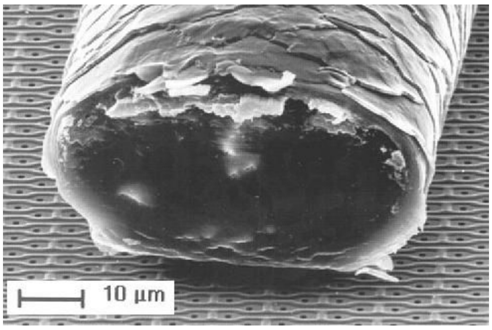
3. Thin Films

3.1 General

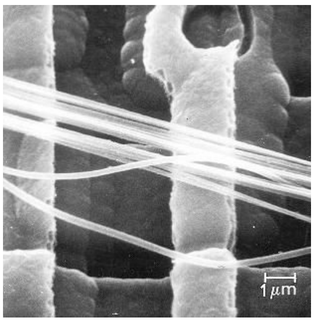
3.1.1 General Remarks and Some Definitions

The Meaning of "Thin"

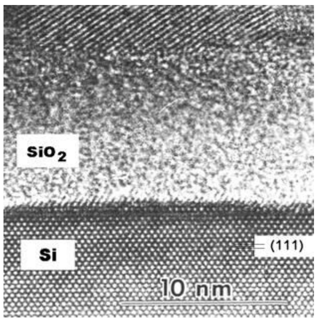
- The expressions "Thin films" and "Semiconductor technology" are almost synonyms. It is true, there is some semiconductor technology that does not need thin films but not much comes to mind right away.
  - There is, however, quite a bit of thin film technology outside of semiconductor technology, e.g., in **optics**. In fact, thin film technology is far older than semiconductor technology. In ancient times, for example, people already knew how to beat gold into a thin film (**< 1 µm** thickness) with hammers and knew how use this "**gold leaf**" for coating all kinds of stuff.
  - When you wax your car, or paint a wall, you are actually applying a thin film - *or are you*?
- How thin does a *thin* film have to be to fall under the notion of "**Thin Film**"? The "Ohring", for example doesn't tell you. The "Smith" doesn't give you a number either but offers the following working definition:
  - **Thin film technology** involves deposition of individual molecules or *atoms.*
    Thick film technology involves deposition of *particles*.
  - Painting thus is *thick film* technology, and evaporation is thin film technology. Good enough, but what about beating gold with hammers to sheets with a thickness of **5 nm**? Or depositing **100 µm** of **Ag** or **Cr** on a metal galvanically? - atom by atom, to be sure.
- All in all, there is no natural distinction between "thick" and "thin", it always has to be practical. In what we look at here, we consider in a first approximation thin films to by typically thinner then **1 µm**, or if needs be a **few µm**. Let's get an idea of what that means:
  - One of the smallest things we still can *see* and touch is a **human hair**. They come fine and coarse, but a typical thickness value is **(30 - 50) µm** as you can see below.



Human hair on top of a **4Mbit DRAM** (around **1990**)



Spider "silk" on top of memory chip. One strand consists of several rather fine strings.



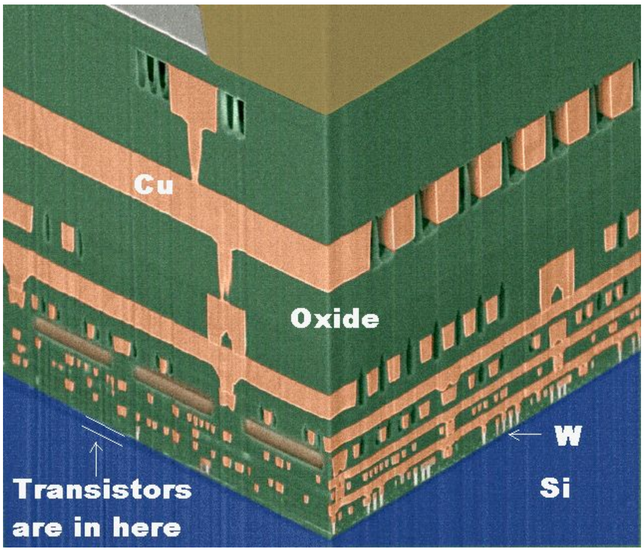
Thin layer of oxide on **Si** (with poly-**Si**on top); atomic resolution. About **10 nm** thick

  - We we can also see the strands of a spider web. Yes - but only because what we see is a bundle of many strings with diameters **> 1µm**. An individual string would be rather invisible to us humans.
  - If we look at a **Si** wafer covered by **10 nm** of oxide we see - nothing whatsoever. It looks exactly like a **Si** wafer with no oxide; at best there might be just a hint of some greyish-brown ***hue***.
- So the word "*see*" is of interest here. If *you* can *see* it - it may not be "thin". The number to remember is the wavelength of light: **<≈ 1 µm**
  - That simply means that if its's smaller than roughly **1 µm** in all dimensions, you can't *see* it anymore.

- This is not quite true, of course, if something is only **< 1 µm** in one dimension, i.e. if we have a thin film. We all have seen **interference colors** from *thin* oil films on water; the thickness then is only some fraction of the wavelength or well below **1 µm.** Actually, the color you see from an otherwise completely colorless and transparent thin film is directly coupled to its thickness **-** we have a first method to actually **measure** the thickness of a thin film

- **Class Exercise:** *How was that? Interference causes the color of a thin film and betrays its thickness?* Use the link for a reminder.

OK **-** so if we want to "see" more than interference effects, we must use **electron microscopes**. That's a simple but costly first conclusion. Let's buy a **scanning electron microscope** or ***SEM*** (take out **€ 200.000 - € 400.000** from your savings account) and look at the cross-section of a modern **IC**, a cut-open chip:



Cross-section of modern chip; colors are artificial.
Picture courtesy IBM

- The first thing to note in the picture above is that **IBM** did not provide a scale. For a Materials Scientist this is not acceptable (=failing grade if *you* provide a picture without a scale). However, the size of the letter "**W**" (=tungsten) is about **1 µm** so you get the idea that there are a lot of (still) thin layers involved. There are actually far more thin films than meet the eye in this picture; just wait.

Anyway, you now have a first impression of the realation between thin films and semiconductor technology. Now let's look a bit more detailed on the meaning of "thin".

The Meaning of "Thin"

Again, we say layers are thin if their thickness $d_z < d_0$ with d_0**=5 µm** for example.

- This is a fine definition (and implicitly used a lot), but it is also arbitrary. Why **5 µm** and not **0.1 µm** or **10 µm**? Well, quite often, without thinking too much about it, d_z is scaled with other typical geometrical dimensions. If we look at a single transistor in a modern integrated circuit, its lateral dimensions are in the **1 µm** region, and we certainly would demand that d_0 must now be smaller than this if we consider *thin* films on *top* of the transistor.

From this example, we get a clue for a good alternative but qualitative definition that helps to keep our perception of thin films focussed:

- A film is *thin* if its thickness is in the same order of magnitude or smaller than some **intrinsic length scale** of the system we are considering. There is a surprisingly large number of such length scales; let's look at a few in the context of semiconductor technology:

Intrinsic length scale	Magnitudes	Remarks
Structural Scales		
Geometric dimensions $d_{x, y, z}$	Any; "Thin" if $d_z \ll d_{x,y}$	Trivial.
Changes in dimensions	$\Delta d \approx \epsilon \cdot d$	Thermal expansion; other stress / strain sources ϵ=strain
Grain size d_{grain}	**nm - cm**	Strong influence on mechanical and electrical properties

Other internal structural sizes (e.g. phases in multi-phase compounds).	From **nm to > 10 µm**	Important in proper context
Roughness amplitude.		
Interfacial layer thickness.		
Radii of curvature.		
(Average) distance between dislocations or other defects.		
Lattice constants $\boldsymbol{a_0}$	**(0.3 - ...10) nm**	Ultimate limit. $\boldsymbol{d_z < a_0}$ doesn't make sense
Wavelength Scales		
Wavelength of interacting radiation - Light (including **IR** and **UV**)	≈ **5 µm - 0.2 µm**	Determines what you "see"
- X-rays - Electron beams	**"≈" nm**	
Internal wavelengths λ - Electrons in conduction band. - Quasiparticles (phonons, excitons, plasmons, polarons, polaritons, Cooper pairs, ...	You don't have to understand that here.	What happens if $\boldsymbol{d_z > \approx \lambda}$
Interaction Scales		
Absorption depths - Light - Electron beams	- **km** (glass fibers) - **nm** (metals) - **nm** - few **µm**	
Mean free paths' - Electron scattering	≈ **10 nm - 1 µm**	
Diffusion length of minorities	≈ **10 nm - 1.000 µm**	
Electrical Scales		
Space charge region width $\boldsymbol{d_{SCR}}$	≈ **10 nm - 10 µm**	
Debye length $\boldsymbol{d_{Debye}}$	**0.1 nm** (metal) - **m** (insulator)	
Scale of doping gradients	≈ **10 nm - 10 µm**	
Critical thickness for electrical break down	≈ **1 nm - 100 µm**	
Critical thickness for tunneling	< ≈**5 nm**	

Wow! Lots of scales - some you (should) know, some will be new. There are even more internal scales, but what we have is enough to get a feeling for:

- **1.** "*Thin*" is indeed a relative measure.

- **2. Properties** of thin films might be quite different from that of the bulk material if that property is some expression of an internal length scale..

The Meaning of "Film"

After we have defined (or confused) the meaning of "*thin*", we will now ponder the meaning of "*film*".

- What we don't mean is the (thin) *film* of water on your wet windshield, nor do we mean the *layer* of dust on your furniture. While thin films of liquid might be legitimate objects of thin film semiconductor technology, and the avoidance of thin films of dust is in fact a major topic in semiconductor technology, in this lecture we concentrate on

  - *Solid* films: single crystalline, poly crystalline, amorphous; whatever.
  - *Adhesive* films: There is some *bonding at the interface*, i.e. the thin film does not easily disattach from its substrate.

That's all. We might go a bit further and demand that the thin film has about the same thickness everywhere, and that it should be homogenous (same properties everywhere), that it should not contain holes or cracks, and so on. But this is either a matter of course or a legitimate special topic in thin film technology that needs to be treated on its own merits.