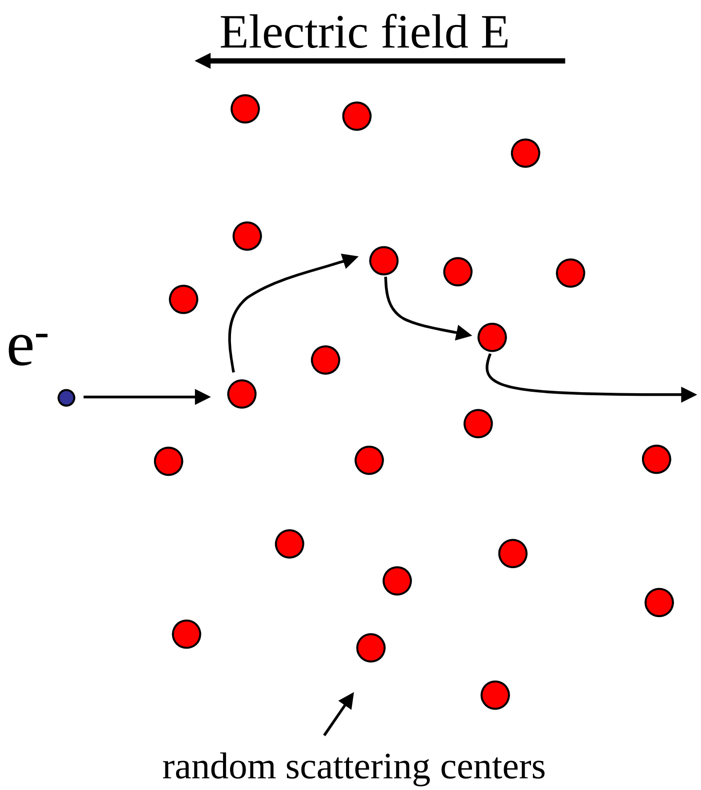
Lecture 2: Current

- Electrical conduction in semiconductors
  - Drift
  - Diffusion
- Haynes/Shockley experiment

Drift: Drude model



$$F = ma$$

$$eE = m \frac{\partial v}{\partial t}$$

$$v_{avg} = \underbrace{\frac{e\tau}{m}}_{\mu} E$$

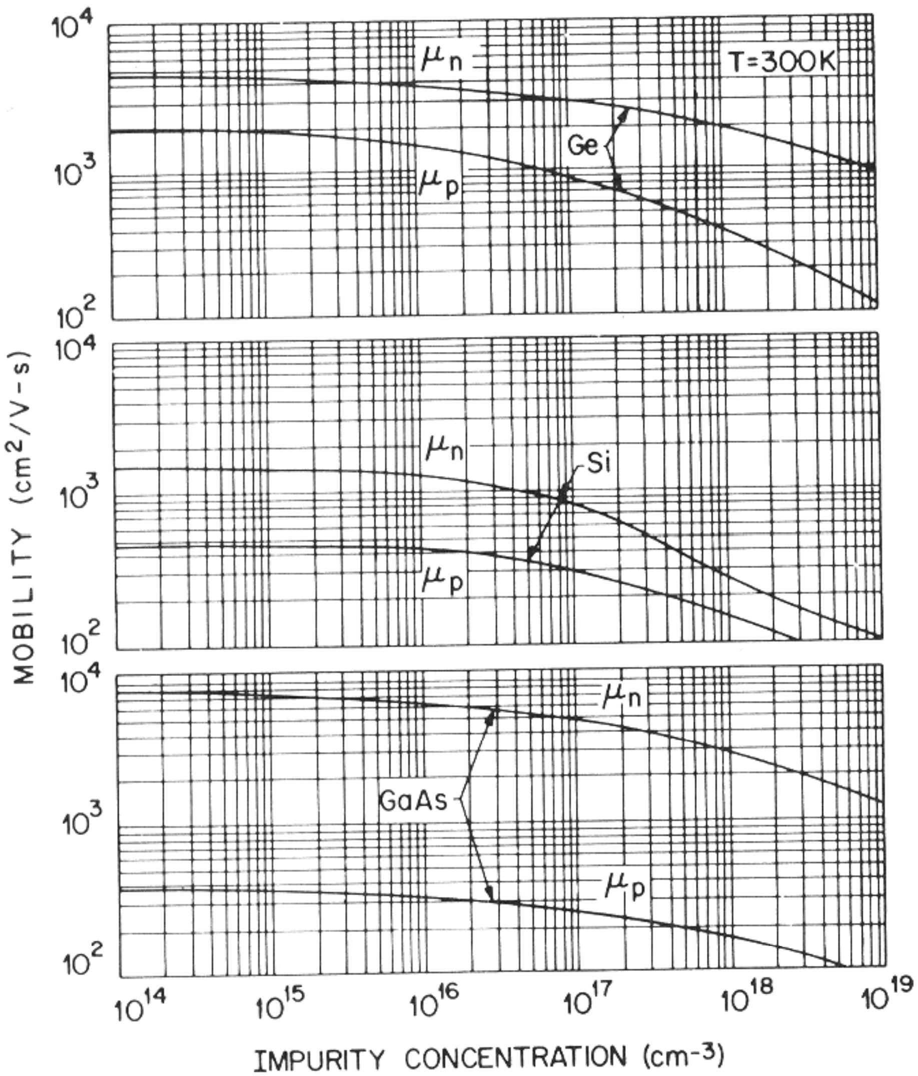
$$j = ne\, v_{avg} = \underbrace{\frac{ne^2\tau}{m}}_{\sigma} E$$

Types of scattering

- Electron-phonon:
  - Very temperature dependent
  - Phonons are lattice vibrations
  - At low temperatures, lattice is “perfectly still”
- Impurity scattering
  - Temperature independent
  - Depends on impurity concentration

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_{electron-phonon}} + \frac{1}{\tau_{impurity}}$$

"Mobility"



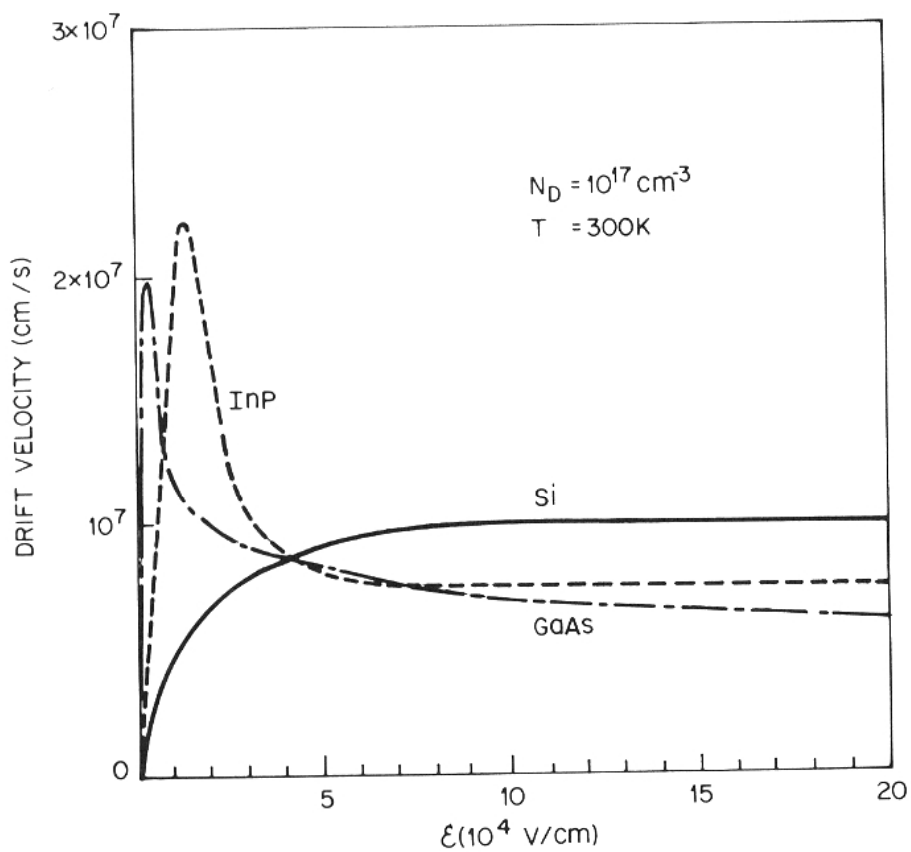
At low impurity concentration, electron-phonon scattering dominates.

At high impurity concentration, impurity scattering dominates.

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_{electron-phonon}} + \frac{1}{\tau_{impurity}}$$

From Sze, Physics of Semiconductor Devices

High-field "drift"

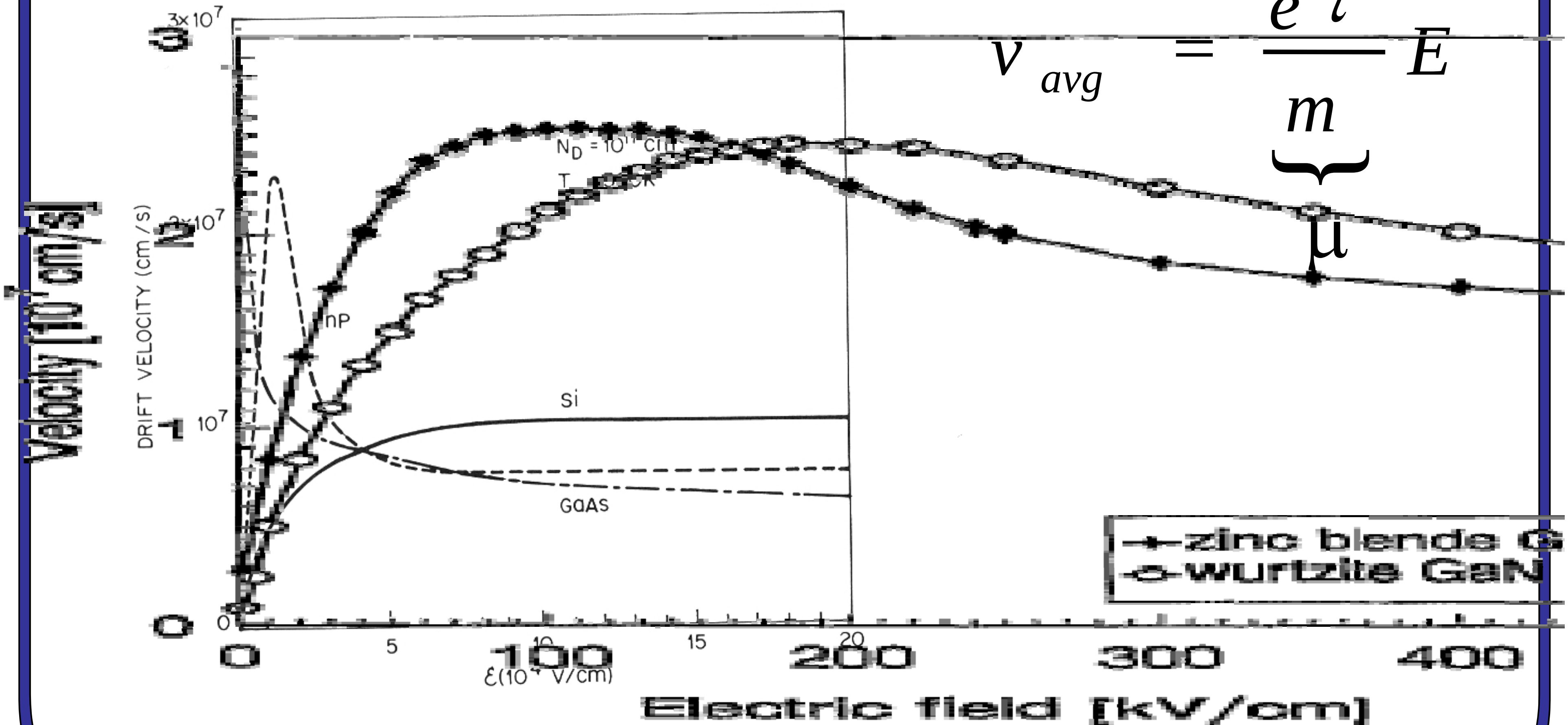


$$v_{avg} = \underbrace{\frac{e\,\tau}{m}}_{\mu} E$$

From Sze, Physics of Semiconductor Devices

High-field "drift"

$$v_{avg} = \underbrace{\frac{e\,\tau}{m}}_{\mu} E$$



From Sze, Physics of Semiconductor Devices

Diffusion current

Now assume n depends on position:

$$J \propto \frac{dn(x)}{dx}$$

(Discuss intuitively.)
Like opening a can of perfume at the back of the room.

$$J = eD\frac{dn(x)}{dx}$$

Einstein relationship:

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

Total current

Electrons:

$$J_n = e \cdot \mu_n \cdot n \cdot E + eD_n \frac{dn(x)}{dx}$$

Holes:

$$J_p = e \cdot \mu_p \cdot p \cdot E - eD_p \frac{dp(x)}{dx}$$

E, n can depend on x!

The entire course will be based on these two equations.

Recombination

If we have more electrons somehow than the equilibrium value, they will tend to recombine with holes to get back to the equilibrium value. Typically this rate is given by:

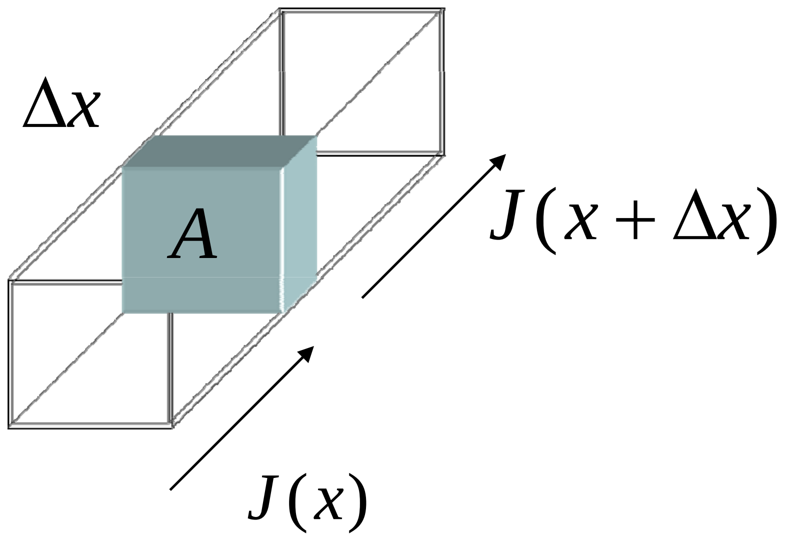
$$\frac{\partial n}{\partial t} = \frac{n - n_o}{\tau}$$

$\tau \sim 10^{-6}$ s in silicon

$\tau \sim 10^{-9}$ s in good GaAs

$\tau \sim 10^{-12}$ s in "dirty" GaAs

Continuity equation



How many electrons in green box after a time Δt?

$$\frac{1}{e} A J(x) \Delta t$$ enter

$$\frac{1}{e} A J(x+dx) \Delta t$$ leave

$$\frac{n-n_o}{\tau} A \Delta x \Delta t$$ recombine

$$G_n A \Delta x \Delta t$$ are generated

Add em up:

$$\Delta N = \frac{1}{e} A\left[J(x) - J(x+dx)\right]\Delta t - \frac{n-n_o}{\tau} A\Delta x\Delta t + G_n A\Delta x\Delta t$$

Divide by: $A\Delta x\Delta t$

$$\Rightarrow \frac{\partial n}{\partial t} = \frac{1}{e}\frac{\partial J(x)}{\partial x} - \frac{n-n_o}{\tau} + G_n$$

Continuity equation

$$\Rightarrow \frac{\partial n}{\partial t} = \frac{1}{e}\frac{\partial J(x)}{\partial x} - \frac{n - n_o}{\tau} + G_n$$

If electric field is non-zero, then

$$J = eD\frac{dn(x)}{dx}$$

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2} - \frac{n - n_o}{\tau} + G_n$$

Continuity equation

$$\Rightarrow \frac{\partial n}{\partial t} = \frac{1}{e}\frac{\partial J(x)}{\partial x} - \frac{n - n_o}{\tau} + G_n$$

If electric field is zero, only current is diffusion current:

$$J_n = e \cdot \mu_n \cdot n \cdot E + eD_n \frac{dn(x)}{dx}$$

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2} + \mu_n \frac{\partial (n \cdot E)}{\partial x} - \frac{n - n_o}{\tau} + G_n$$

Neutrality assumption

$$\delta n \equiv n - n_o = \delta p \equiv p - p_o$$

In the text (read it!), they show that in this case:

For p-type materials:

$$\frac{\partial \delta n}{\partial t} = D_n \frac{\partial^2 \delta n}{\partial x^2} + \mu_n E \frac{\partial(\delta n)}{\partial x} - \frac{\delta n}{\tau} + G_n$$

For n-type materials:

$$\frac{\partial \delta p}{\partial t} = D_p \frac{\partial^2 \delta p}{\partial x^2} + \mu_p E \frac{\partial(\delta p)}{\partial x} - \frac{\delta p}{\tau} + G_p$$

(Not a typo!) Now E is just the external field. (Discuss)

Some aspects of diffusion

- Steady state
- Wave packet spreading
- Drift+diffusion

Steady state

(Assume E=0.)

$$\frac{\partial \delta n}{\partial t} = D_n \frac{\partial^2 \delta n}{\partial x^2} - \frac{\delta n}{\tau} = 0$$

$$\Rightarrow D \frac{\partial^2 \delta n}{\partial x^2} = \frac{\delta n}{\tau}$$

$$\Rightarrow \delta n(x) = \delta n(x=0) \cdot \exp\left(-\frac{x}{\sqrt{D\tau_n}}\right)$$

$$\sqrt{D\tau_n} \equiv \text{diffusion length}$$

Typically about one micron.

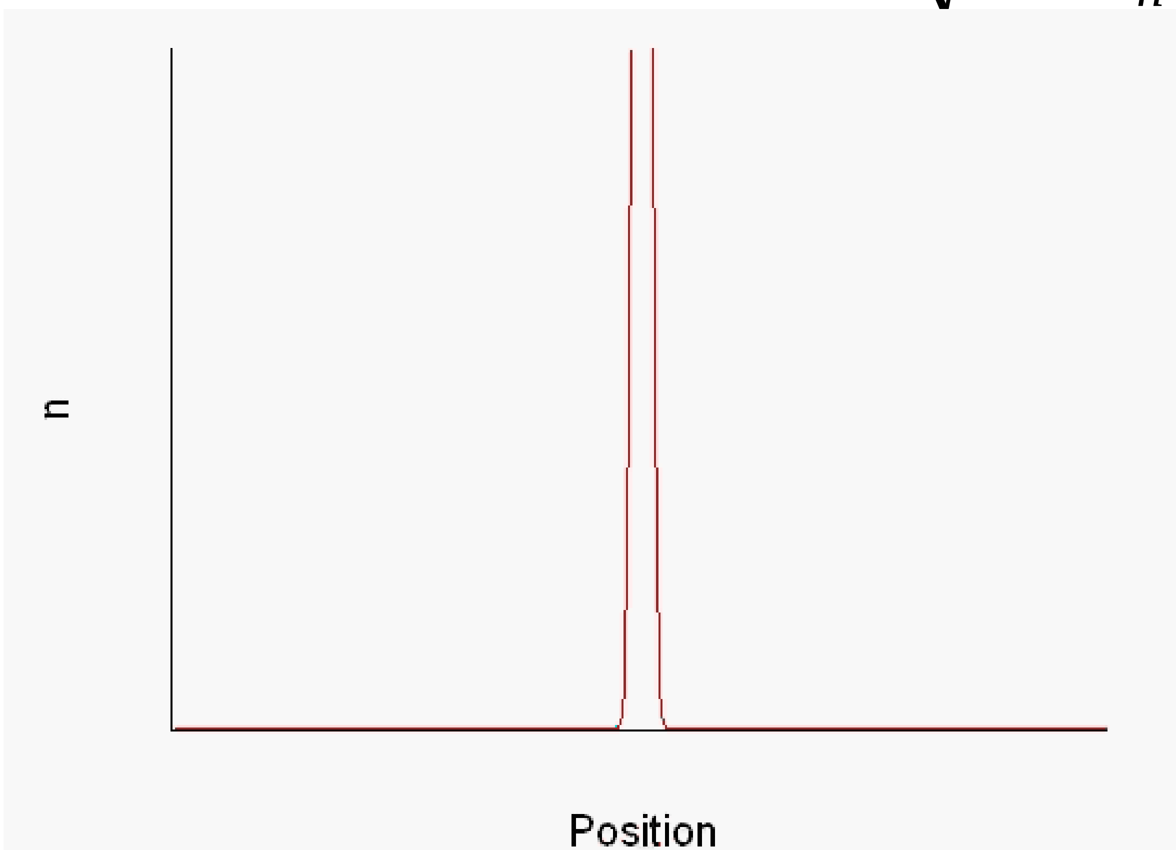
Discuss drunken man analogy.

Wave packet spreading

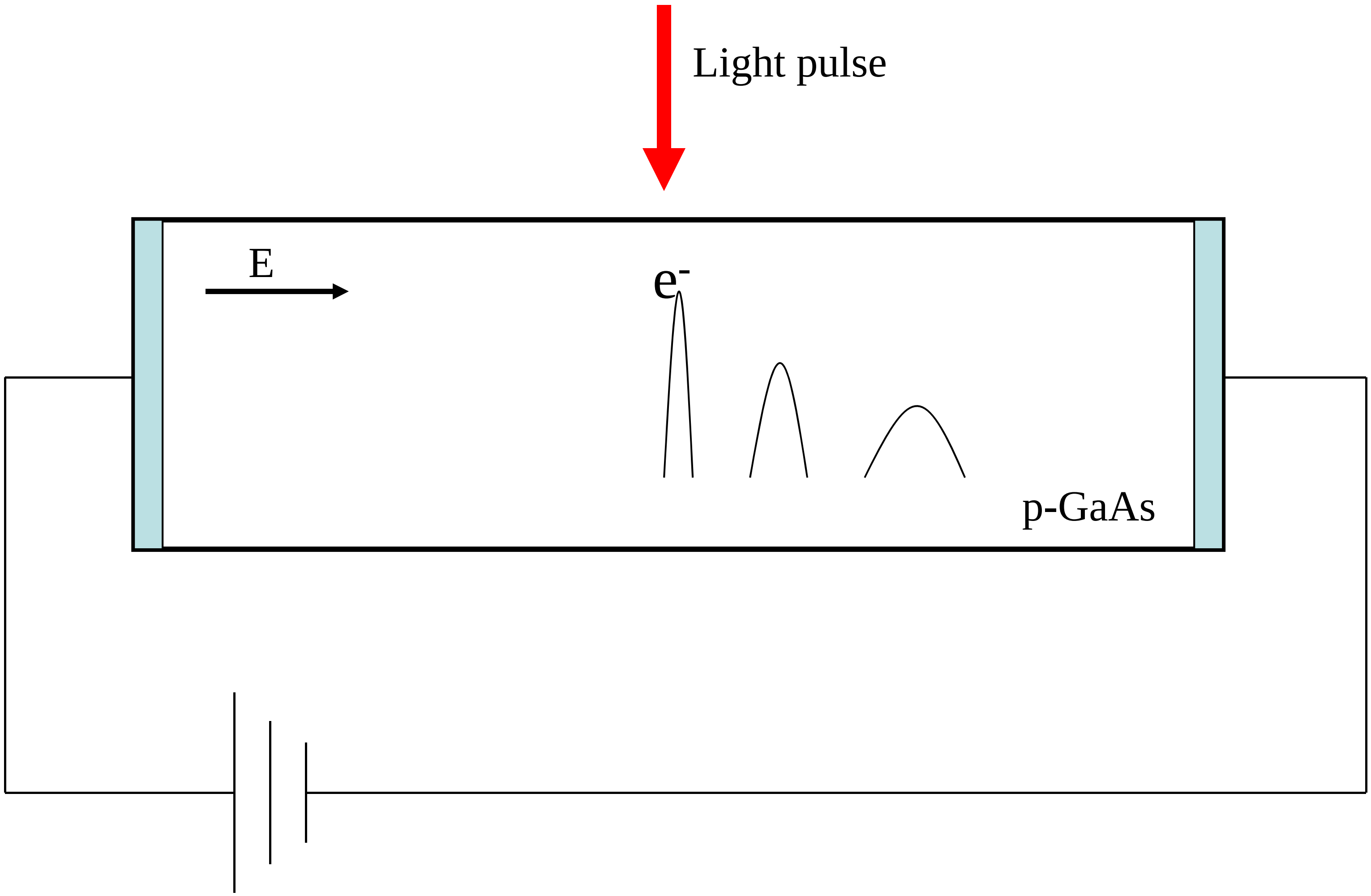
(Assume E=0. Neglect recombination.)

$$\frac{\partial \delta n}{\partial t} = D_n \frac{\partial^2 \delta n}{\partial x^2} \Rightarrow \delta n(x,t) = \frac{N}{\sqrt{4\pi D_n t}} e^{-x^2/4D_n t}$$

(prove on board)



Haynes-Shockley



Haynes-Shockley

(Assume E nonzero. Neglect recombination.)

$$\frac{\partial \delta n}{\partial t} = D_n \frac{\partial^2 \delta n}{\partial x^2} + \mu_n E \frac{\partial(\delta n)}{\partial x} \Rightarrow \delta n(x,t) = \frac{N}{\sqrt{4\pi D_n t}} e^{-(x-\mu_n E t)^2 / 4 D_n t}$$

(prove on board)

Haynes-Shockley

- Spreading of pulse gives diffusion coeffecient D
- Time of arrival of peak of pulse gives mobility μ
- Information obtained is for MINORITY carriers only

Hall Effect

time permitting, discuss on board

Method to measure mobility of majority carriers

$$F = q(E_y - v_x B_z) = 0$$

$$\Rightarrow E_y = v_x B_z$$

$$\Rightarrow V_y = w v_x B_z = \frac{J_x}{en} w B_z$$

Gets you the density, then with resistance measurement you can calculate the mobility.