Section 15
Introduction to Non-Equilibrium

15.2 Recombination & Generation Overview

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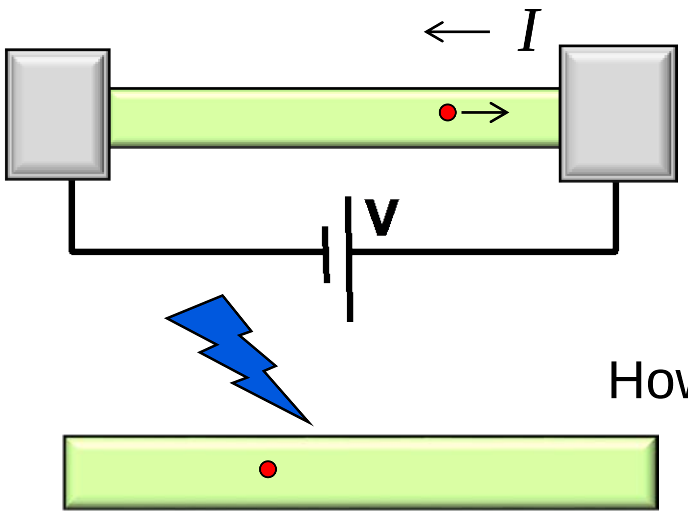
Section 15
Introduction to Non-Equilibrium



$$I = G \times V$$
$$= q \times n \times v \times A$$

charge density velocity area

How does the system go BACK to equilibrium?

- Materials, composition, crystals
- Tabulated for "known" bulk materials

⇒ Quantum Mechanics Mechanics
- Concepts of density of states and masses

⇒ Equilibrium Statistical Mechanics
- Occupation factors

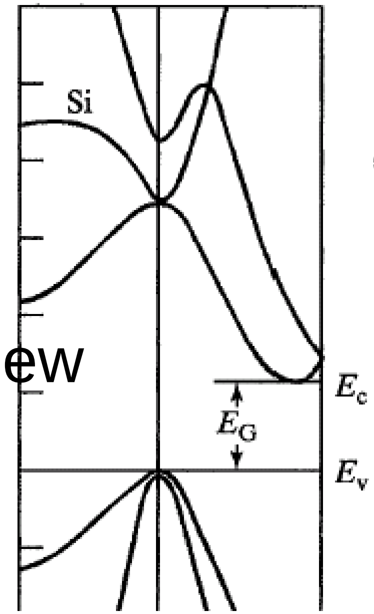
Transport with scattering, non-equil, Stat. Mech.
- Drift-diffusion eq. with recombination-generation

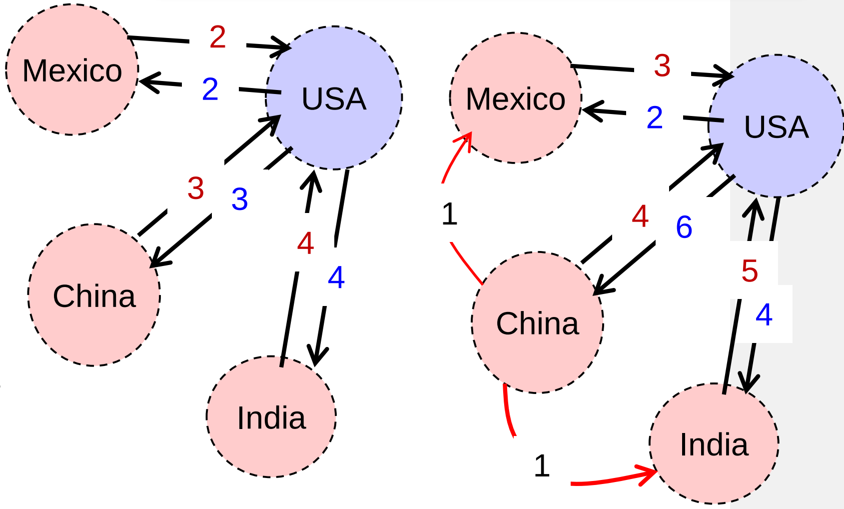
Understanding device transport
- Diodes, BJT/HBT, MOS

Video

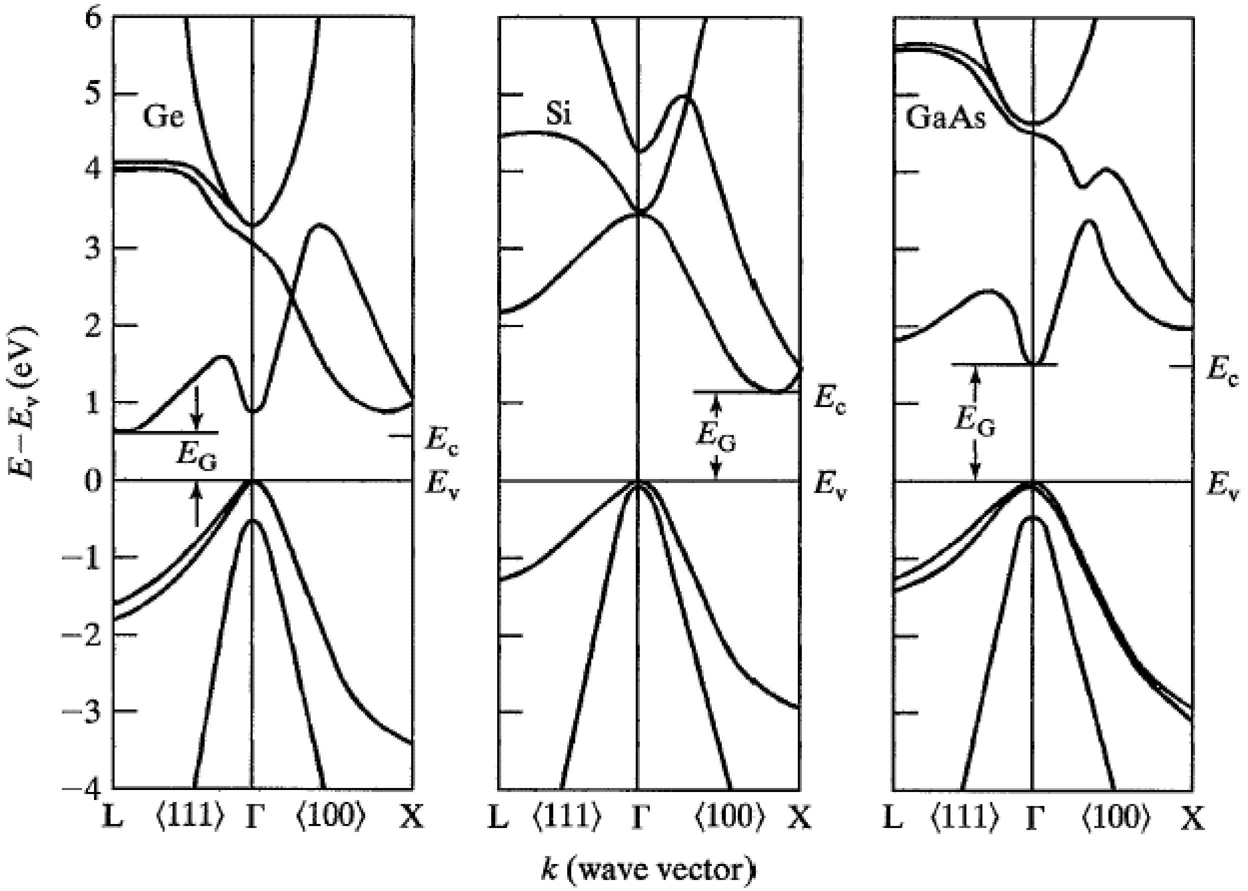
Video

- 15.1 Steady State, Transient, Equilibrium
  - »Critical conceptual differences!
  - »Need to understand these!
- 15.2 Recombination & Generation Overview



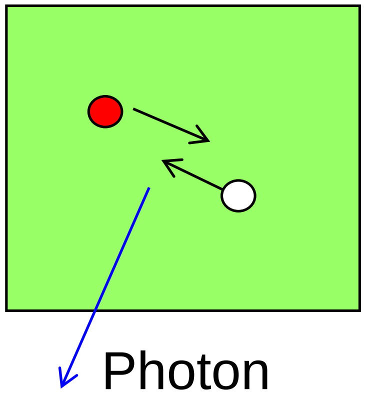


Indirect vs. Direct Bandgap



The top & bottom of bands do not align at same wavevector k for indirect bandgap material

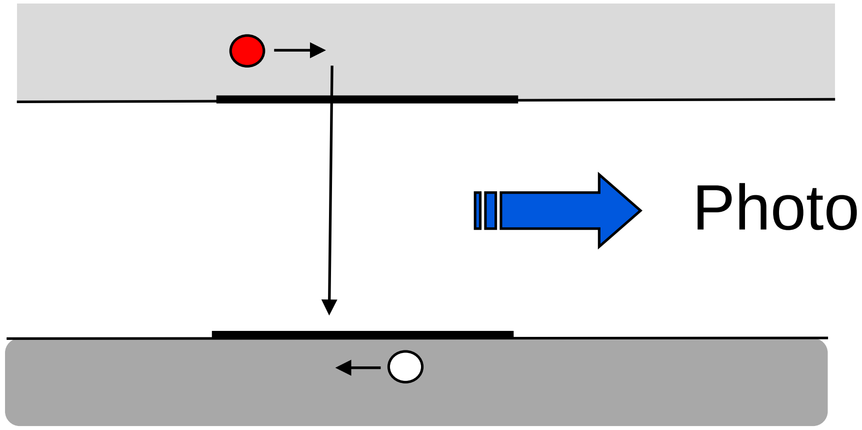
In real space …



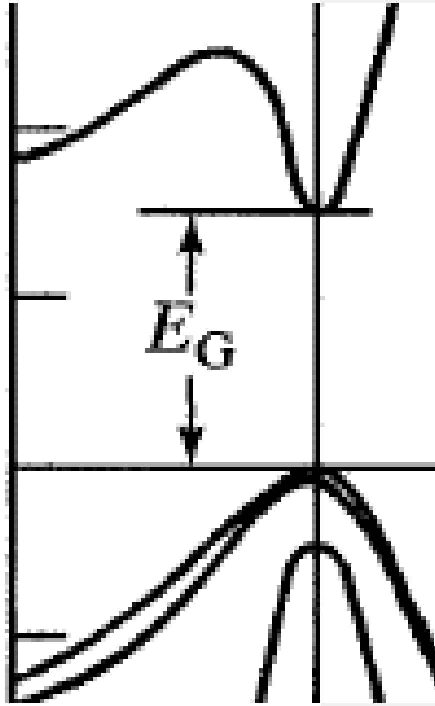
Photon

e and h must
have same wavelength
1 in 1,000,000 encounters

In energy space …



Photon



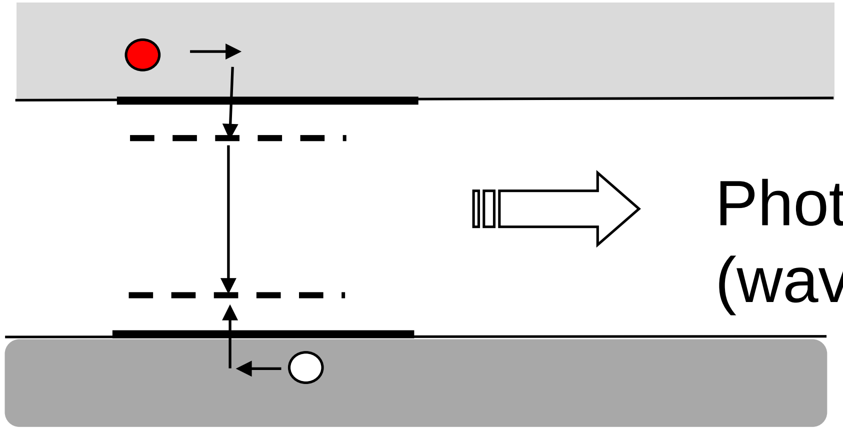
Direct transistion –
direct gap material

GaAs, InP, InSb (3D)

Lasers, LEDs, etc.

Direct Excitonic Recombination

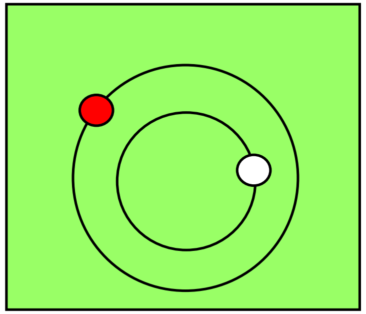
In energy space …



Mostly in 1D systems
Requires strong
coulomb interactions

Photon
(wavelength reduced from bulk)

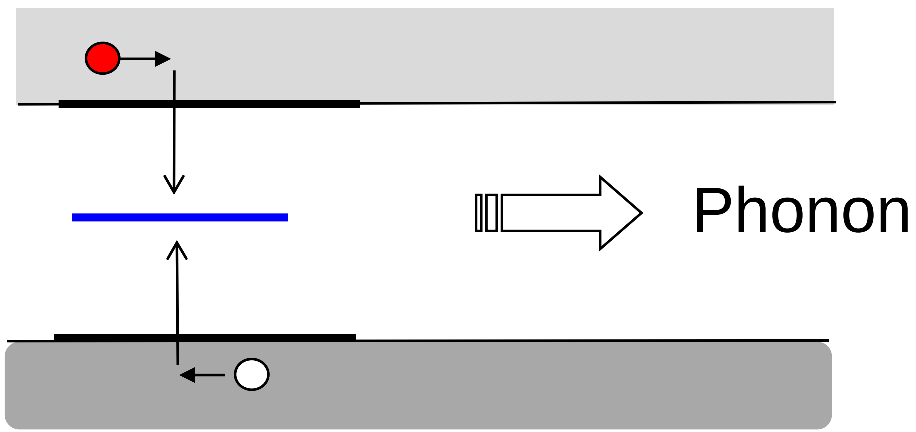
In real space …



CNT, InP, ID-systems

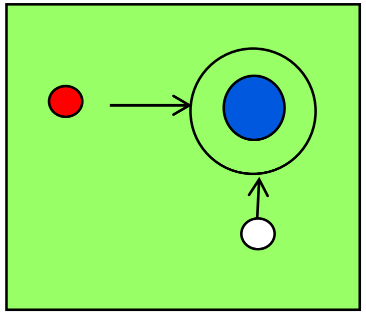
Transistors, Lasers, Solar cells, etc.

Indirect Recombination (Trap-assisted)



Trap needs to be mid-gap to be effective.
Cu or Au in Si

States close to Ec or Ev do not help efficiently.

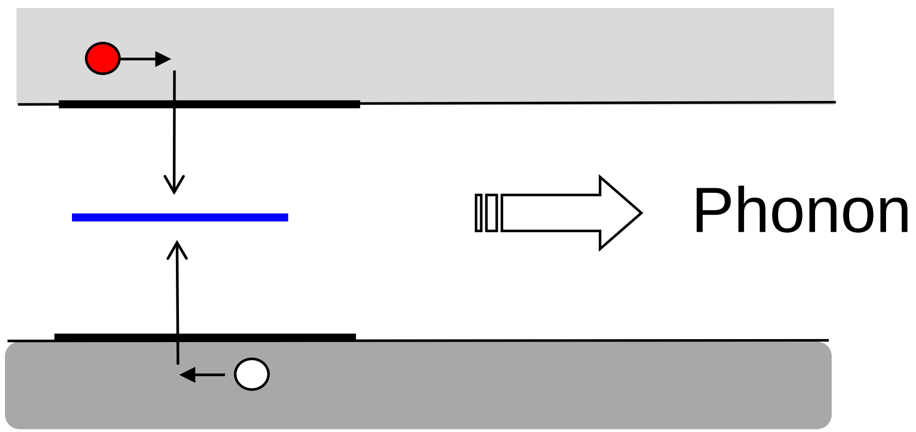


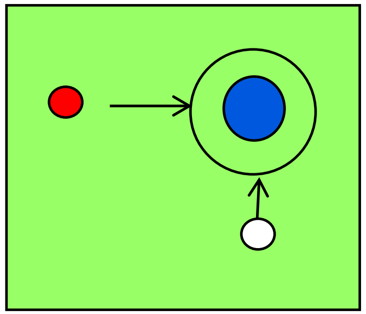
Ge, Si, ….

Transistors, Solar cells, etc.

Cu in Si is extremely efficient in providing recombination
Cu in Si was avoided completely for many years
Intel introduced Cu for interconnects – special precautions so Cu does not enter the Si.

Indirect Recombination (Trap-assisted)





Trap needs to be mid-gap to be effective.
Cu or Au in Si

States close to Ec or Ev do not help efficiently.
Ge, Si, …..

Transistors, Solar cells, etc.

Recombination rate is in general slower than direct via photon.

Why?

1 electron and one hole need to localize AND find a trap. … less likely event.

Cu in Si is extremely efficient in providing recombination
Cu in Si was avoided completely for many years
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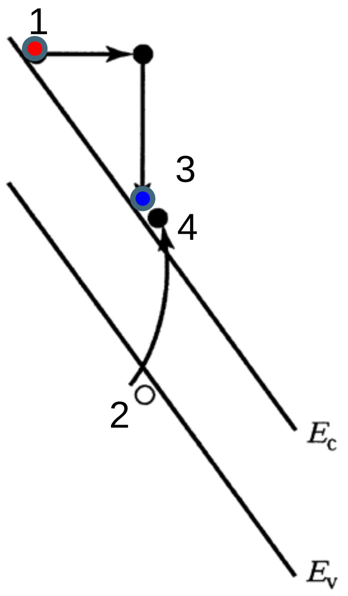
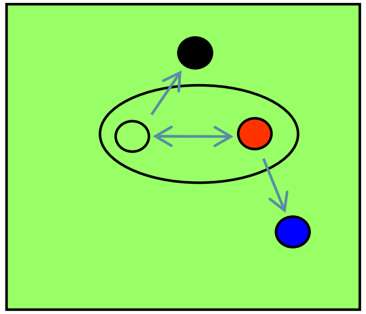
Impact Ionization - A Generation Mechanism

Requires very high electric field



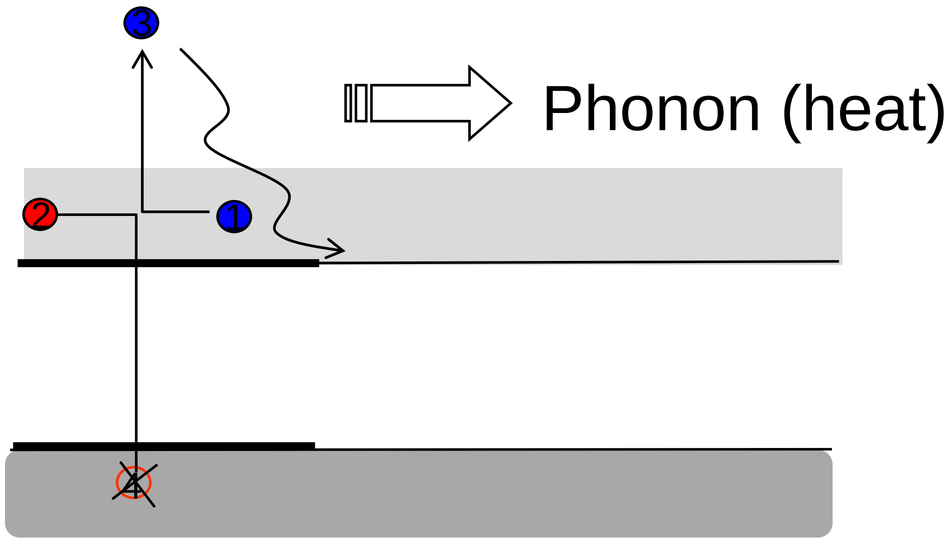
Inverse of the Auger recombination



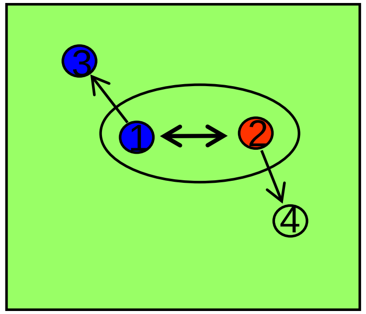
Si, Ge, InP

Lasers, Transistors, etc.

Auger Recombination



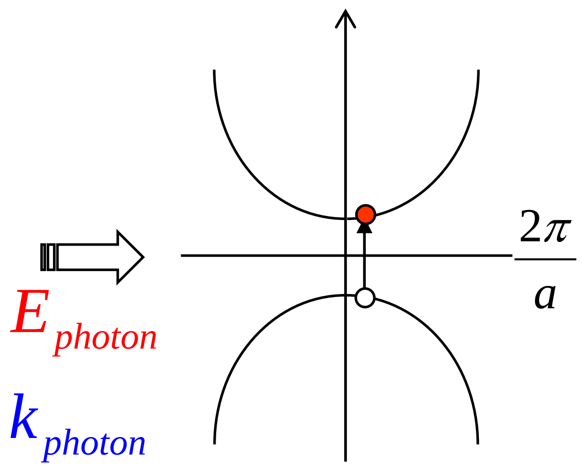
Requires very high electron density



InP, GaAs, …

Lasers, etc.

Photon Energy and Wavevector



$$E_V + E_{photon} = E_C$$

$$\hbar k_V + \hbar k_{photon} = \hbar k_C$$

$$E_{photon}(red\ HeNe):\ \lambda = 633nm$$

$$E_{photon}(green\ YAG):\ \lambda = 532nm$$

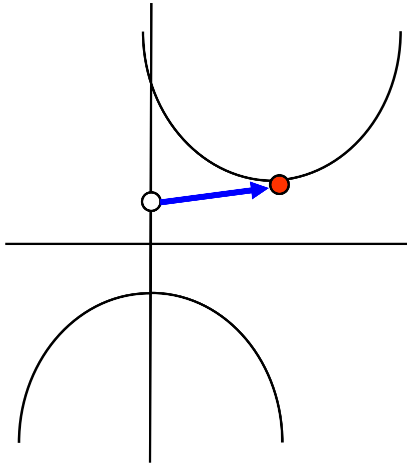
Si lattice: $a = 0.5nm$

$$k_{photon} = \frac{2\pi}{\lambda}$$

$$<< \frac{2\pi}{a}$$

Photon has large energy for excitation through bandgap, but its wavevector is negligible compared to size of BZ

Phonon Energy and Wavevector



$$E_V + E_{phonon} = E_C$$

$$\hbar k_V + \hbar k_{phonon} = \hbar k_C$$

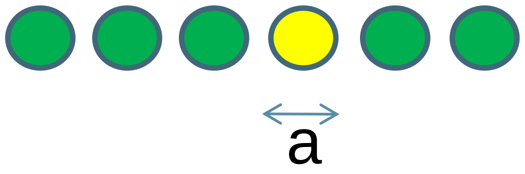
$v_{sound} \sim 10^3$ m/s << $v_{light} = c \sim 10^6$ m/s

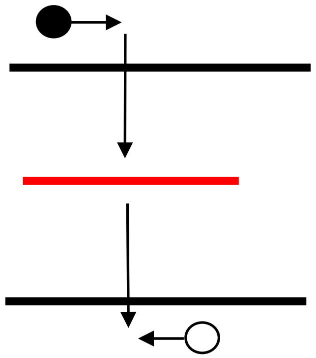
$\lambda_{sound} >> \lambda_{light}$

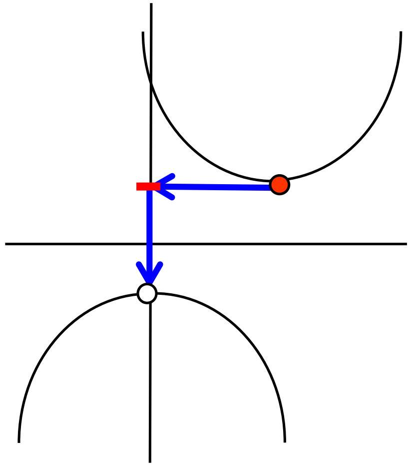
$$k_{phonon} = \frac{2\pi}{\lambda} = \frac{2\pi}{\hbar \upsilon_{sound} / E_{phonon}} \approx \frac{2\pi}{a} = \frac{2\pi}{5\times 10^{-4}\ \mu\text{m}}$$

Phonon has large wavevector comparable to BZ, but negligible energy compared to bandgap

Localized Traps and Wavevector





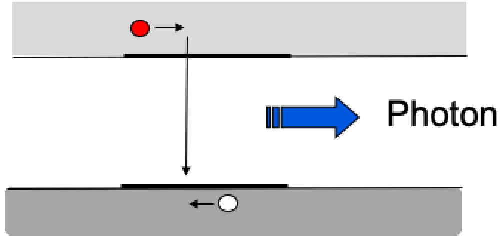


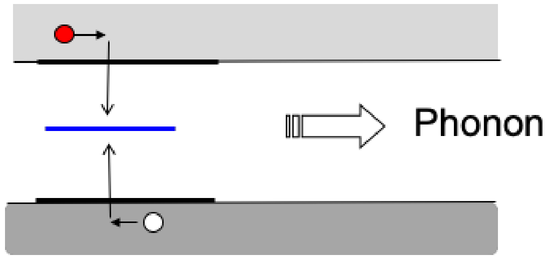
$$k_{trap} \approx \frac{2\pi}{a} \sim \frac{2\pi}{5\times10^{-4}\ \mu m}$$

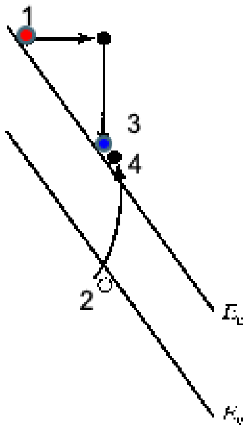
Trap provides the wavevector necessary for indirect transition

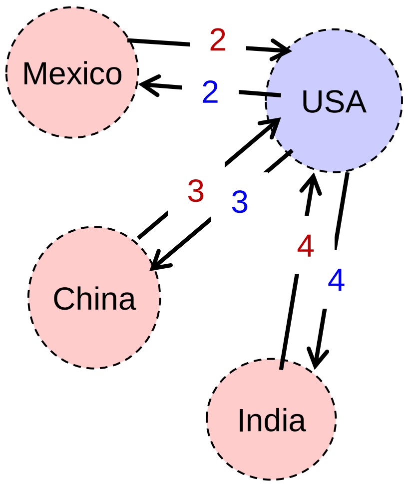
Conclusions

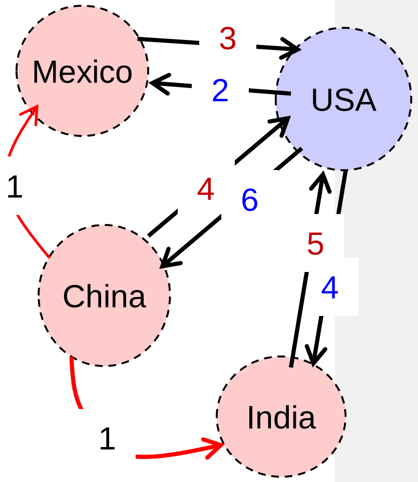
1) Concepts of equilibrium, steady state, and transient dynamics should be clearly understood.
2) There are wide variety of generation-recombination events that allow restoration of equilibrium once the stimulus is removed.
3) Direct recombination is photon-assisted, indirect recombination phonon assisted.











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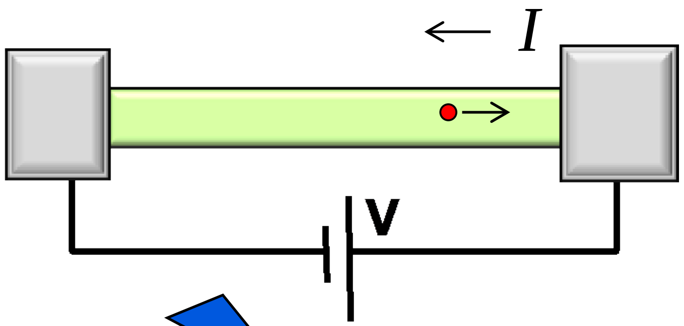

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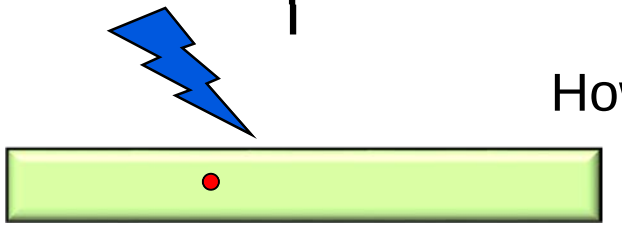
charge density velocity area



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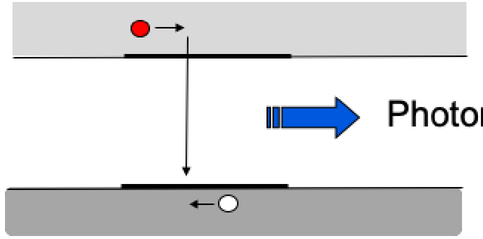

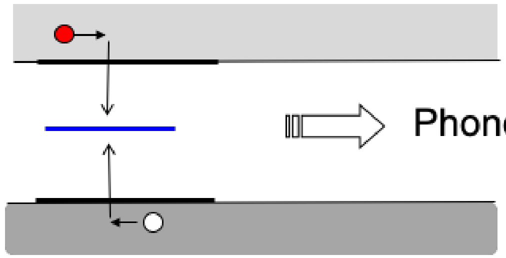

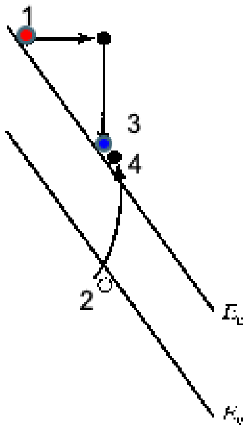

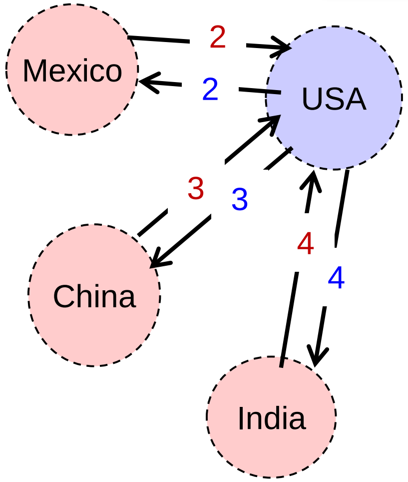

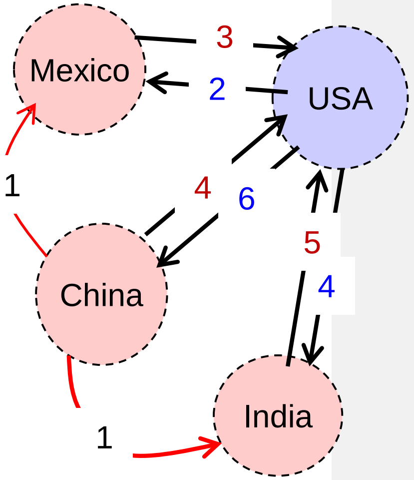

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Quantum Mechanics

density of states and masses

Section 16
Recombination & Generation

Transport with scattering, non-equil, Stat. Mech.

- Drift-diffusion eq. with **recombination-generation**

equilibrium?

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