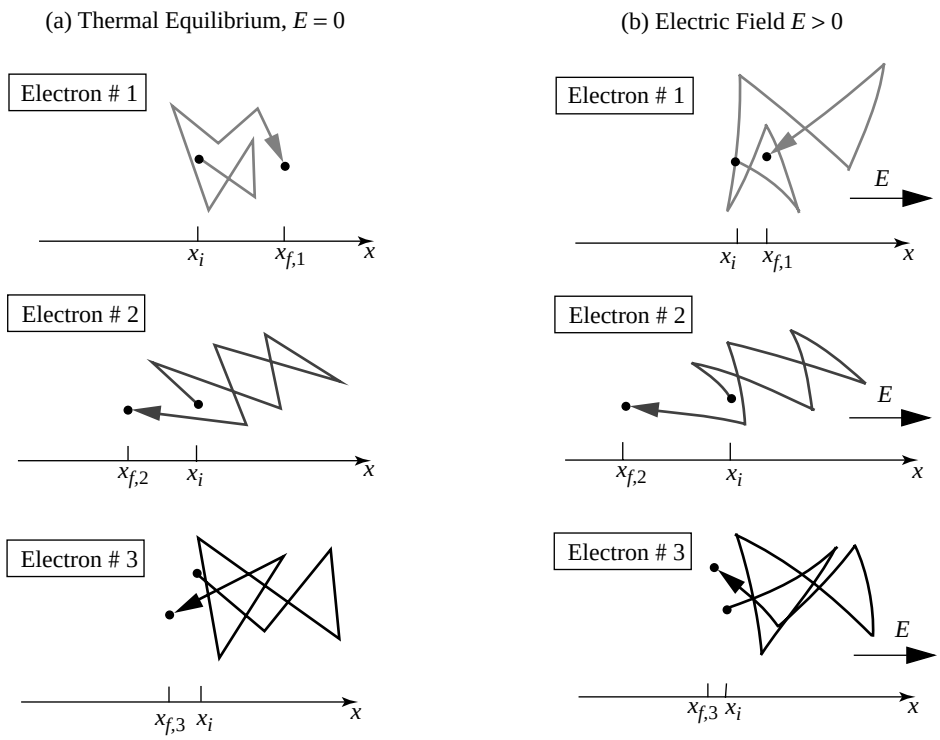
Carrier Transport: Drift

- If an electric field is applied to silicon, the holes and the electrons "feel" an electrostatic force $F_e = (+q \text{ or } -q)E$.
- Picture of effect of electric field on representative electrons: moving at the thermal velocity = 10^7 cm/s ... *very fast*, but colliding every 0.1 ps = 10^{-13} s. Distance between collsions = 10^7 cm/s x 10^{-13} cm = 0.01 μm



* x_i = initial position * $x_{f,n}$ = final position of electron n after 7 collisions

- The average of the position changes for the case with $E > 0$ is $\overline{\Delta x} < 0$

Drift Velocity and Mobility

- The *drift velocity* v_{dn} of electrons is defined as:

$$v_{dn} = \frac{\overline{\Delta x}}{\Delta t}$$

- Experiment shows that the drift velocity is proportional to the electric field for electrons

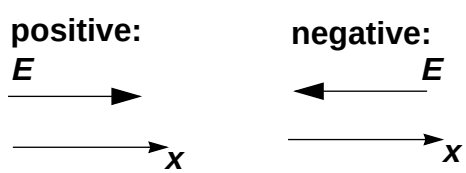
$$v_{dn} = -\mu_n E,$$

with the constant μ_n defined as the *electron mobility.*

- Holes drift in the direction of the applied electric field, with the constant μ_p defined as the *hole mobility.*

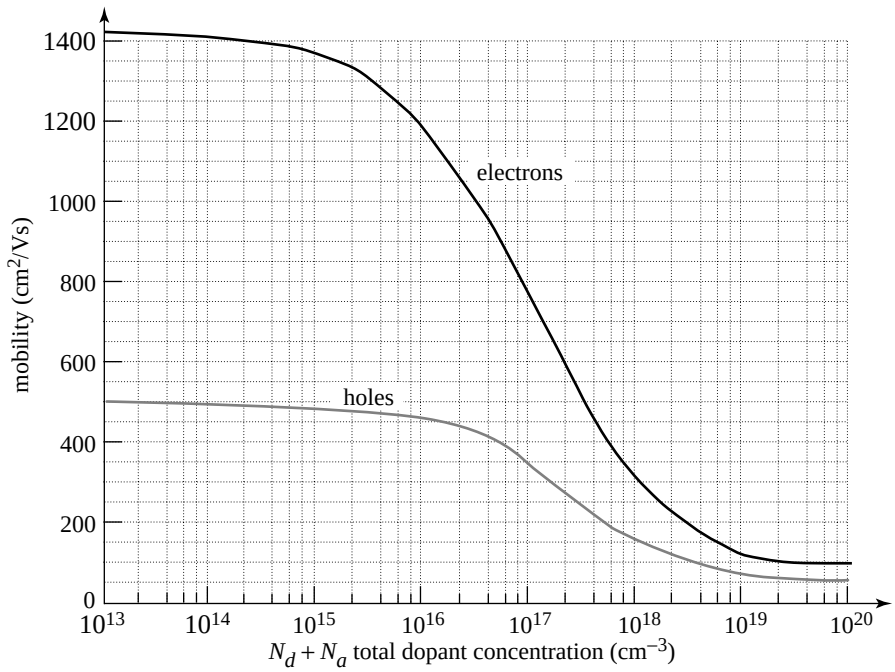
$$v_{dp} = \mu_p E$$

How do we know what's positive and what's negative?



Electron and Hole Mobilities

- mobilities vary with doping level -- plot is for 300 K = room temp.



- "typical values" for bulk silicon - assuming around 5 x 10^{16} cm^{-3} doping

$$\mu_n = 1000\ cm^2/(Vs)$$

$$\mu_p = 400\ cm^2/(Vs)$$

- at electric fields greater than around 10^4 V/cm, the drift velocities saturate --> max. out at around 10^7 cm/s. Velocity saturation is very common in VLSI devices, due to sub-micron dimensions

Carrier Transport: Drift Current Density

Electrons drifting opposite to the electric field are carrying negative charge; therefore, the *drift current density* is:

$$J_n^{dr} = (-q)\, n\, v_{dn} \qquad \text{units: Ccm}^{-2}\ \text{s}^{-1} = \text{Acm}^{-2}$$

$$\boxed{J_n^{dr} = (-q)\, n\, (-\mu_n E) = q\, n\, \mu_n E}$$

Note that J_n^{dr} is in the *same* direction as the electric field.

For holes, the mobility is μ_p and the drift velocity is in the same direction as the electric field: $v_{dp} = \mu_p E$

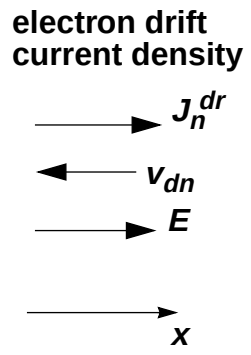
The hole drift current density is:

$$J_p^{dr} = (+q)\, p\, v_{dp}$$

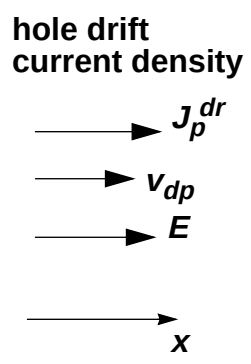
$$\boxed{J_p^{dr} = q\, p\, \mu_p E}$$

Drift Current Directions and Signs

- For electrons, an electric field in the $+x$ direction will lead to a drift velocity in the $-x$ direction ($v_{dn} < 0$) and a drift current density in the $+x$ direction ($J_n^{dr} > 0$).



- For holes, an electric field in the $+x$ direction will lead to a drift velocity in the $+x$ direction ($v_{dp} > 0$) and a drift current density in the $+x$ direction ($J_n^{dr} > 0$).



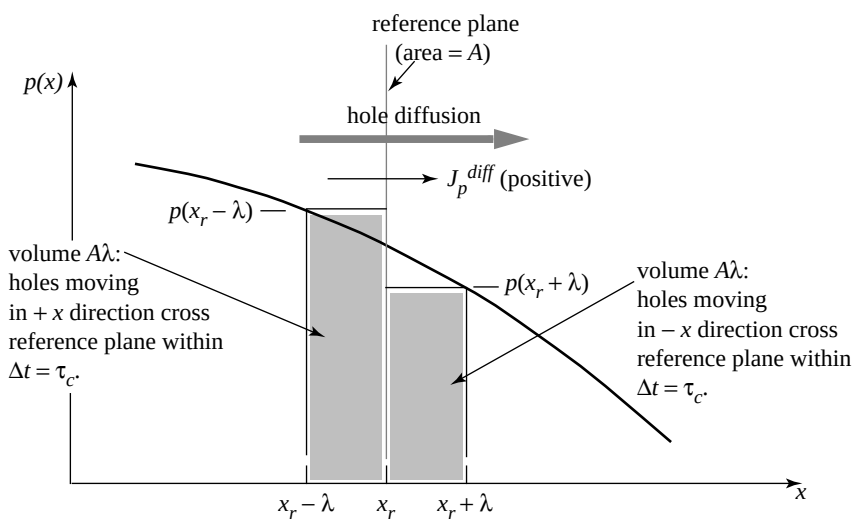
Carrier Transport: Diffusion

Diffusion is a transport process driven by gradients in the concentration of particles in random motion and undergoing frequent collisions -- such as ink molecules in water ... or holes and electrons in silicon.

Mathematics: find the number of carriers in a volume $A\lambda$ on either side of the reference plane, where λ is the mean free path between collisions.

- Some numbers: average carrier velocity = $v_{th} = 10^7$ cm/s, average interval between collisions = $\tau_c = 10^{-13}$ s = 0.1 picoseconds

  mean free path = $\lambda = v_{th}\,\tau_c = 10^{-6}$ cm = 0.01 μm



- half of the carriers in each volume will pass through the plane before their next collision, since their motion is random

Carrier Transport:
Diffusion Current Density

- Current density = (charge) x (# carriers per second per area):

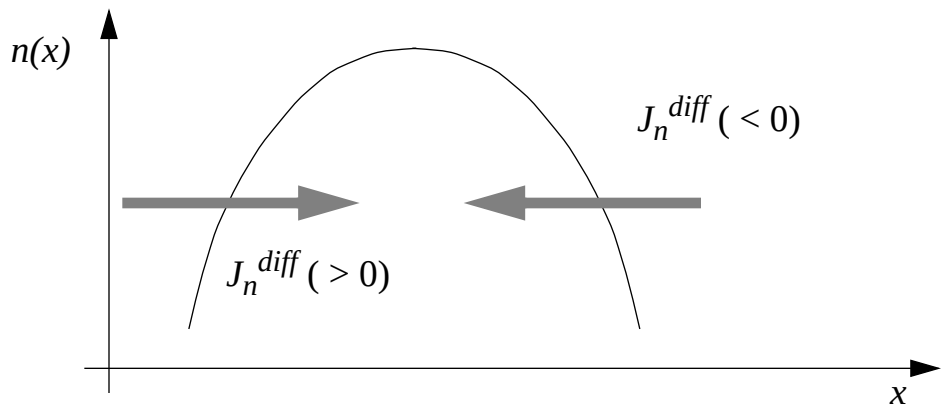
$$J_p^{diff} = q\left[\frac{\frac{1}{2}p(x-\lambda)A\lambda - \frac{1}{2}p(x+\lambda)A\lambda}{A\tau_c}\right]$$

- If we assume that λ is much smaller than the dimensions of our device, then we can consider $\lambda = dx$ and use Taylor expansions :

$$J_p^{diff} = -qD_p\frac{dp}{dx}\ ,$$ where $D_p = \lambda^2 / \tau_c$ is the diffusion coefficent

Electron Transport by Diffusion

- Electrons diffuse down the concentration gradient, yet carry negative charge --> electron diffusion current density points in the direction of the gradient



- Total current density: add drift and diffusion components for electrons and for holes --

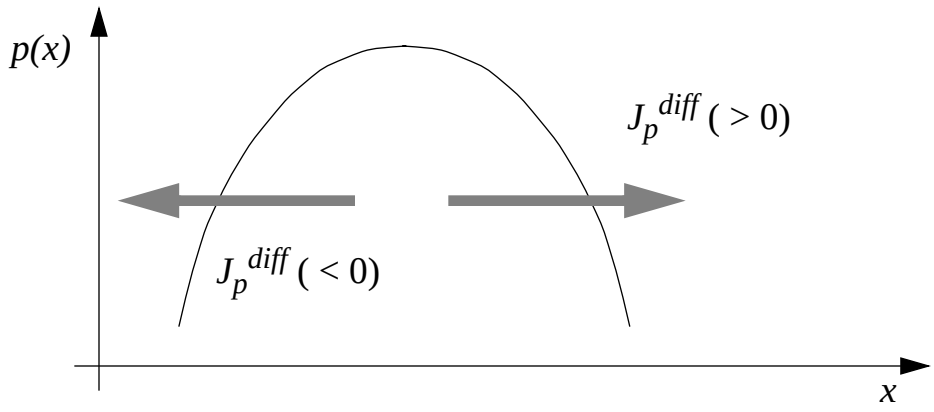
$$J_n = J_n^{dr} + J_n^{diff} = qn\mu_n E + qD_n \frac{dn}{dx}$$

$$J_p = J_p^{dr} + J_p^{diff} = qp\mu_p E - qD_p \frac{dp}{dx}$$

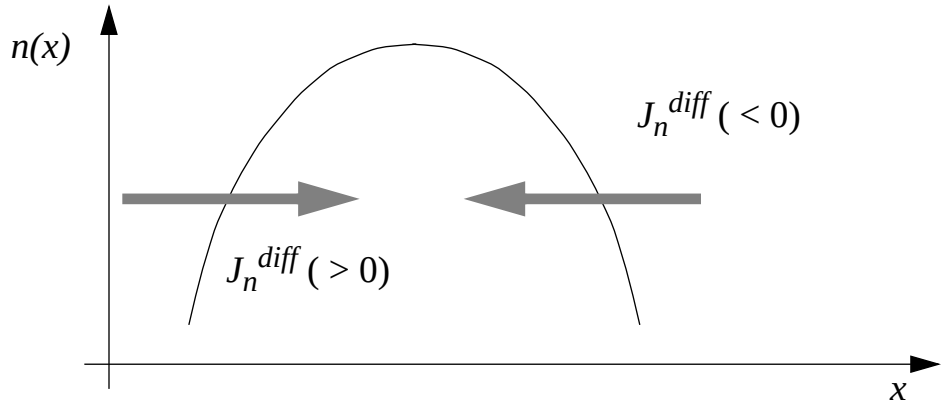
- Fortunately, we will be able to eliminate one or the other component in finding the internal currents in microelectronic devices.

Carrier Transport by Diffusion

- Holes diffuse “down” the concentration gradient and carry a positive charge --> hole diffusion current has the *opposite* sign to the gradient in hole concentration *dp/dx*



- Electrons diffuse down the concentration gradient, yet carry a negative charge --> electron diffusion current density has the *same* sign as the gradient in electron concentration *dn/ dx*.



Electron Diffusion Current Density

- Similar analysis leads to

$$J_n^{diff} = qD_n \frac{dn}{dx},$$

where D_n is the electron diffusion coefficient (units: cm^2/s)

- Numerical values of diffusion coefficients: use Einstein's relation

$$\boxed{\frac{D_n}{\mu_n} = \frac{kT}{q}}$$

- The quantity kT/q has units of volts and is called the *thermal voltage*, V_{th}:

$$V_{th} = \frac{kT}{q} = 25 - 26\,\text{mV},$$

at "room temperature," with 25 mV for a cool room (62 ^{o}F) and 26 mV for a warm room (83 ^{o}F).

We will pick 25 mV or 26 mV depending on which gives the "roundest" numbers.

Total Current Densities

- Add drift and diffusion components for electrons and for holes --

$$J_n = J_n^{dr} + J_n^{diff} = qn\mu_n E + qD_n \frac{dn}{dx}$$

$$J_p = J_p^{dr} + J_p^{diff} = qp\mu_p E - qD_p \frac{dp}{dx}$$

- Fortunately, we will be able to eliminate one or the other component of the electron or the hole current in our analysis of semiconductor devices.

IC Fabrication Technology

- History:

  1958-59: J. Kilby, Texas Instruments and R. Noyce, Fairchild
  1959-70: Explosive growth in US (bipolar ICs)
  1970-85: MOS ICs introduced, RAMs, microprocessors, Japan catches up to US in volume
  1985-95: PC revolution, improved design software for complex CMOS integrated systems, US leads in micro-processors, Japan in RAMs
  1996-2000 > 10^8 devices/chip (= 1000 Mbit dRAM), US remains competitive -- even dominates -- sectors of the market; spin-offs from IC technology in MEMS (micro electro-mechanical systems) for sensing acceleration

- Key Idea: *batch fabrication* of electronic circuits

  An entire circuit, say 10^6 transistors and associated wiring -- can be made in and on top of a single silicon crystal by a series of process steps similar to printing.

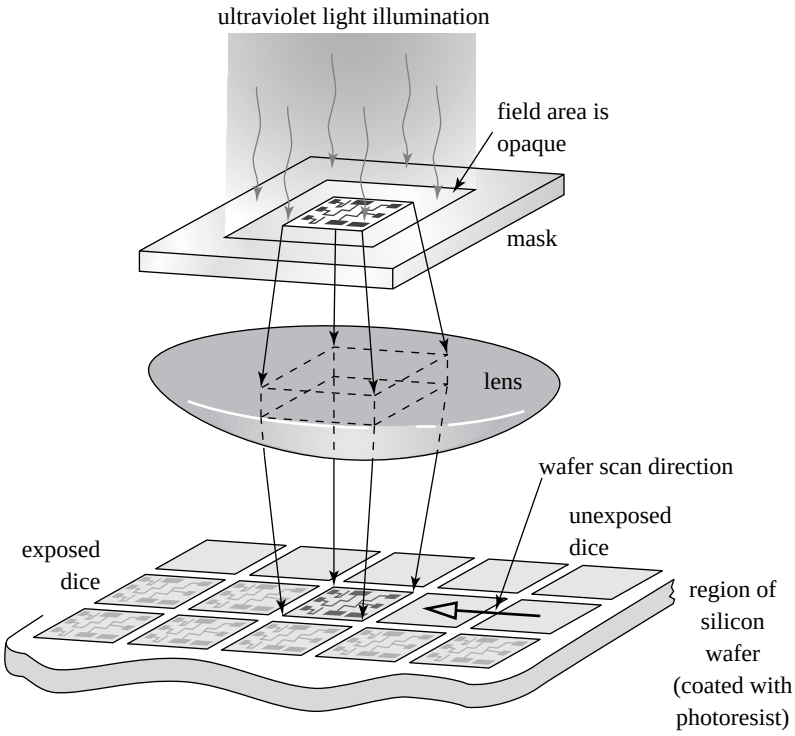
  The silicon crystal is a thin disk about the size of a small dinner plate (ca. 1996) called a *wafer*. More than 100 copies of the circuit are made at the same time.

- Results:

1. Complex systems can be fabricated reliably
2. Cost per function drops as the process improves (e.g., finer printing), since the cost per processed wafer remains about the same

Photolithography

- The essential process step: makes possible the transfer of a series of patterns onto the wafer -- all aligned to within 0.1 μm
- Process "Tool" -- *wafer stepper*

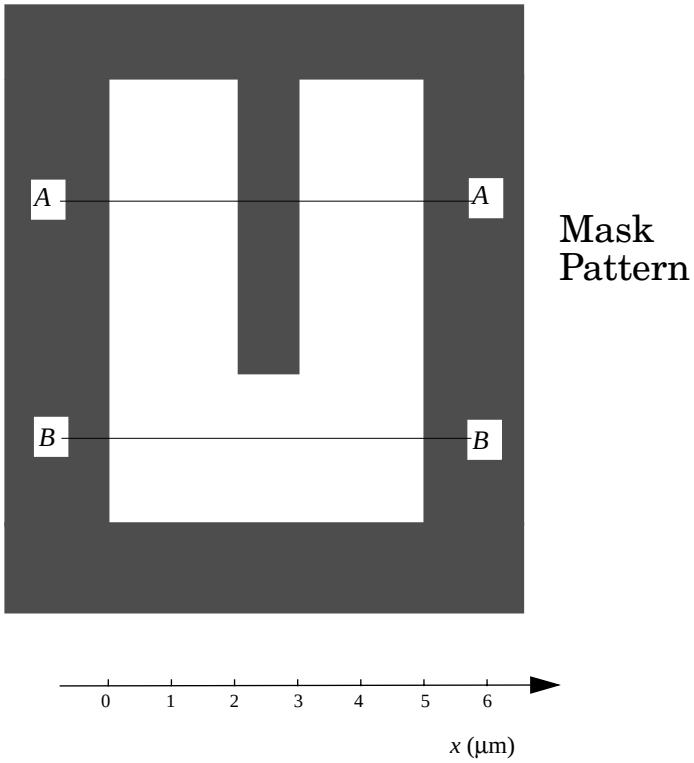


- UV-sensitive film is called *photoresist.* Regions exposed to UV dissolve in developer (for *positive* photoresist -- the type we will consider)

Exposure, Development, and Pattern Transfer

- Simple example of a *layout* and a *process* (or *recipe*)

  * *Layout* is the set of mask patterns for particular layers (one in this case)

  * *Process* is the sequence of fabrication steps

- Visualize by generating *cross sections* through the structure as it is built up through the process