

3.4.3 Special Properties of Thin Films

- ▶ The fact that there is a subchapter on thin film *properties* gives a hint that they might be different from the *bulk* properties of the same material.
 - The *bad* news is that there are a hell of a lot of special thin film properties - check the [next subchapter](#) where we discuss how to measure them - and there is no way that we can compare bulk and volume properties and discuss everything in detail.
 - The *good* news is that *some* thin film properties are often *far better* than the bulk properties. This may have trivial or tricky reasons.
- ▶ So let's only glance at some key properties and see if that helps to get a feeling for why thin films are "special" with respect to some properties.
- ▶ There is simple guideline of how to figure out if you could expect large property changes in a thin film: Ask yourself what *causes* the property in question.
 - Is it a property determined just by the *bonding* - for example, Young's modulus, the thermal expansion coefficient, or the dielectric constant - or does it have a *defect sensitive* part as, e.g., the carrier concentration in semiconductors or the minority carrier diffusion length?
 - Next, ask yourself, what *typical length scale* goes with the property. With "*bonding*" for example, goes the length scale "lattice constant"; with *minority carrier diffusion length* perhaps the average distance between point defects in the lattice.
 - Now you are done. If the thickness of your thin layer is far larger than the length scale in question, you cannot reasonably expect that its properties differ much from those of the bulk - and vice versa!
- ▶ This is not necessarily an easy *recipe*, nor will it get everything right all the time. But the rule makes sense and provides a guideline.
- ▶ **Mechanical properties**
 - The **elastic moduli** shouldn't be all that different - they are coming from the [atom-atom bonds](#) which are the same in the bulk and in thin films. Only if the number of atoms at or close to the surface is comparable to the total number of atoms in your thin film, you may need to think twice about this. In other words: only if you consider *thin* to be in the order of atomic dimensions, your bonding situation is so severely disturbed that you might find large differences between bulk and thin films elastic moduli.
 - Parameters of [plastic deformation](#) like the [critical yield strength](#) (or [hardness](#)) can be far larger than bulk values. The reasons for this depend on many things (not least on the type of film), but if you look at what determines the [critical yield strength in bulk crystals](#), you will find intrinsic length scales like the dislocation density (always ties up with some average distance between dislocations) or the grain size. In thin film the grain size in one direction is at most the thin film thickness, and the dislocation density in areas with lateral extension some **10** times the film thickness is often zero - even for high dislocation densities, because the average distance between dislocations might be far larger than the film thickness.
 - Those are good news, because they mean that our thin films can take a lot of stress before they do something drastically.
 - There is a trivial, but perhaps unexpected property of thin films. If you deposit a perfectly brittle material like **Si** on a flexible substrate, you can roll up your substrate like a rolo - and your thin film will not break. It's simply a matter of the the radius of curvature being far larger than the film thickness; the [link](#) contains the equations.
- ▶ **Optical properties**
 - There is not much to say here. The **index of refraction** is tied to the bonding once more ("[polarization mechanisms](#)") and should not change much. If your bulk material is transparent at some wave length, the thin film will be even more so. Bulk materials that appear *opaque* because the absorption length of light is shorter than, say **5 μm**, may be fully transparent as a thin layer. Even some very thin metal layers (e.g. **Au**) become transparent to visible light.
- ▶ **Electrical properties**
- ▶ *Specific conductivity* σ :
 - We always have $\sigma = \sum_i (q_i \cdot n_i \cdot \mu_i)$ with q , n , μ = charge, carrier concentration, and mobility, respectively, of the carriers involved.
 - Going from bulk to a thin film may change the carrier concentration if the film is so thin that the system becomes a two-dimensional electron gas. What may change at larger thicknesses is the mobility μ . We expect something to happen as soon as the film thickness comes into the same order of magnitude as the [mean free path](#) of the carriers.
 - If you think about it, chances are good that the conductivity will *decrease*. That is not so good, but in real life the effect is usually not dramatic.
- ▶ *Electrical break down field strength* E_{BD} :

- Take a flat piece of quartz **1 mm** thick and put it between the two plates of a parallel-plate capacitor. Now crank up the voltage **U** . At some (high) value of the voltage, the contraption will go up in smoke with a big bang because you have reached the critical break-down field strength **$E_{BD} = U/l$ V/mm**, which will be some **10.000 V/mm** in your experiment.
- Now do the same thing with a standard **SiO₂** layer from microelectronics, having a thickness of **5 nm**. You will find **$E_{BD} \approx 10.000.000$ V/cm**; a value far above the bulk number, allowing you to run your integrated circuit at unbelievably high voltages of up to **10 V**!
- Why do we have that large improvement? There are several possible reasons; but the issue is actually not all that clear, partially because the [mechanisms of electrical break down in bulk materials](#) are not so clear either

Critical current density j_{crit}

- Take an **Al** or **Cu** wire with a cross-sectional area of **1 mm²** and run some current **I** through it. Crank up your current and watch what will happen. At some critical current density **$j_{crit} = I/l$ mm²** your wire will go up in smoke; before that it became a light bulb for a short time. You will find that **j_{crit}** will be around a few **1.000 A /cm²**.
- Now do the same thing with a thin layer that you have structured into wires with a cross-section of about **1 μm²**. You will find a critical current density of **> 10⁵ A/cm²**, again orders of magnitude larger than the bulk value, enabling you to run tremendous currents of up to **1 mA** through those interconnects in your integrated circuit.
- Again, why do we have that large improvement? In this case it is relatively clear. The volume to surface ratio of a thin film wire allows a much better transport of the heat generated in the wire to the large heat sink "substrate" and the environment.

▶ In case you missed the point: You just learned that microelectronics is **only** possible because thin layers are so much better with respect to some important properties than the bulk materials!