

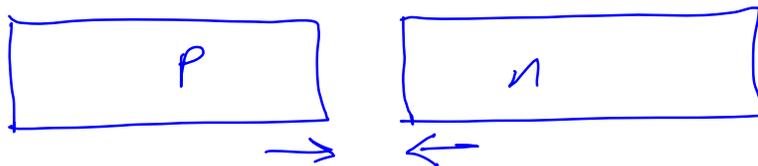
Lecture 11

More Carrier Action

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

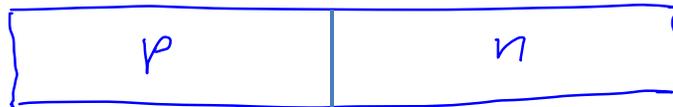
Carriers

- 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



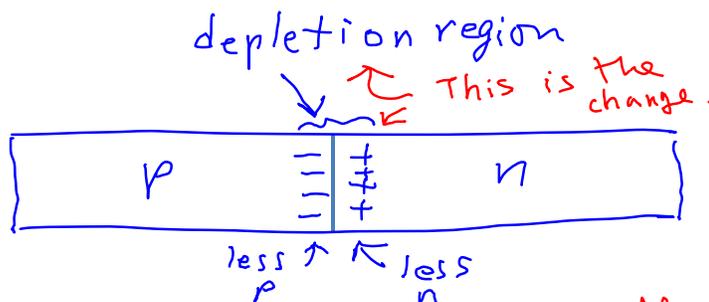
wait for the equilibrium to set

A. Remain the same as before joined.

B. Change.

p-n Junction

- At the junction, there is



A. An electric field.

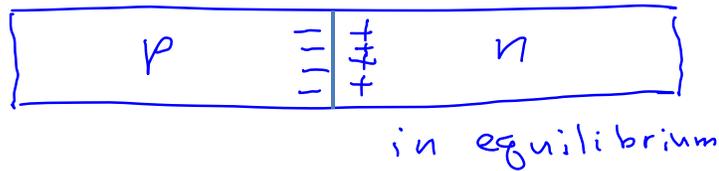
B. No electric field.

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.

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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.

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Band Bending

e-band

no \vec{E} large \vec{E} no \vec{E}

p n

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Band Bending

$$e\vec{E} = \vec{\nabla} E_c = \vec{\nabla} E_i = \vec{\nabla} E_v$$

$\vec{E} = -\vec{\nabla} E_c$
 $\vec{E} = -\frac{\nabla E_c}{-e}$

\vec{E} field
 All other "E"s are negative potentials!
 constant! (equilibrium)

depends on position !!

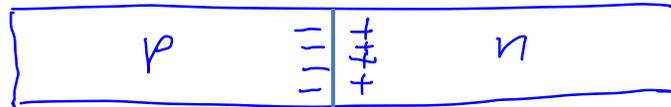
p n

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

$$J_p = e\mu_p p E + eD_p \nabla p$$

$$J_n = e\mu_n n E + eD_n \nabla n$$

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

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

$$J_n = e\mu_n n E + eD_n \frac{dn}{dx} = 0$$

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! \uparrow

$$\frac{dp}{dx} = p \left(\beta \frac{dE_i}{dx} \right) = p \beta e E$$

band bending!

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

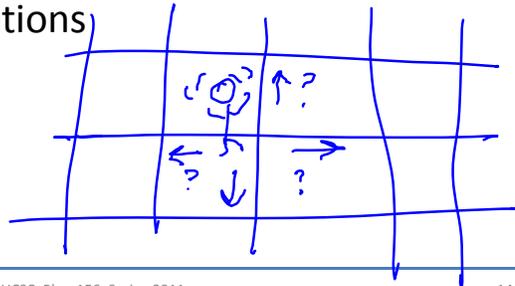
$$\frac{D_p}{\mu_p} = \frac{kT}{e}$$

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

Einstein Relations

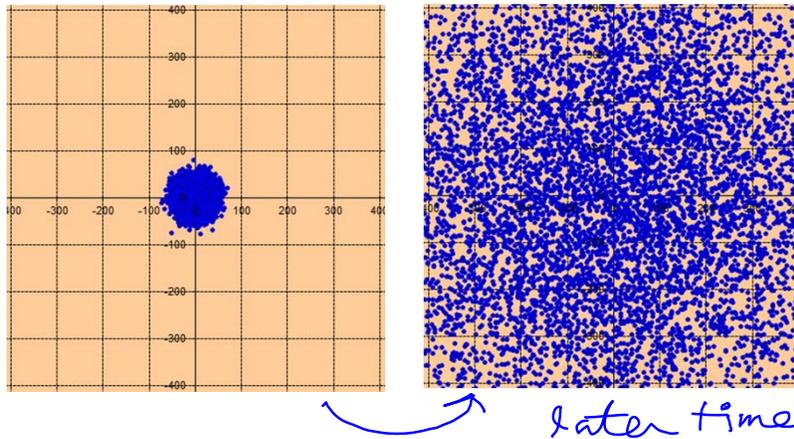
Diffusion

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



Diffusion

random walk causes spreading



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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

$$\langle r^2 \rangle = 2mDt \quad m: \text{spatial dimension}$$

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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.

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Recombination, Generation

- Recombination is like a pair annihilation in particle physics.



- Generation is like a pair production in particle physics.



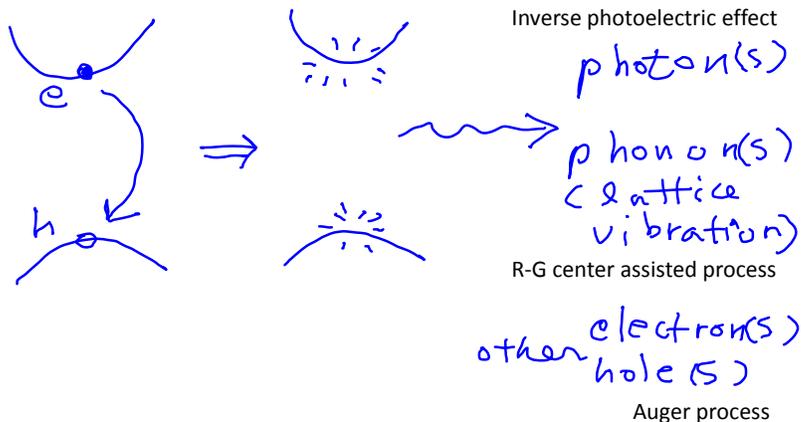
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Recombination, Generation

Recombination



Generation is a time-inverted process of recombination.

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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 $\lambda = 12398/(hv)$, where λ is in Å and hv is in eV. $k \sim O(0.01) \text{ \AA}^{-1}$ 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.

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