# Section 16
# Recombination & Generation
## 16.4 Direct and Auger Recombination

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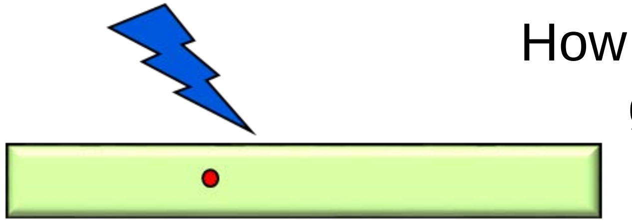
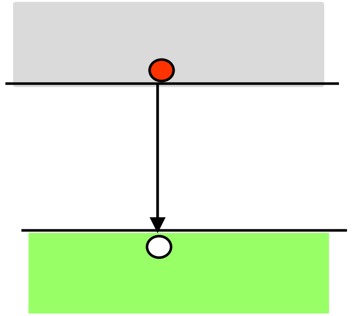
# Section 16
# Recombination & Generation



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
- 16.6
- 16.7

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

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

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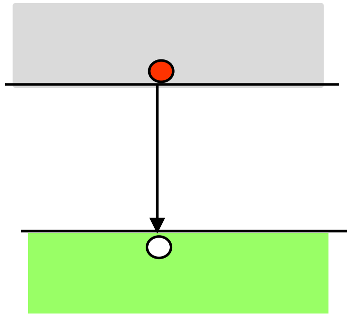
$$R = B\left(np - n_i^2\right)$$ B is a material property



Direct recombination at low-level injection

$$n_0 \ll (\Delta n = \Delta p) \ll p_0$$

$$R = B\left[\left(n_0 + \Delta n\right)\left(p_0 + \Delta p\right) - n_i^2\right] \approx Bp_0 \times \Delta n$$

Direct generation in depletion region

$$n, p \sim 0$$

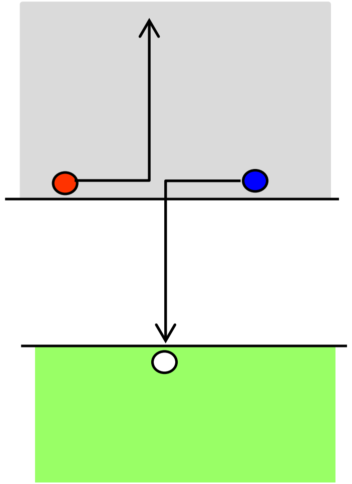
$$R = B\left(np - n_i^2\right) \approx -Bn_i^2$$

# Auger Recombination

2 electron & 1 hole

$$R = c_n\left(n^2 p - n_i^2 n\right) + c_p\left(np^2 - n_i^2 p\right)$$

$$c_n, c_p \sim 10^{-29}\ \text{cm}^6/\text{sec}$$



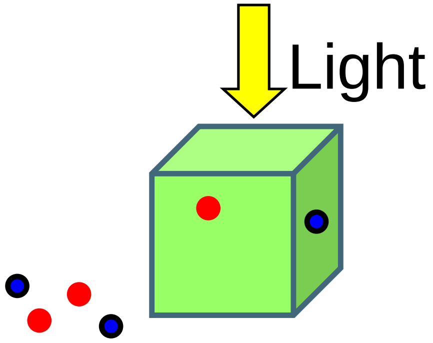
Auger recombination at low-level injection

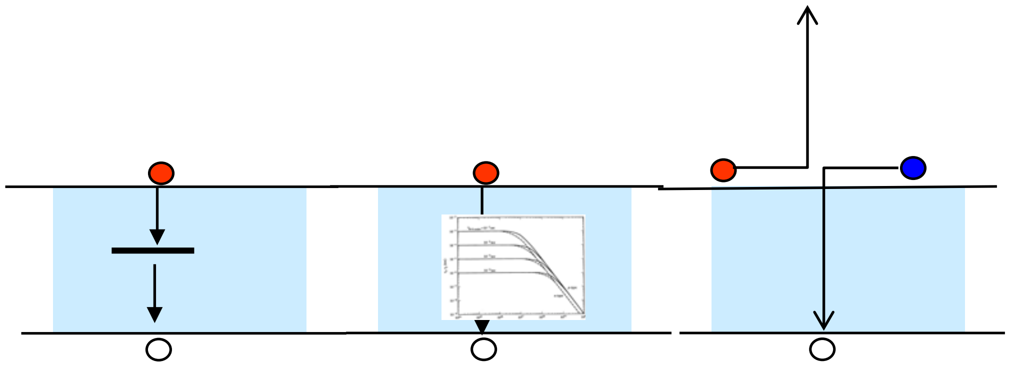
$$n_0 \ll (\Delta n = \Delta p) \ll (p_0 = N_A)$$

$$R \approx c_p N_A^2 \Delta n = \frac{\Delta n}{\tau_{auger}} \qquad \tau_{auger} = \frac{1}{c_p N_A^2}$$

Dominant recombination in heavy doped semiconductors

# Effective Carrier Lifetime

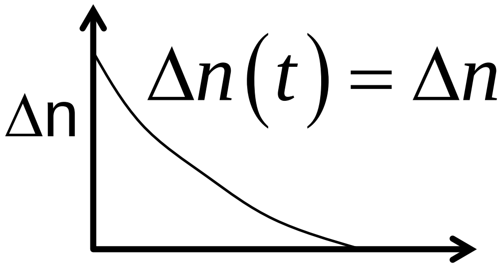


$$R = R_{SRH} + R_{direct} + R_{Auger}$$

$$= \Delta n \left( \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{direct}} + \frac{1}{\tau_{Auger}} \right)$$

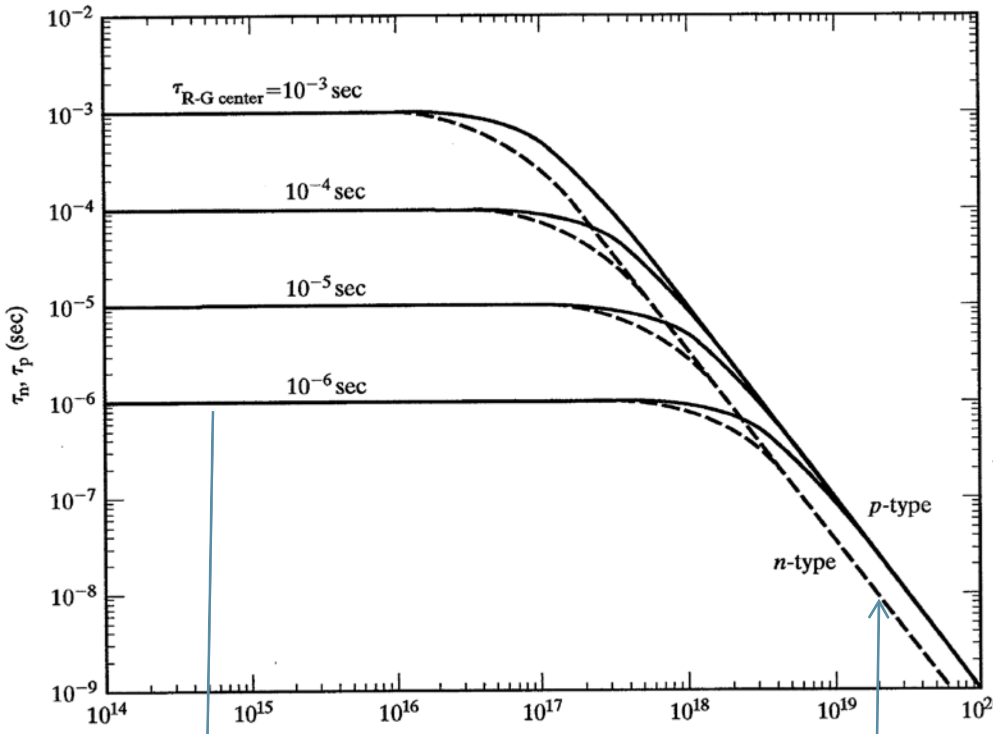
$$= \Delta n \left( c_n N_T + B N_D + c_{n,auger} N_D^2 \right)$$



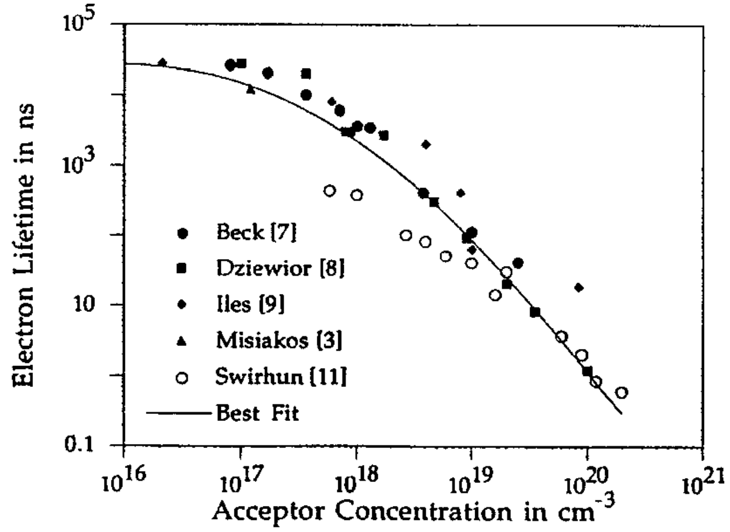

$$\Delta n(t) = \Delta n(t=0)\, e^{-\frac{t}{\tau_{eff}}}$$

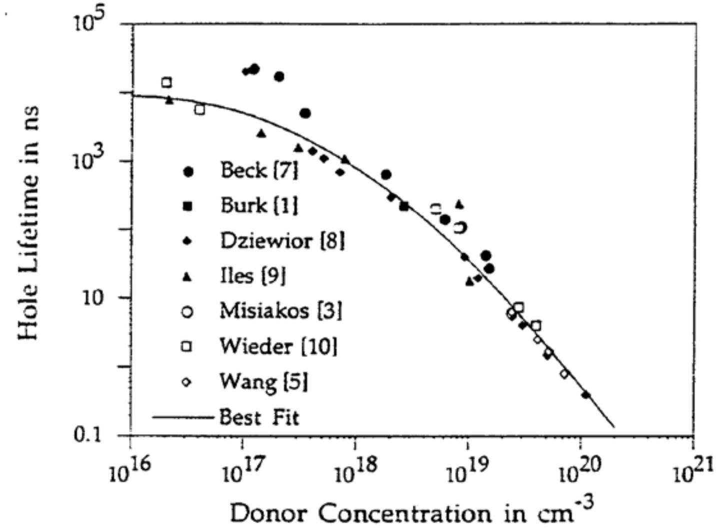
$$\tau_{eff} = \left( c_n N_T + B N_D + c_{n,auger} N_D^2 \right)^{-1}$$

# Effective Carrier Lifetime with all Processes




$N_D$



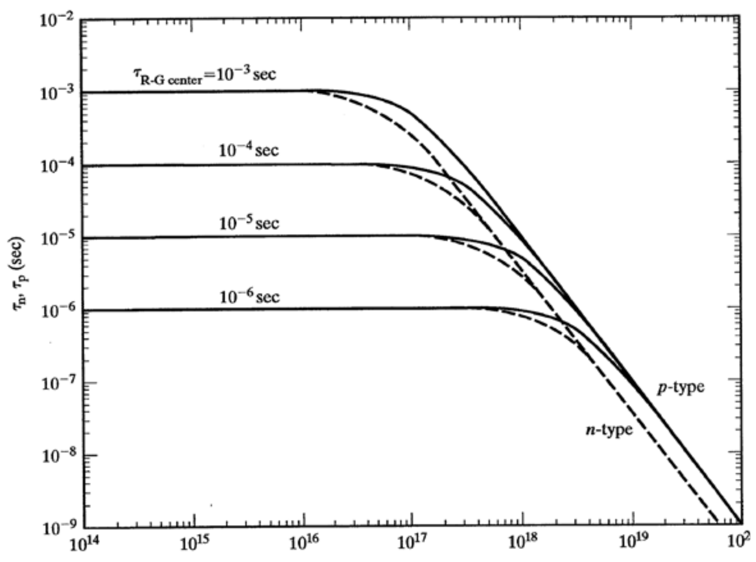



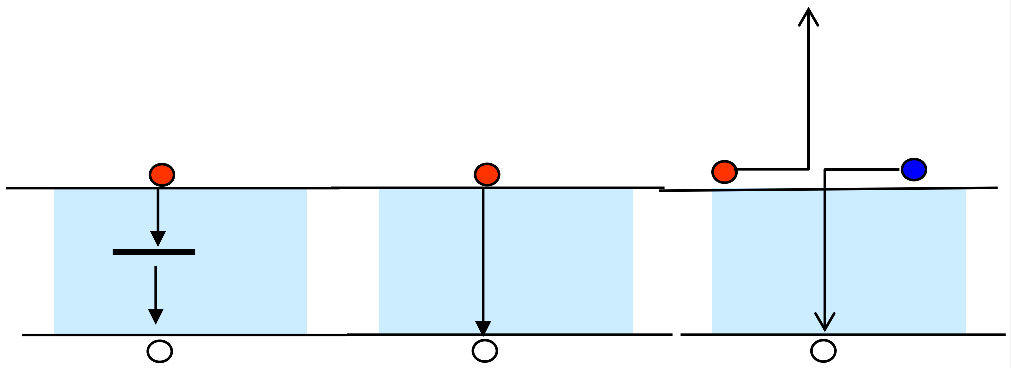

$$\tau_{eff} \approx c_{n,auger} N_D^{-2}$$

$$\tau_{eff} = \left( c_n N_T + B N_D + c_{n,auger} N_D^2 \right)^{-1}$$

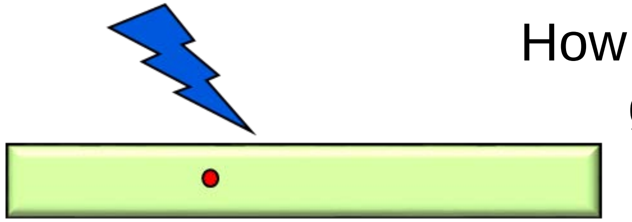
Elec. Dev. Lett., 12(8), 1991.

# Conclusion



- SRH is an important mechanism in important semiconductors like Si and Ge.
- SRH formula is complicated
  => simplification for special cases are often desired.
- Direct band-to-band and Auger recombination
  => can also be described with simple phenomenological formula.
- Expressions widely validated by measurements.



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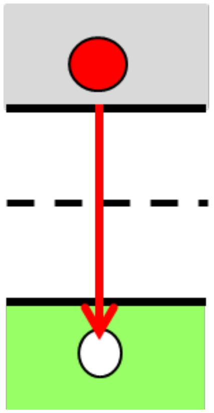

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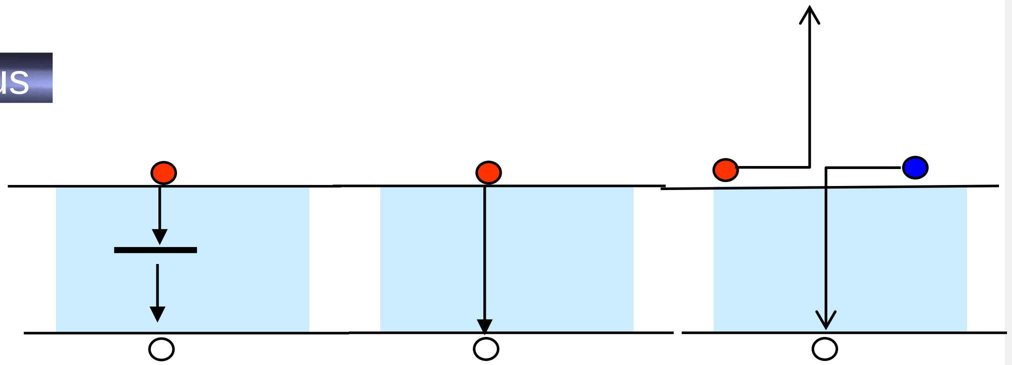

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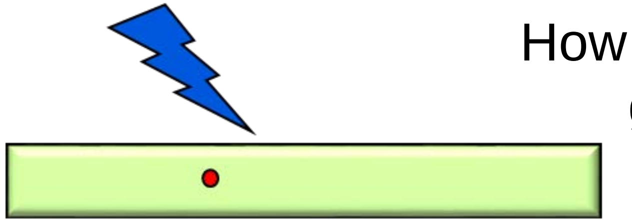

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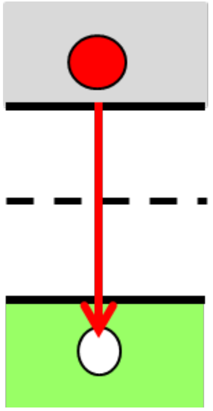

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