# Lecture3: Basic physics of semiconductor (3)

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

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

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# Review

- 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, $np = n_i^2$

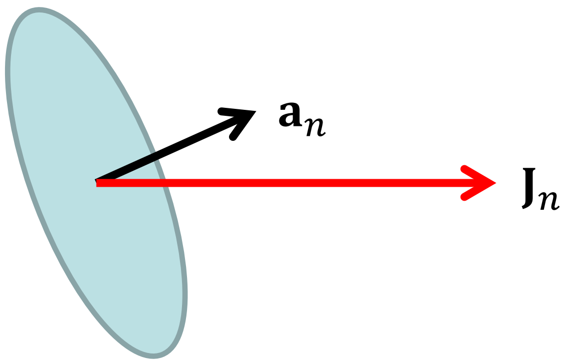
- Nonequilibrium
  - Various ways to generate the nonequilibrium case
  - Flow of charged particles!

# 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 $\mathbf{J}_n \cdot \mathbf{a}_n$




Unit area

# Current densities

- Electron current density

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

- Hole current density
  - Similarly,

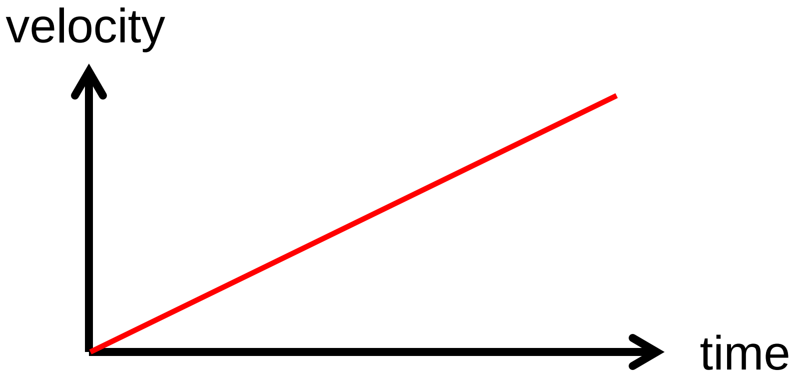
$$\mathbf{J}_p = qp\mathbf{v}_p$$

- Particle current density
  - Sum of these two terms

- Anything else?

# Drift

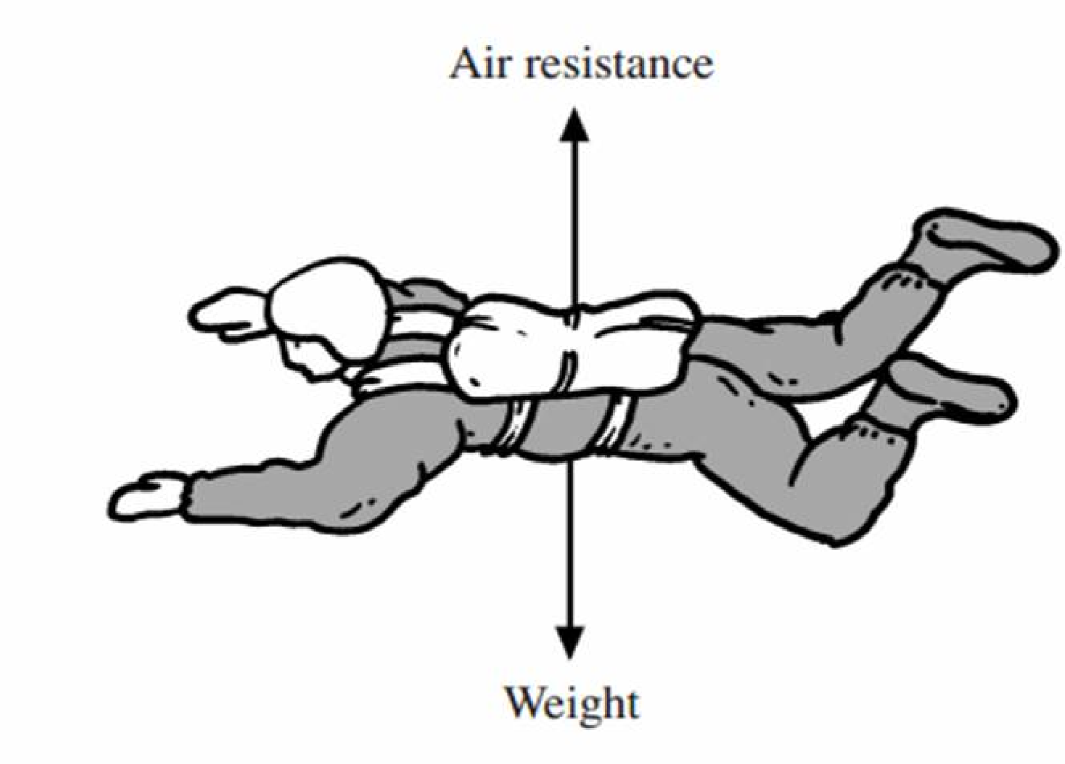
- Caused by an electric field
  - Since electrons/holes are charged particles, they are accelerated by an electric field, $\mathbf{E}$. (Unit: [V/cm])
  - For electrons, $\mathbf{F} = -q\mathbf{E}$ (For holes, the sign is the opposite.)
  - Then, the average velocity satisfies $\frac{d\mathbf{v}_n}{dt}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

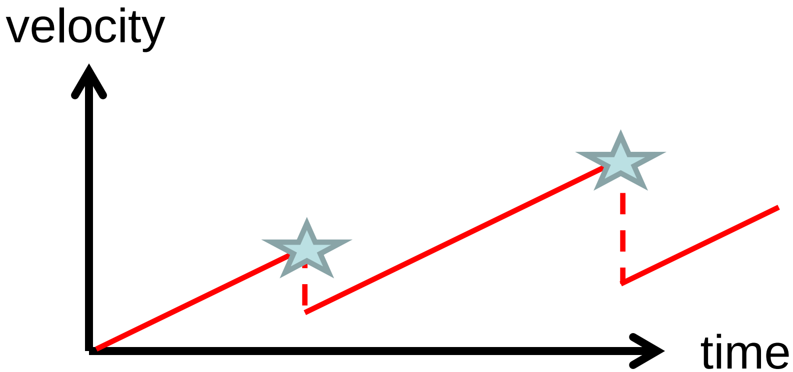
- Terminal velocity
  - For a skydiver, the gravity is the driving force.
  - For electrons, the electric field is the driving force.
  - Then, which mechanism plays a similar role of “air resistance”?




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 $\frac{d\mathbf{v}_n}{dt} = -\frac{q\mathbf{E}}{m_n} - \underline{\frac{\mathbf{v}_n}{\tau}}$
  - Here, $\tau$ 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

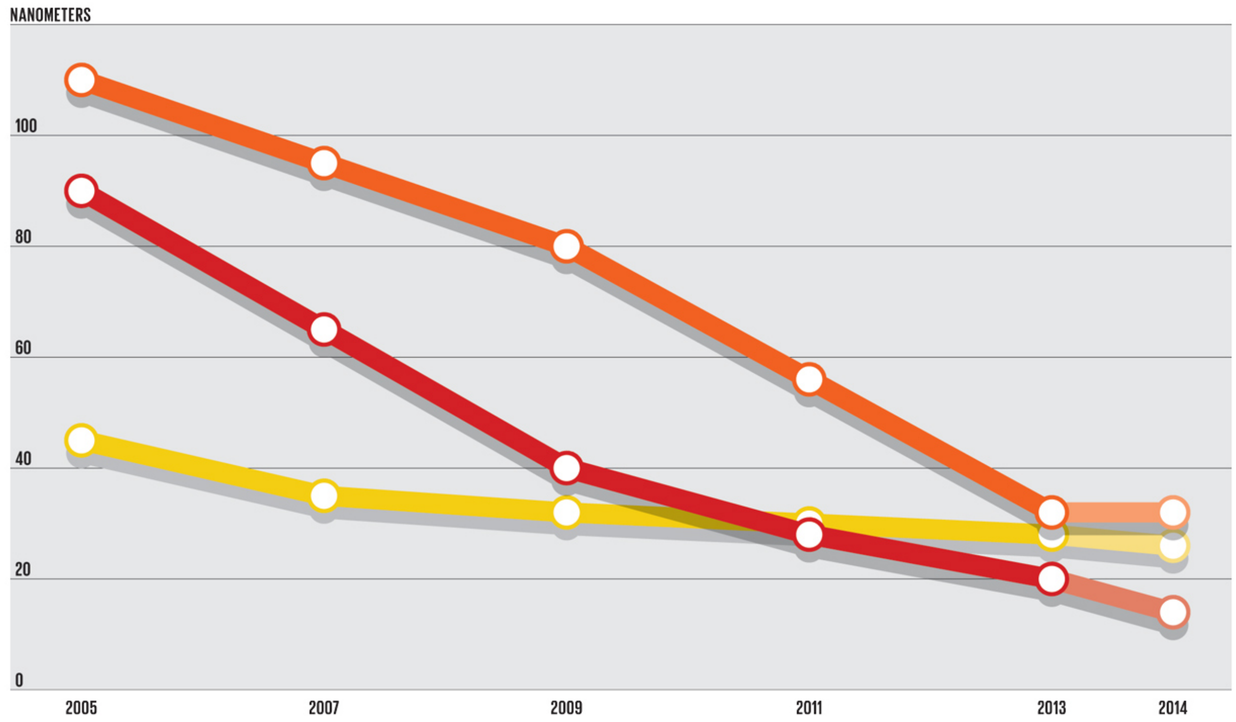
- With which car, on which road
  - Can you drive faster?
  - *Which one is the mass? Which one is the relaxation time?*


A sport car and a towing car
(Google image)

Good road and bad road
(Google image)

# Importance of mobility?

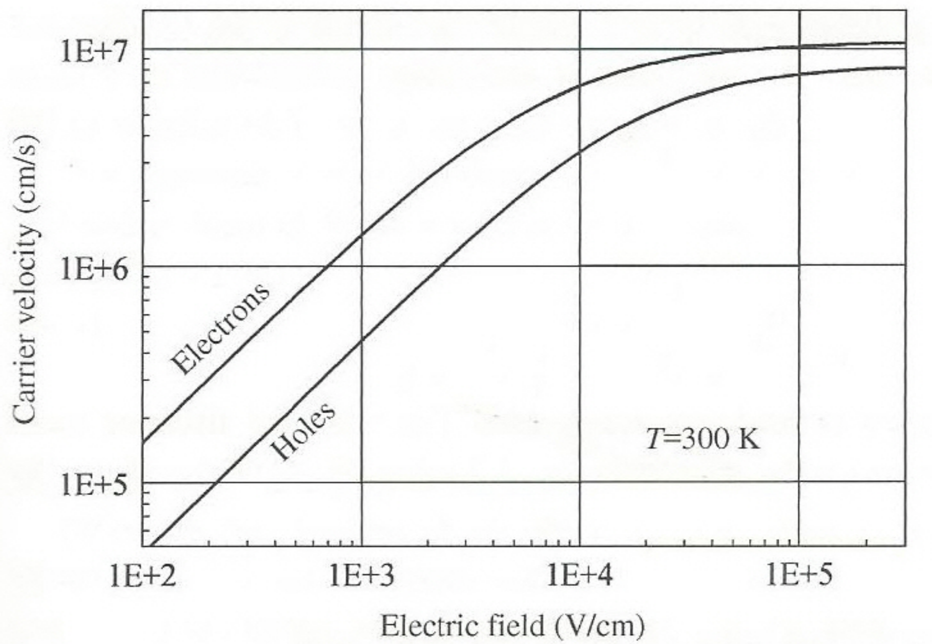
- In the electronic devices, critically important!
  - Yellow means the physical gate length. *Is it being scaled down?*




Dimensions of several technology nodes (IEEE Spectrum)

# 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, $\nabla n$, 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 $\mu_n$ 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?