Section 16
Recombination & Generation

16.7 Surface recombination in depletion region

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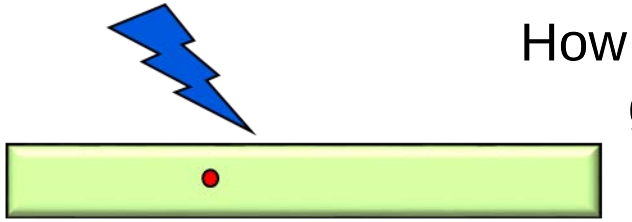
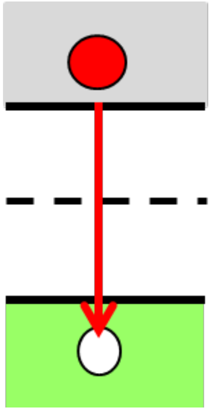
Section 16
Recombination & Generation



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
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- 16.3 Application of SRH formula for special cases
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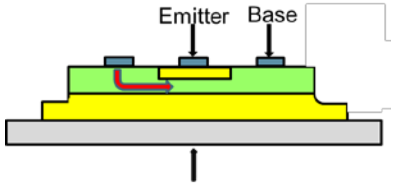
$$R = \frac{pn - n_i^2}{\tau_p(n + n_1) + \tau_n(p + p_1)}$$

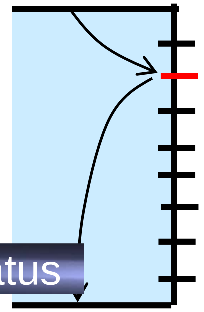
$$R = \frac{\Delta n}{\tau_n}$$



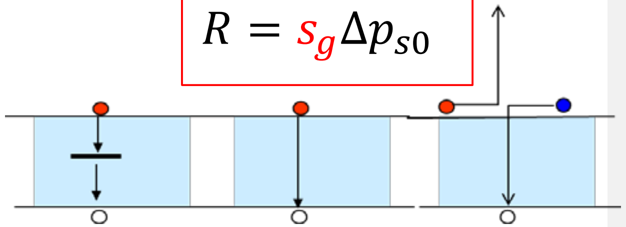
$$R = \frac{\Delta n}{(\tau_n + \tau_p)}$$

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

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



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



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Case 2: Recombination in Depletion

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

Depletion
=> No free carriers

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

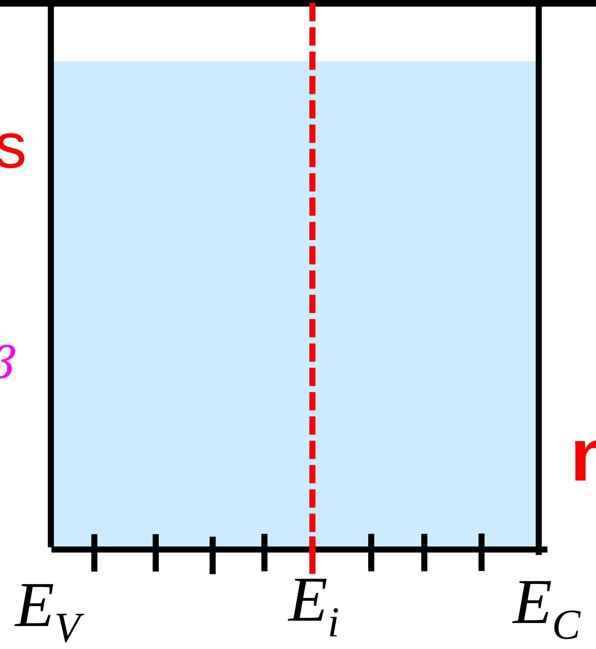
$$n_{1s} = n_i e^{(E-E_i)\beta}$$

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

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

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

p_s~0

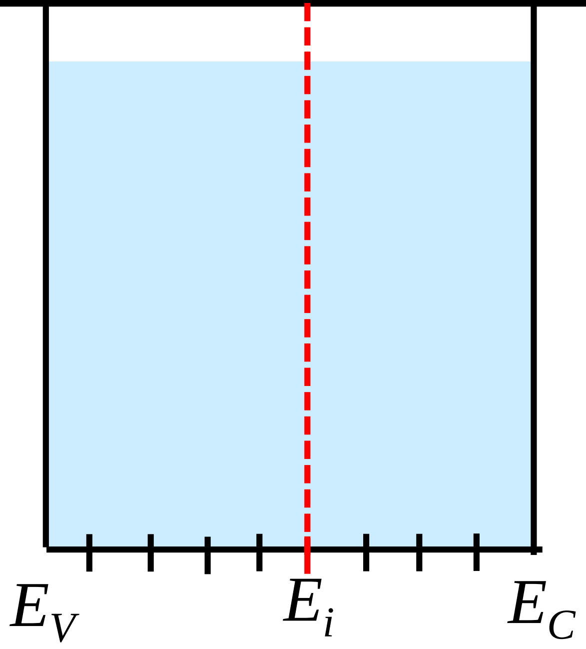


n_s~0

Case 2: Recombination in Depletion

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

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



Case 2: Recombination in Depletion

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

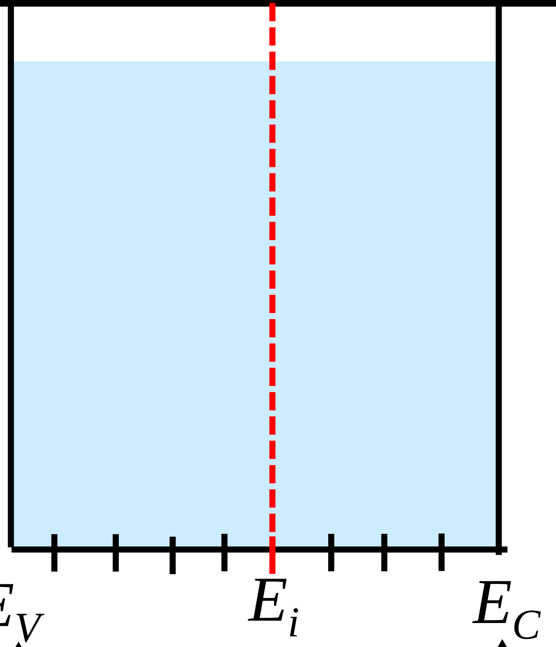
$$R(E_i) = -\frac{A(E)}{e^{x} + a e^{-x}} dE$$

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

$$\text{a} = \frac{c_{ps}}{c_{ns}}$$

$$A(E) = c_{ps} n_i D_{IT}(E)$$

$$\text{f}(x) = \frac{1}{e^{x} + a e^{-x}}$$

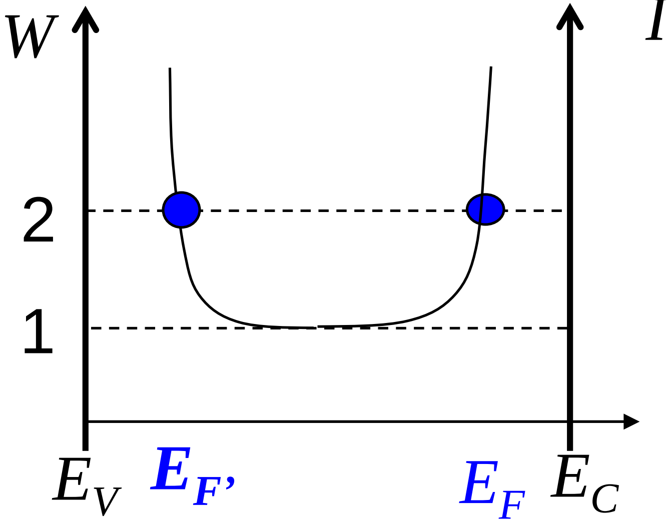


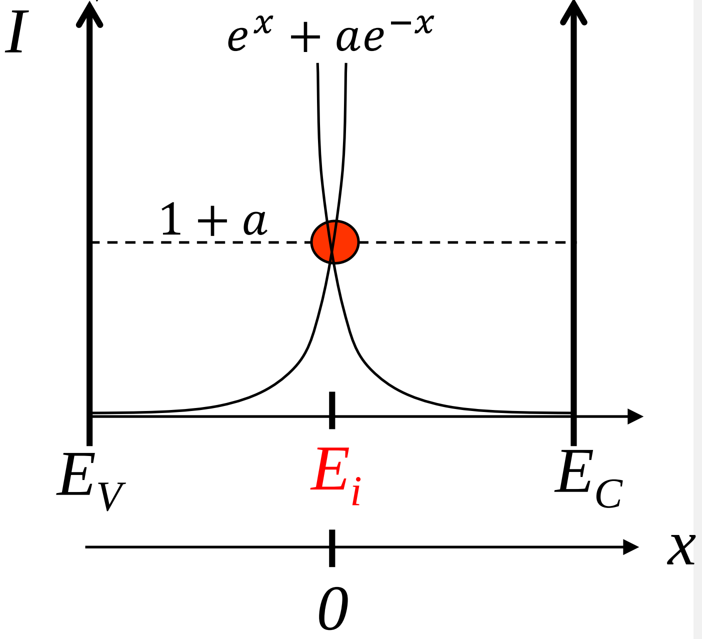
Case 1: Minority Carrier Recombination

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

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

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





Case 2: Recombination in Depletion

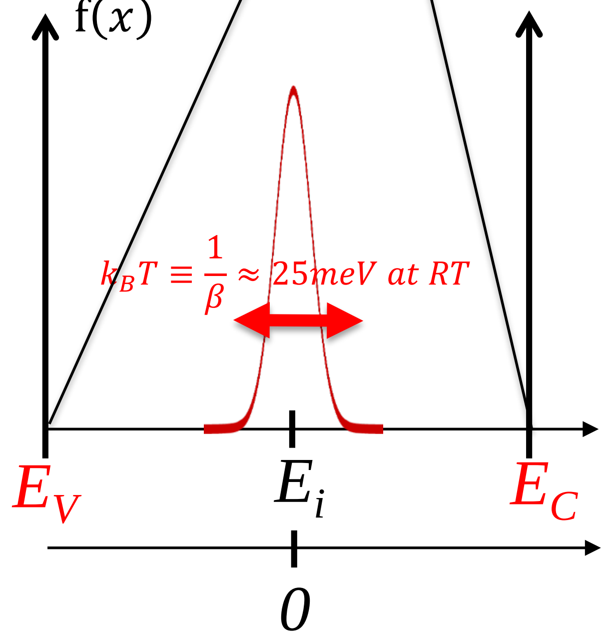
$$R(E) = -\frac{A(E)}{e^{x} + ae^{-x}}\,dE \qquad A(E) = c_{ps} n_i D_{IT}(E) \qquad f(x) = \frac{1}{e^{x} + ae^{-x}}$$

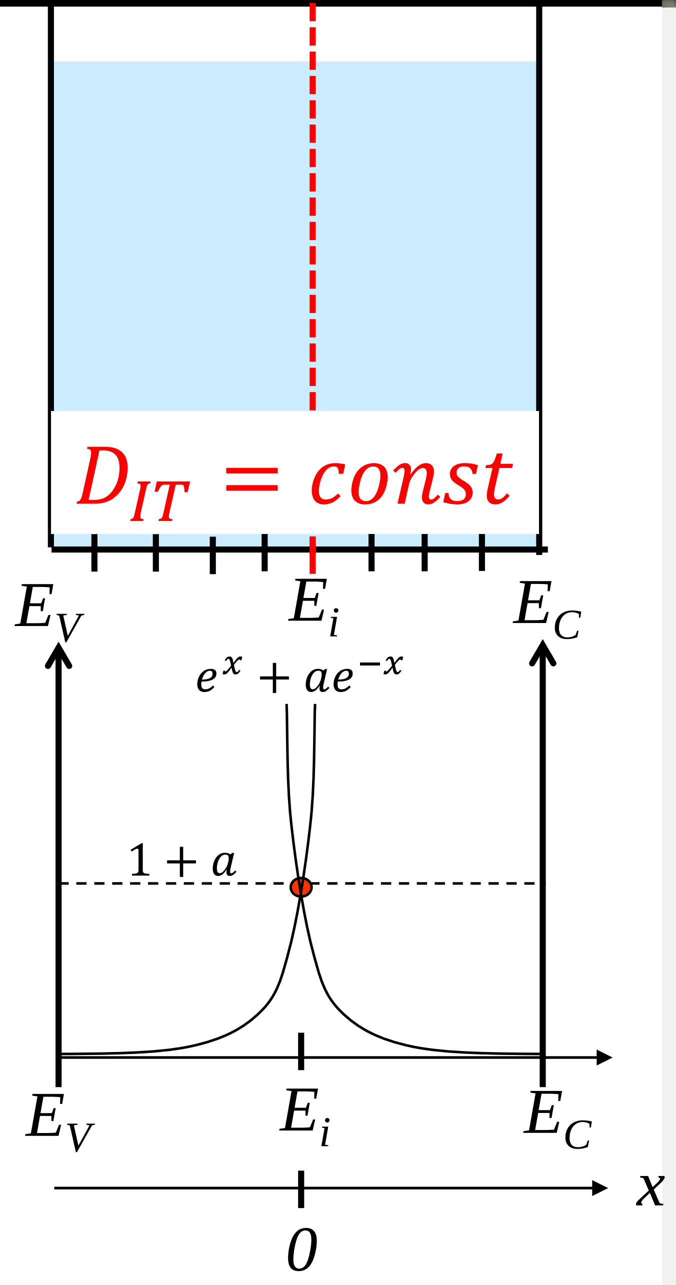
$$x(E) \equiv \beta(E - E_i)$$

$$A(E) \approx A(E_i) = c_{ps} n_i D_{IT}(E_i) \qquad a = \frac{c_{ps}}{c_{ns}}$$

$$R = \int_{E_V}^{E_C} R(E)\,dE = -A(E_i) \int_{E_V}^{E_C} f(x) \frac{dx}{dE}\,dE = -A(E_i)\beta^{-1} \int_{E_V}^{E_C} f(x)\,dx$$

$$R \approx A(E_i)\beta^{-1} \int_{-\infty}^{\infty} f(x)\,dx$$





Case 2: Recombination in Depletion

$$R(E) = -\frac{A(E)}{e^x + ae^{-x}} dE \qquad A(E) = c_{ps} n_i D_{IT}(E)$$

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

$$A(E) \approx A(E_i) = c_{ps} n_i D_{IT}(E_i) \qquad \text{a} = \frac{c_{ps}}{c_{ns}}$$

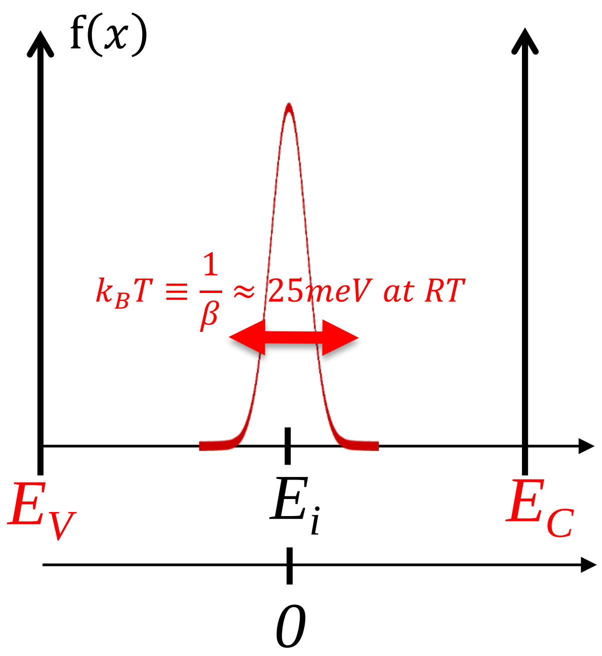
$$R = \int_{E_V}^{E_C} R(E) dE = -A(E_i) \int_{E_V}^{E_C} f(x) \frac{dx}{dE} dE = -A(E_i)\beta^{-1} \int_{E_V}^{E_C} f(x)\, dx$$

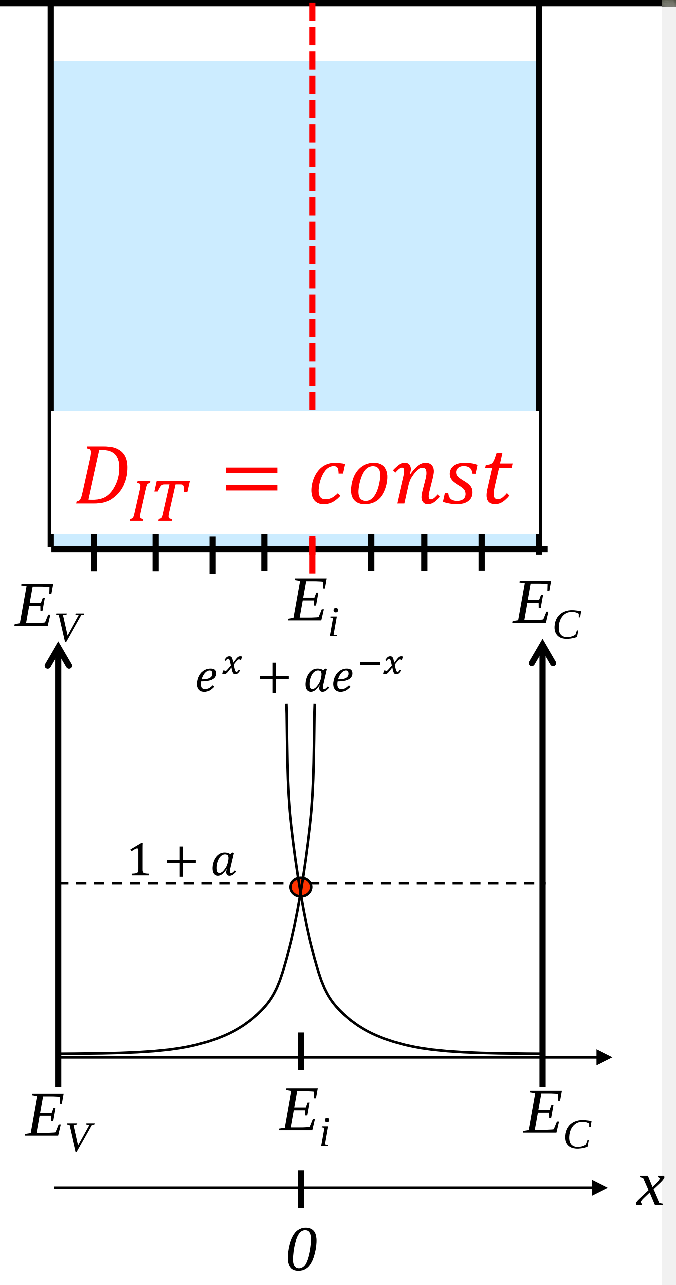
$$R \approx A(E_i)\beta^{-1} \int_{-\infty}^{\infty} f(x)\, dx$$

$$\text{f}(x) = \frac{1}{e^x + ae^{-x}}$$

$$\text{F}(x) = \int f(x) dx = \frac{1}{\sqrt{a}} \tan^{-1}(e^x/\sqrt{a}) + C$$

$$\text{I} = \int_{-\infty}^{\infty} f(x) dx = \frac{\pi}{2\sqrt{a}}$$





Case 2: Recombination in Depletion

$$R(E) = -\frac{A(E)}{e^{x} + ae^{-x}}dE \qquad A(E) = c_{ps}n_i D_{IT}(E) \qquad f(x) = \frac{1}{e^{x} + ae^{-x}}$$

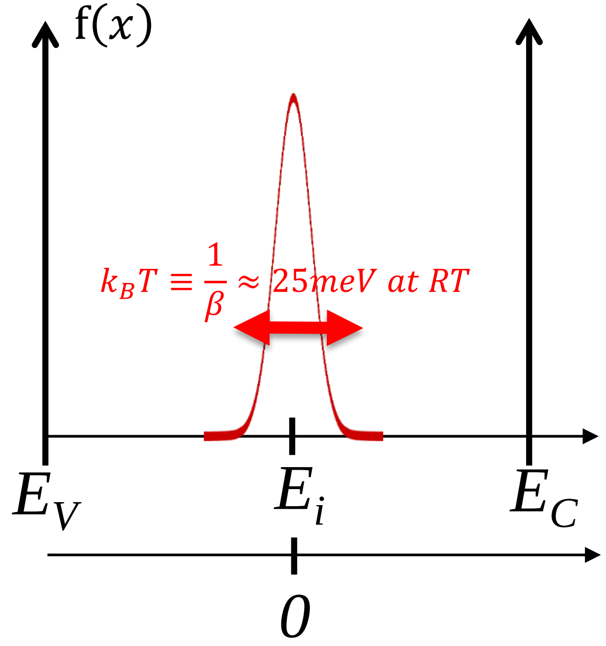
$$x(E) \equiv \beta(E - E_i)$$

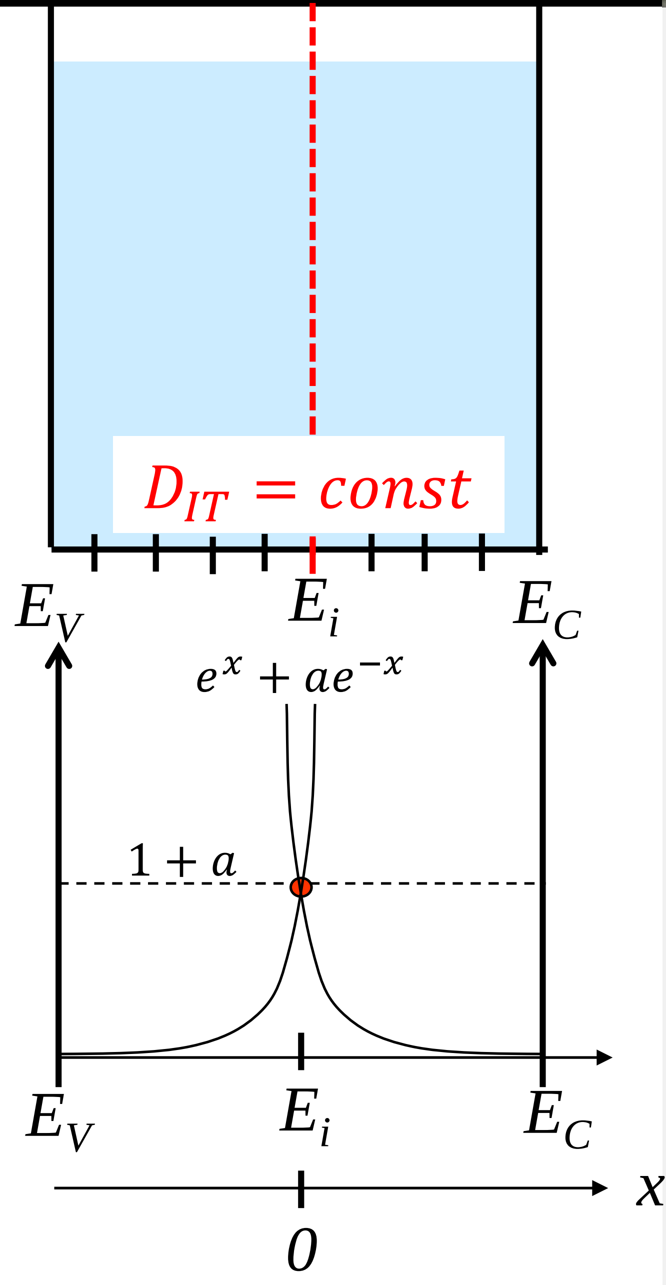
$$A(E) \approx A(E_i) = c_{ps}n_i D_{IT}(E_i) \qquad a = \frac{c_{ps}}{c_{ns}}$$

$$R = \int_{E_V}^{E_C} R(E)dE = -A(E_i)\int_{E_V}^{E_C} f(x)\frac{dx}{dE}dE = -A(E_i)\beta^{-1}\int_{E_V}^{E_C} f(x)\,dx$$

$$R \approx -A(E_i)\beta^{-1}\int_{-\infty}^{\infty} f(x)\,dx = -A(E_i)\,\beta^{-1}\frac{\pi}{2\sqrt{a}}$$

$$I = \int_{-\infty}^{\infty} f(x)dx = \frac{\pi}{2\sqrt{a}}$$





Case 2: Recombination in Depletion

$$R(E) = -\frac{A(E)}{e^x + ae^{-x}}\,dE \qquad A(E) = c_{ps} n_i D_{IT}(E)$$

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

$$f(x) = \frac{1}{e^x + ae^{-x}}$$

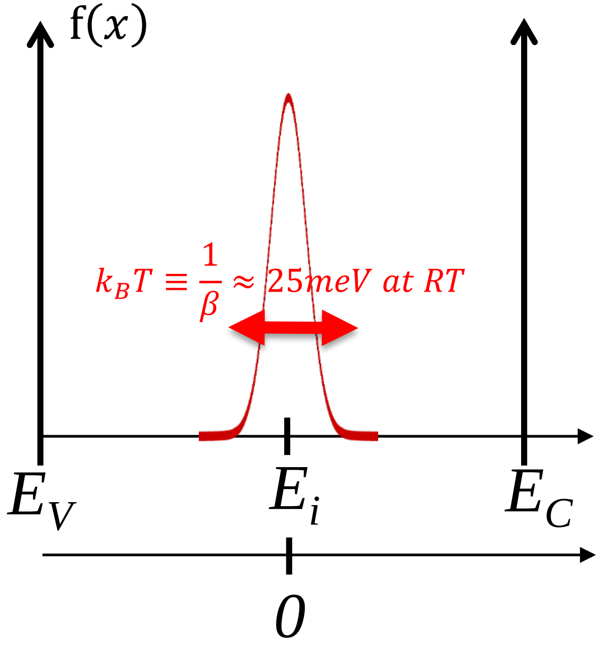
$$A(E) \approx A(E_i) = c_{ps} n_i D_{IT}(E_i) \qquad a = \frac{c_{ps}}{c_{ns}}$$

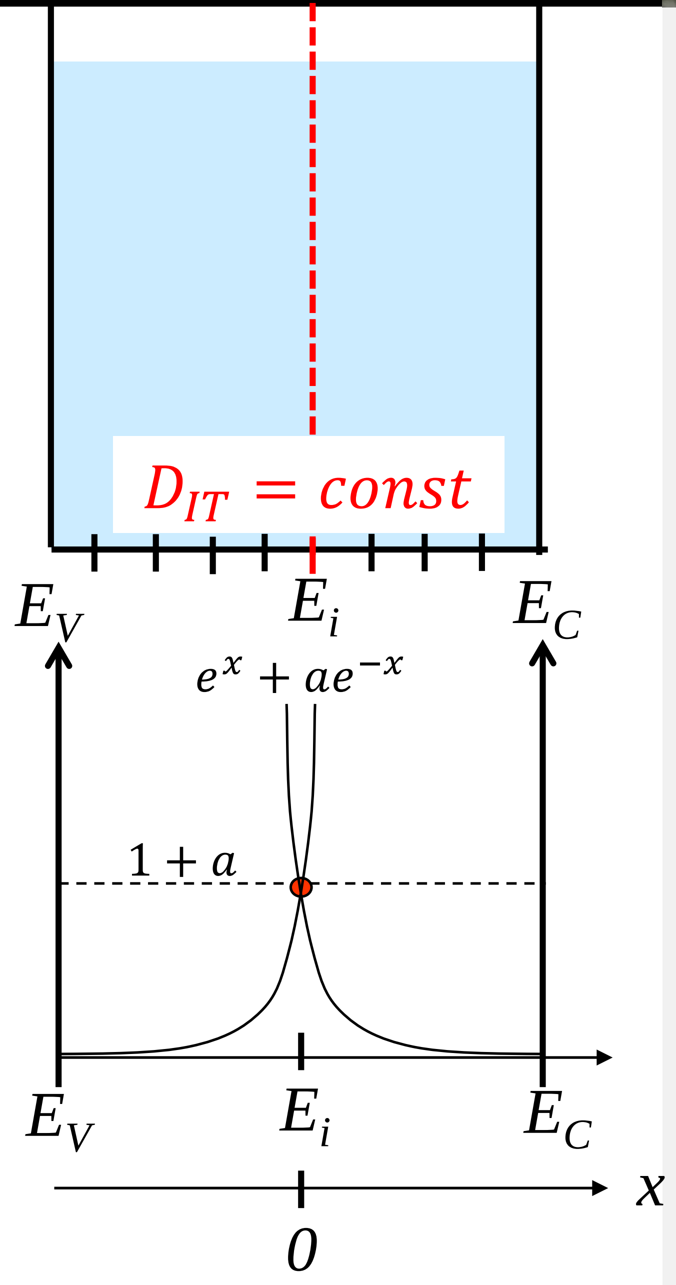
$$R = \int_{E_V}^{E_C} R(E)dE$$

$$R \approx -A(E_i)\beta^{-1} \int_{-\infty}^{\infty} f(x)\,dx = -A(E_i)\,\beta^{-1}\,\frac{\pi}{2\sqrt{a}}$$

$$R \approx -c_{ps} n_i D_{IT}(E_i)\,\beta^{-1}\,\frac{\pi}{2}\sqrt{c_{ns}/c_{ps}}$$

$$R \approx -\frac{\pi}{2}\sqrt{c_{ps}c_{ns}}\;k_BT\;D_{IT}\;n_i$$

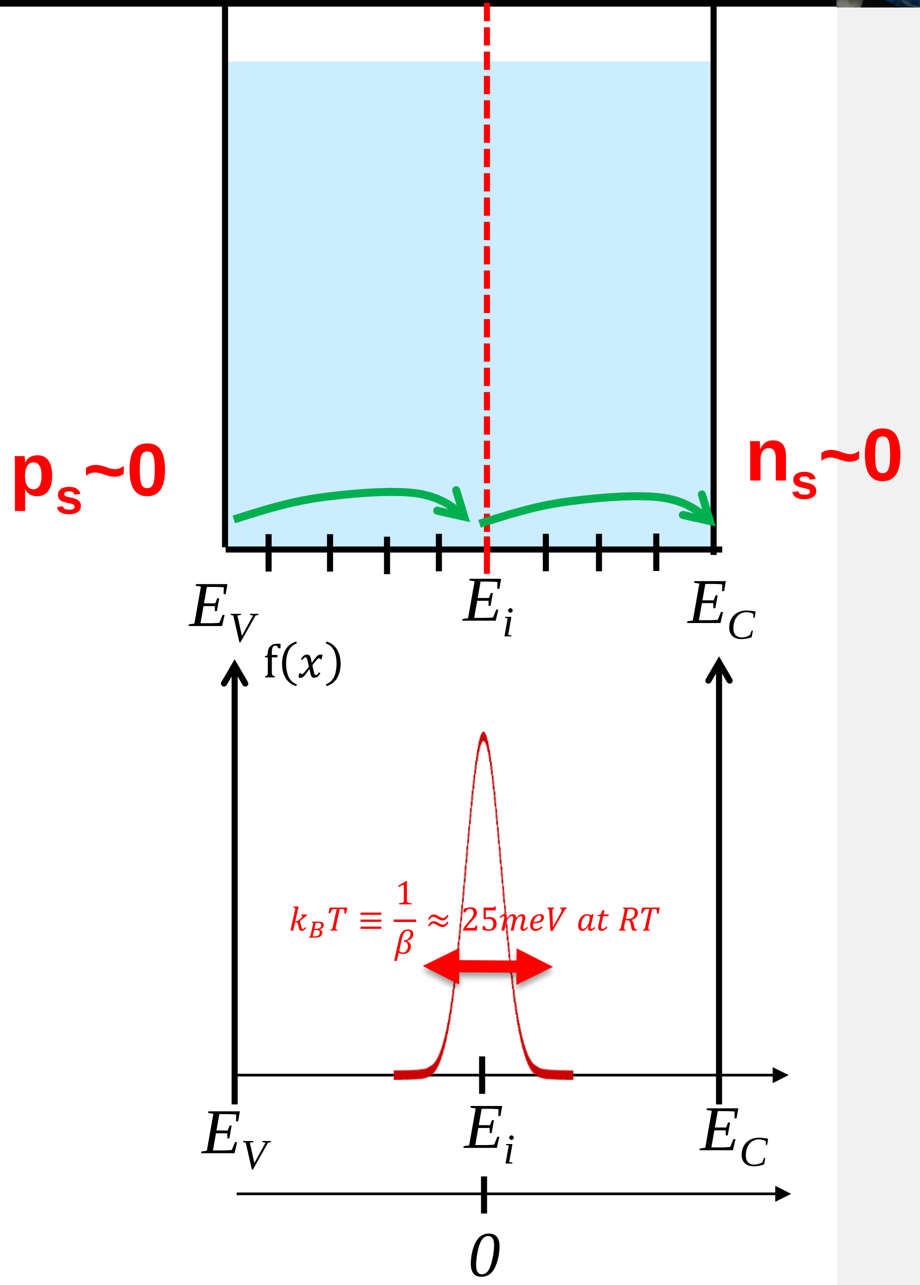




Case 2: Generation in Depletion

$$R \approx -\frac{\pi}{2}\sqrt{c_{ps}c_{ns}}\, k_B T\, D_{IT}\, n_i$$

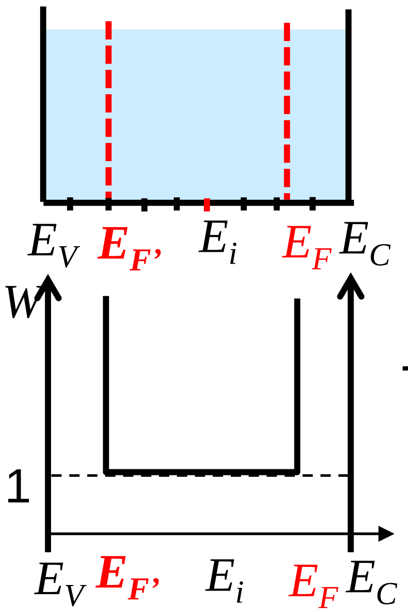
$$G \approx \frac{\pi}{2}\sqrt{c_{ps}c_{ns}}\, k_B T\, D_{IT}\, n_i$$



Compare Case 1 and Case 2

Case 1: Minority Carrier Recombination

Case 2: Generation in Depletion



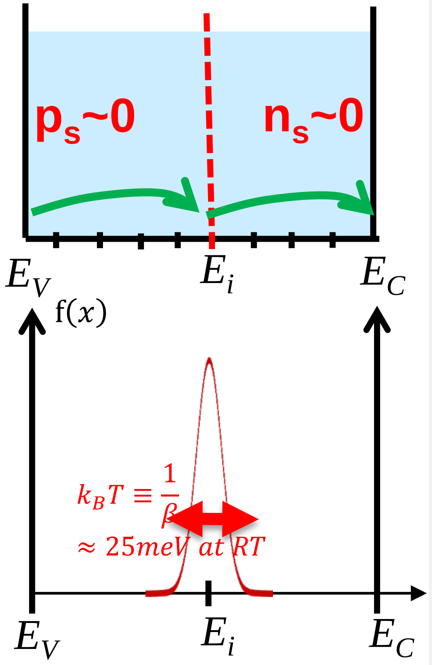
Donor doped

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

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

$$R \approx -\frac{\pi}{2}\sqrt{c_{ps}c_{ns}}\, k_BT\, D_{IT}\, n_i$$

$$G \approx \frac{\pi}{2}\sqrt{c_{ps}c_{ns}}\, k_BT\, D_{IT}\, n_i$$



Assume: $c_{ps}D_{IT} = c_{ns}D_{IT} = A$

$$R_{MC} = A\,\Delta E\ \ \Delta n$$

$$G_D \approx \frac{\pi}{2} A\,\Delta E\,\Delta n$$

$$\Delta E = E_F - E_{F'} \approx 1.000eV$$

$$\Delta E = k_BT \approx 0.025eV$$

$N_A \gg \Delta n \gg n_i$ $\qquad$ $\Delta n \approx 10^{16}cm^{-3}$

$\Delta n = n_i \approx 10^{10}cm^{-3}$

Energy loss through many states & carriers

$$\frac{R_{MC}}{G_D} \approx 10^8$$

Thermal energy gain through few states & carriers

Summary

$$R \approx -\frac{\pi}{2}\sqrt{c_{ps}c_{ns}}\, k_B T\, D_{IT}\, n_i$$

Interface (depletion)

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

Interface (minority)

$$R = c_p N_T \Delta p$$

Bulk (minority)

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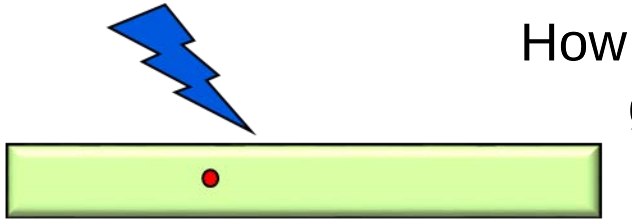
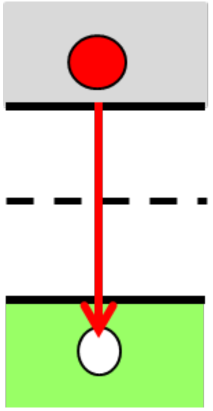


How does the system go BACK to equilibrium?



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

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

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

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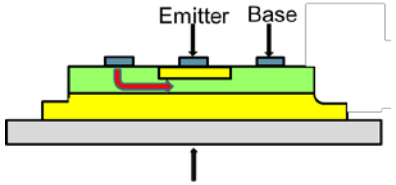
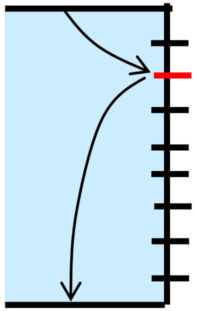
$$R = \frac{pn - n_i^2}{\tau_p(n + n_1) + \tau_n(p + p_1)}$$

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



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

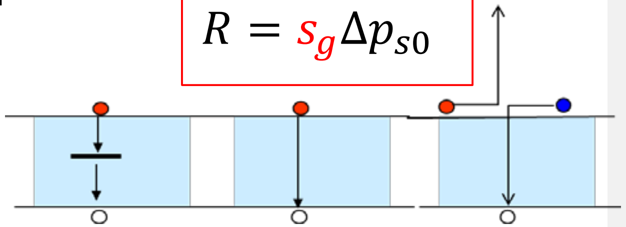
$$R(E) = \frac{(n_s p_s - n_i^2) D_{IT}(E) dE}{\frac{1}{c_{ps}}(n_s + n_{1s}) + \frac{1}{c_{ns}}(p_s + p_{1s})}$$



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

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

$$R \approx -\frac{\pi}{2}\sqrt{c_{ps} c_{ns}}\, k_B T\, D_{IT}\, n_i$$



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