Semiconductor: Drift current

day05

1. Review

$$n = \frac{(N_D - N_A) \pm \sqrt{(N_D - N_A)^2 + 4n_i^2}}{2} \quad \text{and} \quad p = \frac{n_i^2}{n} \tag{1}$$

1.1. When to approximate?

We as Engineers use approximations **all the time**. They make calculations easier or less complex, while still being accurate *enough* for the purpose.

> But how do you know what is "close enough"?

The key skill is being aware of how much precision is needed for the final result or design. For example:

- The clock's frequency needs to be within ±X % so the timer is off by less than 1 second per day. (compute this X value!)
- The amplifier's gain needs to be 10±1 V/V.
- The diode's forward voltage at 25 °C and 1 mA of current needs to be 650 mV ±1%.

The Razavi book *only* uses the approximation and skips even showing the accurate formula for charge carrier density with doping. Assume that $N_A = 0$ and the material is only doped with donors.

$$n \approx N_D \quad \text{and} \quad p \approx \frac{n_i^2}{N_D} \tag{2}$$

- So, when can you use the approximation for an error less than X%?

One nice way to figure this out is to come up with a relationship between the size of the variables that, when true, let you safely use the easy equation.

> For less than 1% error, N_D should be (less/greater) than ____________ compared to n_i. Compute this condition.

2. Current in semiconductors

This content is mirrored at Electronics Tour Book - 2.5. Semiconductor currents .

How is drift current *constant* instead of *accelerating*?

Youtube: The Price is Right former biggest Plinko win - start at 2:49

2.1. Summary

As usual, we lead with the punchline —results first, then back-fill with its creation story.

Types of charge movement

Drift constant velocity proportional to E-field

Diffusion movement from high to low concentration

Two mechanisms of movement with two types of charge carriers yields four types of current in a semiconductor.

Table 1. Four currents in a semiconductor (A/cm²)

	electrons	holes
drift	$q \cdot n \cdot \mu_n \cdot \vec{E}$	$q \cdot p \cdot \mu_p \cdot \vec{E}$
diffusion	$q \cdot D_n \cdot \frac{\mathrm{d}\,n}{\mathrm{d}x}$	$-q \cdot D_p \cdot \frac{\mathrm{d}\,p}{\mathrm{d}x}$

2.2. Drift

2.2.1. Physics phundamentals

- An electron in an electric field experiences a force.
- This force causes the electron (which has mass) to accelerate.
- **Why** does this not therefore cause an *increasing* current in a material?

▶ Think about this question, then <**click to reveal**>

The average electron velocity is proportional to the applied E-field.

$$v \propto \vec{E} \tag{3}$$

The constant of proportionality is called **mobility** (μ_n for electrons and μ_p for holes) and must have units of $\frac{\mathrm{cm}^2}{\mathrm{V{\cdot}s}}$.

For silicon, these values are around:

- $\mu_n = 1350 \ \frac{\mathrm{cm}^2}{\mathrm{V{\cdot}s}}$
- $\mu_p = \ \ 480 \ \frac{\mathrm{cm}^2}{\mathrm{V{\cdot}s}}$

Recall that the **electric potential difference** that we commonly name by its units of **volts** is only and truly the *path integral of the electric field*. Fortunately, the E-field is a *conservative field*, so the result of the integration only depends on the end points:

$$\mathrm{V(olts)_{ab}} = -\int_a^b \vec{E}\,dl \tag{4}$$

For holes

$\vec{v}_h = \mu_p \vec{E}$, movement in the same direction as the $\vec{E}$ field vector.

For electrons

$\vec{v}_e = -\mu_n \vec{E}$, movement in the **opposite** direction as the $\vec{E}$ field vector.

2.2.2. Current flow in a bar

> *Imagine a bar of silicon*

Let’s begin by considering the current that flows due to electrons.

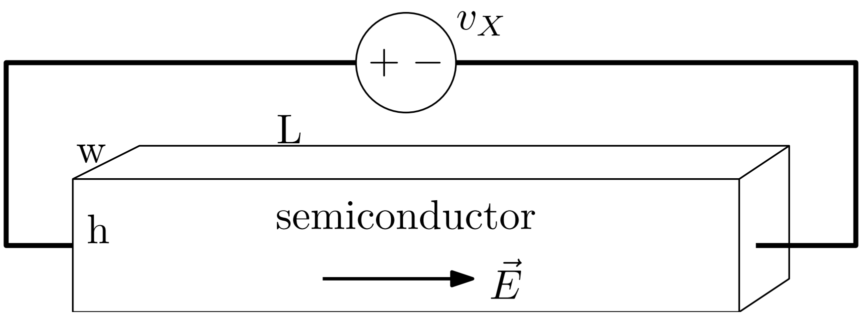

Figure 2. Voltage source connected across a (semi)conductor bar.

We know the electron (average) velocity, the density of (free) electrons, and the geometry of the bar.

$$I_e = \underbrace{-}_{\text{electrons are negatively charged!}} \; \underbrace{-\mu_n \vec{E}}_{\text{velocity opposite field direction } (cm/s)} \cdot \underbrace{W \cdot h}_{\text{area normal to direction of travel } (cm^2)} \cdot \underbrace{n \cdot q}_{\text{charge density } (C/cm^3)}$$

C/cm

$C/s \rightarrow A$

> Notice the double negative! Each negative has a different origin even though the net result is a positive sign.

Let’s normalize this into a current **flux** by dividing by the cross-sectional area $W \cdot h$.[2]

$$J_n = \frac{I_n}{W \cdot h} = \mu_n \vec{E} \cdot n \cdot q \tag{5}$$

> J_n has units of A/cm^2 which is the units of a flow per unit area or **flux**. In an unfortunate naming convention, everyone else calls this term electron **current density**.

By the same reasoning, we can find the hole **current density**

$$I_h = \underset{\text{holes are positively charged!}}{+} \; \underbrace{+\mu_p \vec{E}}_{\text{velocity same as field direction } (cm/s)} \cdot \underbrace{W \cdot h}_{\text{area normal to direction of travel } (cm^2)} \cdot \underbrace{p \cdot q}_{\text{charge density } (C/cm^3)}$$

C/cm

$C/s \rightarrow A$

$$J_p = (\text{hole velocity})\,(\text{charge density}) \tag{6}$$

$$= \left(\mu_p \vec{E}\right)(p \cdot q) \tag{7}$$

The total **drift current density** is then

$$J_{total}(\text{drift}) = J_n + J_p \tag{8}$$

$$= q\left(\mu_n n + \mu_p p\right) \cdot \vec{E} \quad \text{A/cm}^2 \tag{9}$$

Finding the **current** that you would measure with an ammeter from this expression merely requires multiplying by the cross-section area of the bar.

But… look back at Figure 2 and see that we are applying a **voltage** across the ends of the bar (using an ideal voltage source)—what is $\vec{E}$?

An easy-ish way to remember what to do is to recall the *units* of the electric field: volts per meter. We get our voltage back by multiplying by meters, or the *L*ength of the bar.

$$\vec{E} = \frac{V_{ab}}{L} \tag{10}$$

> This only works if the cross-section area is uniform along the length of the bar.
>
> Think about what would happen if the middle of the bar was necked down to a smaller area. KCL forces the **current** to be constant so therefore {insert thinking here}.

2.2.3. Mobility changes with doping :(

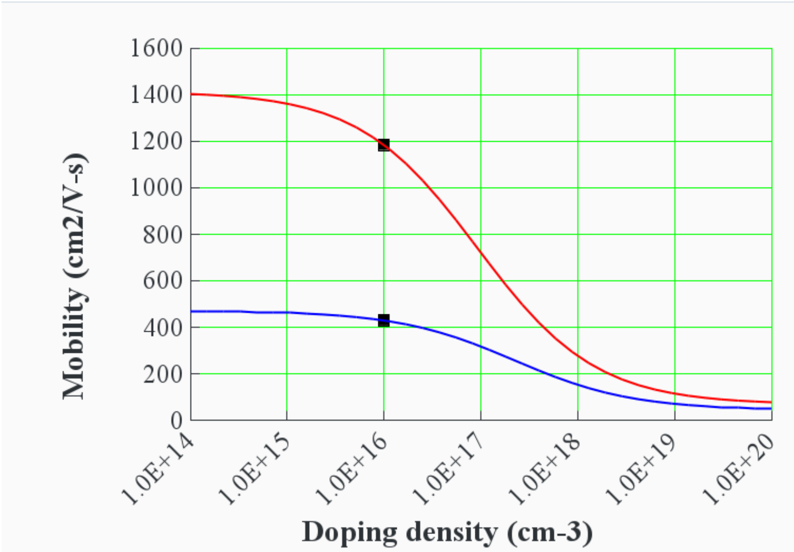

Figure 3. Mobility versus doping. From B. Van Zeghbroeck, Principles of Electronic Devices.

B. Van Zeghbroeck, Principles of Electronic Devices

Wayback Machine archive of the pages

▸ What causes this second-order effect? Does this mean that conductivity *decreases* with more doping?? <think first, then click to reveal>

2.2.4. Velocity saturation

It hopefully makes sense that the charge *velocity* can't increase so much as to exceed the speed of light, so this is the obvious speed limit. (Light speed is about $3 \times 10^{10}\ \mathrm{cm/s}$)

The velocity (therefore current) approaches a lower limit and no longer varies linearly at large E-field strengths (voltage). In a circuit context, this means that the device changes from behaving like a **resistor** to more like a **constant current source**.[3] **Velocity saturation** is very common in modern integrated circuits.

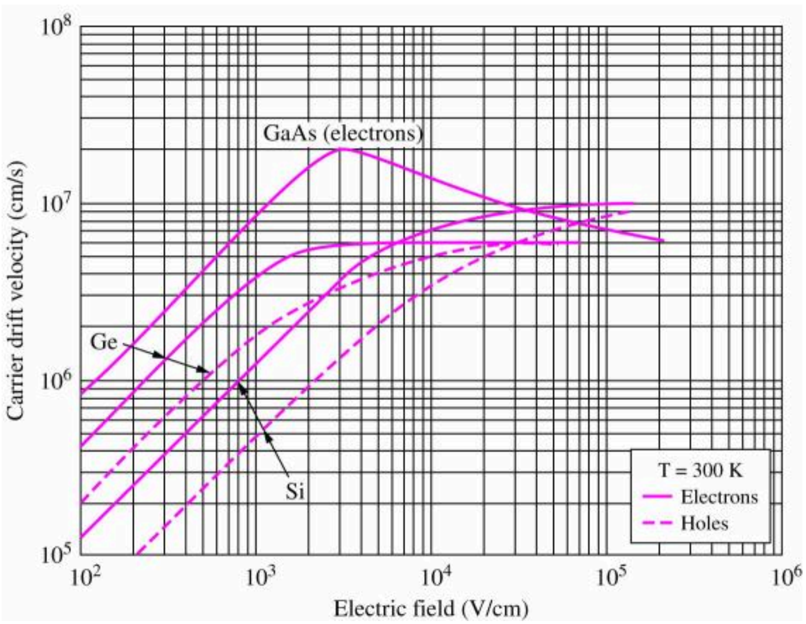

Figure 4. Drift velocity versus E-field. From Jaeger, Microelectronic Circuit Design

A $130\ \mathrm{nm}$ chip process uses a $1.2\ \mathrm{V}$ supply voltage, giving internal E-fields of

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>>> print('%2.2g V/cm' % (1.2 / 130e-9 / 100) )
 9.2e+04 V/cm
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which is well within the velocity saturation regime according to Figure 4.

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1. and therefore also creating a magnetic field!
2. Everyone *else* calls *J* "current density," but the quantity is flow / area, which is a **flux** in my book (and the customary term from calculus).
3. that still absorbs energy