Solution to Exercise 2.1-3

What does it take to build a 4 GHz Microprocessor?

A typical **MOS** transistor of **200x (x = 0 .... 5)** vintage has a "gate length" (= distance between source an drain) of about **0.5 µm** and is run at about **3 V**

First Task: What is the mobility the material (= semiconductor) must have for **4 GHz** operation frequency? 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* deform 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 I_{SD} smaller and / or 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 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 takes highly qualified engineers and scientists to do the job. It takes what *you* will be in a few more years if you keep to it!