Solution to Exercise 1.3-3

What does it take to build a 4 GHz Microprocessor?

First Task: What is the mobility the material (= semiconductor) must have? Discuss the result in considering the following points

- Transistor speed = device speed ???
- Mobility range for a given material ??
- Could we have powerful **PCs** without micro- or nanotechnology ??

The essential equation is

$$t_{SD} = \frac{l_{SD}^2}{\mu \cdot U_{SD}} \approx \frac{1}{f_{max}}$$

The necessary mobility thus is given by

$$\mu = \frac{l_{SD}^2}{t_{SD} \cdot U_{SD}} = \frac{f_{max} \cdot l_{SD}^2}{U_{SD}} = \frac{4 \cdot 10^9 \cdot 2.5 \cdot 10^{-13}}{3} \cdot \frac{m^2}{s \cdot V} = 0.33 \cdot 10^{-3} \frac{m^2}{s \cdot V} = 3.3 \frac{cm^2}{s \cdot V}$$

What is the mobility of typical semiconductors? Finding values in the Net is not too difficult; if you just turn to the Hyperscript "Semiconductors" you should find this link

Well, all "useful" semiconductors seem to be OK, their mobilities are much larger than what we need. But perhaps we are a little naive?

Yes, we are! If a device combining some **10.000.000** transistors is to have a limit frequency of **4 Ghz**, an individual transistor "obviously" must be much faster. If you don't see the obvious, think about the routing of many letters by the mail through a few million post offices (with different routes for every letter) and compare the individual and (average) total processing times.

Bearing this in mind, mobilities of about a factor of **100** larger than the one we calculated do not look all that good anymore!

The mobility table in the link shows large variations in mobility for a given material - obviously **μ** is not really a material constant but somehow depends on the detailed structure.

We do not need to understand the intricacies of that table - we already know that **μ** is directly proportional to the mean free path length ***l*** and thus somehow inversely proportional to defect densities.

It is very clear, then, that for high-speed devices we need rather perfect crystals! So let's try to have single crystals, with no dislocations (or at least only small densities, meaning that the crystal must *never* plastically), and the minimum number of extrinsic and intrinsic point defects.

Quite clear - but do you see the *intrinsic* problem? A more or less perfect crystal is *not* a device! To make a device from a crystal, we must do something to the crystal. And whatever you do to a *perfect* crystal - the result can only be a less perfect crystal!

In other words: Making a device means to start with very good crystals and only induce the minimum of defects that is absolutely necessary.

Could we have **4 GHz** without microelectronics?

Well, take for l_{SD} a value **100** times larger, and your highest frequency will be **10.000** times smaller - **400 kHz** in the example. Of course, the **4 GHz** of modern processors is not only determined by mobility values of the materials used, but the argument is nevertheless valid.

So, without microelectronics (or by now nanoelectronics) life would by much different, because you can just about forget everything you do as a direct (and indirect!) present-day "user" of electronics. But would it be worse? The answer is a definite: Yes - it would be worse! Trust me - I have been there! It's not that long ago that **400 kHz** was considered a pretty high frequency.

Second Task: How could you increase the speed for a given material

- In principal
- Considering that there limits. e.g. to field strength

- In principal it is simple: Make $\boldsymbol{I}_{SD}$ smaller and / or $\boldsymbol{U}_{SD}$ larger.
- It is so simple, that you now should wonder, why it's not done immediately? Why not make a **40 GHz** or **400 GHz** microprocessor now **-** always, of course, only as far as it concerns the mobility?

Well, there are limits that are not so easily overcome. To name just two:

- Things are structured by "painting" with light. And just as much as you can't make a line thinner than than the size of your brush or pencil, you can't make structures smaller than the wavelength of the light you use, which is in the **0.5 µm** range.
- Funny coincidence to the $\boldsymbol{I}_{SD}$ we used, don't you think so?

OK, so we increase the voltage; let's say from **3 V** to **300 V**.

- This increases the field strength from **3/5 · 10^5 V/cm** to **3/5 · 10^7 V/cm** or **600.000 V/mm**.
- In other words: A **1 mm** thick layer of your material should be able to isolate a high-voltage cable carrying **600.000 V**. Seems a bit strange, given the fact that they still hang lousy **300.000 V** cables high up on poles to have many meters of air (a very good insulator) because otherwise you would have to use many **cm** of some really good insulating solid.
- To put it simple: no material withstands field strength of more than **10 MV/cm** (give or take a few **MV**). If you try to exceed that value, you will get interesting and very loud fire works. Whenever mother nature tries it, we call it a thunderstorm.
- And only a few very good *insulators* will even come close to that number. Semiconductors, not being insulators, by necessity, can take far less. Our **60.000 V/cm** are pretty much the limit. So forget about higher voltages, too.

Does this mean **4 GHz** is the end of the line?

- No it's not. It just means it is not easy to go beyond. It take a lot of knowledge, understanding, and skills to make existing devices "better". It take highly qualified engineers and scientists to do the job. It takes what you will be in a few more years if you keep to ít!