Some Issues from Advanced Lithography

Advanced

General

- A somewhat better equation than the one in the backbone for the resolution limit or minimal feature size d_{min} of an optical system is

$$d_{min} \approx \frac{k \cdot \lambda}{NA}$$

  - λ is the wave length. The parameter ***k*** lumps together the effects of, e.g., photoresist response, or reticle properties.
  - The numerical aperture ***NA*** can be defined as $NA = n \cdot \sin\Phi$ with ***n*** = refractive index of the medium above the photo resist, and Φ = largest angle of converging rays hitting the resist at a "point".
- If we want the ultimate in resolution, we have to work at all three parameters

Wavelength

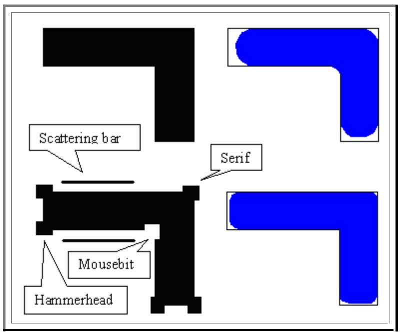
- The visible range of wavelengths extends from about **780 nm** (red) to **380 nm** (violet). Obviously we need to go to even smaller wavelengths in the ultraviolet part of the spectrum if we want to make structures in the **100 nm** region. Obvious, so where is the problem? Well, there are two major problems with this approach.
- *First*, we need a *powerful* and fairly *monochromatic* illumination source, and *second* we need materials to make an extremely good lens from.
- Let's look at the illumination source issue first:
  - A *powerful* light source we need because we cannot afford to wait forever before an exposure is finished. The maximum exposure time should be below a second or so, and you simply need intense light for that.
  - *Monochromatic* light we need, because we cannot possible built a supreme lens for many wavelengths (there are things like chromatic aberration and so on). Taking a small part of the spectrum out of some blackbody radiation (the spectrum emitted by something hot like a light bulb), however, leaves very little intensity.
- The solution lies in going for an intense line in the emission spectrum of some element - mercury (**Hg**) in this case.
  - In the **80**ties, the so-called **G**-line at **436 nm** was used (coming from a high-pressure **Hg** discharge lamp). Next came the **I**-line at **365 nm**, and then a **250 nm** line.
  - But that was already pushing the **Hg** lamp to its limits, and it was soon replaced by so-called **DUV** (for deep ultraviolet) **excimer lasers**.
  - Excimer lasers are based on rather strange materials: Compounds of noble gases like **KrF**, or **ArF**. Rather unstable stuff, but emitting at **248 nm** (**KrF**) or **193 nm** (**ArF**). With the **KrF** system, dimensions down to **130 nm** have been realized, but this is already pushing it quite a bit.
  - The **ArF** excimer laser has been used from about **2003**, so it is still in its infancy. It is expected to cover the "**65 nm** node", and possibly also the **45 nm** node.
  - That will be the end. After that, the age of "**EUV**" (extreme ultraviolet) might start, at a wavelength around **12 nm** (its really rather soft **X**-rays). There is no way of having a lens anymore, "optical processing" must then be done with mirrors.
- If we now look at the *lens* issue, we first should realize that high-aperture lenses are generally difficult to make. But the overwhelming issue is to find suitable materials that have a sufficiently large index of refraction at the wavelength considered.
  - We already looked at this issue, e.g. in the context of the frequency dependence of the dielectric constant, so we need not repeat the problems encountered here. Check the following links:
    - General remarks to the frequency dependence of ε and ***n***
    - Dielectrics and optics
    - The CaF_2 lens
- Illumination source and lens materials are not the only problems encountered by switching to a smaller wavelength. Of course, there are many others, too.
  - To mention just one: The "pellicles", the thin foils protecting the mask, will turn dark in intense **UV** illumination. Not good, so let's take a better material. Easy fix, but do you know a better material? No? Too bad - since nobody else does either, you missed your change of getting rich quickly.

Numerical Aperture

- In air, ***NA*** obviously than has a maximum value of **1**. The best lenses built so far have a ***NA*** of about **0.8**; but **0.9** is already aimed for
  - Keep in mind that what you gain in resolution by increasing ***NA***, you loose in the depth of focus. Large ***NA*** lenses thus only make sense in the context of rather perfect **planarization**.
- Nevertheless, increasing ***NA*** even more helps, and there is - in principle - a simple way of doing it: Replace the air between your lens and the wafer with something that has an appreciable index of refraction, e.g. oil.
  - "Oil immersion objective lenses" have been used for about a century in conventional optical microscopes; in this way the numerical aperture and thus resolution can be increased in a rather simple way by up to **40%**.
  - But this is far easier said than done. Just consider that the name "stepper" comes from the fact, that you *step* the wafer (rather rapidly) below the lens. How do you keep you oil in place? And how will the wafer respond to be covered with oil?
  - Well, let's not use oil, let's use high-purity water (***n* = 1.437** at **193 nm**), but that only solves some of many problems and creates some new one (your **CaF$_2$** lens, for example, will dissolve in water).
  - Nevertheless, "**liquid immersion lithography**" will most likely be the next big fashion in lithography, with the potential to keep microelectronics alive well into the next decade (i.e. after **2010**).

Recticles and Resists

- What is left is to make the parameter ***k*** as small as possible, i.e. to pay some attention to *reticles* and *resist*, or, more general, to resolution enhancing techniques.
  - There is quite a potential here, "historically" parameter ***k*** has decreased steadily form about **0.8** in the **1980**s to **0.4** today.
  - While optimizing the resist is critical, it does not introduce new principles, and we will not cover it here.
  - That leaves the reticle and the way it is illuminated. There is quite a bit that can be done, but you must pay the prize of sharp increases in complexity.



  - The proper catchwords giving some idea to what is meant are:
    - Off-axis illumination
    - Optical proximity correction (OPC)
    - Phase shift masks (PSM)
  - For the latter two cases the general idea is to have a structure on the reticle that is different from what you want to have projected into the resist on the wafer. If, for example, a sharp corner is "smeared out" to a roundish image, than make the corner look different. The figure gives a rough idea what that means
  - In phase shift masks you add structures that do not only manipulate the amplitude of the light transmitted through the mask, but also the phase.
  - In this way you can produce constructive or destructive interference in the image plane in places where that is helpful to sharpen the image.

- Of course, all these additional features on the mask must first be computed (not easy), than made (very difficult), and finally tested (exceedingly difficult).
  - Testing your mask is essential, that any mistake in the mask will automatically be transferred to the chip and, remember Murphy's law, more likely than not kill the chip.
- In the grand total a set of masks will quickly cost you up to **2.000.000 €**. You must a sell a hell of a lot of chips (at a profit) just to recover that cost
  - For customized chips, that are not made by the untold millions, its simply not possible to pay that prize.
  - This drives a large-scale effort to find some better solutions. For mor details (and for the source of some of the data here), refer to "Materials today" from Feb. **2005**.