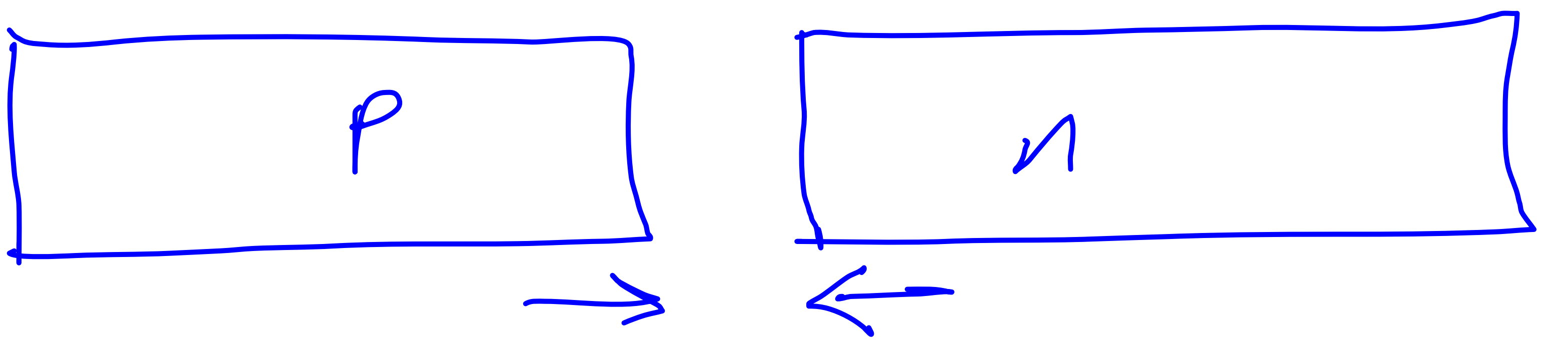
Lecture 11

More
Carrier Action

Please use this power point as a guide to reading the textbook.

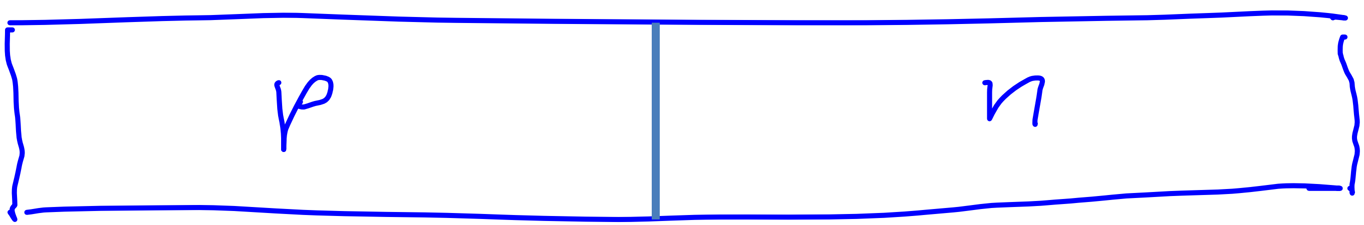
Carriers

- We learned that the current flows as
$$J = e\mu_p pE + e\mu_n nE$$
- Consider now two pieces of semiconductors, one a p type and the other n type.



p-n Junction

- In a p-n junction device, the two pieces of semiconductor



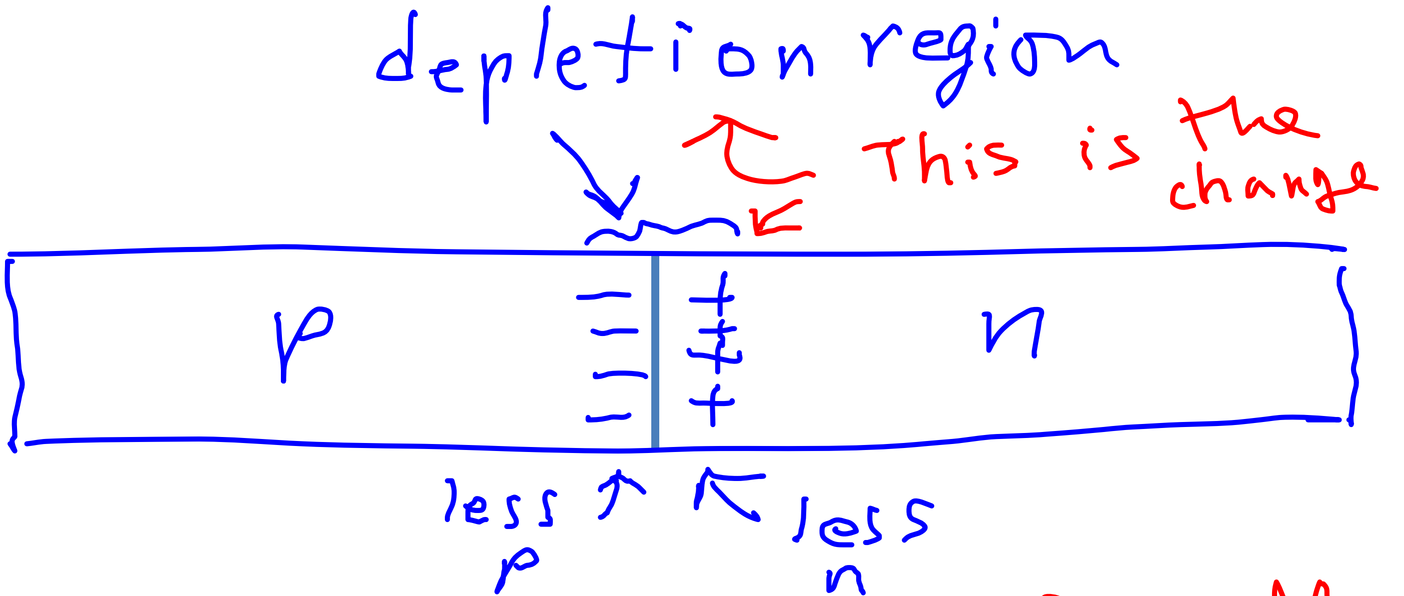
wait for the equilibrium to set

A. Remain the same as before joined.

B. Change.

p-n Junction

- At the junction, there is



A. An electric field.

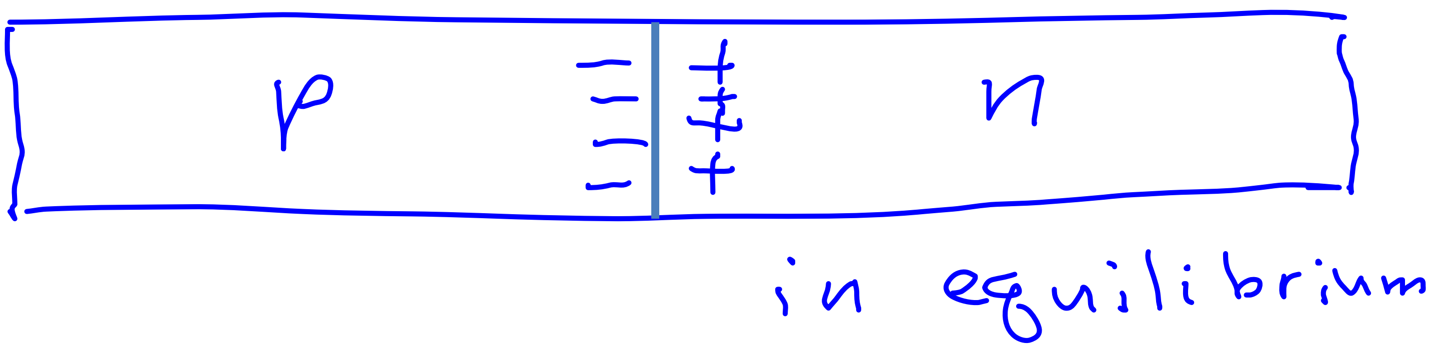
B. No electric field.

Basically a dipole layer of charges.

p-n Junction

- For this device, there is

The p-n junction device
free
not connected to anything



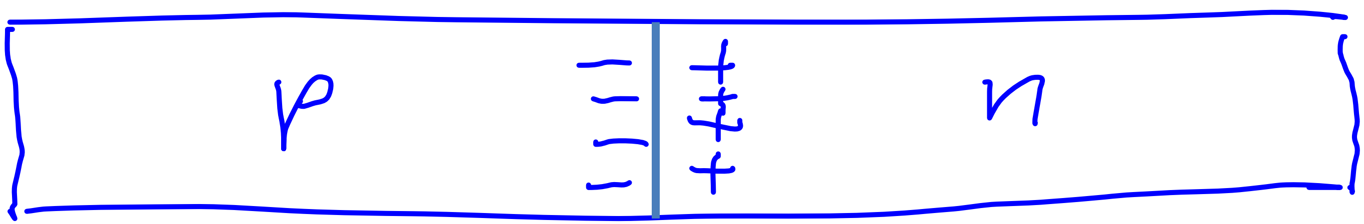
A. A current.

B. No current.

p-n Junction

- For this device, the **Fermi level (E_F)** is

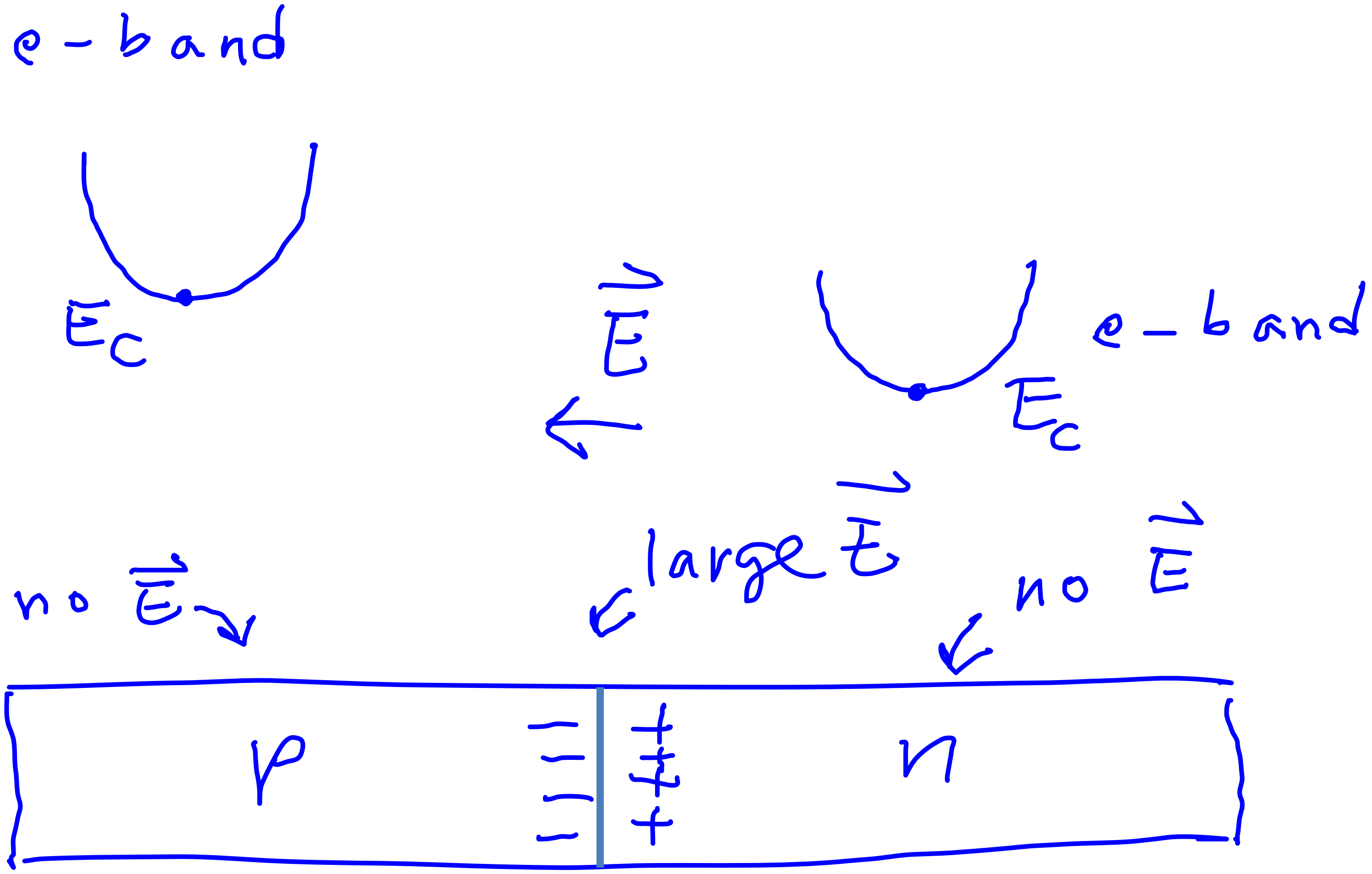
The p-n junction device
free
not connected to anything



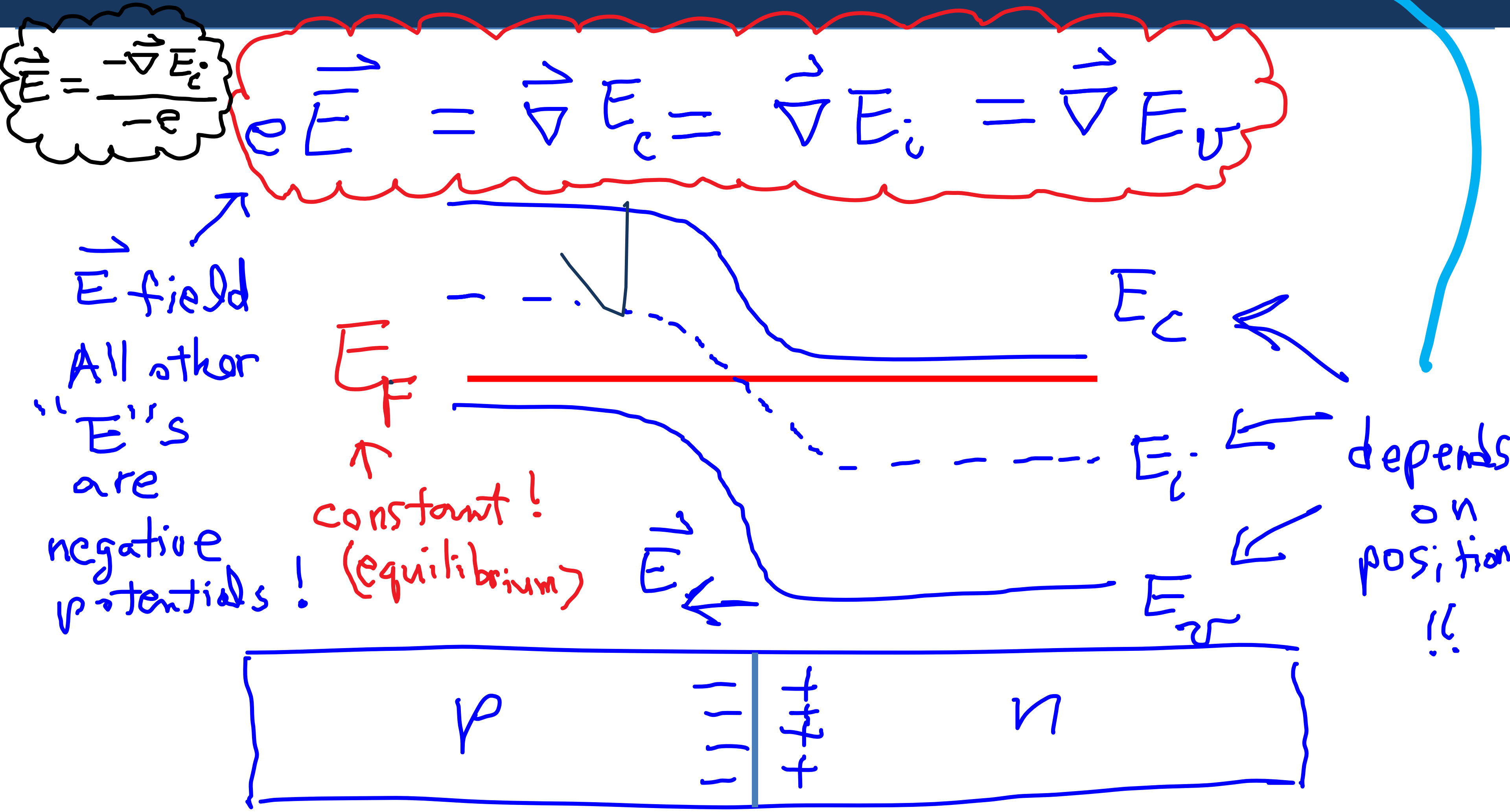
A. Constant throughout.

B. Position-dependent at the junction.

Band Bending



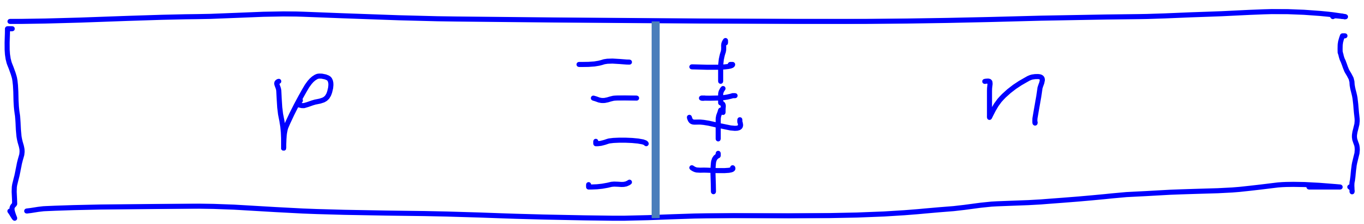
Band Bending



How is it possible?

- We learned that the current flows as

$$J = e\mu_p pE + e\mu_n nE$$



- But there is no current for this device, unbiased and in equilibrium.

General case for any device

- Clearly, this

$$J = e\mu_p pE + e\mu_n nE$$

is not enough. Why? Only for uniform n, p.

- But, n or p can and will have position dependence – **Diffusion**!
- Each n and p is a different sub-system by itself, and $J_n = 0$ and $J_p = 0$ separately at any position of the sample!

Diffusion

- $F = -D\,\nabla\eta$ (Fick's law)
- F is particle flux $\left(\frac{1}{m^2 s}\right)$ and η is the density.
- D is the diffusion coefficient $\left(\frac{m^2}{s}\right)$
- Diffusion current density (J) is given by charge times F
- In the case of non-uniform density (band bending in junction devices, e.g.)

$$J_p = e\mu_p pE + eD_p\nabla p$$
$$J_n = e\mu_n nE + eD_N\nabla n$$

drift current

diffusion current

Einstein Relation

- In an equilibrium, there must be no current. For junction devices, we must have a non-uniform distribution of charge. So the drift current is non-zero!
- In the case of un-uniform density (junction devices, e.g.) with non-uniformity along the x direction

$$J_p = e\mu_p pE - eD_p \frac{dp}{dx} = 0$$

$$J_n = e\mu_n nE + eD_N \frac{dn}{dx} = 0$$

Einstein Relation

In the case of un-uniform density (junction devices, e.g.) with non-uniformity along the x direction

$p = p(x) \rightarrow$ $$p = n_i e^{\beta(-E_F+E_i)}$$ $\leftarrow E_i = E_i(x)$

$E_F =$ position independent in equilibrium!

band bending!

$$\frac{dp}{dx} = p\left(\beta\,\frac{dE_i}{dx}\right) = p\beta eE$$

$$J_p = e\mu_p pE - eD_p\,\frac{dp}{dx} = \mu_p pE - eD_p\,p\beta\,E = 0$$

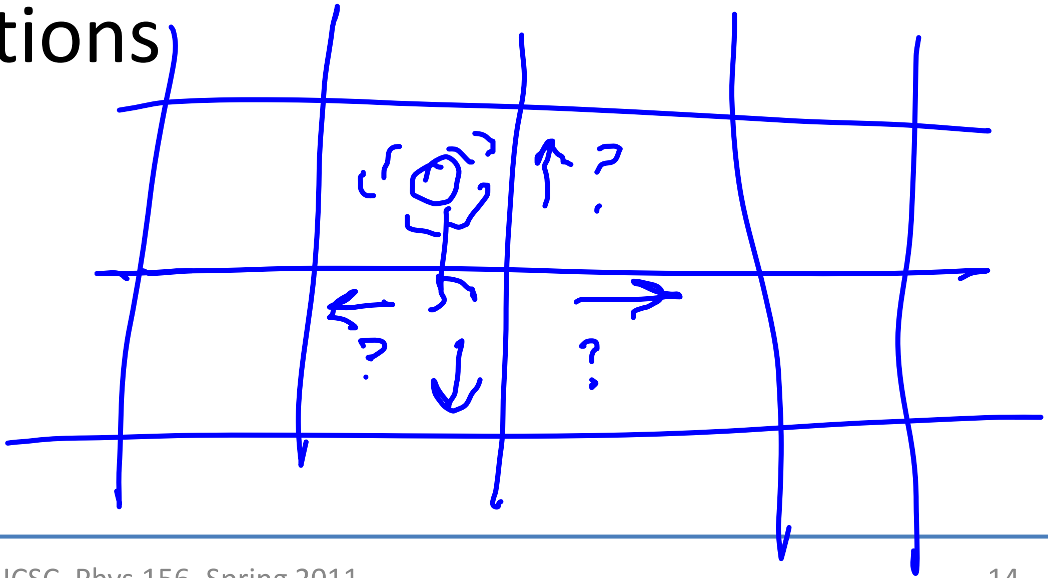
$$\frac{D_P}{\mu_p} = \frac{kT}{e}$$

$$\frac{D_N}{\mu_n} = \frac{kT}{e}$$

Einstein Relations

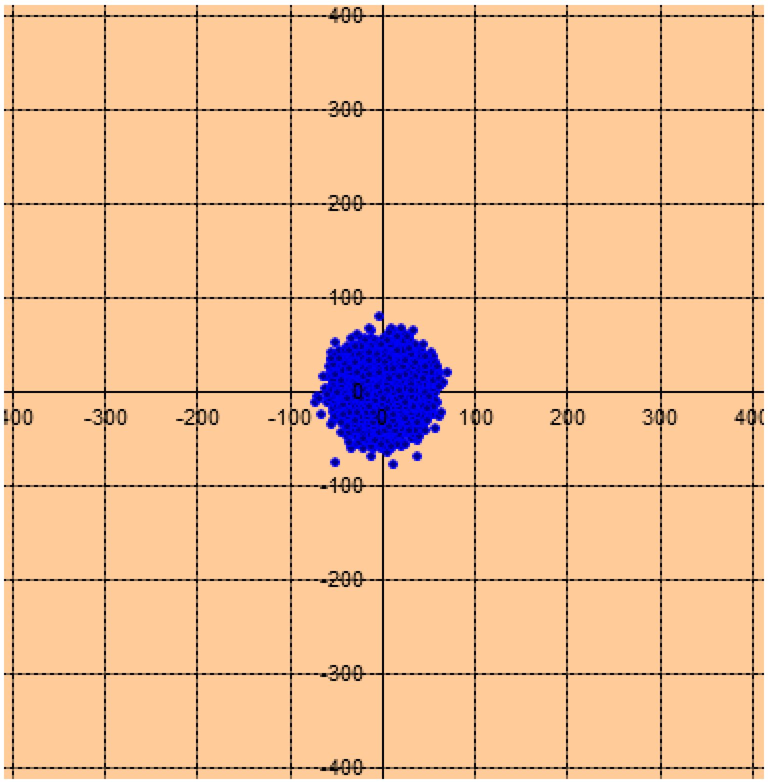
Diffusion

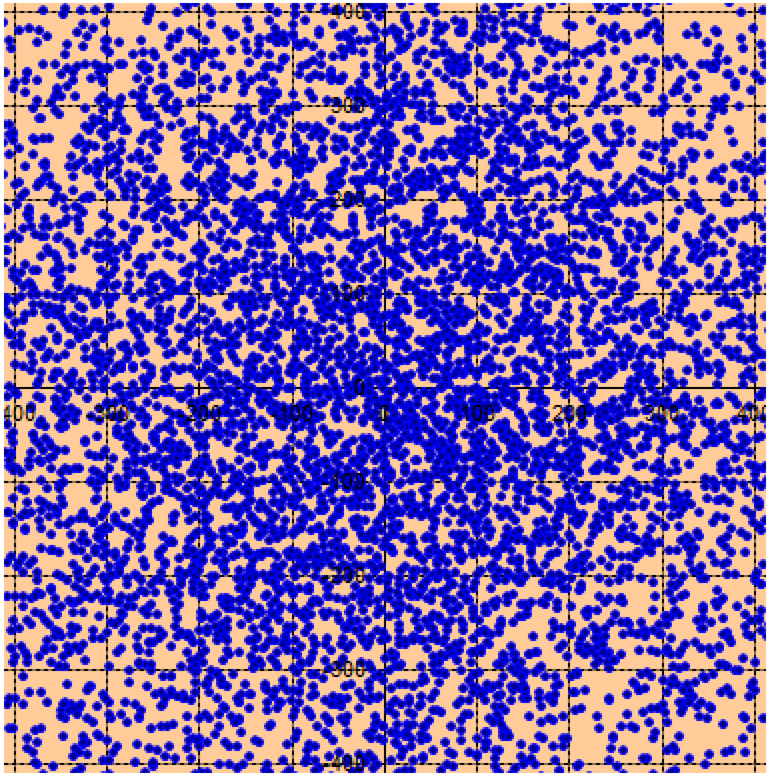
- Ink drop in water
- Smell
- Charge carriers in semiconductors (!)
- Crystal growth on surface
- Geological formations
- Drunken man



Diffusion

random walk causes spreading





later time

Diffusion

- The average position of the particles is

  A. 0   B. Non-zero

- The spreading of the particle, or the standard deviation of the radius of the particle distribution, scales as

  A. t B. $\sqrt{t}$ C. t^2

$$\langle r^2 \rangle = 2 m D t$$

m: spatial dimension

Fluctuation-Dissipation Theorem

Totally optional slide

- **Diffusion**? We understand this as the result of "random walk" (a "drunken-man" walking). On average, the random walk does not lead to anywhere, but there is an increased coverage of space – this is the diffusion. The diffusion rate/constant is limited by scattering, and can be described as the response of the system by its own density **"fluctuation"** of the **equilibrium** state.
- **Mobility**? It is also limited by the same scattering, and describes the **"dissipation"** (resistivity and Joule heating) in the **non-equilibrium** state.
- The two are related by the **fluctuation-dissipation theorem**, of which Einstein relation is an example.

Recombination, Generation

- Recombination is like a pair annihilation in particle physics.

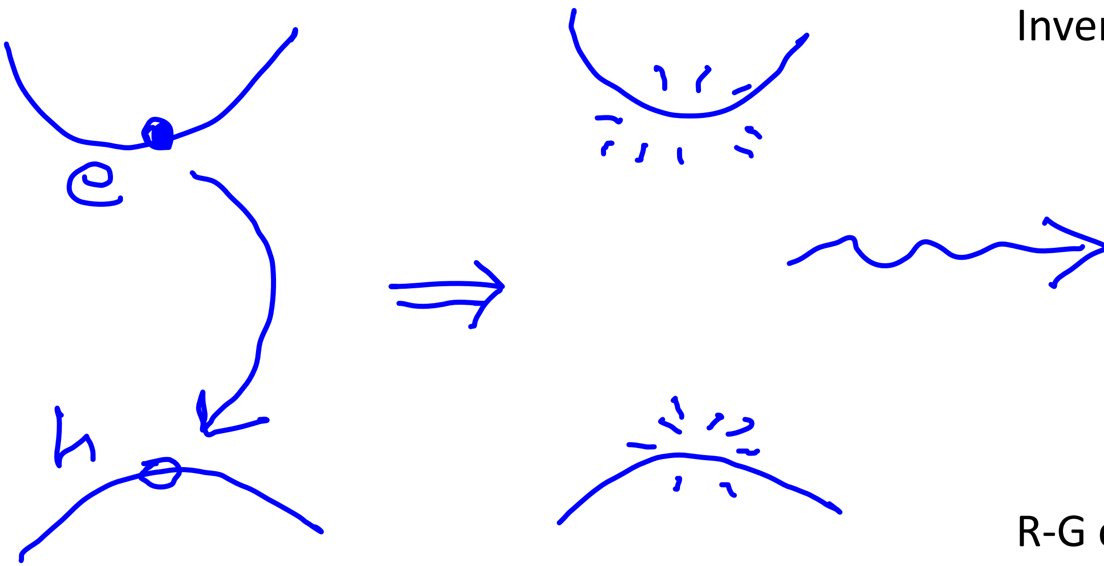
$$e + h \longrightarrow \text{other particle(s)}$$

- Generation is like a pair production in particle physics.

$$\text{other particle(s)} \longrightarrow e + h$$

Recombination, Generation

Recombination



Inverse photoelectric effect

photon(s)

phonon(s)
(lattice
vibration)

R-G center assisted process

other electron(s)
hole(s)

Auger process

Generation is a time-inverted process of recombination.

Recombination, Generation

Please refer to the book and your lecture note taken during class for more details.

- Photon – Important for direct semiconductors (GaAs), not important for indirect ones (Si, Ge, GaP, …). **Crystal momentum conservation** important. Photon momentum small, since $\lambda = 12398/(h\nu)$, where λ is in Å and $h\nu$ is in eV. $k \sim O(0.01)$ Å^{-1} which means a **vertical transition**.
- **R-G Center** – "R-G Centers" are impurities (or defects) with impurity levels deep in the gap, unlike normal donors or acceptors. Thus, two successive transitions with such an impurity level "as a stepping stone" can result in a recombination or a generation. Mostly **phonon** (quantum of lattice vibration) assisted. Particularly important for indirect semiconductors, since this is the main mechanism for them, but also important for direct semiconductors as well.
- Auger process – this is due to a **Coulomb interaction**, which is an exchange of **a virtual photon by two electrons**. Not important in semiconductors in normal cases due to small number of electrons.