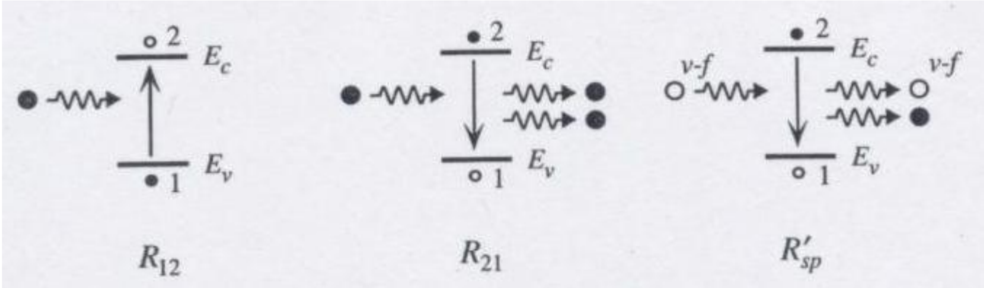
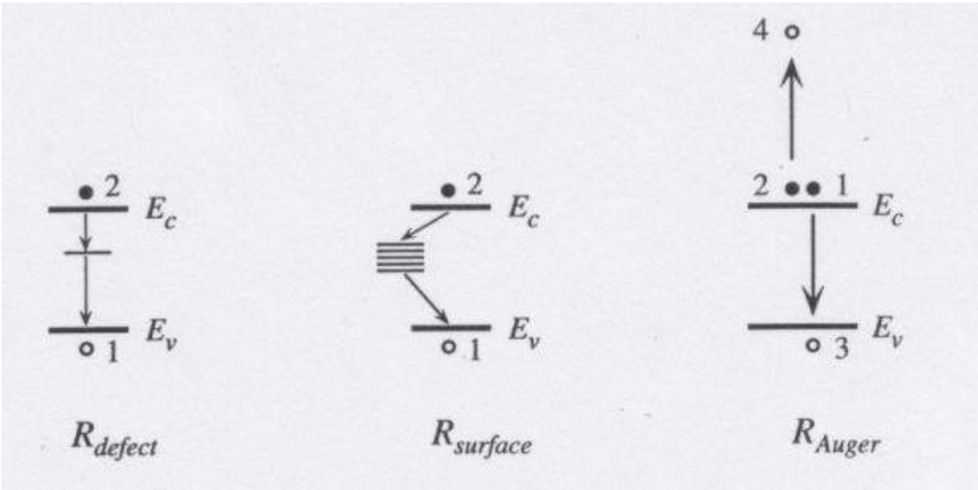
ECE 227B

1/20/2010

Radiative and nonradiative transitions

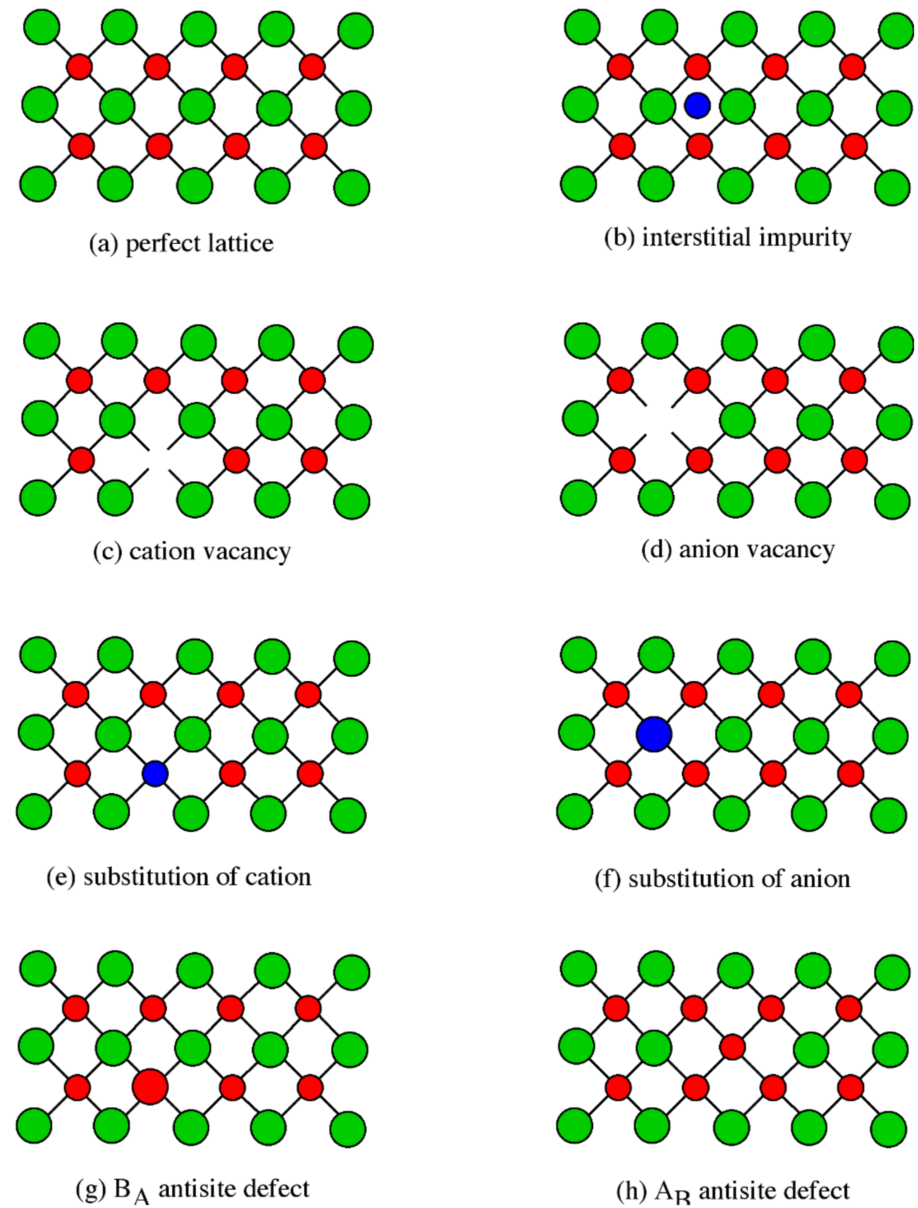
- Radiative transitions
  - Stimulated emission
    - Optical gain
  - Spontaneous emission
- Non-radiative transitions
  - Minimize in laser diodes
  - Need tools to quantify
  - Three main processes:
    - Defect
    - Surface
    - Auger





Defect and Impurity Recombination

- Energy level in the middle of the gap
- Causes
  - Lattice defects (void, extra atom)
    - Dangling bonds
  - Impurities
    - Similar to dopants (but middle of the gap)
      - Oxygen (particularly bad in Al compounds)



Shockley-Read-Hall theory

- 4 possible transition rates
- Setting the rates equal in thermal equilibrium
  - Recombination rate derived
- In Boltzman limit
  - τ_h – time to capture hole (all traps full)
  - τ_e – time to capture electron (all traps empty)
  - N* and P* calculated as if $E_f = E_{trap}$
    - Only deep level traps important, dominate

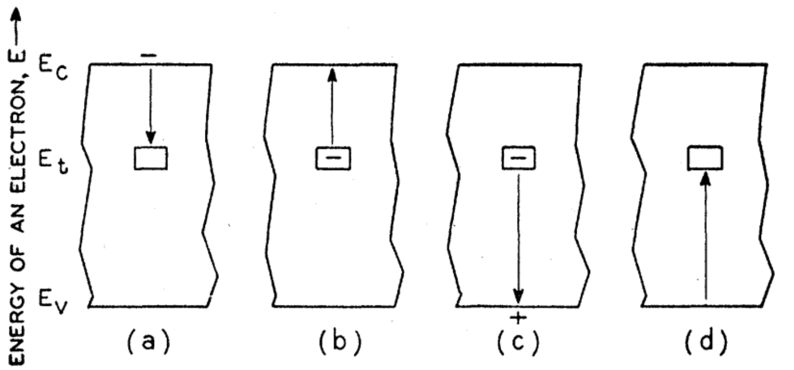


FIG. 1. The basic processes involved in recombination by trapping: (a) electron capture, (b) electron emission, (c) hole capture, (d) hole emission.

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

SRH - limiting cases

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

- High level injection, $P=N \gg N_i$, N^*, P^*
  - Important for lasers

$$R_d = \frac{N}{\tau_h + \tau_e}.$$

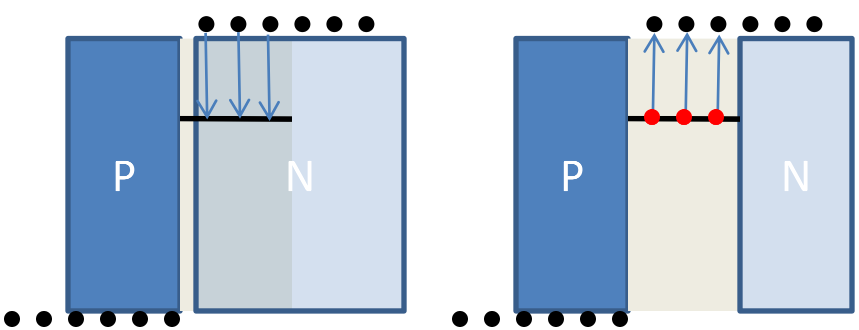
- Low level injection, deep traps (neglect N_i, N^*, P^*)

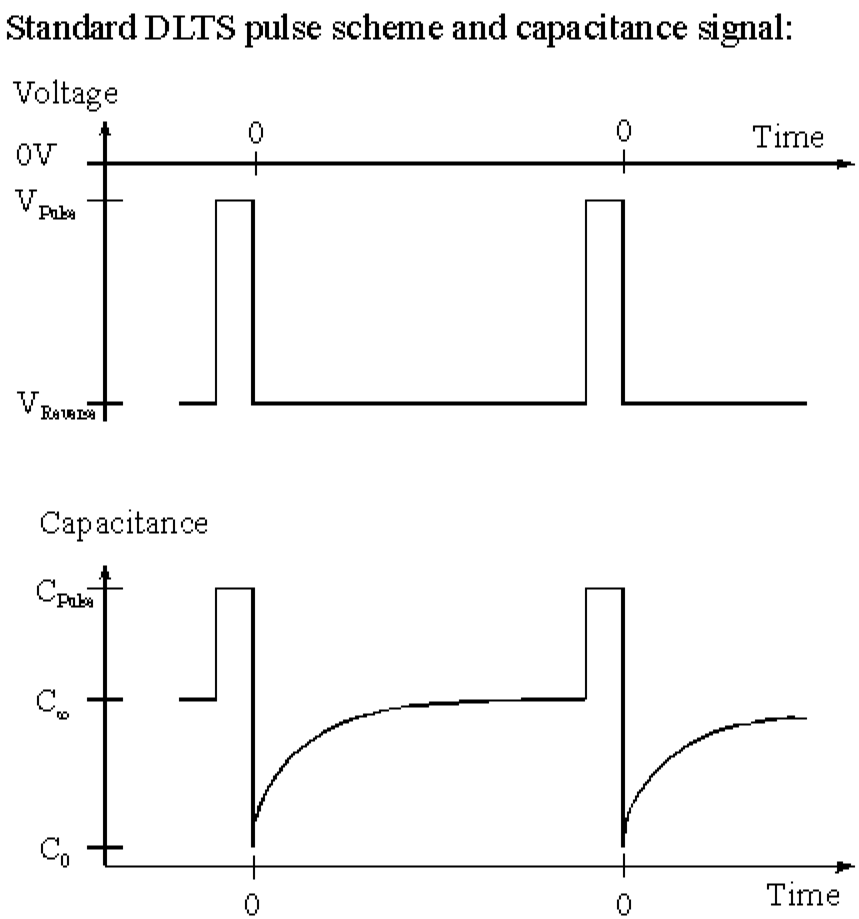
$$R_d = \delta N \frac{N_0 + P_0}{N_0\tau_h + P_0\tau_e}$$

- In both cases
  - Linear dependence with excess carrier density
  - Lifetime increases with increased pumping

Deep level transient spectroscopy

- A typical method for evaluating deep energy levels
- Method – decrease and increase reverse bias voltage
  - Measure capacitance





Conclusions

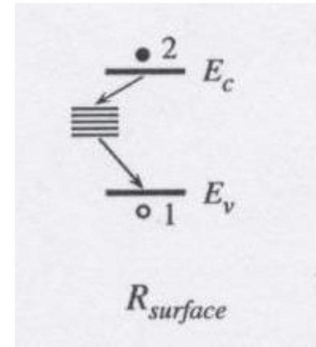
- Recombination problem for minority carriers
  - In heavily doped materials, majority current unaffected
    - Doping concentration
- Avoid defective/impure materials in active region
  - But cladding may be fine
- Modern growth techniques
  - 10^{16} cm^{-3} or better
  - Threshold current increase – indication of impurity/leak problems

Defects and Aging of Lasers

- With aging (15-30 years in service), thermal cycles cause stress to crystal
  - Stress causes small defects to spread and grow large
  - Dark line defects
- Strained layer materials
  - Thick strained layers full of defects
  - Techniques for blocking defect propagation exist
    - Example – GaAs/AlGaAs on Si substrate

Surface and Interface Recombination

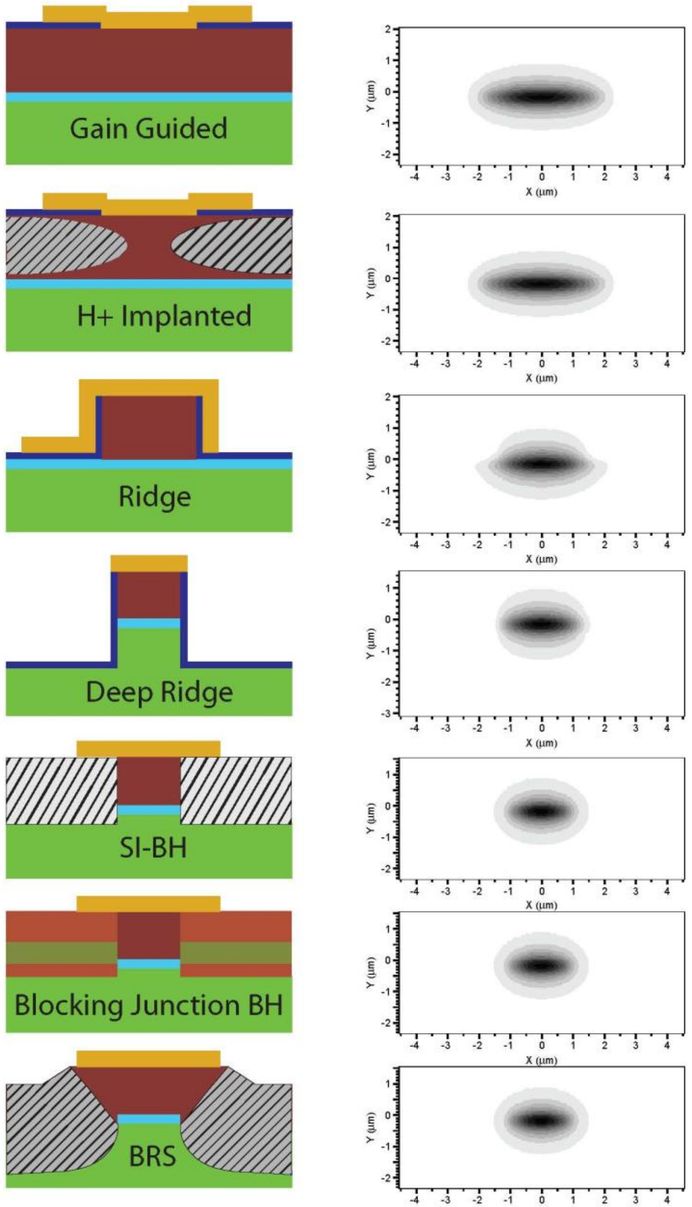
- Process analogous to defect and impurity recombination
- Cause – lattice termination
  - Surface
  - Interface between two materials



- Dangling bonds occur in very high density
  - They form a miniband (not a single trap level)
- Characterized by surface (sheet) density
  - Very important process in cases where surface to volume ratio is large (VCSEL)
- Regrowth

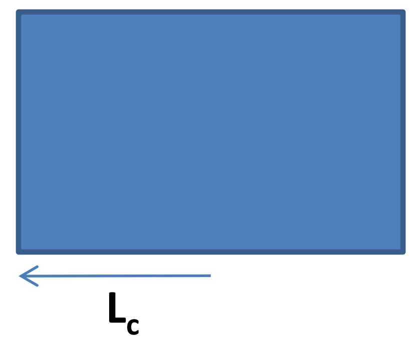
Examples – In plane confinement

- Gain guided and implanted
  - Apertured current
- Ridge
  - Current and weak photon
- Deep ridge
  - Strong photon, current
- Buried
  - All tree confinement types



Surface and Interface Recombination

- Quantification and description accomplished via SRH theory
  - Instead of capture time, we define a capture rate, $\mathbf{L_c/\tau}$ and capture length, $\mathbf{L_c}$
  - Capture velocity
    - Larger length means larger rate



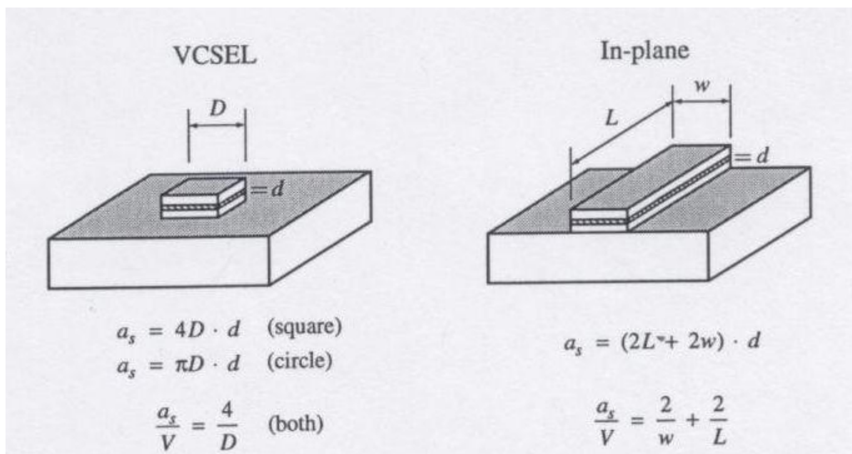
  - Velocity significance
    - Maximum capture velocity is determined by average [thermal velocity]
    - Upper limit of 10^7 cm/s
      - In most semiconductors, capture velocity 10x or more smaller

Surface and Interface Recombination

- From SRH theory, using capture velocities

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

- First term, a_s/V, distributes exposed surface area over volume



- Again, surface recombination important for small pillar, narrow ridge cases

High injection case and current

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

- High level injection, P=N >> N_i
  - Important for lasers

$$R_{sr} = \frac{a_s}{V} v_s N \qquad \frac{1}{v_s} = \frac{1}{v_h} + \frac{1}{v_e}$$

- Surface recombination velocity is average for holes and electrons (limited by slower carriers)
- Surface recombination current is given by

$$I_{sr} = q a_s v_s N \quad \text{and} \quad J_{sr} = q v_s N \left(\frac{a_s}{V} d \right)$$

- Question: how to estimate carrier density?

Measurement of recombination velocity

- Low level injection

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

  - Measured value depends on the type of doping (v_s)

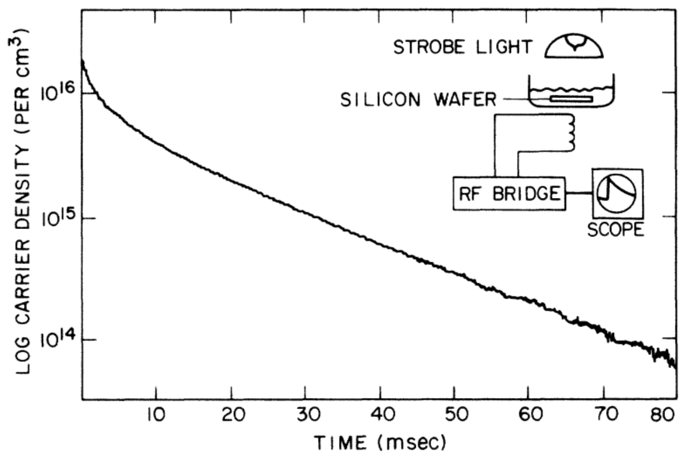
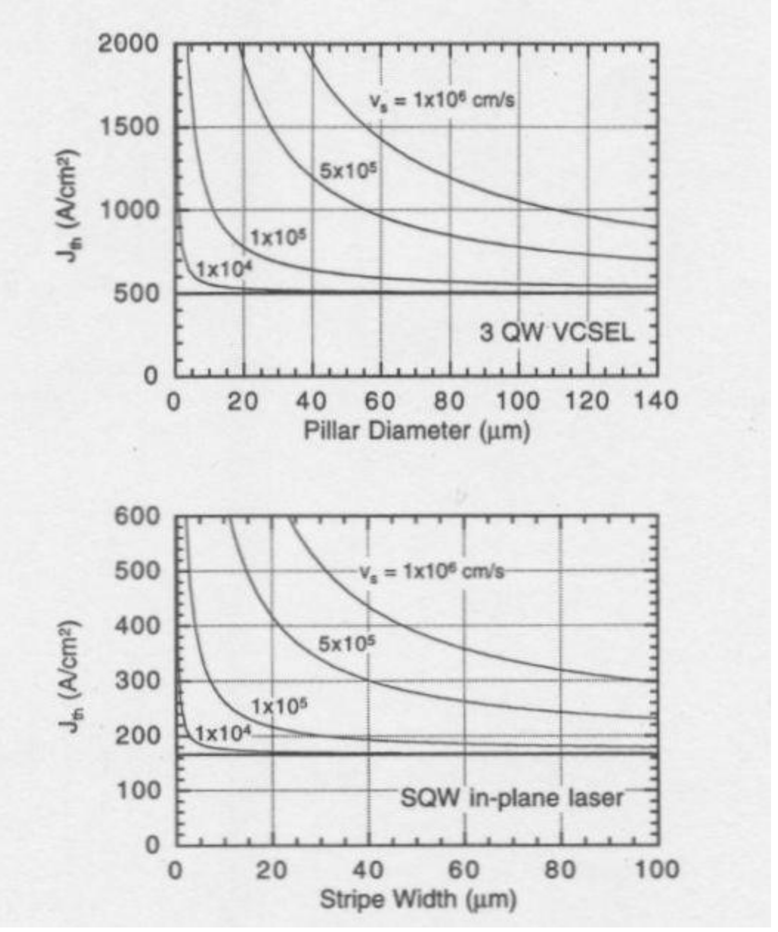


FIG. 1. Semilog plot of the carrier-density decay from a particularly long-lived 250-μm-thick Si⟨111⟩ sample immersed in HF acid.

- Threshold current measurements vs laser geometry
  - Losses vs geometry an issue

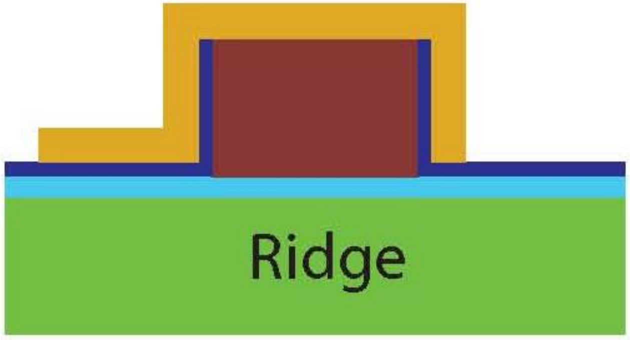
Values for common materials

- GaAs – v_s = 4-6 10^5 cm/s
- InGaAs – v_s = 1-2 10^5 cm/s
- InP – v_s = <10^4 cm/s
- Estimate on the right
  - Double VCSEL threshold for 10 um pillar
- Small VCSELs of interest
  - Option I – don't etch through active
  - Option II - passivate



Lateral outdiffusion

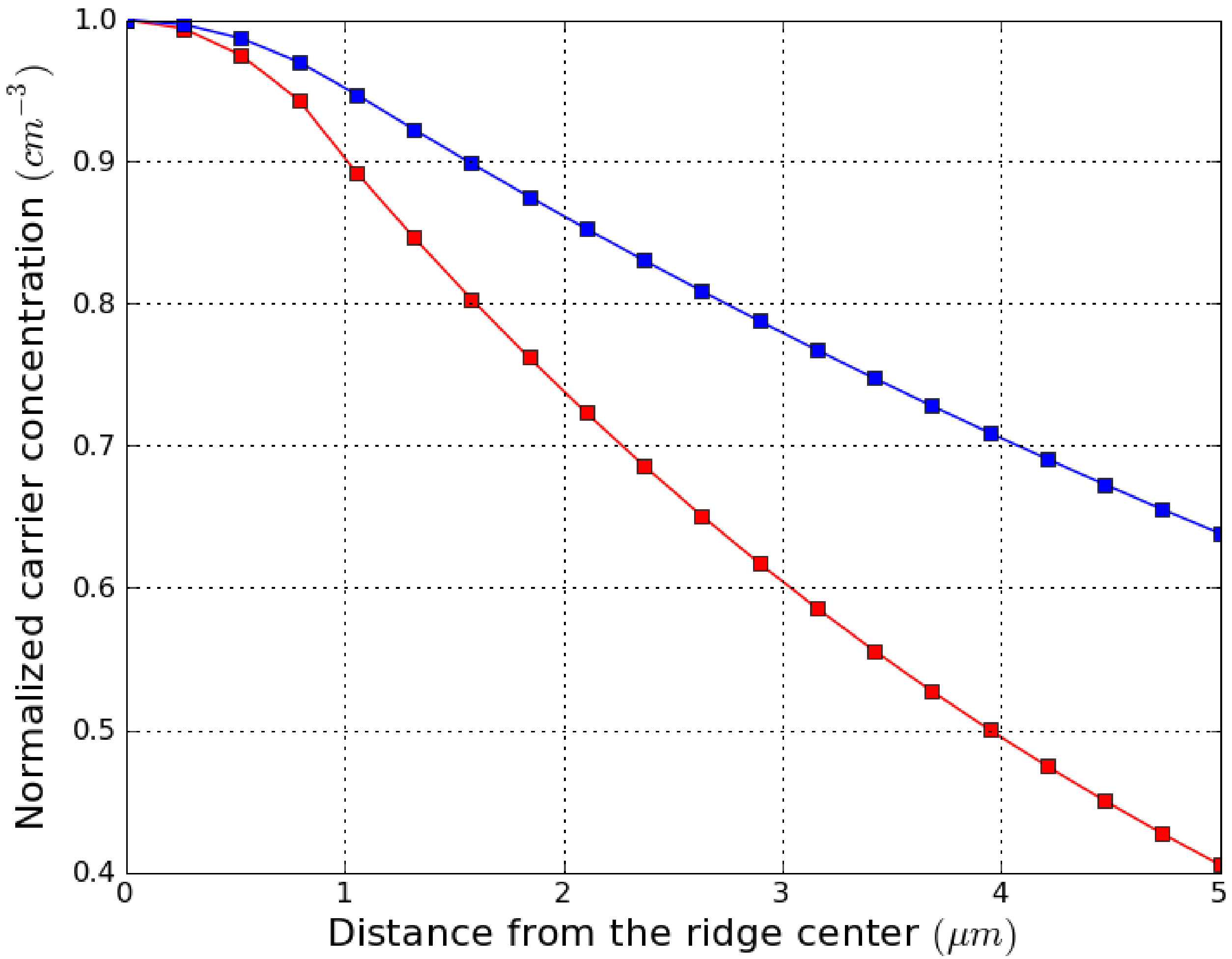
- No surface recombination
- Still, carriers escape through diffusion
- Ambipolar diffusion of carriers equivalent to surface recombination



$$v_{sD} \equiv \frac{D_{np}}{L_{np}} = \sqrt{\frac{D_{np}}{\tau_{np}}} = 1\times10^5 \text{ cm/s} \cdot \left[\frac{D_{np}}{20 \text{ cm}^2/\text{s}} \frac{2\mu\text{m}}{L_{np}}\right]$$

- Example

Solutions



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
1
2
3
4
5
Normalized carrier concentration (cm^{-3})
Distance from the ridge center (μm)