ps}}{c_{ns}}\frac{n_i}{N_D}\, e^{-(E_{F\prime}-E_i)\beta}$$

$$(E_i - \widetilde{E_{F'}}) = (E_F - E_i)$$

$$e^{\Delta E \beta} = \frac{c_{ps}}{c_{ns}}$$



Donor doped

Approximate $\widetilde{W}$

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

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

$$\widetilde{W}(E) = \begin{cases} 1 & \text{for } E_{F'} \le E \le E_F \\ \infty & \text{otherwise} \end{cases}$$

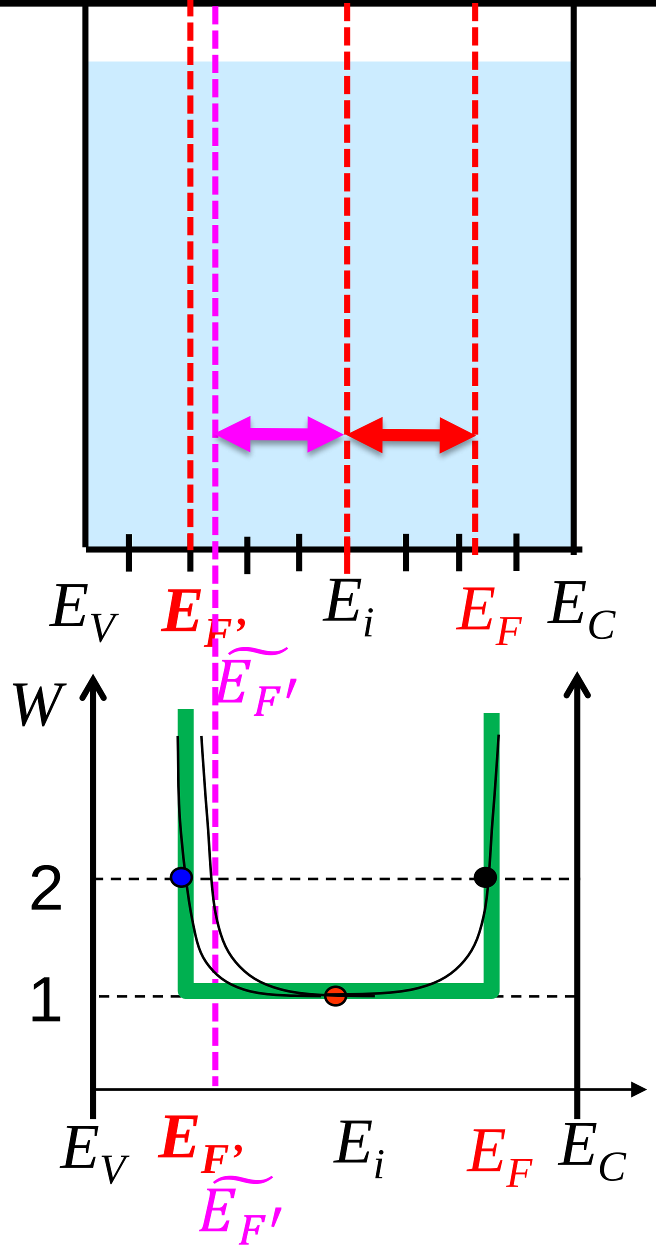
$$1 = \frac{c_{ps}}{c_{ns}}\frac{n_i}{N_D}e^{-(E_{F'}-E_i)\beta}$$

$$E_{F'} = \widetilde{E_{F'}} + \Delta E$$

$$(E_i - \widetilde{E_{F'}}) = (E_F - E_i)$$

$$e^{\Delta E\beta} = \frac{c_{ps}}{c_{ns}}$$

$$\Delta E = k_B T \ln\left(\frac{c_{ps}}{c_{ns}}\right)$$



Donor doped

Approximate $\widetilde{W}$

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

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

$$\widetilde{W}(E) = \begin{cases} 1 & for\ E_{F'} \le E \le E_F \\ \infty & otherwise \end{cases}$$

$$1 = \frac{c_{ps}}{c_{ns}}\frac{n_i}{N_D} e^{-(E_{F'}-E_i)\beta}$$

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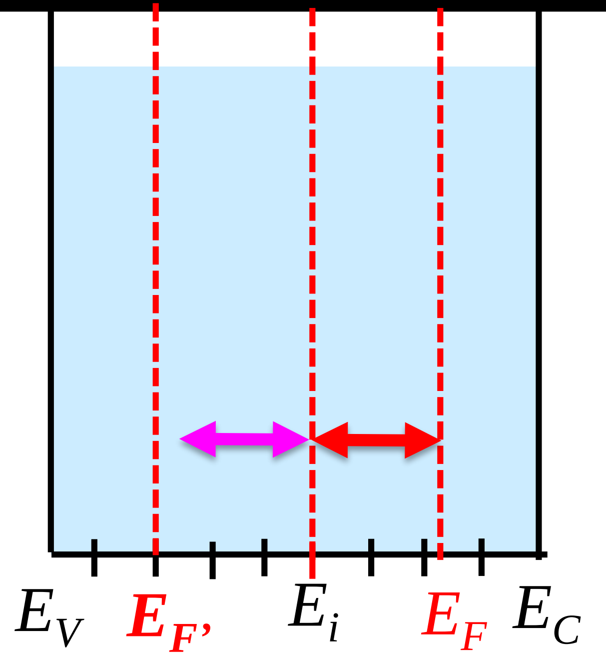
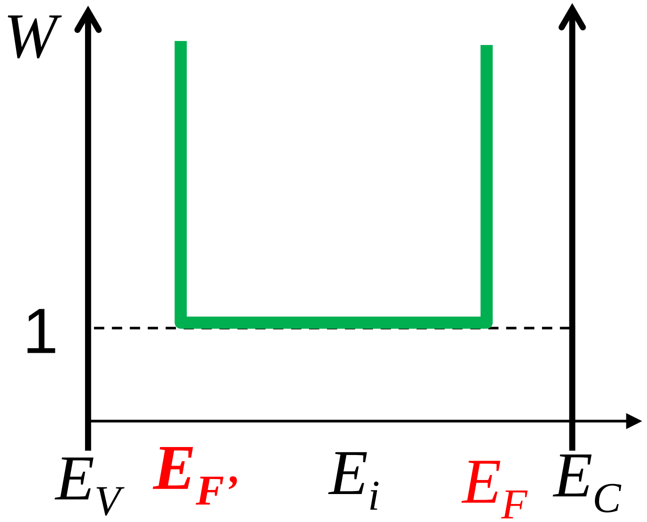
$$\Delta E = k_B T \ln\left(\frac{c_{ps}}{c_{ns}}\right)$$





Donor doped

Case 1: Minority Carrier Recombination

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

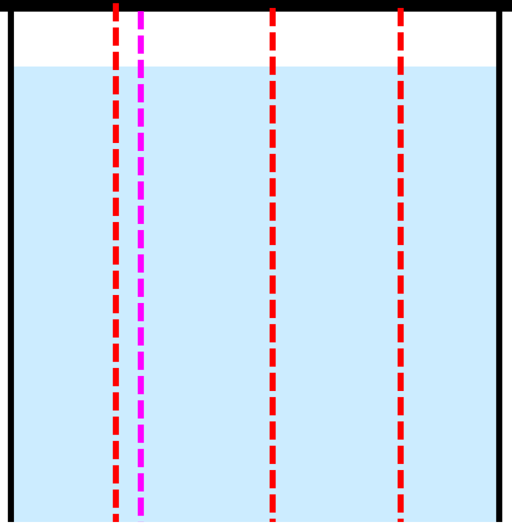
$$\widetilde{W}(E) = \begin{cases} 1 & for\ E_{F'} \le E \le E_F \\ \infty & otherwise \end{cases}$$

$$1 = \frac{c_{ps}}{c_{ns}} \frac{n_i}{N_D} e^{-(E_{F'}-E_i)\beta}$$

$$E_{F'} = \widetilde{E_{F'}} + \Delta E$$

$$(E_i - \widetilde{E_{F'}}) = (E_F - E_i)$$

$$e^{\Delta E \beta} = \frac{c_{ps}}{c_{ns}}$$



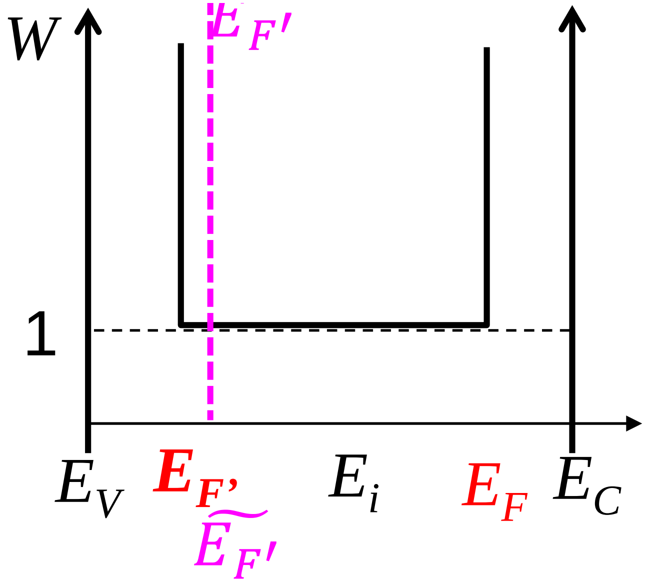
Small Detour - A Very Critical Insight

$$R(E) = \frac{\cdots}{W(E)}$$

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

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

Ready to evaluate this integral



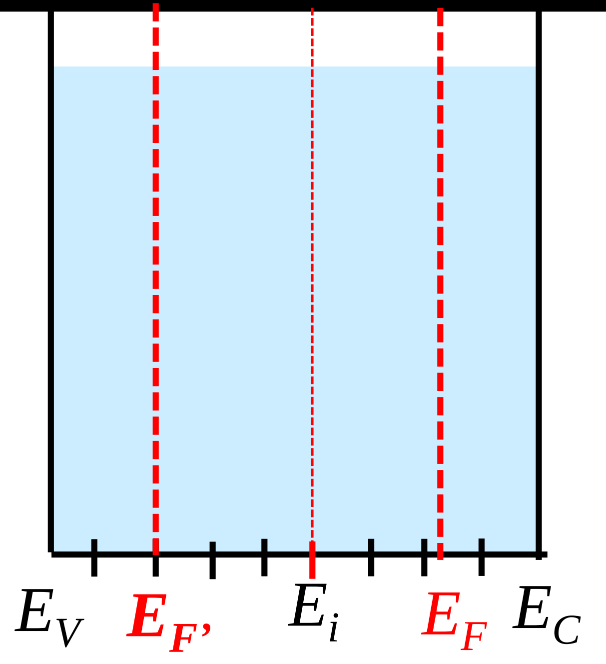
Small Detour – A Very Critical Insight

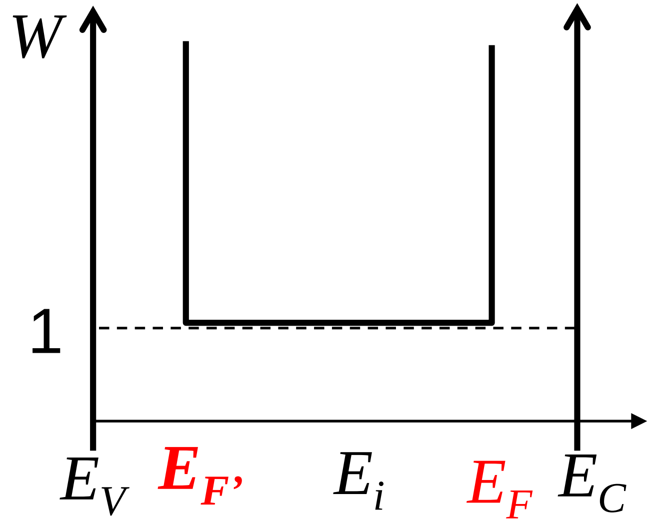
$$R \approx \int_{E_{F'}}^{E_F} c_{ps} \Delta p_{s0} D_{IT}(E) dE$$

We considered trap state density at the Surface $\dfrac{D_{IT}(E)dE}{W(E)}$

Only mid-gap traps act as recombination centers

$$\widetilde{W}(E) = \begin{cases} 1 & for\ E_{F'} \leq E \leq E_F \\ \infty & otherwise \end{cases}$$





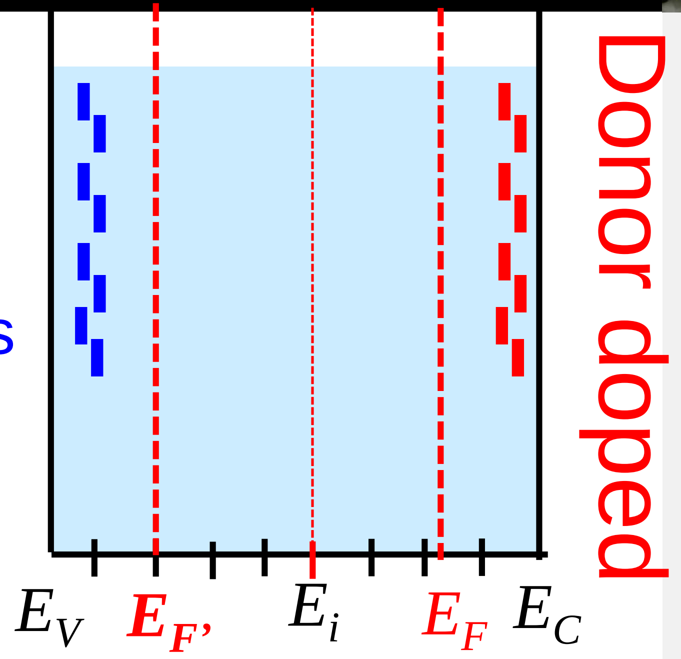
Donor doped

Small Detour - A Very Critical Insight

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

$10^{18} cm^{-3}$ donor traps
donors do not act as recombination centers

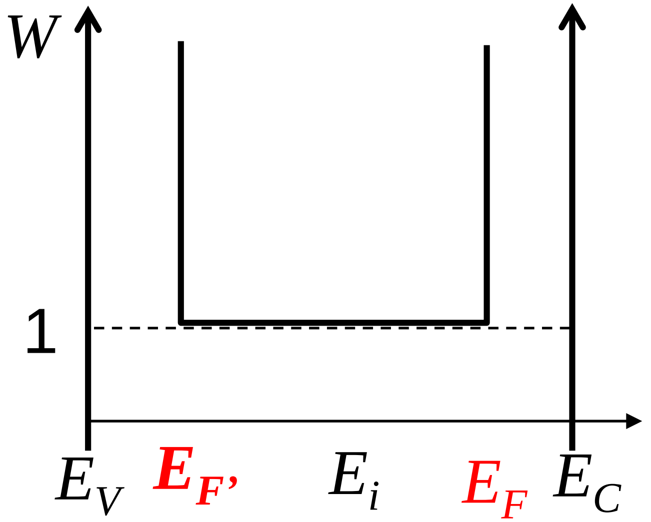
acceptors do not act as recombination centers



We considered trap state density at the Surface $D_{IT}(E)dE$

Only mid-gap traps act $W(E)$ as recombination centers

$$\tilde{W}(E) = \begin{cases} 1 & for\ E_{F'} \leq E \leq E_F \\ \infty & otherwise \end{cases}$$



These approximations are crude and purely analytic

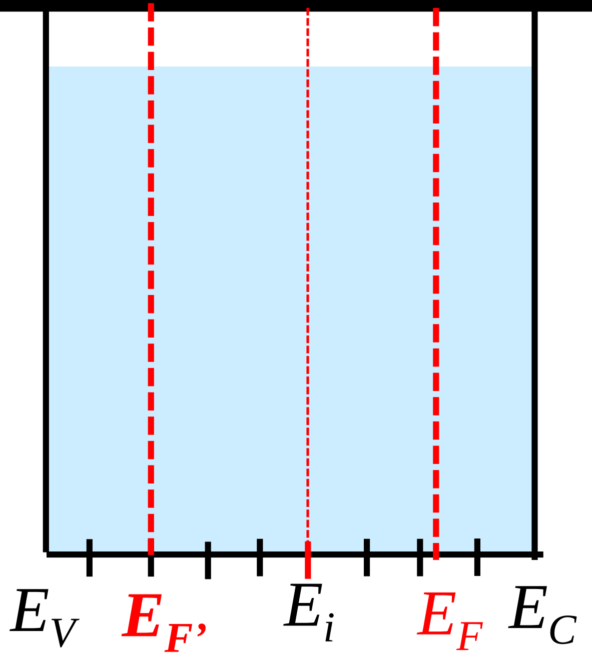
These approximations gave critical insights in the 1950s

Case 1: Minority Carrier Recombination

Now let's evaluate this integral

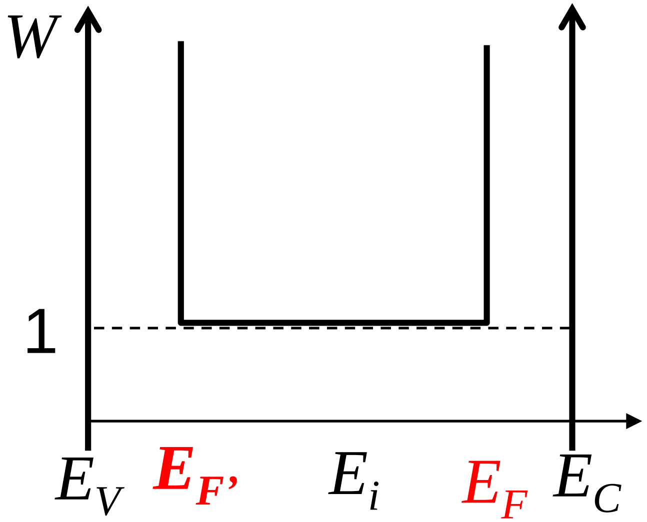
$$R \approx \int_{E_{F'}}^{E_F} c_{ps}\Delta p_{s0} D_{IT}(E)dE$$

What does $D_{IT}(E)$ look like? $\frac{D_{IT}(E)dE}{W(E)}$



Donor doped

$$\tilde{W}(E) = \begin{cases} 1 & for\ E_{F'} \le E \le E_F \\ \infty & otherwise \end{cases}$$



These approximations gave critical insights in the 1950s

Surface Recombination Velocity

Now let's evaluate this integral

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

$$R \approx (E_F - E_F')c_{ps}D_{IT}\Delta p_{s0}$$

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

$$s_g \approx (E_F - E_F')c_{ps}D_{IT}$$

Surface recombination velocity

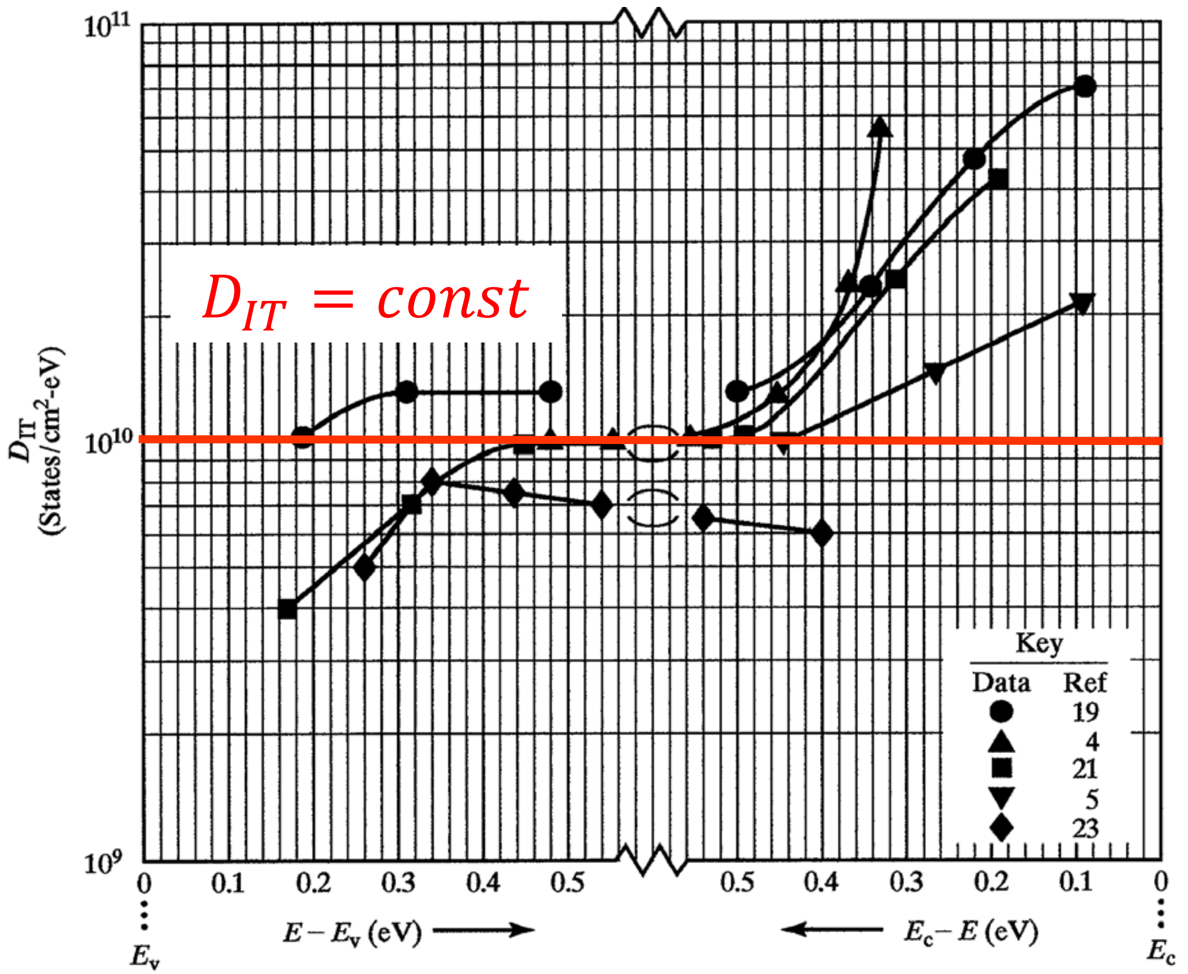
Experimental fitting/ measurement!

Quality of surface and process

Industry:

Process control

What does $D_{IT}(E)$ look like?



How important is $\Delta E \approx \pm 2.3 k_B T \approx 0.060eV$

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

$$R \approx (E_F - E_F') c_{ps} D_{IT} \Delta p_{s0}$$

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

$$s_g \approx (E_F - E_F') c_{ps} D_{IT}$$

Surface recombination velocity

Experimental fitting/ measurement!

Quality of surface and process

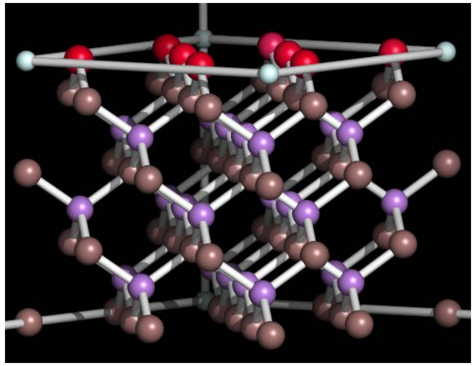
Industry:

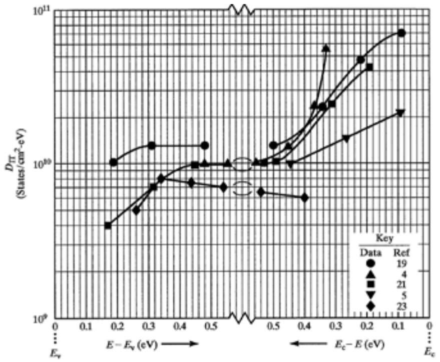
Process control

Research:

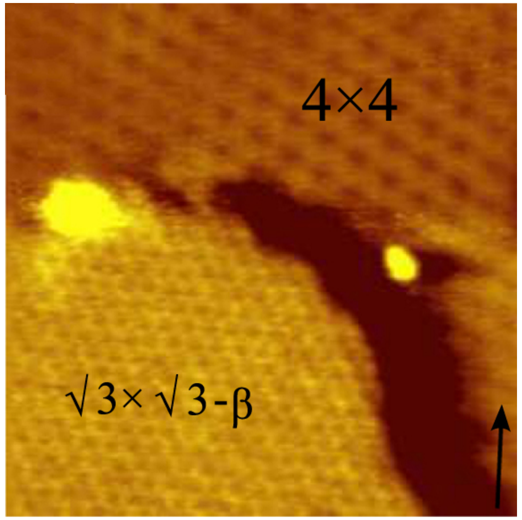
Developing new materials & processes

What does $D_{IT}(E)$ look like?



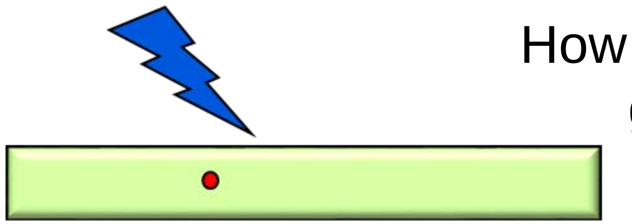


How many dangling bonds?

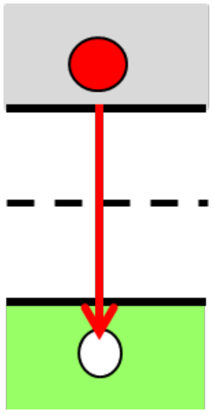


STM image of the first (4×4) and second layers (√3×√3-β) of silicene grown on a thin silver film. Image size 16×16 nm.

https://commons.wikimedia.org/wiki/File:Silicene-Ag_STM5_crop.jpg



How does the system go BACK to equilibrium?



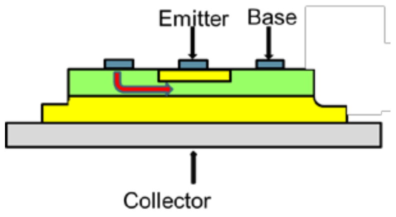
$$\tau_n = \frac{1}{c_n N_T} \qquad \tau_p = \frac{1}{c_p N_T}$$

$$n_1 = n_i g_D e^{\beta(E_T - E_i)}$$

$$p_1 = n_i g_D{}^{-1} e^{\beta(E_i - E_T)}$$

$$R = \frac{pn - n_i^2}{\tau_p(n + n_1) + \tau_n(p + p_1)}$$

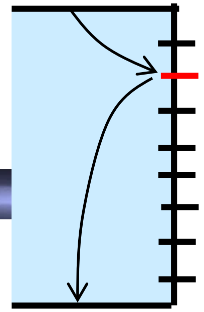
$$R = \frac{\Delta n}{\tau_n}$$



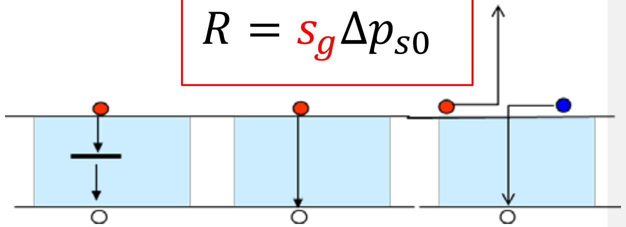
$$R = \frac{\Delta n}{(\tau_n + \tau_p)}$$

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

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



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



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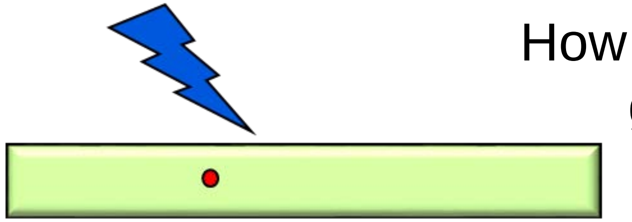
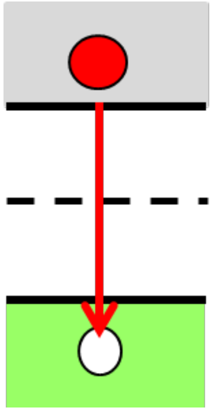
Section 16
Recombination & Generation



How does the system go BACK to equilibrium?



$$\tau_n = \frac{1}{c_n N_T} \qquad \tau_p = \frac{1}{c_p N_T}$$

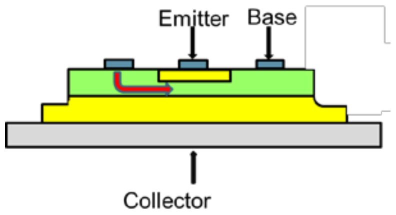
$$n_1 = n_i g_D e^{\beta(E_T - E_i)}$$

$$p_1 = n_i g_D{}^{-1} e^{\beta(E_i - E_T)}$$

- 16.1 Capture coefficient & Capture Cross Section
- 16.2 Derivation of SRH formula (Shockley, Reed, Hall)
  - » 16.2.1 Trap Assisted Recombination Rates
  - » 16.2.2 Capture and emission relationship (n_1 and p_1)
  - » 16.2.3 Steady State Trap Population
  - » 16.2.4 Recombination-Generation Rate
- 16.3 Application of SRH formula for special cases
  - » Low level, high-level injection, depletion region
- 16.4 Direct and Auger recombination
- 16.5 Nature of interface states
- 16.6 SRH formula adapted to interface states
- 16.7 Surface recombination in depletion region

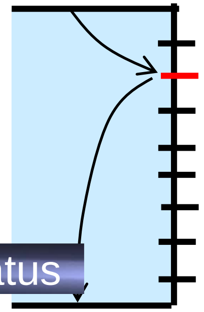
$$R = \frac{pn - n_i^2}{\tau_p(n + n_1) + \tau_n(p + p_1)}$$

$$R = \frac{\Delta n}{\tau_n}$$



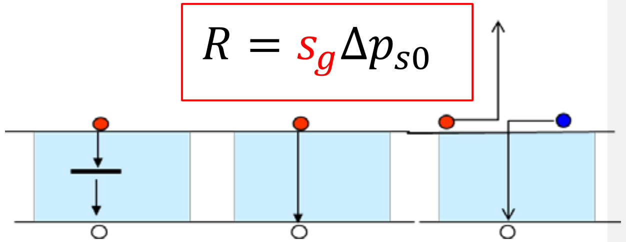
$$R = \frac{\Delta n}{(\tau_n + \tau_p)}$$

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



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

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



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