8.1.2 Basic Time Consuming Processes

- The first essential point to note is that a modulation of an output signal obtained by modulating some input *always* requires a *change or modulation in some internal state* of the device.
  - And changing something always takes some time. Nothing happens instantaneously, changing something *consumes some time*. We thus may start by listing the *time consuming processes* that we already encountered.
- What kind of typical *time constants* in semiconductors did we encounter so far? Think about it for a minute. Well, we had
  - The *minority carrier life time* τ . It measures the average time that a minority carrier "lives" before it recombines with a majority carrier. It can be rather large for very clean indirect semiconductors (**ms**), and rather small for indirect semiconductors (**ns**). The numerical value of a minority carrier life time implies that you cannot change the minority carrier concentration at a frequency much larger than **1/τ**.We have a *first limit* to how fast you can change an internal state.
  - The *dielectric relaxation time* τ_d. It measures the average time that *majority carriers* need to respond to some disturbance of their distribution. It was rather small, typically in the **ps** range and given by

$$\tau_d = \frac{\epsilon\epsilon_0}{\sigma}$$

- Those were the two fundamental material related time constants that we encountered so far. But there are more time constants which are not so directly obvious:
- *First*, we have the "trivial" *electrical time constant* τ_{RC} inherent in any electrical system, simply given by the $R \cdot C$ product. ***R*** is the ohmic resistivity, and ***C*** the capacitance of the circuit (part) considered.
  - ***R*** and ***C*** need not be actual resistors or capacitors *intentionally* included in the system, but unwanted, nevertheless unavoidable, components. The resistivity of **Al** metallization lines together with the parasitic capacitance of this line in a **Si** integrated circuit. e.g., gives a τ_{RC} of roughly 10^{-9} **s**, and this value (per **cm** line length) is directly determined by the product of the specific resistivity ρ of the conducting material times the relative dielectric constant $\epsilon_r$of the dielectric separating individual wires - it is thus a rather intrinsic *material property*.
  - The *physical meaning* of τ_{RC} is clear: It is the time needed to charge or discharge the capacitors in the system. Clearly, you cannot change internal states very much at frequencies much larger than **1/τ_{RC}**. And note that space charge regions, or **MOS** structures *always* have a capacity ***C***, too.
- *Second*, if we turn to Lasers for a moment, we have seen that we need to feed some of the light produced by stimulated emission back into the semiconductor by using a suitable mirror assembly.
  - Light bounces back and forth between the two mirrors in the simple system considered - and that means that even after you turned off the current through the Laser diode, some light will still bounce back and forth and thus come out until everything eventually calmed down. There is an obvious time constant

$$\tau_Q = \frac{N_r \cdot L \cdot n_r}{c}$$

  - With N_r = average number of reflections, L = distance between the mirrors, n_r = refective index of the material, and **c** = vacuum velocity of light.
  - If, for an order of magnitude guess, we take L = **100 µm** and consider **10** reflections; the "last" photons to come out would have to travel **10 · 100 µm = 1 mm**, which takes them a time $\tau_Q = N_r \cdot L \cdot n_r/c \approx 10^{-11}$ **s = 10 ps**.
  - In other words, for the example given, it would not be possible to modulate the light intensity with frequencies in excess of about **100 GHz**. This seems to be a respectable frequency, but keep im mind that data can now (**2001**) be transmitted through fibre optics at frequncies in the **THz** regime.
- This example, while a bit far-fetched, gives us an important insight: There is a general relation between a *time constant* of a system and a *typical length* of a system mediated by the speed with which things move. This means that the *size of a device* may be important for its frequency response.
  - In other words, we can always ask: How much time does it take to move things over a distance ***l***? And whenever the output ***O*** is some distance away from the input ***In***, the question of how long it takes to move whatever it takes from ***In*** to ***O*** produces a typical time constant of the system.
  - In straight-forward simple mechanics ***l*** is linked to its time constant τ_l by the *speed* of the moving "things" - for the photons considered above this was clearly the speed of light (in the medium, to be correct).
  - For our moving statistical ensembles, we have somewhat more involved relations, e.g. .

$L = \left(D \cdot \tau \right)^{1/2}$	for the relation between the diffusion length of the minority carrier and their lifetime
$L_{Dn} = \left(D \cdot \tau_d \right)^{1/2}$	for the relation between the Debye length L_{Dn} and the dielectric relaxation time

- What are the moving things? Well, besides photons, we essentially are left with electrons and holes; everything else that might be of interest is usually immobile (dopants, localized excitons), or so slow that it should not matter for *electronic* signals (phonons, mechanical movements (e.g. vibrating parts) in **MEMS** devices)
  - This brings us to a first simple and important question: How long does it take electrons or holes to move from the source to the drain in a **MOS** transistor. Clearly, this will give us another maximum frequency for operating said transistor.
  - The relevant velocity in this case is the **drift velocity v_D** of the carriers, usually proportional to the field strength E as driving force for the movement, and better expressed via the carrier mobility

$$\mu = \frac{v_D}{E}$$

  - With the source-drain distance l_{SD} , and the source drain voltage U_{SD} , we have $E = U_{SD} / l_{SD}$ and a "travel time"

$$\tau_l = \frac{l_{SD}}{v_D} = \frac{l_{SD}^2}{\mu \cdot U_{SD}}$$

  - To get a feeling for orders of magnitude, we take a source-drain distance l_{SD} **= 1 µm** and a source-drain voltage U_{SD} **= 5V**, obtaining a field strength of $E_{SD} = 5 \cdot 10^4$ **V/cm**. Typical mobilities are μ_{Si} **= 1000 cm²/Vs** for **Si**. This gives us a drift velocity of

$$v_D = 1000 \frac{\text{cm}^2}{\text{Vs}} \cdot 5 \cdot 10^4 \frac{\text{V}}{\text{cm}} = 5 \cdot 10^7 \frac{\text{cm}}{\text{s}}$$

  - Is that a large or small velocity? It might be good to look up at an old exercise at this point
  - The "travel time" τ_l then is

$$\tau_l = l_{SD} \cdot v_D = \frac{10^{-4}}{10^7} \text{ s} = 10^{-11} \text{ s}$$

  - A "**1 µm** " **Si MOS** transistor thus would not be able to switch frequencies beyound about 10^{11} **Hz = 100 GHz** *if* τ_l would be the only limiting time constant of the system.
- Last, there are some ultimate limits that we should be aware off:
  - Nothing moves faster than **c**, the the speed of light (in vacuum). The consideration for the Laser from above already gives an example for this limit.
  - The movement of electrons and holes has some intrinsic constant of its own: The *average time between scattering processes* and the average distance or mean free path in between. While we are not very aware of the values for these parameters, the mean free path is in the order of **100 nm**.
- This has an important consequence: We only can use *average* quantities like drift velocities, if individual carriers could have many collisions.
  - Turning this around implies: If we look at travel scales around and below **100 nm**, everything may change. For transistors this small, electrons (or holes) might just speed from source to drain without any collisions in between - much faster than at larger distances. This is the case of **ballistic carrier transport** which must be considered separately.