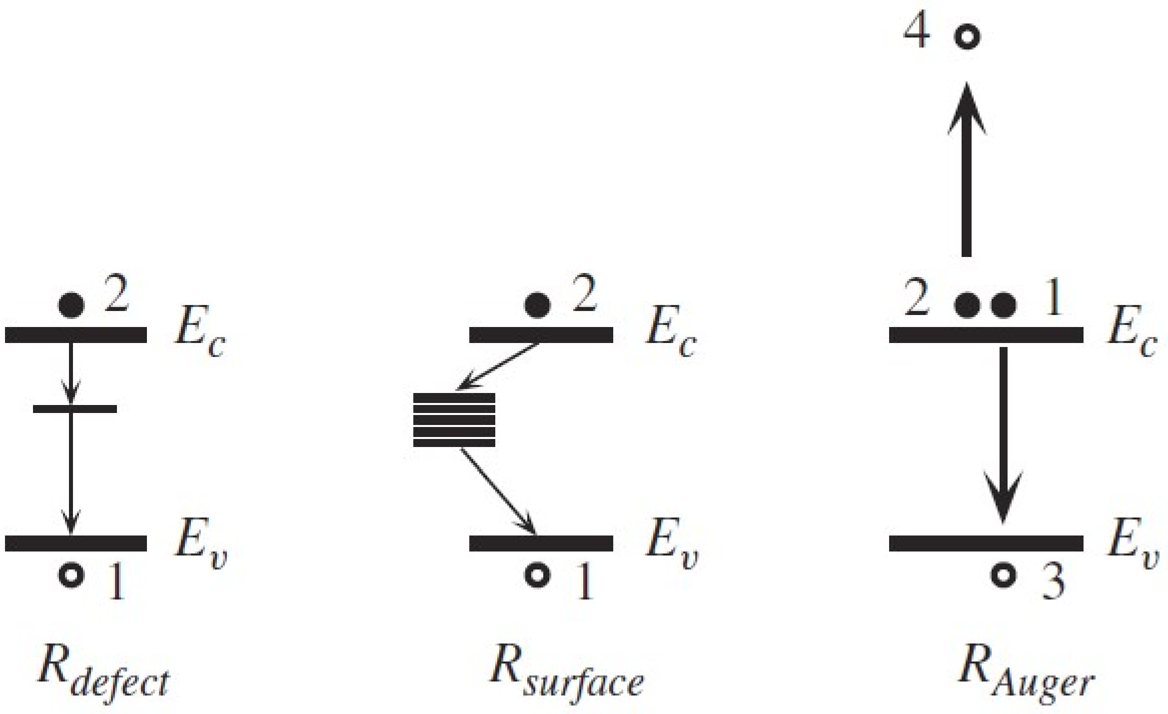
Lecture 11

- ☐ Nonradiative transitions

Nonradiative transitions

- ☐ Three common types of nonradiative transitions are defect and impurity recombination, surface and interface recombination, and Auger recombination.



Defect and impurity recombination

- ❑ Defect or impurity forms an energy level in the middle of the gap, which serves to trap an electron from the conduction band temporarily before releasing it to the valence band.
- ❑ The defect and impurity recombination rate is given by the Shockley-Read-Hall recombination theory.

$$R_d = \frac{NP - N_i^2}{(N^* + N)\tau_h + (P^* + P)\tau_e}$$

- ❑ Where N_i is the intrinsic carrier concentration, tau is the time required to capture an electron/hole to the traps, and the capture rate is proportional to the trap density. N^* and P^* is the carrier density that would exist if the Fermi level was aligned with the trap energy level, and either increases if the trap level is close to either band edge, and thus reducing the recombination rate.

Defect and impurity recombination

- ❑ Thus, the most effective non-recombination centers are those with energy levels close to the middle of the gap, so-called deep-level traps.
- ❑ At high injection levels, P=N>>N$_i$, N*, P*, then the relation simplifies to

$$R_d = \frac{N}{\tau_h + \tau_e} = A_{non} N$$

- ❑ At low injection levels, N*, P* are negligible. The non-equilibrium carrier densities is described by excess carriers

$$N = N_0 + \delta N; P = P_0 + \delta N;$$

Then, the recombination rate becomes

$$R_d = \frac{N_0 + P_0}{N_0 \tau_h + P_0 \tau_e} \delta N;$$

$$\Rightarrow$$

$$R_d = \frac{1}{\tau_h} \delta N, \text{ for n-doping}; R_d = \frac{1}{\tau_e} \delta N, \text{ for p-doping};$$

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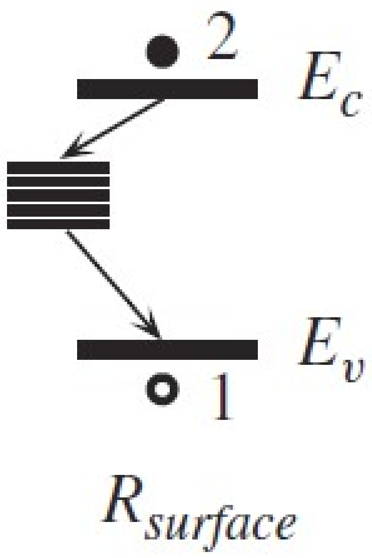
Defect and impurity recombination

- ☐ The defect density and the impurity density in semiconductors grown by MBE or MOCVD are usually less than 10^{15} cm^{-3}, and at most 10^{16} cm^{-3}. In most cases, the non-recombination rates are negligible in typical laser applications.
- ☐ The defect impacts the aging of lasers through the thermal variation induced stress to the crystal, and then leads to the dark-line effects. Finally, the threshold current increases and eventually the laser will die.
- ☐ In expitaxial growth of strained layers, when the layer is thicker than a certain critical value, the defect will propagates and the lattice will break to its native form without strain.

Surface and interface recombination



- ❑ On the surface of crystals, there are surface states in the form of minibands, as apposed to individual energy levels. This miniband leads to the surface or interface recombination. This kind recombination becomes stronger when the device dimension is reduced (high surface to volume ratio).
- ❑ Interface recombination is minimal in usual materials, but is a problem in the regrowth technology.

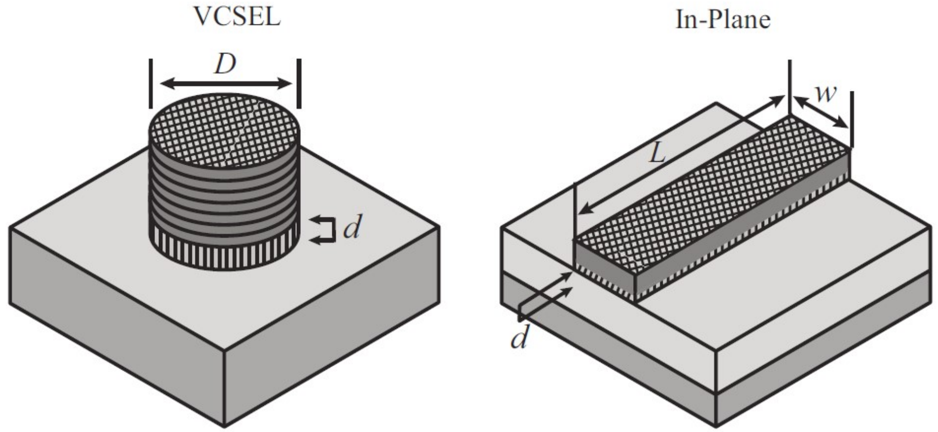
- ❑ The surface recombination is described by the capture velocity, which is usually less than 10^6 cm/s, and at most 10^7 cm/s, limited by the thermal velocity of carriers

Surface and interface recombination

- ☐ From the Shockley-Read-Hall theory, the surface recombination rate per unit volume is

$$R_{sr} = \frac{a_s}{V}\frac{NP - N_i^2}{N/v_h + P/v_e}$$

- ☐ Where a_s is the surface area, V is the active region volume, v_h and v_e are the capture velocities.



$a_s = 4D \cdot d$ (square)

$a_s = \pi D \cdot d$ (circle)

$\frac{a_s}{V} = \frac{4}{D}$ (both)

$a_s = (2L + 2w) \cdot d$

$\frac{a_s}{V} = \frac{2}{w} + \frac{2}{L}$

Surface and interface recombination

- ☐ From the Shockley-Read-Hall theory, the surface recombination rate per unit volume is

$$R_{sr} = \frac{a_s}{V} \frac{NP - N_i^2}{N / v_h + P / v_e}$$

- ☐ Under high-level injection, P=N>>N$_i$,

$$R_{sr} = \frac{a_s}{V} v_s N$$

$$\frac{1}{v_s} = \frac{1}{v_h} + \frac{1}{v_e}$$

Surface and interface recombination

- The required surface recombination current and current density are

$$\frac{I_{sr}}{qV} = R_{sr} = \frac{a_s}{V} v_s N$$

$$\Rightarrow I_{sr} = a_s q v_s N;\ J_{sr} = a_s q v_s N \frac{d}{V}$$

- Under low injection level (not for laser),

$$R_{sr} = \frac{a_s}{V} \frac{N_0 + P_0}{N_0 / v_h + P_0 / v_e} \delta N$$

Surface and interface recombination

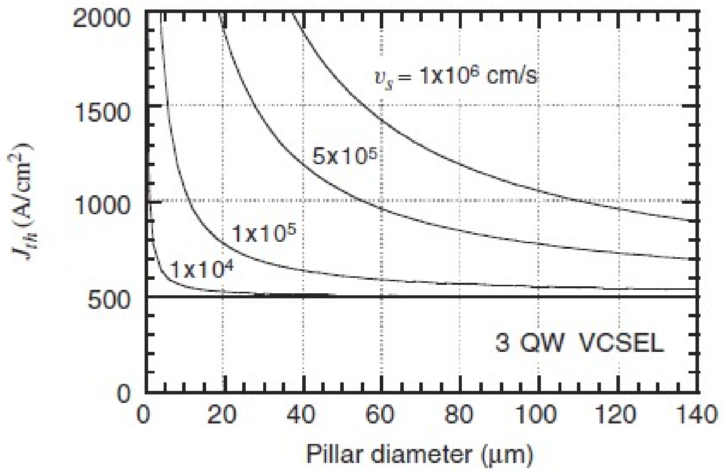
- ❑ Capture velocities are dependent on the material system

$$v_s \approx 4-6\times10^5 \text{ cm/s (GaAs, bulk and Qwell)}$$

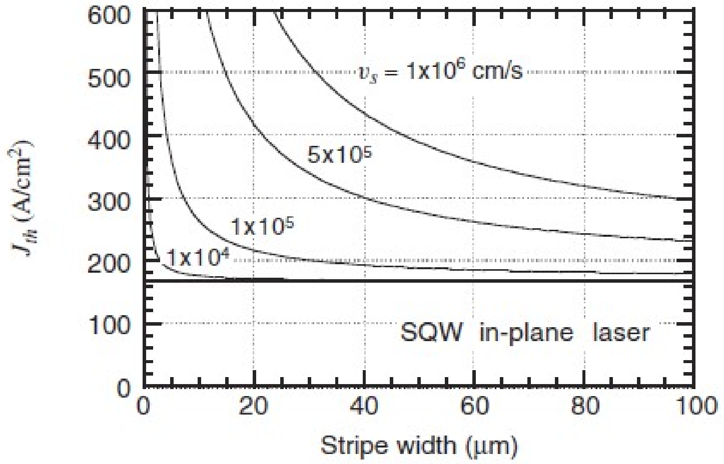
$$v_s \approx 1-2\times10^5 \text{ cm/s (InGaAs/GaAs, strained Qwell)}$$

$$v_s \leq 10^4 \text{ cm/s (InP, bulk)}$$

$$v_s \approx 5\times10^4 \text{ cm/s (GaN, bulk)}$$



- ❑ The surface recombination impacts is stronger for small size devices, in the aspect of the threshold;
- ❑ The threshold increases for high capture velocity



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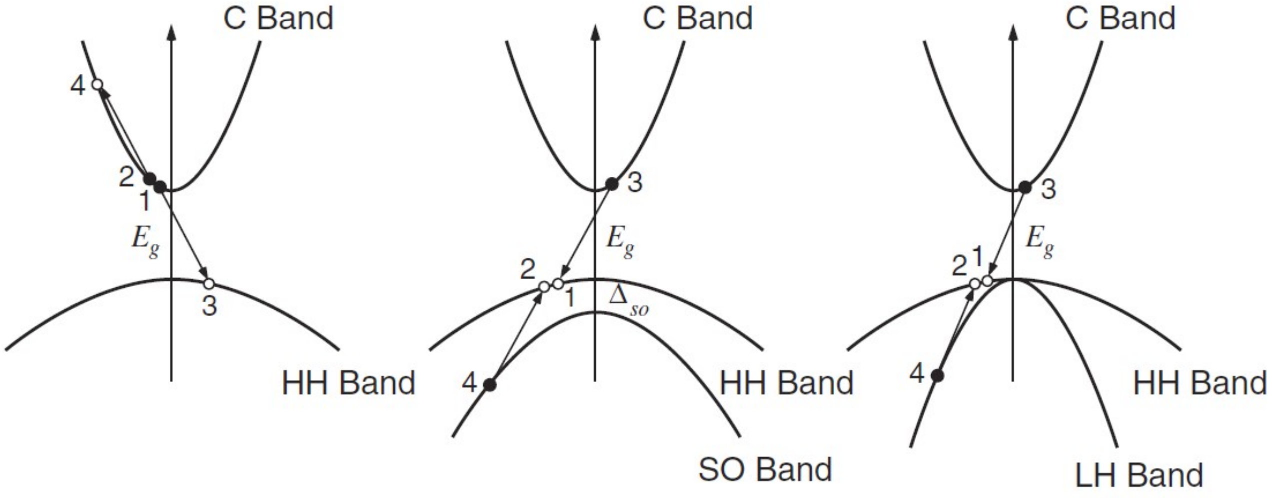
Auger recombination

- A collision between electrons that knocks one electron down to the valence band and the other to a higher energy state in the conduction band. The high-energy electron eventually thermalizes back down to the bottom of the conduction band, releasing the excess energy as heat to the crystal lattice.
- Three types Auger processes are CC->CH, HH->CS, HH->CL;



CCCH Process CHHS Process CHHL Process

- For Qwell lasers, it includes subband-to-subband, and bound-to-unbound transitions.

Auger recombination

- The Auger transition Fermi factors:

$$P_{1\to 3} = f_{c1} f_{c2} (1 - f_{v3})(1 - f_{c4}),\ \text{(CCCH)}$$

$$P_{3\to 1} = (1 - f_{v1})(1 - f_{v2}) f_{c3} f_{v4},\ \text{(CHHS and CHHL)}$$

- Using the Boltzmann approximation, (low carrier density, $E_{Fc} << E_c$, $E_{Fv} >> E_v$)

$$\frac{N}{N_c} \approx \exp\left(-\frac{E_c - E_{Fc}}{kT}\right); \quad \frac{P}{N_v} \approx \exp\left(-\frac{E_{Fv} - E_v}{kT}\right)$$

- The occupation probabilities:

$$f_c \approx \exp\left(-\frac{E - E_{Fc}}{kT}\right) = \frac{N}{N_c} \exp\left(-\frac{E - E_c}{kT}\right);$$

$$1 - f_v \approx \exp\left(-\frac{E_{Fv} - E}{kT}\right) = \frac{P}{N_v} \exp\left(-\frac{E_v - E}{kT}\right);$$

Auger recombination

- Then, the transition probabilities (the fourth is assumed always available) are

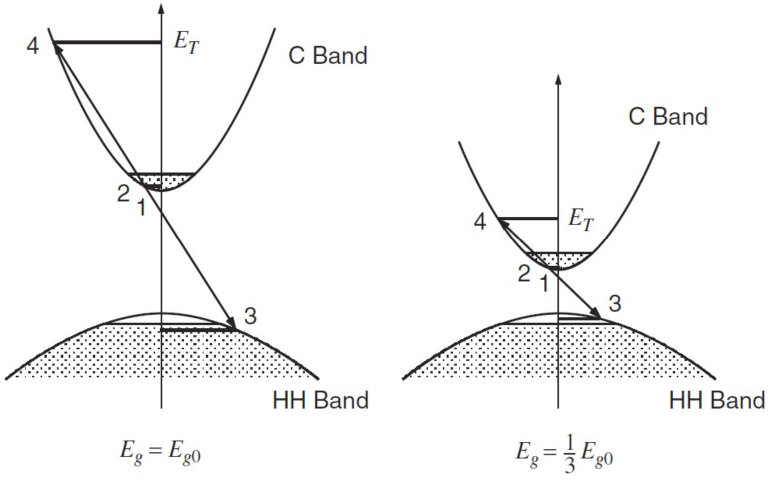
$$P_{1\to 3} = \frac{N^2 P}{N_c^2 N_v} \exp\left(-\frac{\Delta E_1 + \Delta E_2 + \Delta E_3}{kT} \right), \text{ (CCCH)}$$

$$P_{3\to 1} = \frac{N P^2}{N_c N_v^{\ 2}} \exp\left(-\frac{\Delta E_1 + \Delta E_2 + \Delta E_3}{kT} \right), \text{ (CHHS and CHHL)}$$

- That is, the CCCH process is proportional to N^2P, while the CHHS and CHHL processes are proportional to NP^2.
- The probability increases exponentially with the temperature.
- It is higher for carriers close to the band edge.

Auger recombination

- The Auger recombination strongly depends on the bandgap of the material, due to the energy and momentum conservation. The Auger recombination occurs closer to (not at) the band edge, where there are more electrons and holes.



- For narrow gap materials, the Auger recombination rate is higher due to the more presence of holes at state 3 for the same overall carrier density (CCCH).
- For narrow gap materials, the initial electron states 1 and 2 are closer to the band edge, further enhancing the Auger recombination rate due to more carriers.

Auger recombination

- The energy conservation of the CCCH process requires that (E_c is the reference)

$$\Delta E_1 + \Delta E_2 = \Delta E_4 - \left(E_g + \Delta E_3\right) \Rightarrow$$

$$\Delta E_1 + \Delta E_2 + \Delta E_3 = \Delta E_4 - E_g$$

- The Auger recombination is maximized when Delta_E4 is minimized. The mimimum value is referred as the threshold energy E_T for the Auger process.

$$E_T = \frac{2m_c + m_H}{m_c + m_H} E_g \quad \text{(CCCH)}$$

$$E_T = \frac{2m_H + m_c}{2m_H + m_c - m_S} \left(E_g - \Delta_{so}\right) \quad \text{(CHHS)}$$

$$E_T = \frac{2m_H + m_c}{2m_H + m_C - m_L} E_g \quad \text{(CHHL)}$$

- The threshold energy is proportional to the bandgap.

Auger recombination

- ☐ The maximum probability of CCCH Auger transition is at the threshold energy

$$P_{1\to 3} \approx \frac{N^2 P}{N_c^2 N_v} \exp\left(-\frac{E_T - E_g}{kT}\right)$$

$$= \frac{N^2 P}{N_c^2 N_v} \exp\left(-\frac{aE_g}{kT}\right)$$

$$\text{with } \; a = \frac{E_T}{E_g} - 1, \; (0.1 \sim 0.2)$$

- ☐ It is clear that the maximum probability for Auger transitions increases exponentially as the bandgap is decreased. So Auger recombination is a severe problem for long-wavelength lasers. (example)

Auger recombination

- Another Auger transition involves phonons, which assists the momentum conservation. Thus, make the Auger transition less sensitive to the bandgap and temperature. However, it is much weaker than that only includes electrons/holes.

- Phonon-assisted Auger transition is only important for large gap materials, low carrier densities, and/or low temperatures. Otherwise, it is less likely to occur overall, since it involves an additional particle.

Auger recombination

- ☐ The Auger recombination rate per unit volume is empirically given by

$$R_A = C_n N^2 P + C_p N P^2;$$

- ☐ In lightly doped active region, N=P at high injection level:

$$\boxed{\begin{aligned} &R_A = CN^3 = \frac{I_{Auger}}{qV}; \\ &C = 10^{-29}\ \text{cm}^6/\text{s} \sim 10^{-28}\ \text{cm}^6/\text{s} \end{aligned}}$$

$$C = 2-3\times 10^{-29}\ \text{cm}^6/\text{s (bulk 1.3 InGaAsP)}$$

$$C = 7-9\times 10^{-29}\ \text{cm}^6/\text{s (bulk 1.55 InGaAsP)}$$

$$C = 4-5\times 10^{-30}\ \text{cm}^6/\text{s (bulk GaAs)}$$

$$C = 2\times 10^{-30}\ \text{cm}^6/\text{s (InGaN Qwell)}$$

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- ☐ Low-dimensional structure and strained structure

  can reduce the Auger recombinations.

Auger recombination

- In common III-V semiconductors, the CHHS process dominates the Auger recombination process, while the CCCH process is one order of magnitude smaller. The CHHL process is several orders of magnitude smaller, and thus is negligible.