Section 16
Recombination & Generation
16.2 Derivation of SRH formula (Shockley, Reed, Hall)
16.2.3 Steady State Trap Population

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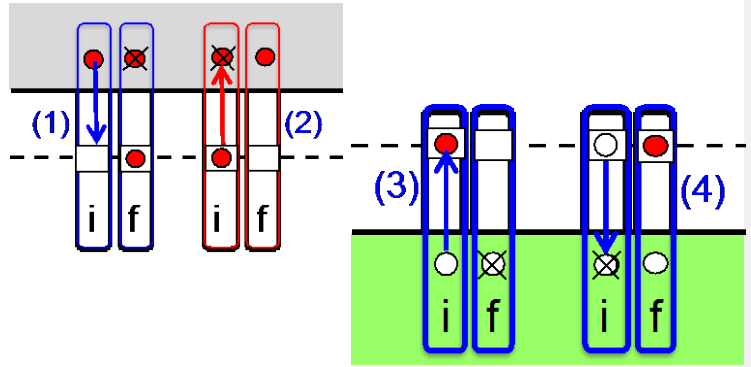
Section 16.2.3
Steady State Trap Population

Vid

- 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

status



$$N_T = p_T + n_T \qquad p_T = N_T - n_T$$

$$\left.\frac{\partial n_0}{\partial t}\right|_{1,2} = -c_{n0} n_0 p_{T0} + e_{n0} n_{T0} = 0$$

$$\left.\frac{\partial p_0}{\partial t}\right|_{3,4} = -c_{p0} p_0 n_{T0} + e_{p0} p_{T0} = 0$$

$$e_{n0} = c_{n0}\, n_1$$

$$e_{p0} = c_{p0}\, p_1$$

$$n_1 \equiv \frac{n_0 p_{T0}}{n_{T0}}$$

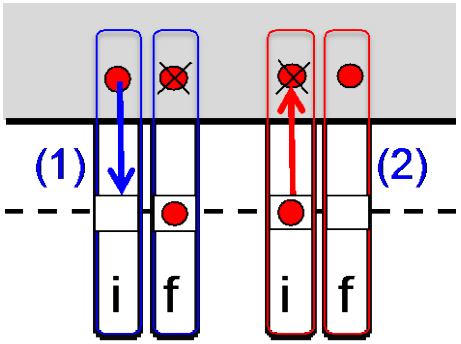
$$p_1 \equiv \frac{n_0 n_{T0}}{p_{T0}}$$

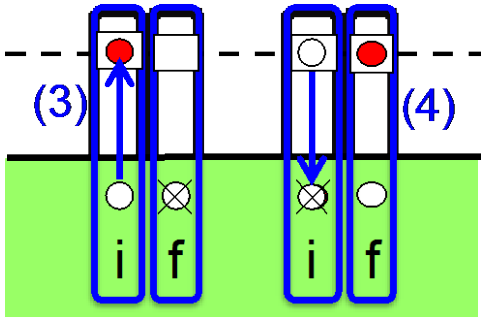
$$n_1 = n_i g_D e^{\beta(E_T - E_i)}$$

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

$$p_1 n_1 = n_i^2$$

Focus on Trap Population





$$\left.\frac{\partial n_0}{\partial t}\right|_{1,2} = -c_{n0} n_0 p_{T0} + e_{n0} n_{T0}$$

$$\left.\frac{\partial p_0}{\partial t}\right|_{3,4} = -c_{p0} p_0 n_{T0} + e_{p0} p_{T0}$$

n_T electron-filled traps

p_T hole-filled (empty) traps

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

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

$$p_1 n_1 = n_i^2$$

c_n electron capture coef.

e_n electron emission coef.

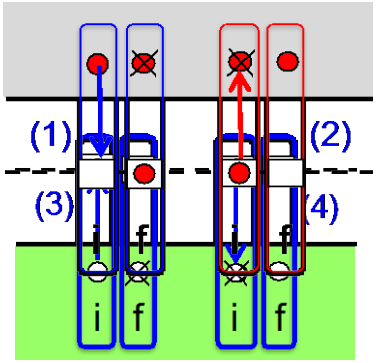
c_p hole capture coef.

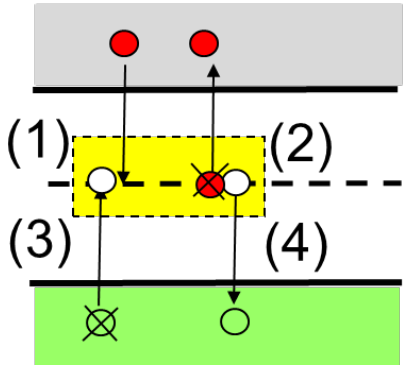
e_p hole emission coef.

$$e_{n0} = c_{n0}\ n_1$$

$$e_{p0} = c_{p0}\ p_1$$

Focus on Trap Population





$$\left.\frac{\partial n_0}{\partial t}\right|_{1,2} = -c_{n0} n_0 p_{T0} + e_{n0} n_{T0}$$

$$\left.\frac{\partial p_0}{\partial t}\right|_{3,4} = -c_{p0} p_0 n_{T0} + e_{p0} p_{T0}$$

n_T electron-filled traps

p_T hole-filled (empty) traps

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$$p_1 n_1 = n_i^2$$

c_n electron capture coef.

e_n electron emission coef.

c_p hole capture coef.

e_p hole emission coef.

$$e_{n0} = c_{n0}\ n_1$$

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Dynamics of Trap Population

$$\left.\frac{\partial n_0}{\partial t}\right|_{1,2} = -c_{n0} n_0 p_{T0} + e_{n0} n_{T0}$$

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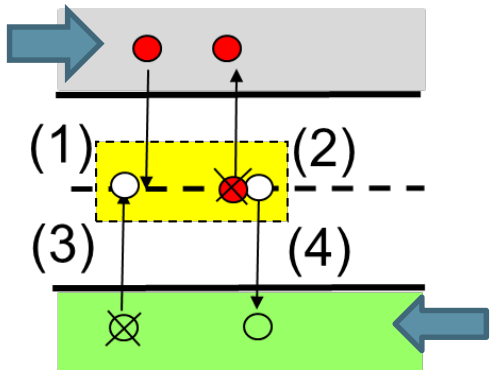

$$\frac{\partial n_T}{\partial t}$$

n_T electron-filled traps

p_T hole-filled (empty) traps

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$$p_1 n_1 = n_i^2$$

$$\left.\frac{\partial n}{\partial t}\right|_{1,2} = -c_n n p_T + e_n n_T$$

$$\left.\frac{\partial p}{\partial t}\right|_{3,4} = -c_p p n_T + e_p p_T$$

$$e_{n0} = c_{n0}\ n_1$$

$$e_{p0} = c_{p0}\ p_1$$

c_n electron capture coef.

e_n electron emission coef.

c_p hole capture coef.

e_p hole emission coef.

$$\frac{\partial n_T}{\partial t} = -\left.\frac{\partial n}{\partial t}\right|_{1,2} + \left.\frac{\partial p}{\partial t}\right|_{3,4}$$

$$= c_n\, n\, p_T - e_n n_T - c_p\, p\, n_T + e_p p_T$$

How can we get e_n , e_p and c_n , c_p ?

Determining e_{n0} , e_{p0} was a pain!

Fundamental physical process rates

Determined by material properties (bond lengths, chemistry)

Assume – fundamentals not changed by additional electrons or holes

Dynamics of Trap Population

$$\left.\frac{\partial n_0}{\partial t}\right|_{1,2} = -c_{n0} n_0 p_{T0} + e_{n0} n_{T0}$$

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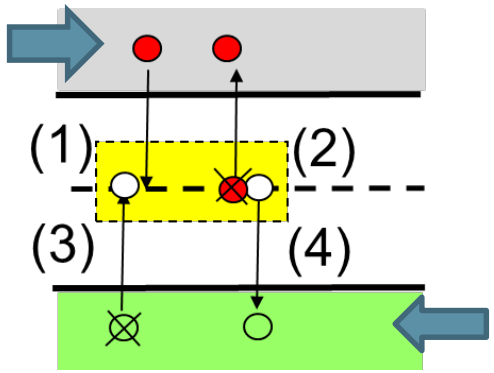

$$\frac{\partial n_T}{\partial t}$$

n_T electron-filled traps

p_T hole-filled (empty) traps

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

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$$p_1 n_1 = n_i^2$$

$$\left.\frac{\partial n}{\partial t}\right|_{1,2} = -c_n n p_T + e_n n_T$$

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$$e_{n0} = c_{n0}\ n_1$$

$$e_{p0} = c_{p0}\ p_1$$

c_n electron capture coef.

e_n electron emission coef.

c_p hole capture coef.

e_p hole emission coef.

$$\frac{\partial n_T}{\partial t} = -\left.\frac{\partial n}{\partial t}\right|_{1,2} + \left.\frac{\partial p}{\partial t}\right|_{3,4}$$

$$= c_n\, n\, p_T - e_n n_T - c_p\, p\, n_T + e_p p_T$$

Assume – fundamentals not changed by additional electrons or holes

$c_n = c_{c0}\,, c_p = c_{p0},$ $e_n = e_{n0}\,, e_p = e_{p0}$

$$e_p = c_p\ p_1$$

$$e_n = c_n\ n_1$$

How can we get $e_n\,, e_p$ and $c_n\,, c_p$?

Determining $e_{n0}\,, e_{p0}$ was a pain!

Dynamics of Trap Population

$$\left.\frac{\partial n_0}{\partial t}\right|_{1,2} = -c_{n0} n_0 p_{T0} + e_{n0} n_{T0}$$

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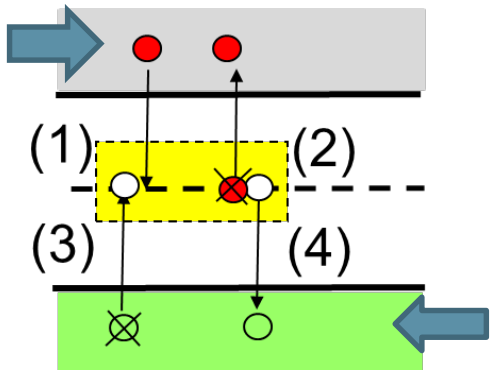

$$\frac{\partial n_T}{\partial t}$$

n_T electron-filled traps

p_T hole-filled (empty) traps

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$$e_{n0} = c_{n0}\ n_1$$

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c_n electron capture coef.

e_n electron emission coef.

c_p hole capture coef.

e_p hole emission coef.

$$\frac{\partial n_T}{\partial t} = -\left.\frac{\partial n}{\partial t}\right|_{1,2} + \left.\frac{\partial p}{\partial t}\right|_{3,4}$$

$$= c_n\, n\, p_T - e_n n_T - c_p\, p\, n_T + e_p p_T$$

Assume – fundamentals not changed by additional electrons or holes

$c_n = c_{c0}\,, c_p = c_{p0},$ $e_n = e_{n0}\,, e_p = e_{p0}$

$$e_p = c_p\ p_1$$

$$e_n = c_n\ n_1$$

How can we get $e_n\,, e_p$ and $c_n\,, c_p$?

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Dynamics of Trap Population

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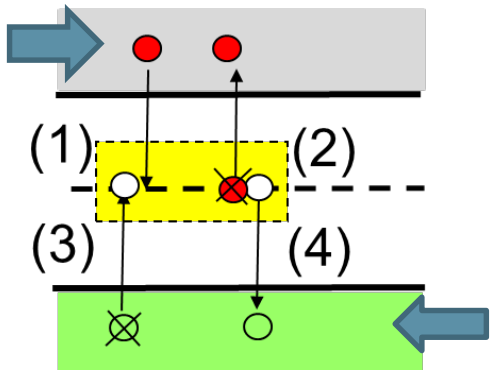

$$\frac{\partial n_T}{\partial t}$$

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c_n electron capture coef.

$e_{n0} = c_{n0}\ n_1$ e_n electron emission coef.

c_p hole capture coef.

$e_{p0} = c_{p0}\ p_1$ e_p hole emission coef.

$$\frac{\partial n_T}{\partial t} = -\left.\frac{\partial n}{\partial t}\right|_{1,2} + \left.\frac{\partial p}{\partial t}\right|_{3,4}$$

$$= c_n\, n\, p_T - e_n n_T - c_p\, p\, n_T + e_p p_T$$

$$\frac{\partial n_T}{\partial t} = c_n \left(n p_T - n_T n_1 \right) - c_p \left(p\, n_T - p_T p_1 \right)$$

Assume – fundamentals not changed by additional electrons or holes

$c_n = c_{c0}\,, c_p = c_{p0},$ $e_n = e_{n0}\,, e_p = e_{p0}$

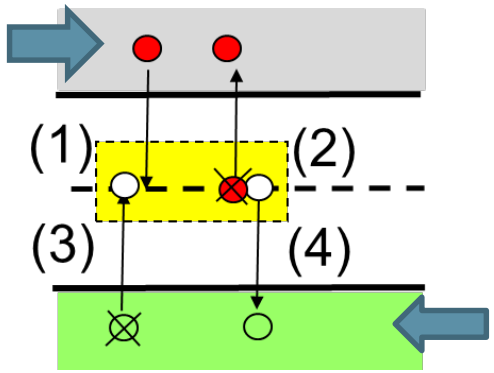
$e_p = c_p\ p_1$

$e_n = c_n\ n_1$

Dynamics of Trap Population

$$\left.\frac{\partial n_0}{\partial t}\right|_{1,2} = -c_{n0} n_0 p_{T0} + e_{n0} n_{T0}$$

$$\left.\frac{\partial p_0}{\partial t}\right|_{3,4} = -c_{p0} p_0 n_{T0} + e_{p0} p_{T0}$$



$$\frac{\partial n_T}{\partial t}$$

n_T electron-filled traps

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$$e_{n0} = c_{n0}\ n_1$$

c_n electron capture coef.

e_n electron emission coef.

c_p hole capture coef.

$$e_{p0} = c_{p0}\ p_1$$

e_p hole emission coef.

$$\frac{\partial n_T}{\partial t} = -\left.\frac{\partial n}{\partial t}\right|_{1,2} + \left.\frac{\partial p}{\partial t}\right|_{3,4}$$

$$= c_n\, n\, p_T - e_n n_T - c_p\, p\, n_T + e_p p_T$$

$$\frac{\partial n_T}{\partial t} = c_n\left(n p_T - n_T n_1\right) - c_p\left(p\, n_T - p_T p_1\right)$$

Assume – fundamentals not changed by additional electrons or holes

$c_n = c_{c0}\,, c_p = c_{p0},$ $e_n = e_{n0}\,, e_p = e_{p0}$

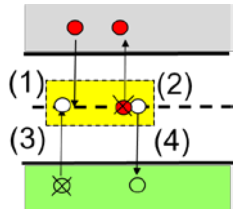
$$\left.\frac{\partial p}{\partial t}\right| = -c_p(p n_T - p_T p_1)$$

$$e_p = c_p\ p_1$$

$$e_n = c_n\ n_1$$

Steady State of Trap Population

$$\frac{\partial n_T}{\partial t} = 0 = c_n\left(np_T - n_T n_1\right) - c_p\left(p\, n_T - p_T p_1\right)$$



Seek expression in terms of occupied traps

$$N_T = p_T + n_T$$

$$p_T = N_T - n_T$$

$$0 = c_n\left(n\left(N_T - n_T\right) - n_T n_1\right) - c_p\left(pn_T - \left(N_T - n_T\right)p_1\right)$$

Solve for n_T

$$n_T\left(c_n n + c_n n_1 + c_p p + c_p p_1\right) = c_n n N_T + c_p p_1 N_T$$

$$n_T = \frac{c_n N_T n + c_p N_T p_1}{c_n\left(n + n_1\right) + c_p\left(p + p_1\right)}$$

n_T trap occupation for a given n,p

$$n_T = \frac{c_n N_T n + c_p N_T p_1}{A} \qquad A = c_n(n + n_1) + c_p(p + p_1)$$

n_T electron-filled traps

p_T hole-filled (empty) traps

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

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

$$p_1 n_1 = n_i^2$$

c_n electron capture coef.

e_n electron emission coef.

c_p hole capture coef.

e_p hole emission coef.

$$e_p = c_p\, p_1$$

$$e_n = c_n\, n_1$$

$$\left.\frac{\partial p}{\partial t}\right| = -c_p(pn_T - p_T p_1)$$

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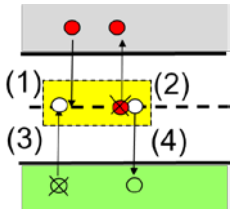

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$$N_T = p_T + n_T$$

$$p_T = N_T - n_T$$

n_T electron-filled traps

p_T hole-filled (empty) traps

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$$p_1 n_1 = n_i^2$$

c_n electron capture coef.

e_n electron emission coef.

c_p hole capture coef.

e_p hole emission coef.

$$e_p = c_p\ p_1$$

$$e_n = c_n\ n_1$$

$$\left.\frac{\partial p}{\partial t}\right| = -c_p(pn_T - p_T p_1)$$

$$n_T = \frac{c_n N_T n + c_p N_T p_1}{c_n\left(n + n_1\right) + c_p\left(p + p_1\right)}$$

n_T trap occupation for a given n,p

$$n_T = \frac{c_n N_T n + c_p N_T p_1}{A}$$

$$A = c_n(n + n_1) + c_p(p + p_1)$$

Section 16.2.4
Recombination-Generation Rate

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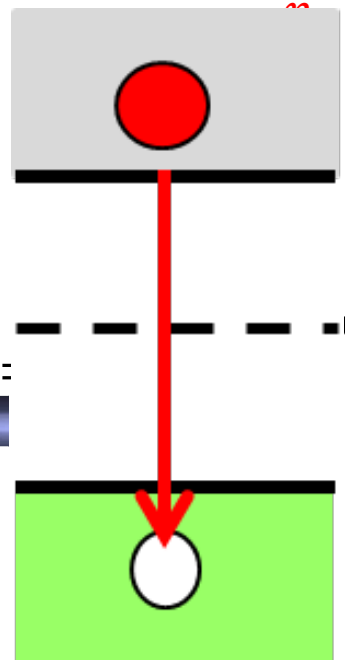

n_T electron-filled traps

p_T hole-filled (empty) traps

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

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

N_T

$c_n n_1 = n_i^2$

p_T

c_n electron capture coef.

e_n electron emission coef.

c_p hole capture coef.

e_p hole emission coef.

$$R = -\frac{dp}{dt}$$

Rate of hole destruction
Net Recombination

$$n_T = \frac{c_n N_T n + c_p N_T p_1}{c_n (n + n_1) + c_p (p + p_1)}$$

n_T trap occupation for a given n,p

$$e_p = c_p\, p_1$$

$$e_n = c_n\, n_1$$

$$\left.\frac{\partial p}{\partial t}\right| = -c_p (p n_T - p_T p_1)$$

$$n_T = \frac{c_n N_T n + c_p N_T p_1}{A}$$

$$A = c_n (n + n_1) + c_p (p + p_1)$$