# Excess carrier behavior in semiconductor devices

**Virtually all semiconductor devices in active mode involve the generation, decay, or movement of carriers from one region to another**

**Carrier population that is different from the population at rest (in an inactive state) is by definition, excess carriers**

**The excess carrier behavior determines how a device work**

# Outline

- **Introduction**
  - ***Devices in active states involve non-equilibrium, and/or non-uniform, and/or transient (non-steady state), and/or non-ohmic carrier injection***
- **Non-equilibrium carrier behavior**
  - **Distribution**
  - **Relaxation and recombination**
  - **Migration: drift and diffusion**
- **Some device examples**
  - **Photodetectors and switches, lasers and LEDs**
  - **Cathodoluminescence, FED displays**

# Introduction

- **Devices in active states can involve non-equilibrium, and/or nonuniform, and/or transient (non-steady state), and/or non-ohmic carrier injection**
- **Non-Ohmic examples:**

  **Optical injection**

  - **Laser, LED: electron-hole non-equilibrium, quasi Fermi level**
  - **Photoconductive detector: bipolar, carriers with non-uniform spatial distribution, transient with short pulses.**

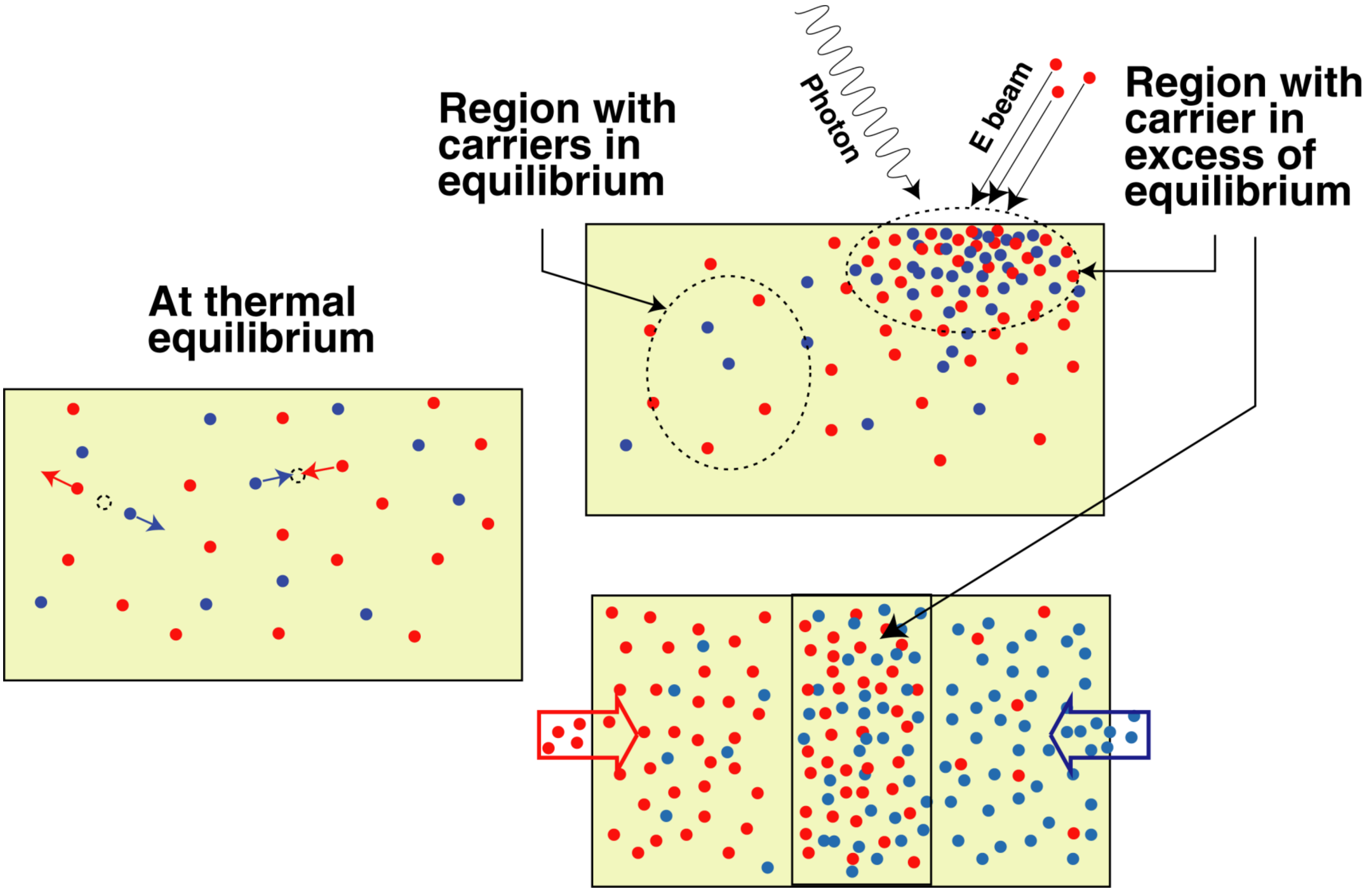
  **E-beam injection**

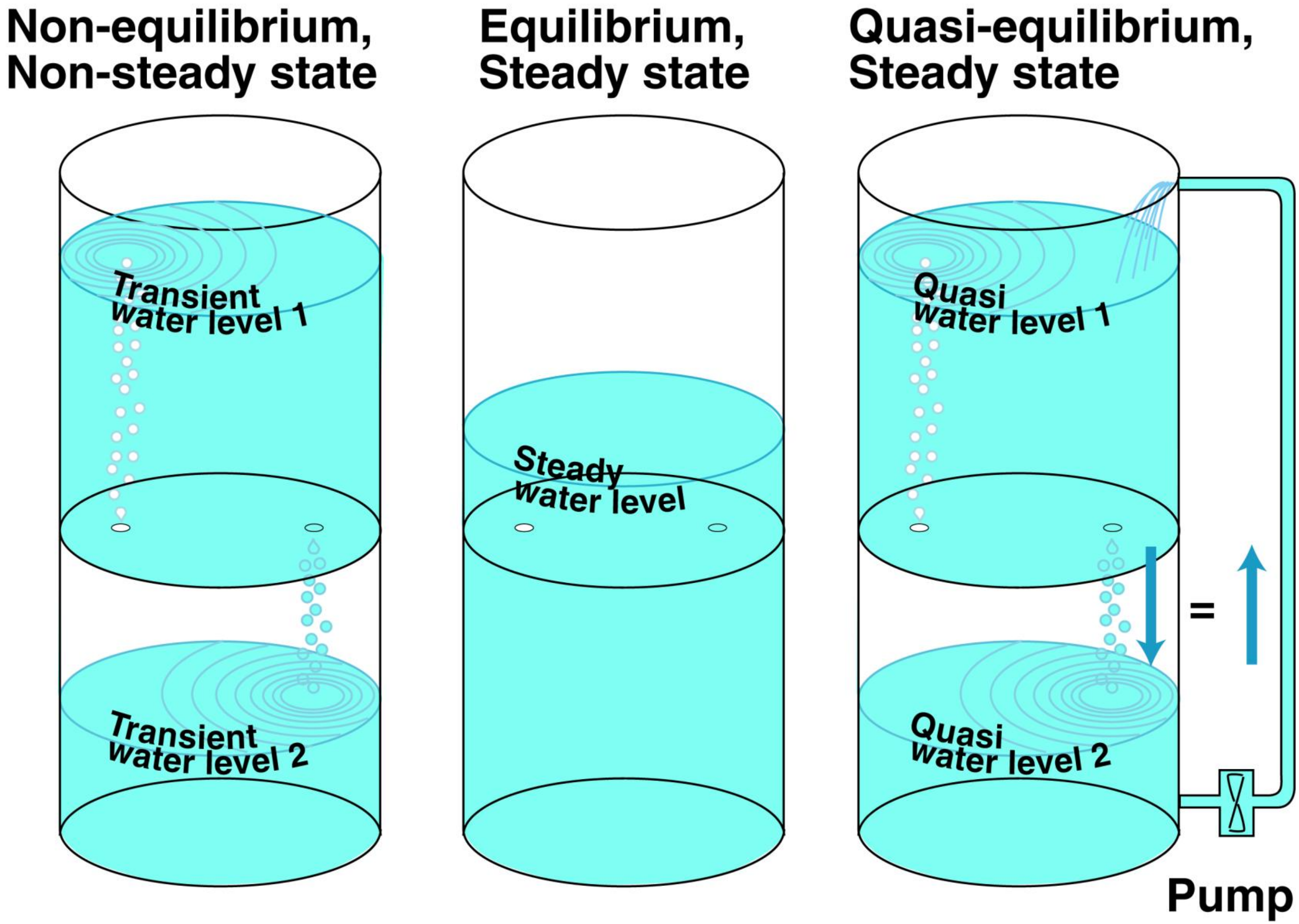
  - **Cathodoluminescence (TV screen, Field-emission display): electron-hole non-equilibrium, hot carriers.**

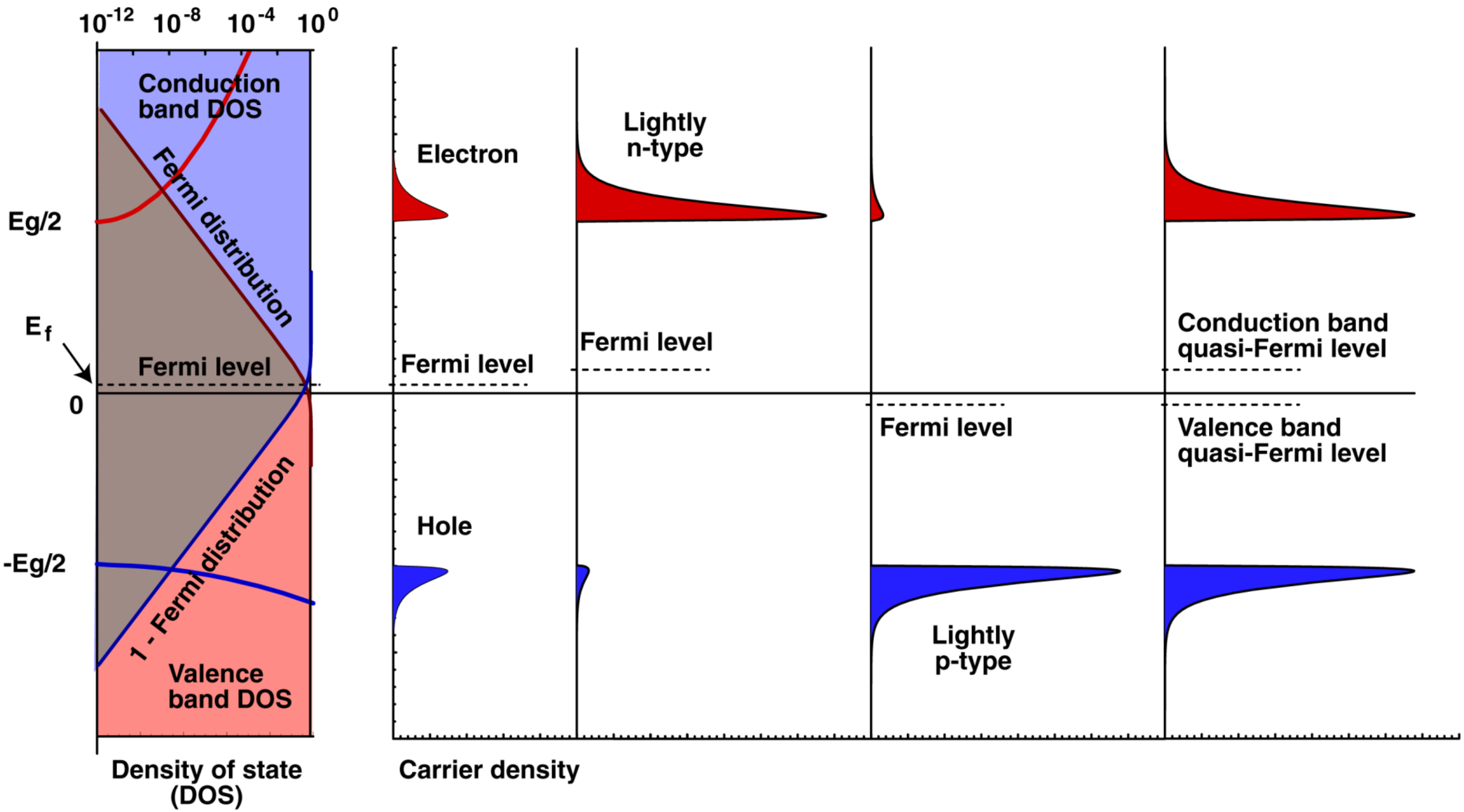
# Non-equilibrium carrier behavior
# Key Concepts

- **Excess carriers, quasi-Fermi levels, electron/hole plasma**
- **Carrier injection, ohmic, optical injection (optical pumping), absorption, e-beam injection (pumping)**
- **Carrier relaxation, recombination, lifetime. Ionization or avalanche. Radiative or direct recombination, non-radiative recombination, trap-mediated recombination. Auger-effect relaxation.**
- **Carrier transport: drift and diffusion**

# Non-equilibrium carrier behavior




Non-equilibrium,
Non-steady state
Equilibrium,
Steady state
Quasi-equilibrium,
Steady state
Transient
water level 1
Transient
water level 2
Steady
water level
Quasi
water level 1
Quasi
water level 2
=
Pump




Density of state (linear scale) and Fermi distribution (log scale)

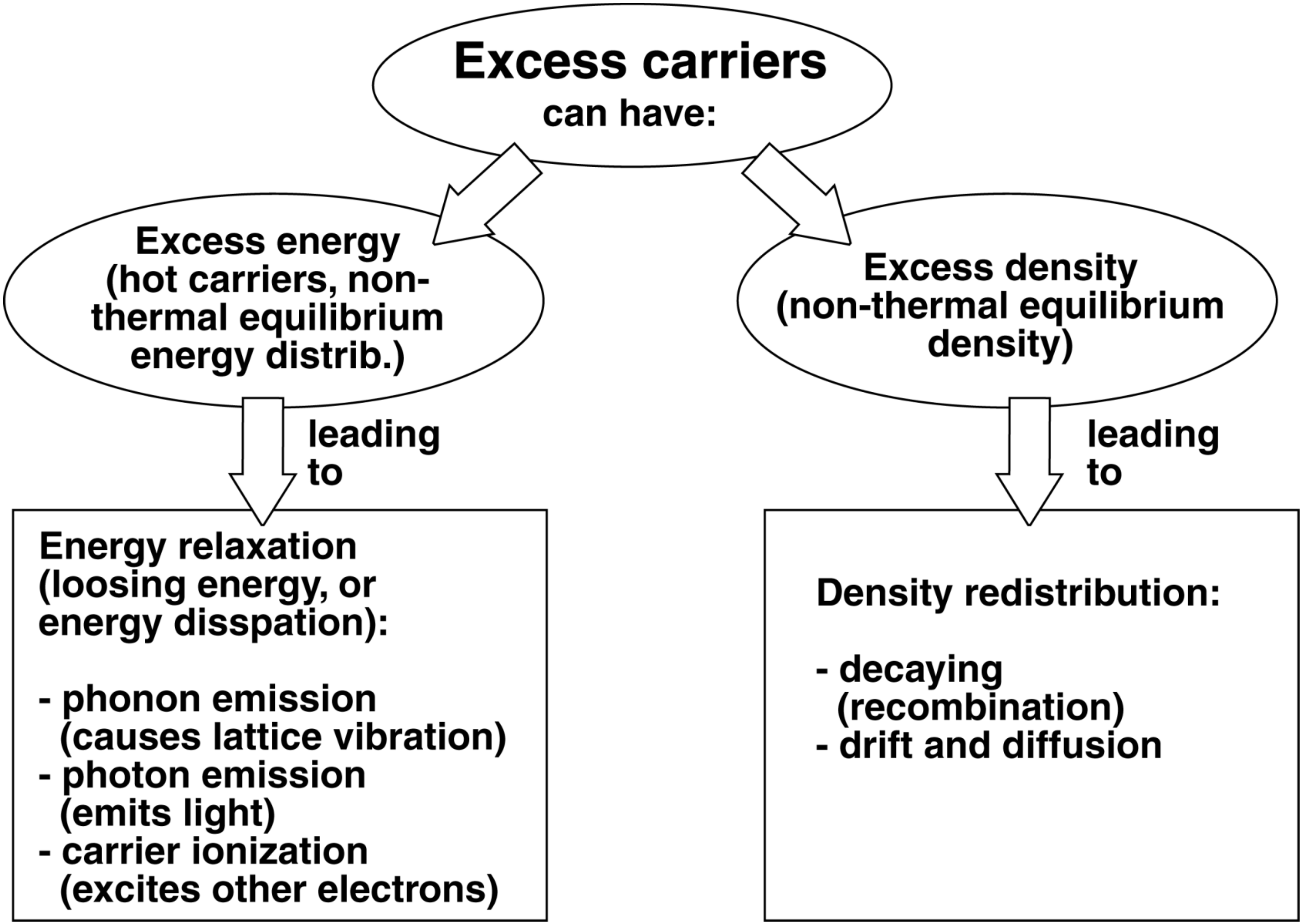
Intrinsic carrier density

Slightly n-type carrier density

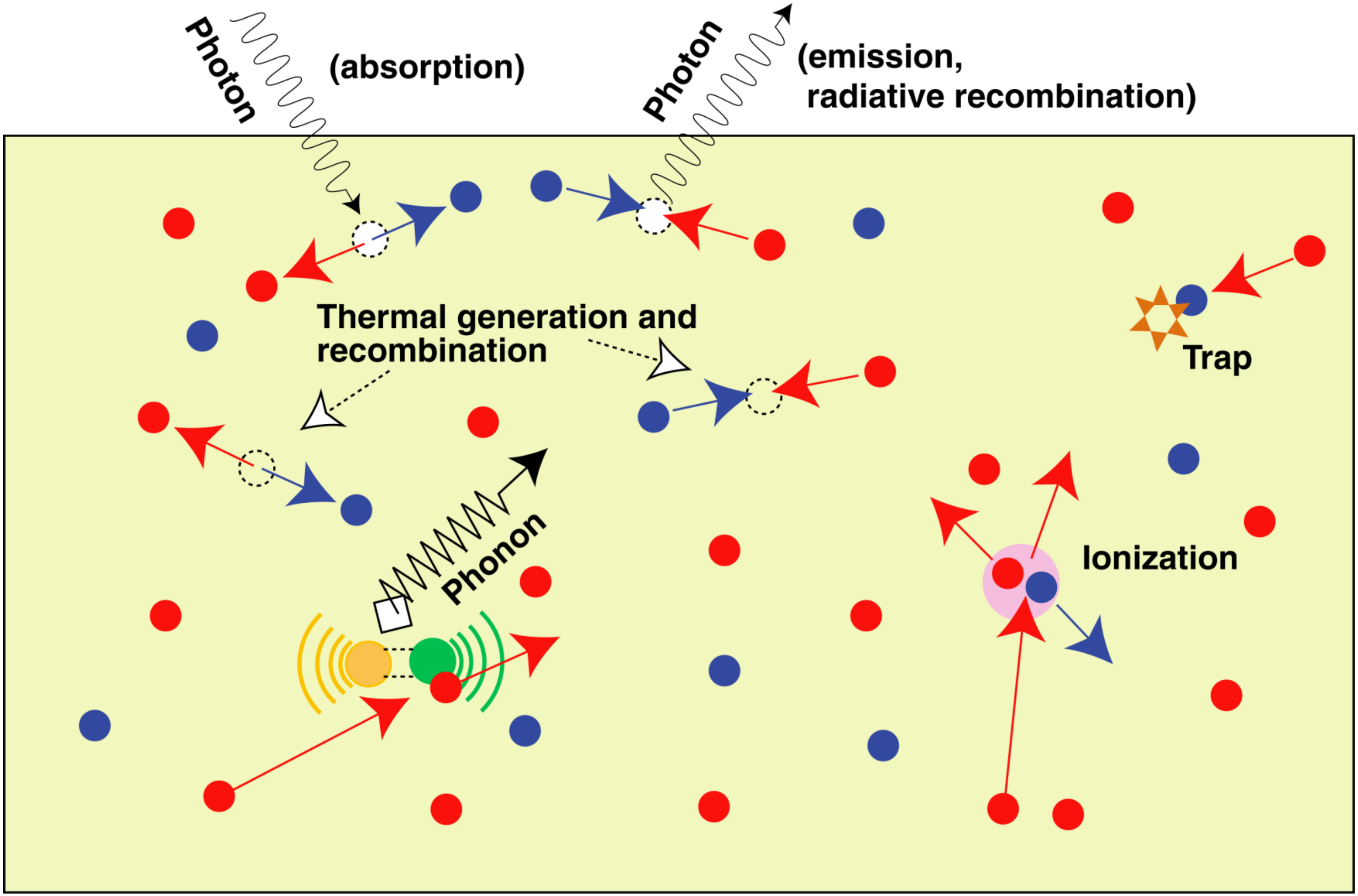
Slightly p-type carrier density

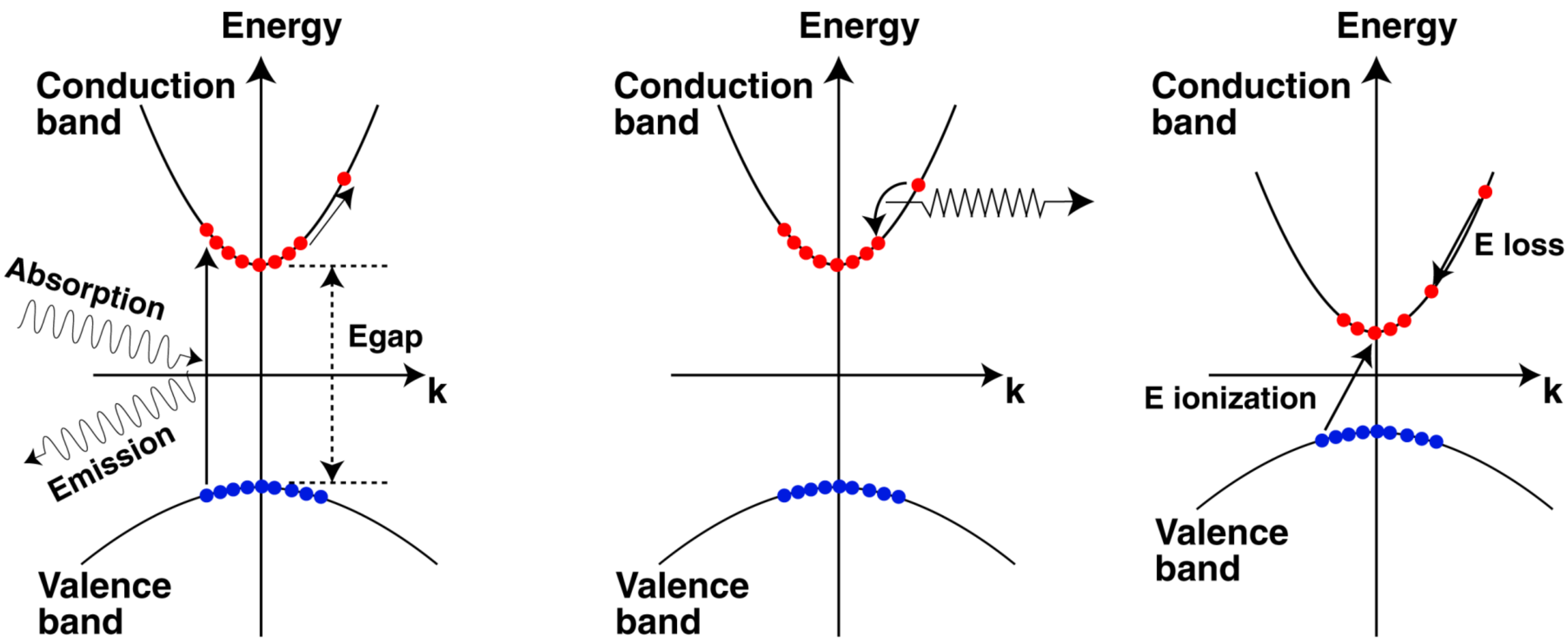
Both n and p, not in thermal equilibrium

# Non-equilibrium carrier behavior



# Excitation and Relaxation






**Momentum and energy conservation:**

$$\mathbf{k}_e + \mathbf{k}_h = \mathbf{k}_{\text{photon}} \approx 0$$
$$E_e + E_h = E_{\text{photon}} = \hbar\omega$$

**Momentum and energy conservation:**

$$\mathbf{k}_{e\,\text{final}} + \mathbf{q}_{phonon} = \mathbf{k}_{e\,\text{init}}$$
$$E_{e\,\text{final}} + E_{phonon} = E_{e\,\text{init}}$$

**Momentum and energy conservation:**

$$\mathbf{k}_{e2} + \mathbf{k}_h = \mathbf{k}_{e1\text{init}} - \mathbf{k}_{e1\text{final}}$$
$$E_{e2} + E_h = E_{e1\text{init}} - E_{e1\text{final}}$$

**Whenever a system is disturbed out of its equilibrium condition, it usually tries to relax back to the equilibrium state. If the disturbing force is maintained, a system may:**

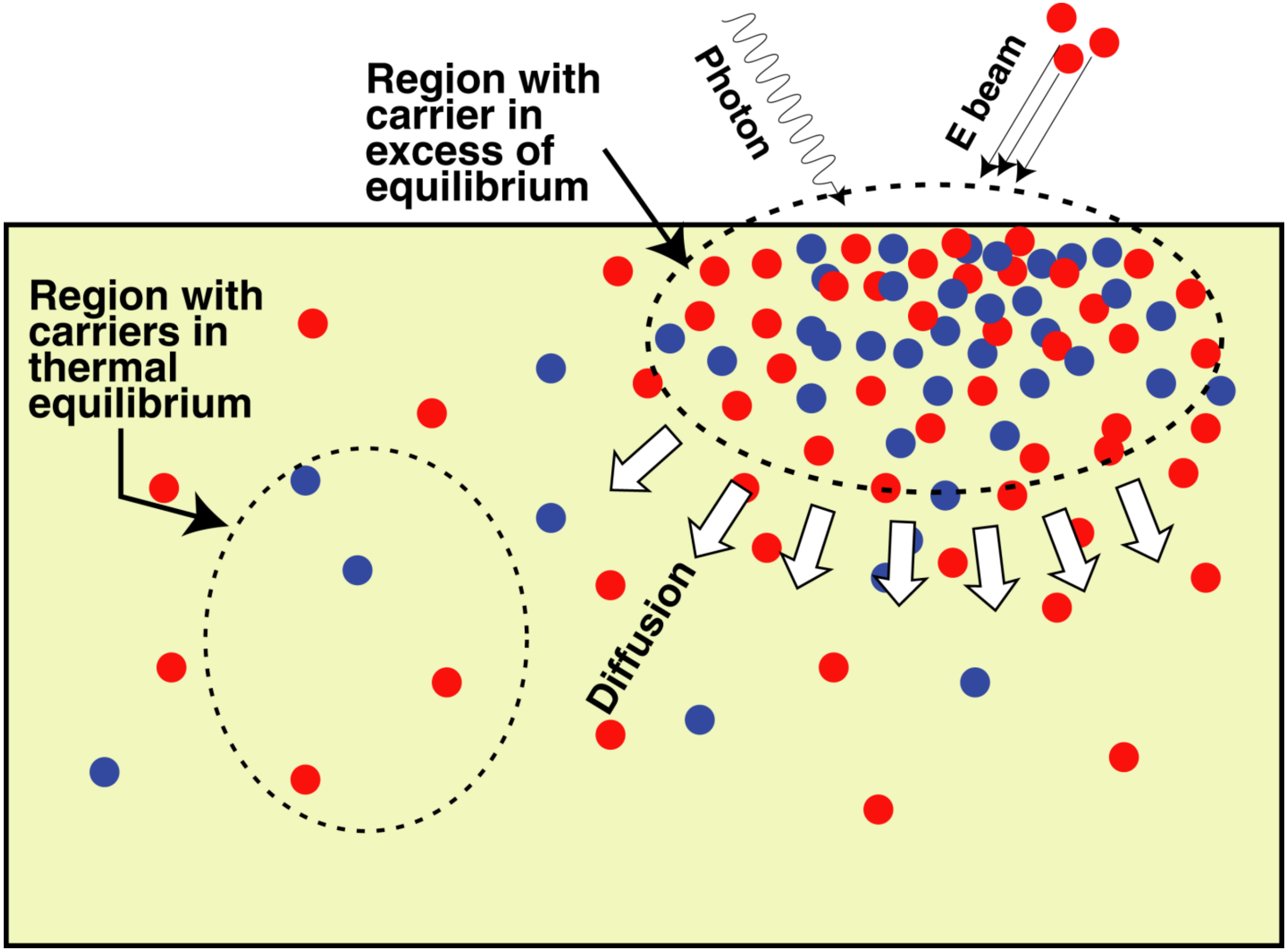
**-** ***reach a steady state, a balance between the disturbing force and its natural tendency***

**-** ***become oscillatory but stable, pulled from one state to another in a tug of war between the two forces***

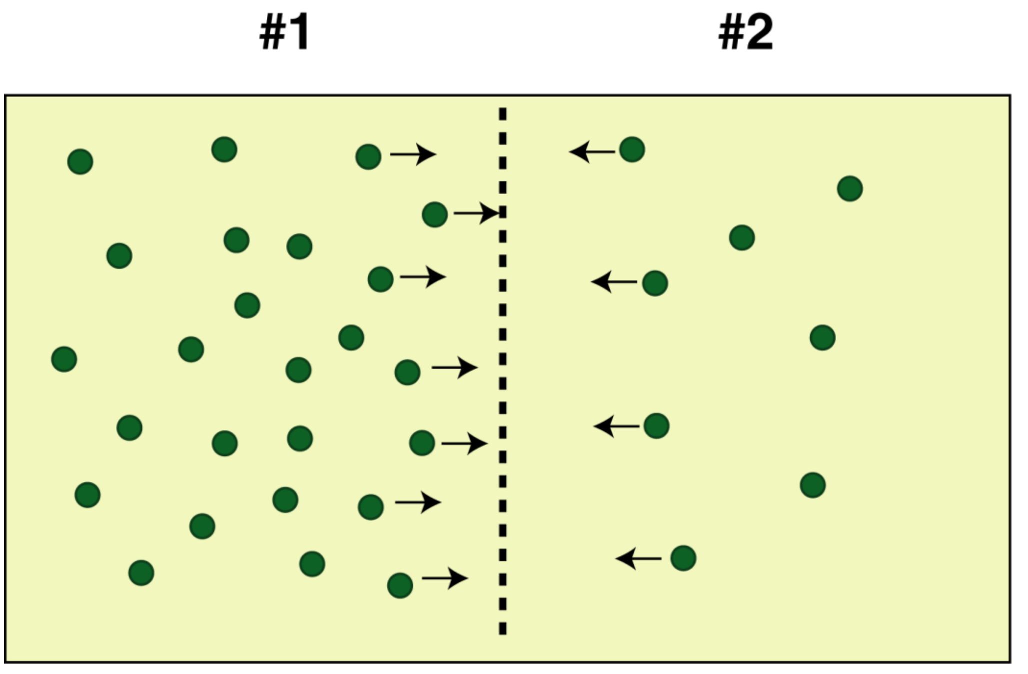
**-** ***become chaotic (Note: chaos is a <u>discipline</u> of math and natural science)***

**Excess carrier in semiconductor is a non-equilibrium condition. It follows the typical behavior for any of such systems**

# Carrier Diffusion: Introduction



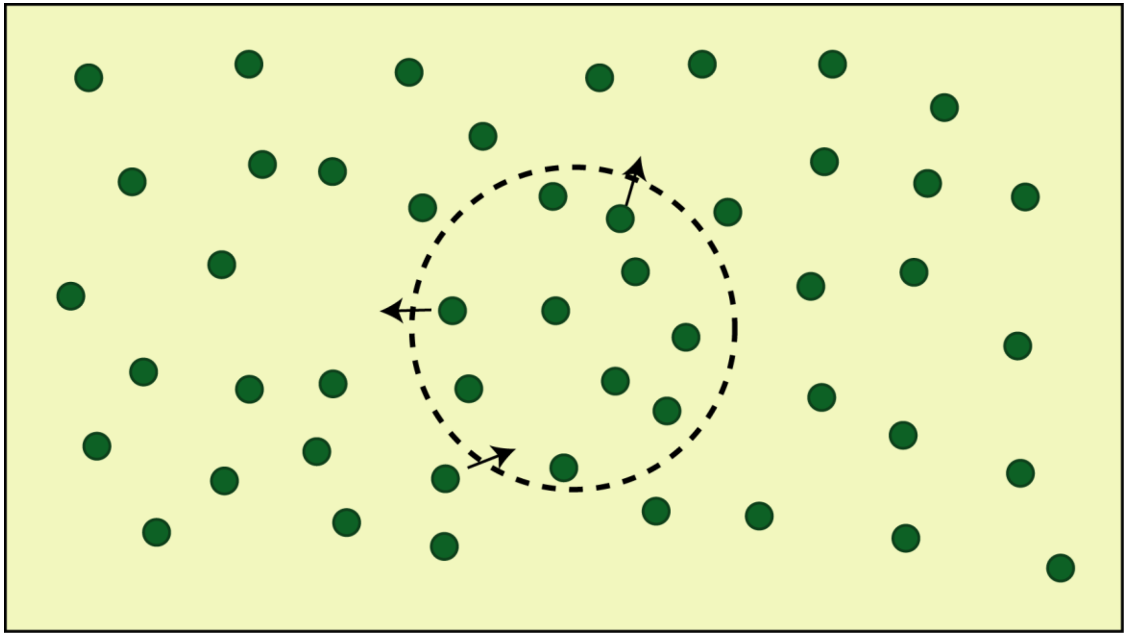
# Diffusion: Quantitative Description




**The left hand side particle is likely to move to the right and vice versa: Net flow (L → R) per second= nL v - nR v**

$$F = -D\frac{dn}{dx} \qquad \mathbf{F} = -D\vec{\nabla}n$$

$D$: diffusion coefficient



**Number of particles change / second = Net number of leaving or entering particles:**

$$\frac{\partial n}{\partial t} = -\vec{\nabla} \bullet \mathbf{F} = D\vec{\nabla} \bullet \vec{\nabla} n = D\nabla^2 n$$

# Current flow

**Electron diffusion current:** $$J_{Dn}(x) = -eF = eD_n \frac{dn}{dx}$$

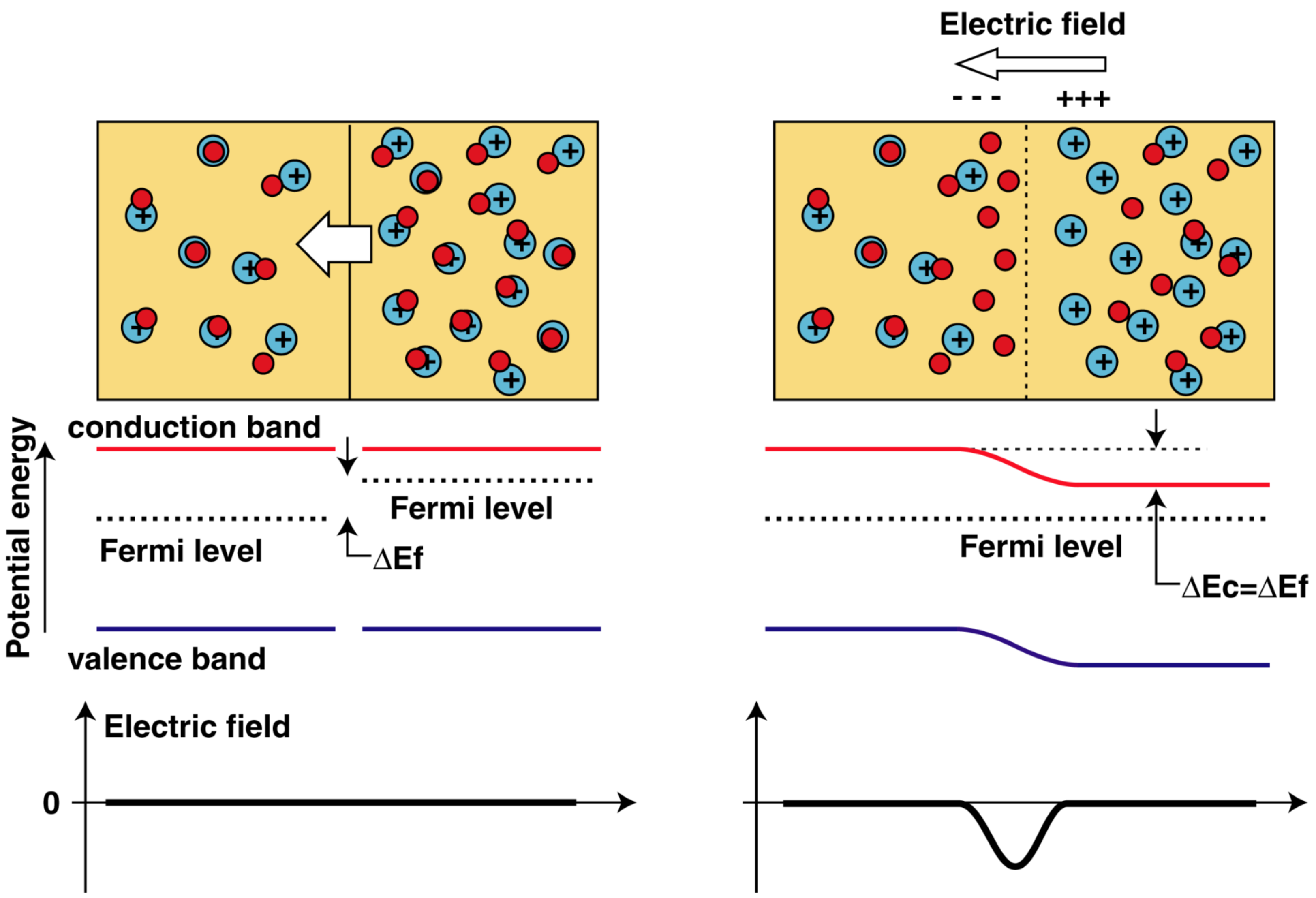
**Hole diffusion current:** $$J_{Dp}(x) = eF_p = -eD_p \frac{dp}{dx}$$

**Net electron current:** $$J_n(x) = e\mu_n n(x)E(x) + eD_n \frac{dn}{dx}$$

**Net hole current:** $$J_p(x) = e\mu_p p(x)E(x) - eD_p \frac{dp}{dx}$$

**Net current:** $$J(x) = J_p(x) + J_n(x)$$

# Example: current across a junction



**In the above example, the net current must vanish at equilibrium. Hence:**

$$0 = J_n(x) = e\mu_n n(x)E(x) + eD_n \frac{dn}{dx} \quad \text{or} \quad E(x) = -\frac{D_n}{\mu_n n(x)}\frac{dn}{dx}$$

**The built-in electric field must be sufficient to cancel out the electron diffusion. But how should the carrier density redistribute itself?**

**Recalling that the principle of detailed balance (Chapter III) stipulates that the Fermi level (which is directly related to the carrier density) be constant across the junction. What this means is that the carrier density must redistribute itself in such a way that Ef is constant and <u>at the same time</u> giving rise to the electric field given by the above equation. Surely something must be related! Let's use the approximation that:**

**Let's use the approximation that:** $n(x) \propto e^{(E_f - E_c)/k_B T}$

**Then:**

$$\frac{1}{n(x)}\frac{dn(x)}{dx} = \frac{d\ln(n(x))}{dx} = \frac{1}{k_B T}\left(\frac{dE_f}{dx} - \frac{dE_c}{dx}\right) = -\frac{1}{k_B T}\frac{dE_c}{dx}$$

**But** $\frac{dE_c}{dx}$ **is** $eE(x)$ **!**

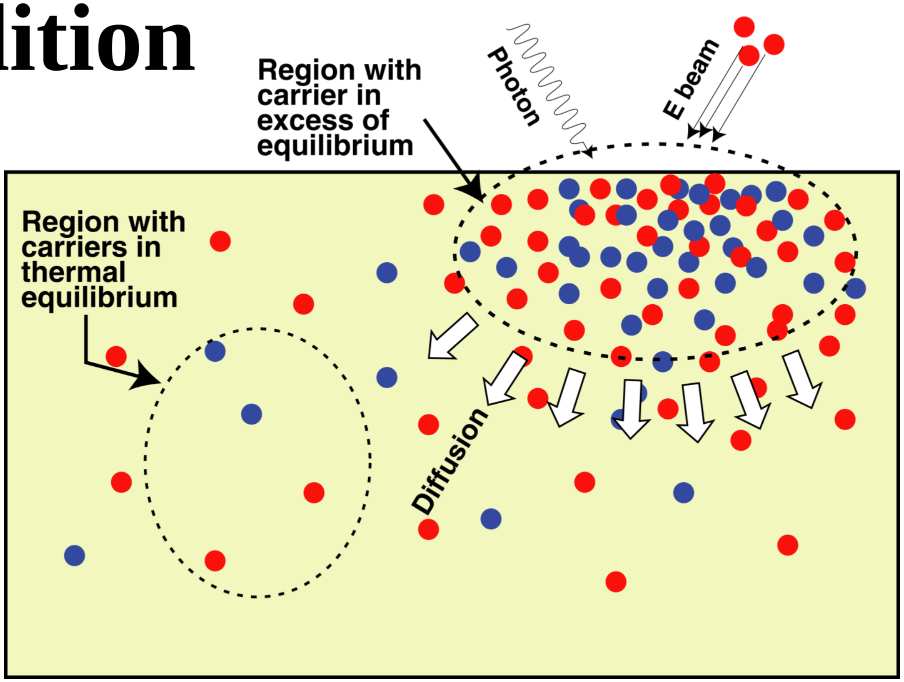
**(gradient of the energy is = charge x gradient of potential energy= charge x electric field). So:**

$$E(x) = -\frac{D_n}{\mu_n n(x)}\frac{dn}{dx} = \frac{D_n}{\mu_n}\frac{1}{k_B T}\frac{dE_c}{dx} = \frac{D_n}{\mu_n}\frac{e}{k_B T}E(x) \Rightarrow \frac{D_n}{\mu_n}\frac{e}{k_B T} = 1$$

**or** $D_n = \frac{k_B T}{e}\mu_n$

**: this is the Einstein relation. The physical meaning of it is the following: the charge carrier can diffuse only as much its mobility allows; and the higher temperature, the more kinetic energy it has to diffuse.** ***Does this make sense?***

# Example: charge diffusion with continuity condition




**In the figure above, if we have continuous injection, will the electron-hole gas keep on building up to a great density and expanding forever?**

**Obviously not. Because the carriers recombine and as it expands, the gradient is smaller and the diffusion is weaker. Intuitively, the harder we pump, the bigger the EH gas volume should be. How do we describe this quantitatively?**

**The change of local carrier density per unit time = Rate on injection – rate of decay (recombination) + net rate of diffusion (in - out)**

$$\frac{\partial n}{\partial t} = P - \frac{n}{\tau} + D\nabla^2 n$$

**P is the pumping rate, $\tau$ is the carrier lifetime that effectively describes that recombination.**

**At steady state:** $$\frac{\partial n}{\partial t} = P - \frac{n}{\tau} + D\nabla^2 n = 0$$

**For one dimension:** $$D\frac{d^2 n}{dx^2} = \frac{n}{\tau} - P$$

$$D\frac{d^2 n}{dx^2} = \frac{n}{\tau} - P \Rightarrow \frac{d^2 n}{dx^2} = \frac{n}{\tau D} - \frac{P\tau}{\tau D} = \frac{n - n_o \left\langle \text{define } n_o \equiv P\tau \right\rangle}{\tau D} = \frac{n - n_o}{L_D^2 \left\langle \text{define } L_D^2 \equiv D\tau \right\rangle}$$

**A solution is:** $$n(x) = n_1 e^{-x/L_D} + n_o$$

**The quantity $L_D$ is defined as diffusion length. So, the electron-hole gas does not expand forever, but maintains a steady exponentially decay profile.**

# Device discussion
## (in class)

- **Photodetectors and switches, lasers and LEDs**

**Cathodoluminescence, FED displays**