HW#1

- Razavi, 2nd edition
  - P2.3
  - P2.5
  - P2.9
  - (Problems will be uploaded.)

- Due: March 16, 2016 (next Wednesday)
  - Submit your HW to Mr. Junsung Park (“quasarp at gist.ac.kr”, SIC Building, C-411)
  - No delayed submission is accepted.

Lecture3: Basic physics of semiconductor (2)

Sung-Min Hong (smhong@gist.ac.kr)

Semiconductor Device Simulation Lab.
School of Information and Communications
Gwangju Institute of Science and Technology

Intrinsic carrier density

- At higher temperatures,
  - There will be a certain amount of electrons and holes.
  - How many “free” electrons? (Assume the intrinsic material.)
  - It is the meaning of the intrinsic carrier density, n_i.

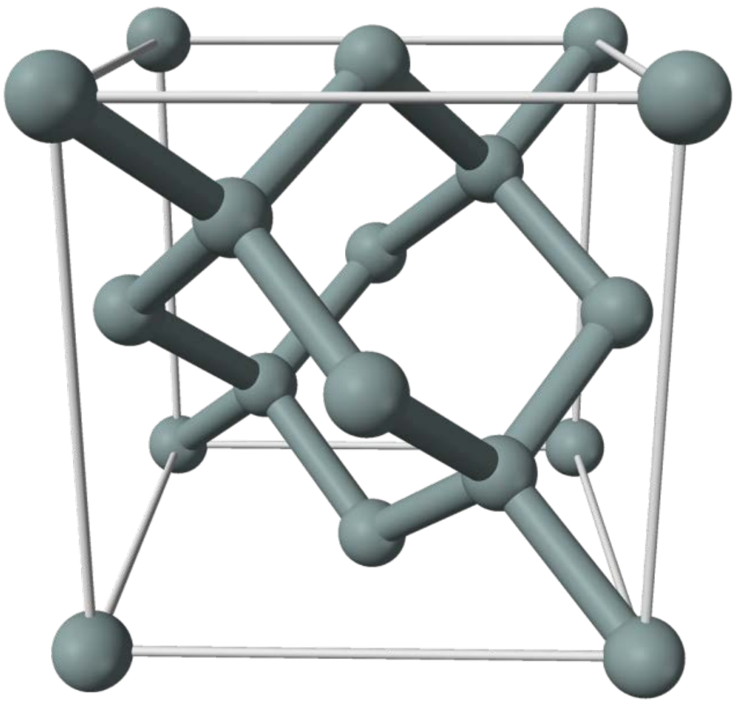
- Expression of n_i

$$n_i = 5.2 \times 10^{15}\, T^{1.5} \exp \frac{-E_g}{2k_B T} \quad [electrons/cm^3]$$

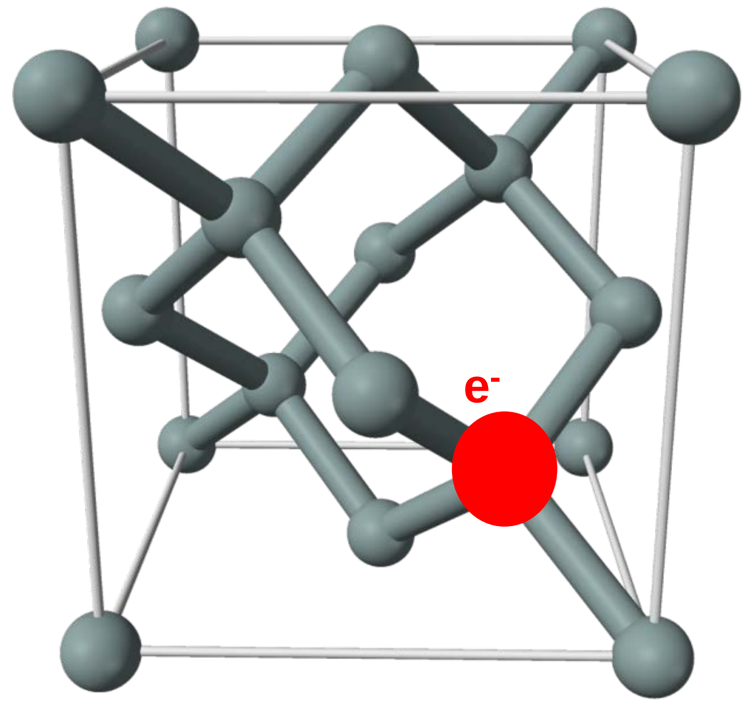
  - Boltzmann constant, k_B
  - At 300K, n_i is roughly 10^{10} $[electrons/cm^3]$.

Impurity atom

- The phosphorus atom has 5 valence electrons.
  - Additional electron (**e$^-$** in the right figure) serves as a charge carrier.



Pure silicon



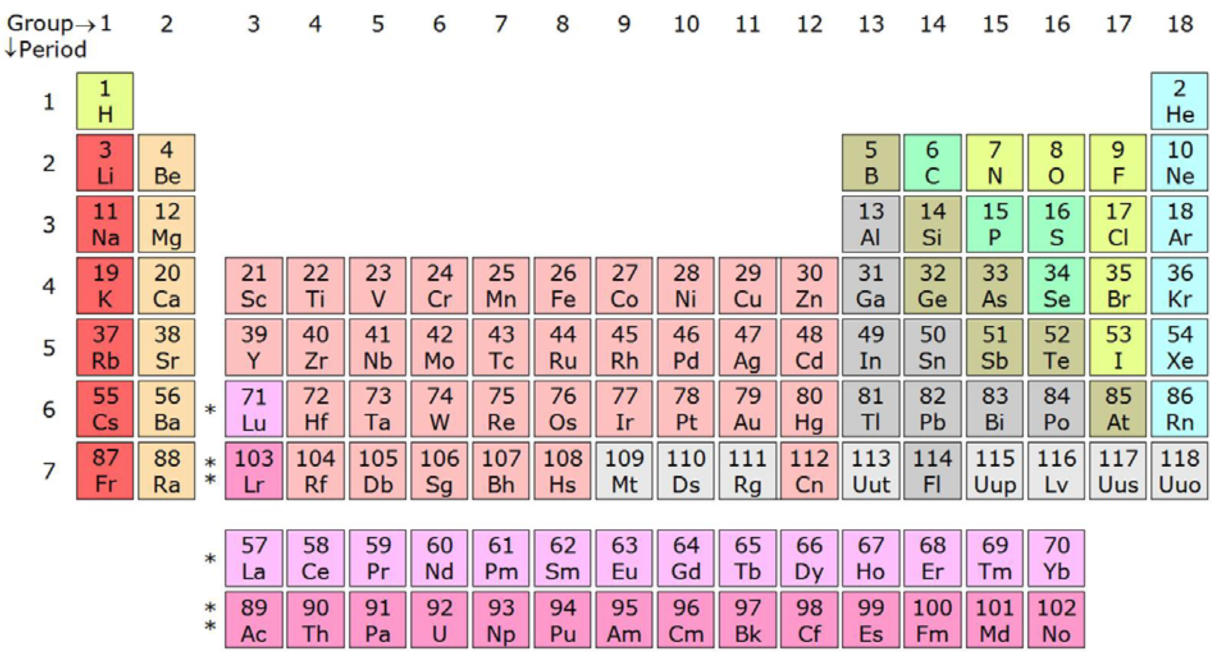
Silicon with “impurity” atom
(For example, phosphorus)

Impurity atoms

- One impurity atom contributes a “free” electron.
  - If 2 (, 3, 4, 5, …) phosphorus atoms are introduced?
  - 2 (, 3, 4, 5, …) additional electrons will be generated!
- More specifically,
  - When the density of the phosphorus atom is $N\ [atoms/cm^3]$,
  - The electron density becomes $N\ [electrons/cm^3]$.
- Typical value? (Feeling about the numbers)
  - $10^{15}\ [atoms/cm^3]$: Almost no impurity
  - $10^{17}\ [atoms/cm^3]$: Low (or moderate) impurity density
  - $10^{19}\ [atoms/cm^3]$: High impurity density (Not extremely high)
- What is it good for?
  - Conductivity can be changed drastically.

n-type? p-type?

- Phosphorus has 5 valence electrons.
  - Therefore, it contributes an electron. (n-type)
- Boron has 3 valence electrons.
  - It cannot provide 4 valence electrons to complete 4 bonds.
  - Instead, it contributes a hole. (p-type)



Periodic table (Wikipedia)

Minority carrier density

- Majority vs. minority
  - In the n-type semiconductor, electrons are majority carriers.
  - On the other hand, holes are minority carriers.

  - At equilibrium,

$$np = n_i^2$$

  - Example)
  - Consider a case of 10^{15} cm^{-3}.

Equilibrium properties

- Intrinsic semiconductor @ finite T
  - Small amount of “free” electron/hole, n_i
  - At 300K, n_i of silicon is about $10^{10}\ cm^{-3}$
- Extrinsic semiconductor @ finite T
  - n-type dopants (P, As) provide electrons.
  - p-type dopants (B) provide holes.
- A relation valid at equilibrium, $np = n_i^2$

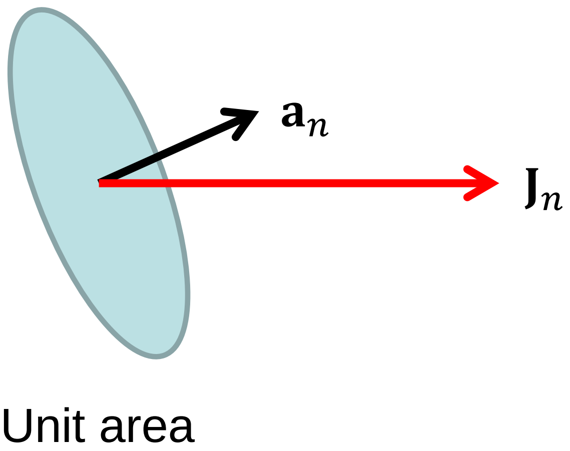
- Nonequilibrium
  - Various ways to generate the nonequilibrium case
  - Flow of charged particles!

Electron current density

- Electron current density

$$\mathbf{J}_n = -qn\mathbf{v}_n = \rho\mathbf{v}_n$$

  - $\mathbf{J}_n$: A vector point function in [A/cm^2]
  - $\mathbf{v}_n$: An average electron velocity in [cm/sec]
  - Amount of charge passing through the unit area (which is normal to $\mathbf{a}_n$) in the unit time is given by $\mathbf{J}_n \cdot \mathbf{a}_n$



Current densities

- Electron current density

$$\mathbf{J}_n = -qn\mathbf{v}_n$$

- Hole current density
  - Similarly,

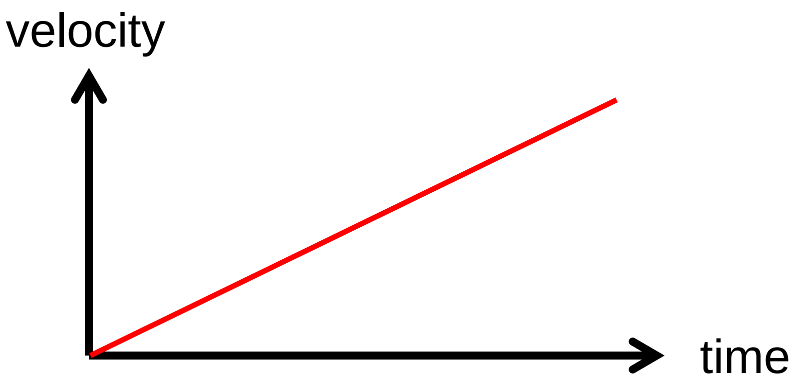
$$\mathbf{J}_p = qp\mathbf{v}_p$$

- Particle current density
  - Sum of these two terms

- Anything else?
  - You know what it is.
  - For a capacitor, $I = C\frac{dV}{dt}$. How?

Drift

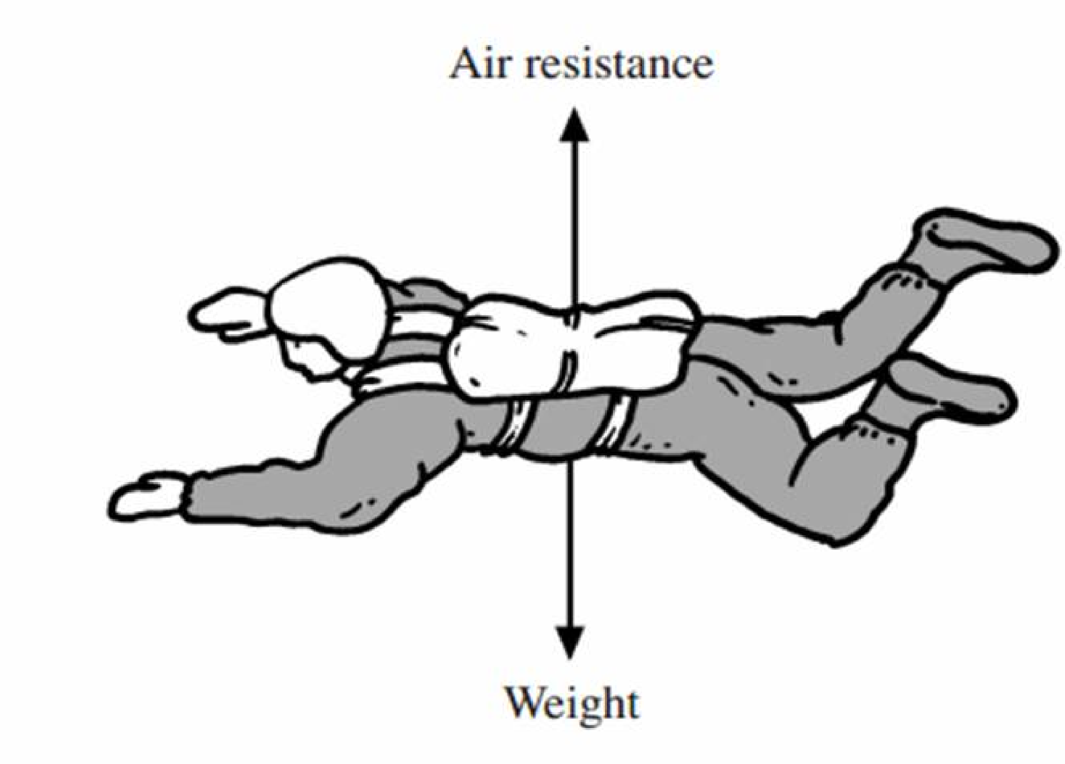
- Caused by an electric field
  - Since electrons/holes are charged particles, they are accelerated by an electric field, $\mathbf{E}$. (Unit: [V/cm])
  - For electrons, $\mathbf{F} = -q\mathbf{E}$ (For holes, the sign is the opposite.)
  - Then, the average velocity satisfies $\frac{d\mathbf{v}_n}{dt} = -\frac{q\mathbf{E}}{m_n}$
  - Here, m_n is the effective mass of electrons.
  - Of course, $\mathbf{v}_n(t) = -\frac{q\mathbf{E}}{m_n}t$ (Obviously wrong…)



Velocity as a function of time.
Initially, zero velocity.

Terminal velocity of skydiver

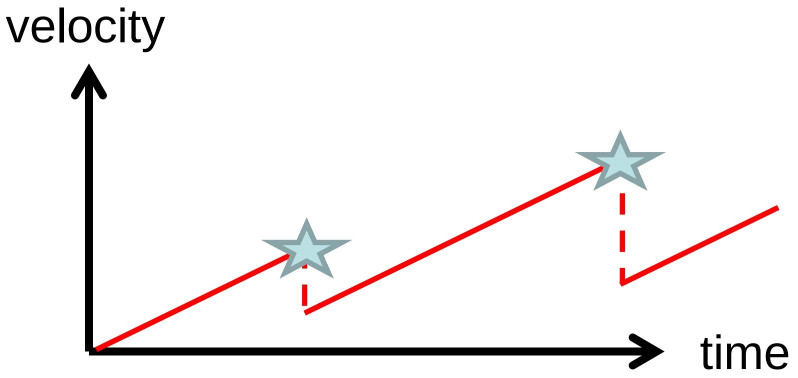
- Terminal velocity
  - For a skydiver, the gravity is the driving force.
  - For electrons, the electric field is the driving force.
  - Then, which mechanism plays a similar role of “air resistance”?



Forces exerted on a skydiver (Google image)

Scattering

- The velocity of the carriers…
  - Does not increase indefinitely under the field acceleration. Why?
  - They are scattered frequently and lose their momentum after each collision.
  - (Representative scatters are lattice vibration (phonon) and ionized impurities.)
  - Therefore, it would be better to write $\frac{d\mathbf{v}_n}{dt} = -\frac{q\mathbf{E}}{m_n} - \frac{\mathbf{v}_n}{\tau}$
  - Here, τ is the momentum relaxation time.



Velocity of an electron as a function of time.
When scattering is considered.

Steady-state solution

- The average velocity at the steady-state condition
  - Can be obtained by setting the time derivative to be zero.
  - Therefore, $\mathbf{v}_n = -\frac{q\tau}{m_n}\mathbf{E}$ for electrons. (For holes, the opposite sign)
  - Proportional coefficient is called as mobility, $\mathbf{u} = -\mu_n \mathbf{E}$

$$\mu_n = \frac{q\tau}{m_n} \quad \text{(Unit: [cm}^2\text{/V/sec])}$$

  - The mobility is proportional to the momentum relaxation time (less frequent collision) and is inversely proportional to the effective mass (heavy particle).
  - When the electron density per unit volume is given by n (Unit: [/cm^3]), the electron current density due to the drift is $\mathbf{J}_n = qn\mu_n\mathbf{E}$. (Drift only)

Two cars, two roads

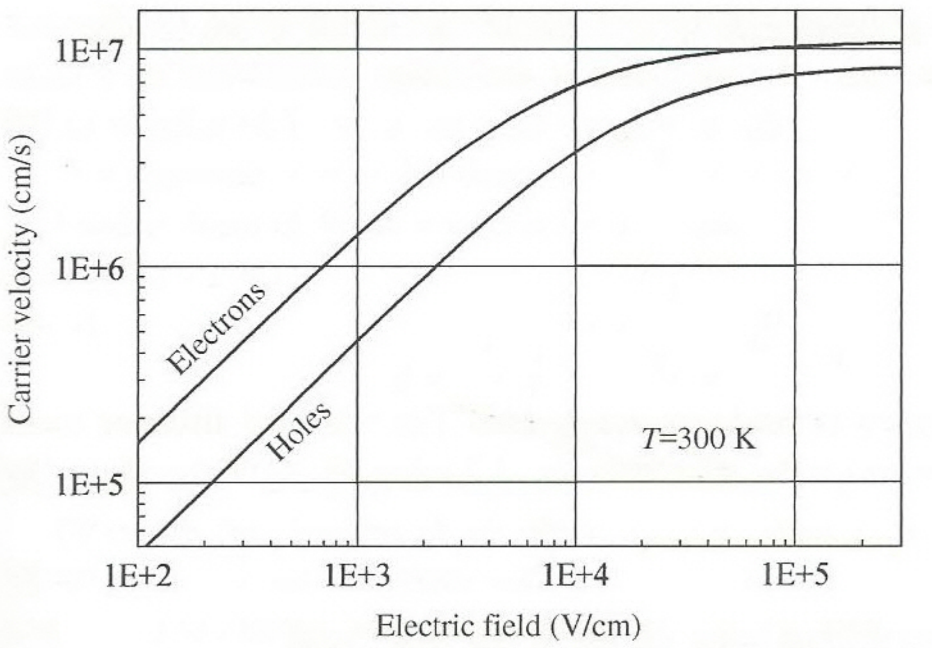
- With which car, on which road
  - Can you drive faster?
  - *Which one is the mass? Which one is the relaxation time?*

A sport car and a towing car
(Google image)

Good road and bad road
(Google image)

Velocity vs. electric field

- Directly affects the DC current
  - At low electric fields, the linear relationship is valid.
  - At high electric fields, the velocity saturation starts to occur. The saturation velocity of Si is about 10^7 [cm/sec].



Velocity-field relationship in Si at 300K
(Y. Taur and T. H. Ning, Fundamentals of modern VLSI devices)

Velocity saturation

- A simple expression
  - A field-dependent mobility

$$\mu = \frac{\mu_0}{1 + bE}$$

- Real expression used
  - An additional parameter

$$\mu = \frac{\mu_0}{(1 + (bE)^{\beta})^{1/\beta}}$$

Diffusion

- Another mechanism
  - "A drop of ink falls into a glass of water."
  - The density gradient, ∇n, will be relaxed by the diffusion.

$$\mathbf{J}_n \propto \nabla n$$

  - Diffusion constant as the proportional coefficient (actually, qD_n)

- Drift and diffusion

$$\mathbf{J}_n = qn\mu_n\mathbf{E} + qD_n\nabla n$$

  - *Consider the temperature dependence of μ_n and D_n.*

Einstein relation

- Valid at equilibrium
  - Mobility and diffusion constant

$$D = \frac{k_B T}{q} \mu$$

  - (Useful number: $\frac{k_B T}{q} \approx 25.85\ mV$ at 300K)

- Why do we have relations valid at equilibrium only?