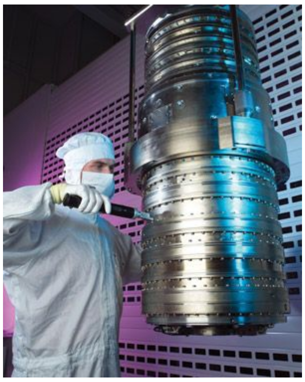
5.3.2 Processing Light

Conventional Lenses, Mirrors and Prisms

Little needs to be said about the Lenses, Mirrors, and Prisms. The basics have been covered before, here we just look at a few specifics to illustrate a few additional points

- Below are two pictures that demonstrate what one can do with lenses and mirrors. They are, after all, still the most important components of most optical systems



Here is a "lens" for a modern production "stepper" i.e. the machine that projects the desired structure onto a light sensitive layer (the resist) on a Si wafer. Steppers are crucial for making **Si microchips**. Here is the link for details.
The producer of this lens is Carl Zeiss SMT AG , Germany.

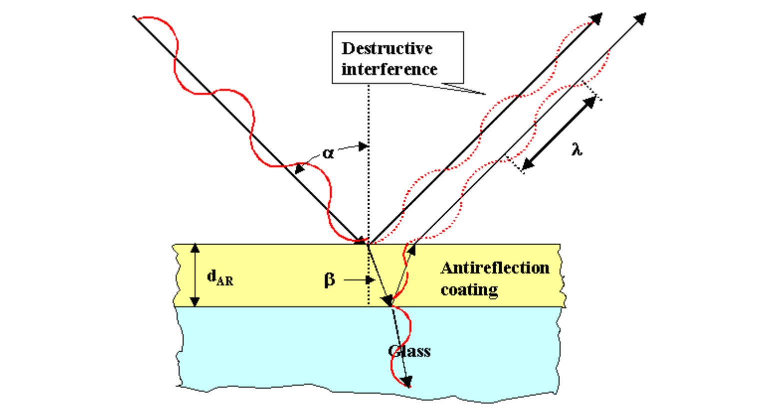
Although designed for manufacturing on a nanoscopic scale, a lithography stepper lens is not small. The Starlith 1900i weighs more than a metric ton, stands several feet tall and is as big around as a tree trunk. A catadioptric lens consisting of reflecting mirrors and refractive optics enables volume semiconductor production at **40 nm** resolution.
The stepper lens has a numerical aperture of NA = **1.35** (*huge!*) and is intended for use in immersion lithography, a technique that replaces the air gap between wafer and stepper with water or another fluid. Zeiss notes that the device is, in some sense, the *end of the art*.
The lens is designed for an **UV** light source with a wave length of **193 nm**, which needs an **ArF** (yes, "Argon Fluoride") Laser. Remember that the visible spectrum ends around **400 nm**. **UV** radiation from the sun, for comparison, spans the range (**315** - **400**) **nm** ("Ultraviolet A") and (**280** - **315**) **nm** ("Ultraviolet B").

That is the kind of "projector" that will move into chip production after lenses have reached the *end of the art*. It needs to operate in vacuum because air starts to absorb light below around **185 nm**.

The " NXE:3100" lithography machine from ASM corporation, employs extreme-ultra-violet (EUV) light with a wave length of **13,5 nm** to provide an imaging capability close to 20 nm. EUV will enabke 27 nm resolution down to to below 10 nm eventually. How one makes an intensive 12.5 nm deep-UV light source is a rather interesting topic in its own right.
The "optics" is based entirel on mirrors - with essentially atomically flat surfaces .
The machine shown is a kind of pre-production prototype that is presently (2011) tested.
It is essentially still a slide projector but a bit more expensive (around (10 - 20) Mio € would be my guess).

> **Note added July 2021:**
> As it turns out, I was a bit conservative in my coist estimation. You can buy the "most complicated machine" (New York Times) now for about 150.Mio $

- From a Materials Science and Engineering point of view, making those machines is a big challenge but nothing more shall be said about them here.
- It goes without saying, however, that for any non-trivial system employing lenses you need **anti-reflection coatings**; check your Fresnel equations!
  - You also need anti-reflection coatings for solar cells (reflected light cannot produce electricity) and in numerous or better almost all "optical" devices. .
    Here is the (known) working principle of a simple antireflection coating (for one wavelength and angle of incidence). Since the two beams reflected from the surface and the interface cancel each other exactly because of the **180^o** phase difference, the incoming beam must go into the material in its entirety. If you noticed the little paradox contained in this statement, activate this link.



Schematic view (don't look too closely at phases) of the working of an antireflection coating.

  - Of course, if you want to minimize reflection for a whole *range* of wavelengths and angles of incidence, you have a problem. The answer to the problem, as ever so often in Materials Science is: compromise! Achieving perfect antireflection for those conditions is next to impossible or at least expensive.

Polarizers, Diffraction Gratings and Filters

- Now that we have lenses and mirrors covered, we need polarizers, diffraction gratings, and filters next.

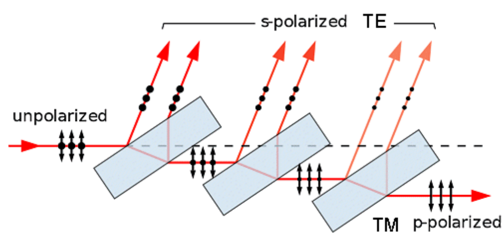
- We have already covered a lot of ground with respect to **polarization** and encountered some ways to produce a polarized beam. There are two basic ways to achieve **linear polarization**:

> **Absorbing polarizers**: the unwanted polarization is absorbed
> **Beam-splitting polarizers**: the unpolarized beam is split into two beams with opposite polarization states.

  - Absorbing linear polarizers are essentially of the "array of conducting rods" type as outlined before. Not much more needs to be said here.
- **Foil polarizers** of this type are used most of the time- whenever utmost quality is not the concern. They are essentially based on Lang's old invention.
  - Instead of (birefringent) herapathite crystals embedded in a stretched plastic foil, we now use aligned (again by stretching) polyvinyl alcohol (***PVA***) foils and dope the molecules with Iodine. In other words, we produce a more or less conducting polymer in one direction. Polarizing foils of this type are most common type of polarizers in use, for example for sunglasses, photographic filters, and liquid crystal displays. They are also much cheaper than other types of polarizer.
  - A modern type of absorptive polarizer is made of elongated silver nanoparticles embedded in thin (≈ **0.5 mm**) glass plates. These polarizers are more durable, and can polarize light much better than plastic Polaroid film, achieving polarization ratios as high as 100,000:1 and absorption of correctly-polarized light as low as 1.5%. Such glass polarizers perform best for short-wavelength infrared light, and are widely used in optical fiber communications.
- **Beam-splitting polarizers** come in many varieties and two basic types:

1. Use simple materials and employ the Brewster angle.

- The reflected light then will be linearly polarized (**TE** case) because the **TM** components of the incident light are not reflected at all (figure it out yourself!)

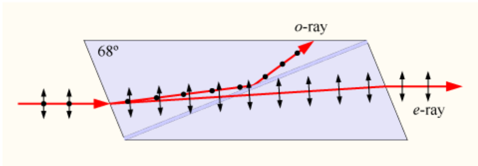


The quality improves with the number of reflections but the intensity goes down.

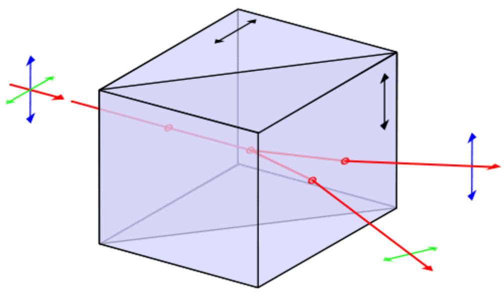
- Doable but not very elegant. Think about using this method for sunglasses or **3-D** glasses. On the other hand, if you need to polarize in the deep **UV** or **IR**, it might be your only choice.

2. Use **tensor materials** or in other words effects like birefringence.

- Use birefringence, e.g. in the form of a **Nicole prism**, **Wollaston prism**, or a number of other "Prisms".



Nicol prism



Wollaston prism

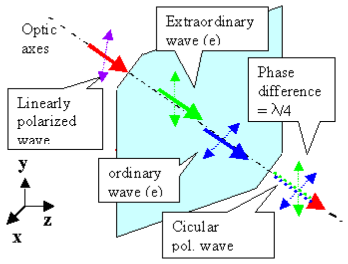
- All those "prisms" use birefringent (or tensor) materials, typically the easy to get or make calcite **$CaCO_3$**. The incoming beam splits into an ordinary and extraordinary beam that can be fully polarized. In the Nicol prism the geometry is chosen in such a way that the extraordinary beam undergoes total reflection at the interface where the two parts of the crystal are joined. The ordinary beam is not only full polarized but continues in the same direction as the incoming beam. The Nicole prism is therefore relatively easy top use in optical equipment.

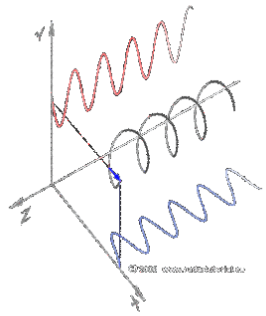
Achieving **circular polarization** is also "easy" in principle. All you need is a linear polarizer and a "**quarter wave plate**".

- A "quarter wave plate" is a (typically thin) piece of material, where a polarized beam goes in, and two beams come out with the following properties:

  1. They two beams are linearly polarized with polarization directions perpendicular to each other
  2. The two beams have equal intensities
  3. One beam is phase shifted by exactly a quarter wave length (**$\lambda/4$**) with respect to the other.

- The two waves thus produced superimpose to a circular polarized wave as shown below:





The incoming beam is polarized at **45°** relative to the principal polarization directions in the anisotropic medium. The two beams exciting the medium produce a circular polarization as shown in the animation (© Wikipedia)

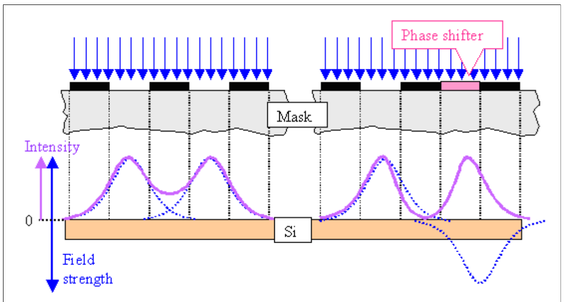
- How is it done? Let's look at the "old" and slightly modified picture above to understand how it is done in principal.
  - We need an anisotropic material oriented with respect to the optical axis in such a way that the ordinary and extraordinary beam are parallel. The two beam than will automatically have defined linear polarizations at right angle to each other.; condition 1 is met.
  - We polarize the incoming beam linearly in such a way that its polarization direction is at **45°** to the polarization direction in the anisotropic crystal. It then will split in two beams that have equal intensities. Condition 2 is met.
  - The ordinary and extraordinary beam travel with different velocities inside the material. The ordinary beam - that's why is is called "ordinary" - travels with $\boldsymbol{c_O = c_o/n_o}$ but the extraordinary beam does not; it travels with a speed $\boldsymbol{c_{EO} = c_o/n_e}$. Whatever the "extraordinary" index of refraction $\boldsymbol{n_e}$ will be, after traveling some distance $\boldsymbol{d}$ the phase shift between the two waves will be **λ/4** Obviously we have

$$d = \frac{\lambda}{4(n_e - n_o)}$$

  - So all we have to do is to cut our anisotropic material to the thickness $\boldsymbol{d}$ and condition 3 is met.
- Looks complicated? Well, that's because it is complicated. In principle and whenever you make your "**lambda quarter plate**" from a single crystal (like mica; the most prominent crystal for doing this)
  - So next time you watch a **3-D** movie, gives those (obviously cheap) glasses you're being handed a closer look. They contain two circular polarizers: one eye with a left-handed polarization, the other one with a right-handed one. And obviously they are really cheap. So how is it done?

Phase Shifters and Holograms

- We want to shift the phase of some light beam for various reasons; here we look at just two:
    - We wan to do sub-micron lithography for making microelectronic chips with structure sizes $\boldsymbol{d_{min}}$ considerably smaller than the wave length λ
    - We wan to make a **hologram**
- Let's look at **phase shift masks** for the ultimate in lithography first.
  - Right above we have data for the ultimate lens for lithography: Numerical aperture **NA = 1,35**, **λ = 193 nm**, so $\boldsymbol{d_{min} = \lambda / 2NA}$ **= 71,5 nm**; larger than what we want to get. So how are we going to beat the limits to resolution dictated by diffraction optics? By using a phase shifting mask (***PSM***). The principle is shown in the figure below:



- Remembering that waves "bend" around corners, it becomes clear that if two corners are very close together as in the schematic outline of a mask (or reticle) used for making the smallest possible structures on a chip, the "around the corner" waves overlap and from an electrical field strength and intensity (field strength squared) profile as schematically shown. The two structures are no longer fully resolved; there is an appreciable intensity below the middle light blocking layer on the mask.
- Now we introduce a "phase shifter", something the shited the phase of the light going through the right part of the struntre by **180^{o}**. This changes the sign of the electricl field strength as shown.

There is far more but let's forget it for this leture course. Go to the next one.