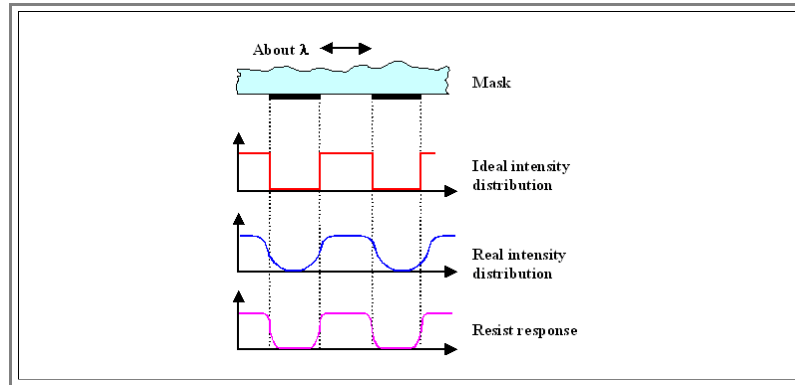


## 6.6.2 Resist and Steppers

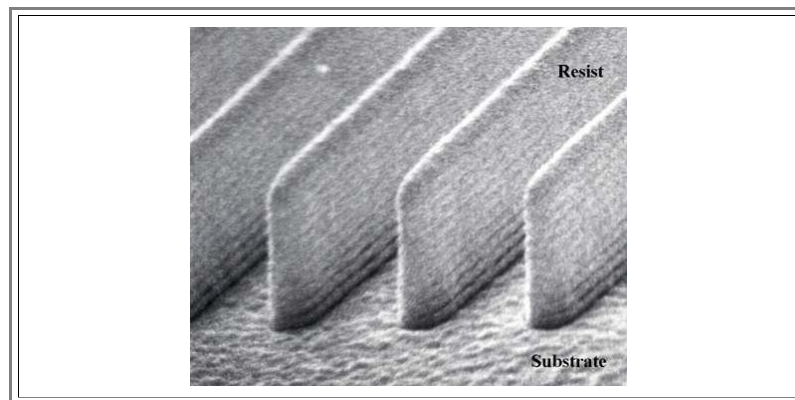
### Photo Resists

Lets just look at a list of requirements for resists. We need to have:

- **High sensitivity** to the wavelength used for imaging, but not for all optical wave lengths (you neither want to work in the dark, nor expose the resist during optical alignment of the reticle which might be done with light at some other wave length). Not easy to achieve for the short wave lengths employed today.
- **High contrast**, i.e. little response (= "blackening") to intensities below some level, and strong response to large intensities. This is needed to sharpen edges since diffraction effects do not allow sharp intensity variations at dimensions around the wavelength of the light as illustrated below.



- **Compatibility** with general semiconductor requirements (easy to deposit, to structure, to etch off; no elements involved with the potential to contaminate Si as e.g. heavy metals or alkali metals (this includes the developer), no particle production, and so on).
- **Homogeneous "blackening" with depth** - this means little absorption. Simply imagine that the resist is strongly absorbing, which would mean only its top part becomes exposed. Removal of the "blackened" and developed resist than would not even open a complete hole to the layer below.
- No **reflection of light**, especially at the interface resist - substrate. Otherwise we encounter all kinds of interference effects between the light going down and the one coming up (known as "**Newton fringes**"). Given the highly monochromatic and coherent nature of the light used for lithography, it is fairly easy to even produce **standing** light waves in the resist layer as shown below. While the ripple structure clearly visible in the resist is not so detrimental in this example, very bad things can happen if the substrate below the resist is not perfectly flat.



- This would call for a **strongly absorbing** resist - in direct contradiction to the requirement stated above. Alternatively, an **anti-reflection coating (ARC)** might be used between substrate and resist, adding process complexity and cost.
- Suitability of the resist as **direct mask** for ion-implantation or for plasma etching.
- Easy **stripping** of the resist, even after it was turned into a tough polymer or carbonized by high-energy ion bombardment. Try to remove the polymer that formed in your oven from some harmless organic stuff like plum cake after it was carbonized by some mild heat treatment without damaging the substrate, and you know what this means.

Enough requirements to occupy large numbers of highly qualified people in resist development!

- Simply accept that resist technology will account for the last **0,2  $\mu\text{m}$**  or so in minimum structure size. And if you do not have the state-of-the-art in resist technology, you will be a year or two behind the competition - which means you are loosing **large amounts of money!**

## Stepper

A stepper is a kind of fancy slide projector. It projects the "picture" on the reticle onto the resist-coated wafer. But in contrast to a normal slide projector, it does not *enlarge* the picture, but *demagnifies* it - exactly fivefold in most cases. Simple in principle, **however:**

1. We need the *ultimate in optical resolution!*

- As everybody knows, the **resolution limit** of optical instruments is equal to about the wave-length  $\lambda$ . More precisely and quantitatively we have

$$d_{\min} \approx \frac{\lambda}{2NA}$$

- With  $d_{\min}$  = **minimal distinguishable feature size**; i.e the distance between two **Al** lines, and **NA** = **numerical aperture** of the optical system (the **NA** for a single lens is roughly the quotient of diameter / focal length; i.e. a crude measure of the size of the lens).
- Blue light has a wave length of about **0.4  $\mu\text{m}$** , and the numerical apertures **NA** of very good lenses are principally **< 1**; a value of **0.6** is about the best you can do (consider that all distortions and aberrations troubling optical lenses become more severe with increasing **NA**). This would give us a minimum feature size of

$$d_{\min} \approx \frac{0.4}{1.2} = 0.33 \mu\text{m}$$

- Since nowadays you can buy chips with minimum features of **0.18  $\mu\text{m}$**  or even **0.13  $\mu\text{m}$** ; we obviously must do better than to use just the visible part of the spectrum.

2. Resolution is not everything, we need some *depth of focus*, too. Our substrate is not perfectly flat; there is some *topography* (not to mention that the **Si** wafer is also not perfectly flat).

- As anyone familiar with a camera knows, your depth of focus  $\Delta f$  *decreases*, if you *increase* the aperture diameter, i.e. if you *increase* the **NA** of the lens. In formulas we have

$$\Delta f \approx \frac{\lambda}{(NA)^2} = \frac{0.4}{0.6^2} = 1.11 \mu\text{m}$$

- Tough! What you gain in resolution with larger numerical apertures, you loose (quadratically) in focus depth. And if you decrease the wavelength to gain resolution, you loose focus depth, too!

3. We need to *align* one exposure *exactly on top of the preceding one*. In other words, we need a wafer stage that can move the wafer around with a precision of lets say **1/5 of  $d_{\min}$**  - corresponding to **0.18/5  $\mu\text{m}$  = 0.036  $\mu\text{m}$  = 36 nm**.

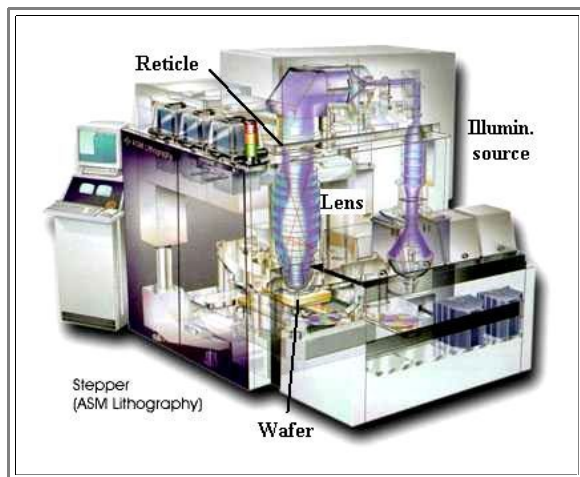
- And somehow you have to control the stage movement; i.e. you must measure where you are with respect to some alignment marks on the chip *with the same kind of precision*. We need some **alignment module** in the stepper.
- Alignment is done optically, too, as an integral (and supremely important) part of stepper technology. We will, however, not delve into details.

4. We need to do it *fast*, *reliable* and *reproducible* - **10 000** and more exposures a day in one stepper.

- Time is money!** You can't afford more than a few seconds exposure time per chip.
- And you also can not afford that the machine breaks down frequently, or needs frequent alignments. Therefore you will put your stepper into separate temperature and humidity controlled enclosures, because the constancy of these parameters in the cleanroom ( $\Delta T \approx 1^\circ\text{C}$ ) is not good enough. You also would need to keep the atmospheric pressure constant, but ingenious engineers provided mechanism in the lens which compensates for pressure variations of a few **mbar**; still, when you order a stepper, you specify your altitude and average atmospheric pressure).

How do we build a stepper? By combining elements from the very edge of technology in a big machine that costs around **10.000.000.000 \$** and that can only be produced by a few specialized companies.

- The picture below gives an impression. The basic imaging lens of the stepper is a huge assembly of many lenses; about **1 m** in length and **300 kg** in weight.



- We need intense monochromatic light with a short wave length. If you use colored light, there is no way to overcome the chromatic aberrations inherent in all lenses and your resolution will suffer.
- The wave lengths employed started with the so-called **g-line (436 nm)** of **Hg**, fairly intense in a **Hg** high pressure arc lamp and in the deep blue of the spectrum. It was good down to about **0.4  $\mu\text{m}$**  as shown in the example above.
- Next (around **1990**) came the **365 nm i-line** in the near ultra violet (**UV**). This took us down to about **0.3  $\mu\text{m}$** .
- Next came **a problem**. There simply is no "light bulb" that emits enough intensity at wavelengths considerably smaller than **365 nm**. The (very expensive) solution were so-called **excimer Lasers**, first at **248 nm** (called deep **UV** lithography), and eventually (sort of around right now (2001)), at **194 nm** and **157 nm**.

- Next comes **the end**. At least of "conventional" stepper technology employing lenses: There simply is **no material** with a sizeable index of refraction at wavelengths considerably below **157 nm** that can be turned into a high-quality lens. Presently, lots of people worry about using **single crystals of  $\text{CaF}_2$**  for making lenses for the **157 nm** stepper generation.

What do you do then? First you raise obscenely **large amounts of money**, and then you work on alternatives, most notably

- Electron-beam lithography**. We encountered it **before**; the only problem is to make it much, much faster. As it appears today (Aug. **2001**), this is not possible.
- Ion beam lithography**. Whatever it is, nobody now would bet much money on it.
- X-ray lithography**. Large-scale efforts to use **X-rays** for lithography were already started in the eighties of the **20** century (involving huge electron synchrotrons as a kind of light bulb for intense **X-rays**), but it appears that it is pretty dead by now.
- Extreme UV lithography** at a wave length around **10 nm**. This is actually soft **X-ray** technology, but the word "**X-ray** lithography" is loaded with negative emotions by now and thus avoided. Since we have no lenses, we use mirrors. Sounds simple - but have you ever heard of mirrors for **X-rays**? Wonder why not? This is what the US and the major US companies favor at present.

Well, let's stop here. Some more **advanced information** can be found in the link.

- But note**: There are quite involved materials issues encountered in lithography in general, and in making advanced steppers in particular.  **$\text{CaF}_2$**  is an electronic material! And the success - or failure - of the global enterprise to push minimum feature size of chips beyond the **100 nm** level, will most likely influence **your** professional life in a profound matter.
- This is so because the eventual **break down** of **Moore's law** will influence in a major way **everything** that is even remotely tied to technology. And what will happen is quite simply a question if we (including you) succeed in moving lithography across the **100 nm** barrier.