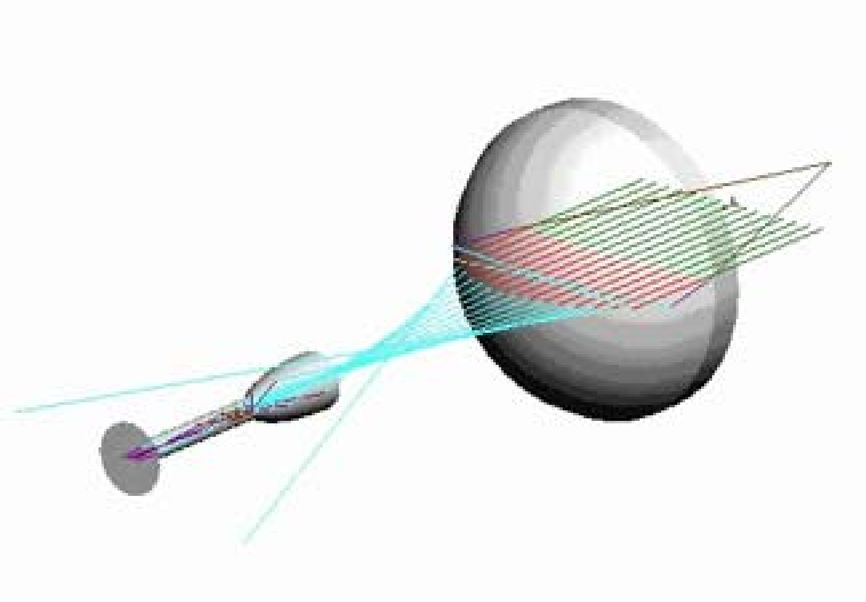
Microlithography For The Masses Part II

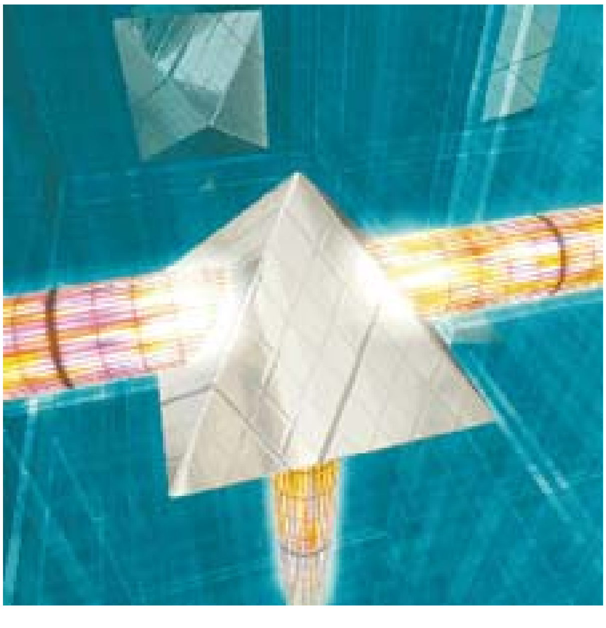
In the previous two chapters we looked at the basic concept of microchip production and outlined the various stages along the manufacturing line in a modern day fabrication plant, then we went on to describe in detail the functionality of a microlithography tool, elaborating on the critical elements & components of it's system.



Following some discussion over at the Monster Hardware forums regarding the future of the megahertz -microchip industry and where today’s technology cannot be used to manufacture sub 100nm architectures, I decided to look into this area more deeply and try to put together a document to answer these questions and outline the industry's goals for the near & seeable future.I would like to point out that this article should at no point be considered an attempt at high level tech mumbo jumbo, that would surely put the most adept disciple of PC hardware enthusiasm to sleep within 3 paragraphs, but more as an attempt to highlight some truly interesting (although, maybe not that useful...) Hi-Tech semiconductor information. I will elaborate on some choice points where I feel it is interesting or imperative.

Roadmap Challenge

The future: 2015 AD, when devices with 9nm gate length and over a billion transistors on die will be produced. This will ensure the continuation of Moore's Law.



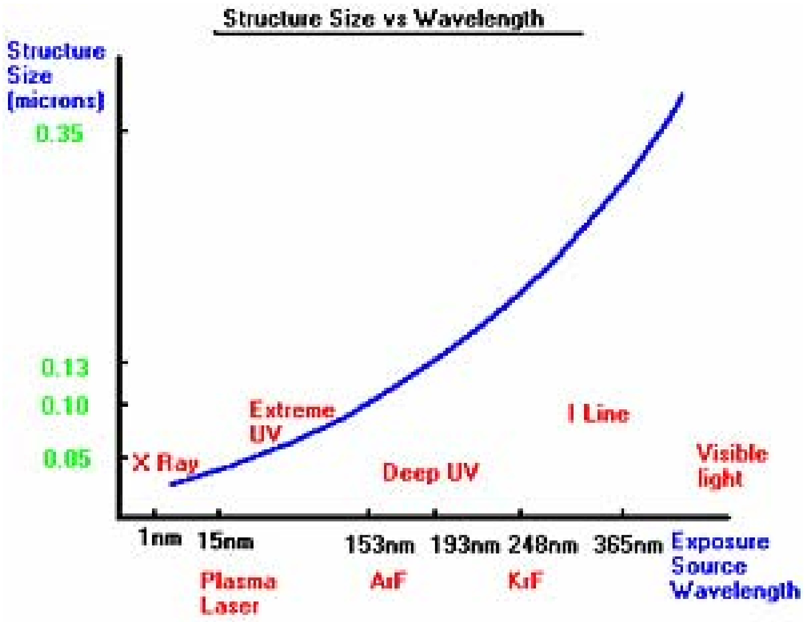
But first, to achieve this, the industry must define what known manufacturable solutions exist, what manufacturable solutions have been identified but require further development and what no-known solutions exist. These definitions will provide the paths the industry will take.

The semiconductor industry is in the process of providing solutions to some common obstacles, such as:

-Making and scaling down devices on a microchip and interconnecting them.
 -Microlithography - 193nm? 157nm? EUV? All need finalized manufacturing oriented solutions.
 -Microchip advanced designs to improve amounts of transistors, improve timing and reduce noise and reduce power consumption.
 -Microchip assembly. Standardization of packages, pin counts, heat dissipation and improved reliability.
 -Funds for the various consortium researches.
 -Reducing costs of materials and improving availability.

In this article we will be taking a peek into the **Microlithography** challenges of NGL.

Optical Lithography



Lithography is the process in semiconductor manufacturing in which chip designs are projected onto silicon wafers. Optical lithography has been the standard of the semiconductor industry for three decades, but is nearing the end of its effectiveness. Performance is still available from optical lithography. While there will always be technical issues to solve, the expertise and creativity of the teams focused on extending optical lithography should not be underestimated. Issues will be identified and problems solved. Optics forever? Probably not, but definitely for the near future.

Here are some of the optical lithography solutions already in use and some in the making

-I - Line: 365nm Lithography
 -DUV: 248nm, 193nm & 157nm Lithography.
 -EUV: 13-15nm Lithography.
 -X-Ray 1nm Lithography.

248nm Lithography

The industry is currently comfortably at the 248nm exposure light source point of time (the purpose of an exposure light source was explained in chapter 2), where 130nm architectures are being achieved quite easily with the microlithography optical tools. When I say comfortably, I point to the fact that all the major players in the industry running fabrication plants are achieving or can achieve this.

The critical optic elements in a 248nm microlithographic tool are made of fused silica material, which does not have any major deteriorating affect when 248nm wavelengths are passed through.

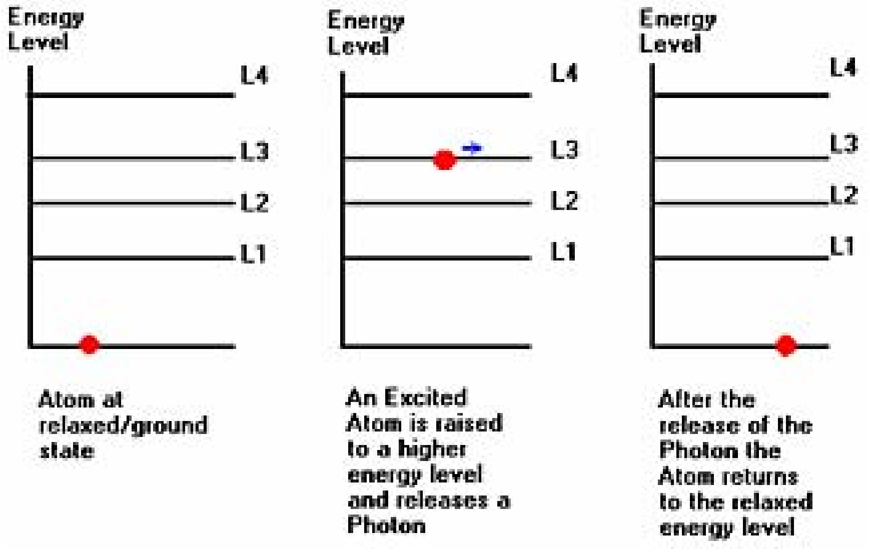
The most common 248nm light sources are Mercury Arc lamps or KrF excimer lasers. Here I will pause to briefly explain the basic concepts of light (those who actually did do their own physics homework please skip ahead):

All light is made up of photons, which behave similar electromagnetic waves. The length of the light waves is simply called wavelength. The wavelength determines the properties of the light. Visible light has wavelengths from aprox. 450(blue)-700(red) nanometers. Light above these wavelengths is known as infra red (IR), light below them is known as Ultra Violet (UV). Deep ultra violet light sources are referred to as DUV light sources and their wavelengths are below 300nm. Yes! Our 248nm Exposure Light source is a DUV light source.

For our 248nm light sources we prefer the KrF excimer laser over the Mercury Arc lamp because it provides a fairly larger amount of energy in a concentrated beam and has a very stable wavelength, uniform light direction, phase & polarization are constant and requires no filtering to get the required 248nm wavelength (does not emit unwanted wavelengths). The name "Excimer" is a contraction of "Excited Dimer," a description of a diatomic molecule in which the component atoms are bound in the excited state, but not in the ground state. The important gas molecules are rare gas halides including Argon, Fluoride, Krypton Fluoride and Xenon Chloride. The development of this type of laser was completed in the late 1970's. How does a Krf Excimer laser work?

As you must well know, the word LASER is an acronym of:

Light
Amplification
By Stimulated
Emission of
Radiation.

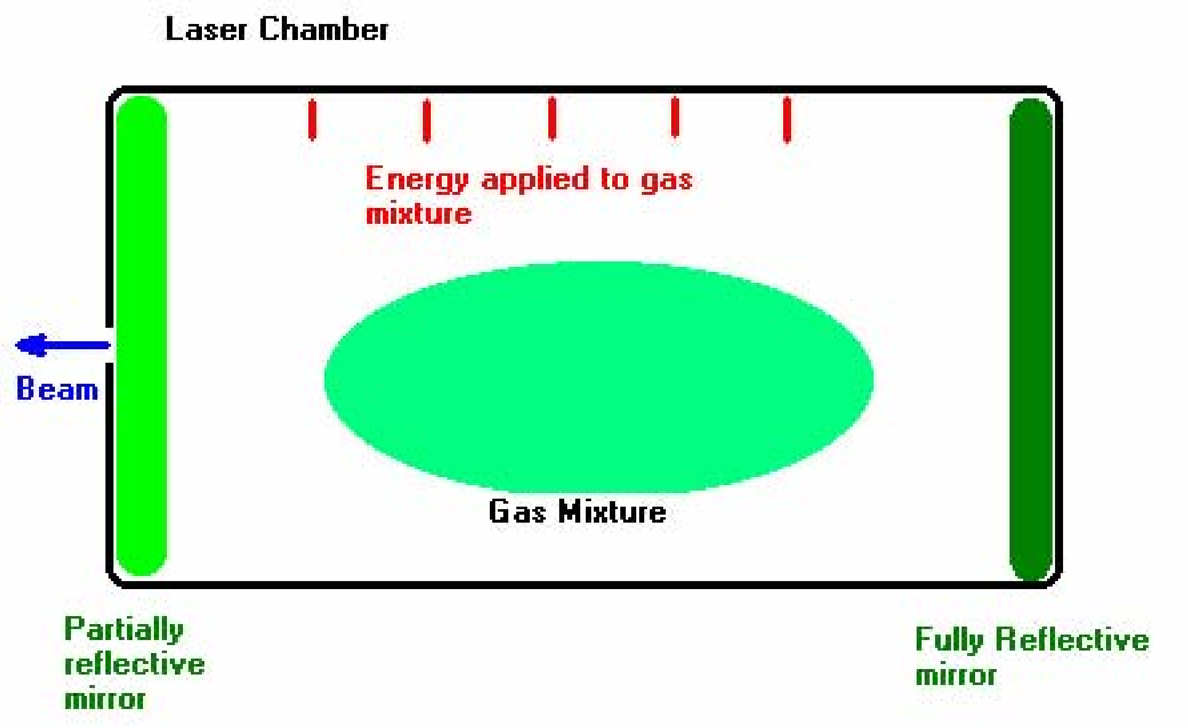


The emission we are referring to is a characteristic of atoms to emit photons ("particles" of light) under certain and reproducible situations. Chemical or electrical influences can be these said situations. To cause a

Spontaneous Emission of a photon from an atom we must "excite" the atom from its 'ground' state and then it will emit a photon and then return to its relaxed/ground state ready for us to excite it again. In controlled circumstances we can cause the first emission to cause a second emission from a neighboring atom. The subsequent emission releases a photon of the same phase and wavelength of the first emission. Exponentially, these chain reactions form a LASER beam of light very useful to us.

Main Laser components:

1) Gain Generator - the gas. In a KrF laser it will be a mixture of Krypton/Fluorine/Neon.
2) Pump Energy - the electricity needed to excite our atoms.
3) Optical resonator - controls and conditions our photon beam of light.
4) Chamber - our controlled environment, where the magic of lasing occurs.



Basically, we fill a chamber full of the gas mixture, apply an electric field and the photons emitted from the excited atoms start to resonate between two mirrors, one partially reflective. The resonating light partially escapes the chamber through the partially reflective mirror; this 'escaped' light is our laser beam! The light remaining in the chamber stimulates the emission of more photons from the gas atoms.

One of the downsides of these lasers is the use of fluorine; it's an extremely toxic corrosive and extremely reactive oxidizer. The gas is a pale yellow color with a sharp, pungent odor that can be detected at very low levels. It can cause severe burns if inhaled or upon skin contact. Numerous precautions and safety measures are taken into account to ensure safety in the production areas where the excimer lasers are located.

Typically these laser units will provide 15-30mw of energy in a 1-2 KHz pulsed beam to be used to expose our wafers in a microlithography tool.

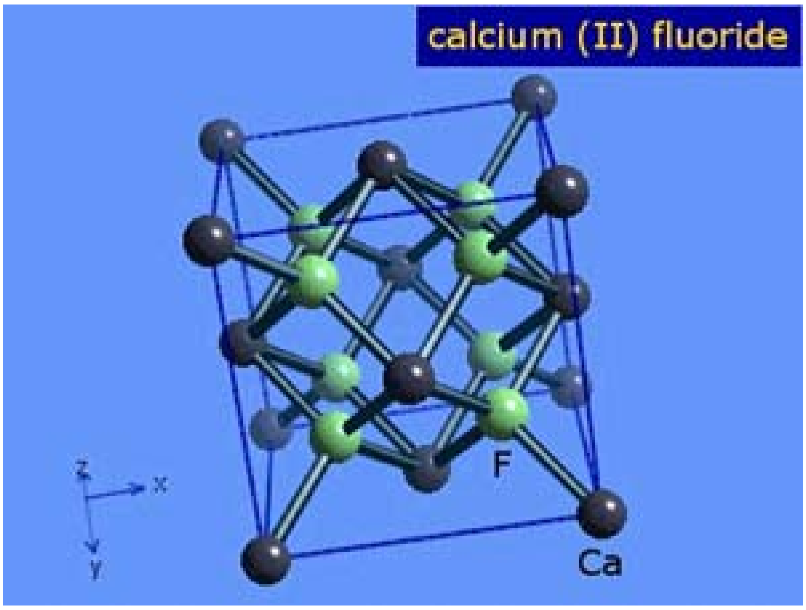
One of the smallest gates ever produced with a 248nm light source was performed by a group from MIT earlier this year. This group demonstrated the fabrication of a 25nm gate length fully depleted SOI transistors, using double exposure chrome less phase-shift masks (PSMs - more on those later on). In fairness, I must point out that electrically the device was not actually functional...

193nm Lithography

The next useful wavelength in the industry is a 193nm wavelength. This wavelength is the proposed solution to bring architectures down to the 0.10micron width. There are no good exposure lamps to be used as a light source, thus the ArF excimer laser is our exposure light source of choice. The functionality of this excimer laser remains the same as the KrF one described earlier, with the exception of the Gain Generator, AKA the gas mixture. Here we will be using a mixture of Aragon/Fluorine/Helium or Neon.

A typical ArF excimer laser will output 10mw @ 1-2 KHz pulses.

The problems start when trying to couple this wavelength to our 'legacy' 248nm optics. The 193nm wavelength radiation is known to be absorbed and damage the fused silica optics within the microlithography tool. The absorption of this wavelength is a high concern due to the reduction of the transmission factor of the light, which directly lowers the wafers throughput of such a system due to higher exposure times required for each field on the wafer.



An additional major concern is the resulting compaction of the optics. Compaction changes the refractive index (air or H20 has the index of 1) of an optical element and also the thickness. This change causes lightwave aberrations and deteriorates the microlithographic process results. The solution: Replace fused silica optics with Calcium Fluoride (CaF_2) optics where it is critical within the optical path (projection optical lens).

Why CaF_2?

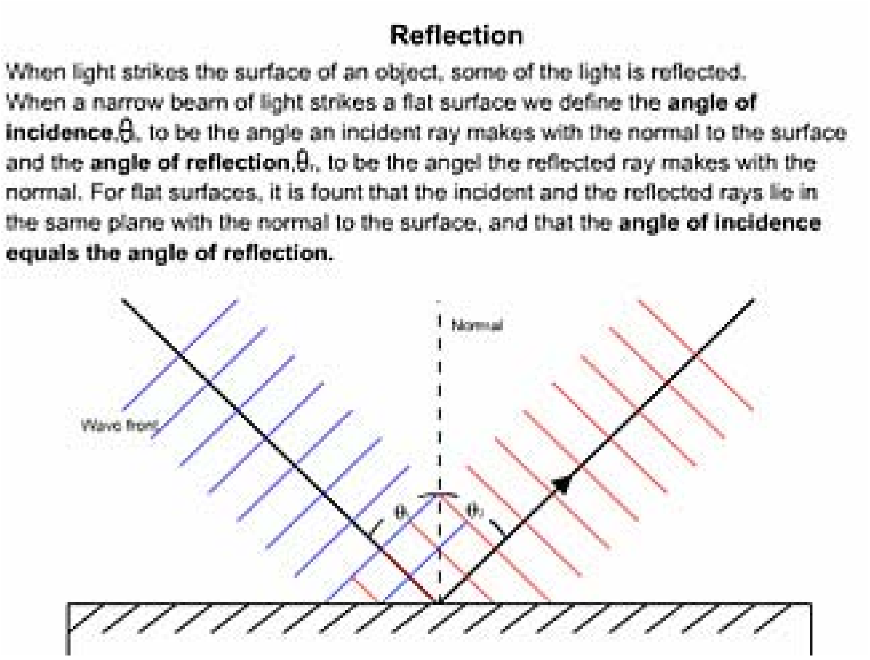
Caf2 reduces the 193nm radiation effects of compaction and poor transmission. The downfall: availability up until recently has been extremely poor, resulting in simply not enough material to mass produce optical lens for the industry. The lack of availability is that the yield of CaF_2 is very poor: around 3% of the grown crystals are actually pure enough (99.9999% purity required) to be used as microlithographic optics. BTW, CaF_2 material, per kilogram, is priced roughly the same as gold.

Crystal manufacturers depend on a technique that has hardly changed for three quarters of a century: The Bridgman-Stockbarger method which relies on good heat conductance inside the growing crystal. But CaF_2 is a heat insulator, which reduces yields. With this old growing method crystal sizes are usually limited to 15 in. diameter sizes.

New growth methods (based on a 20-odd year research by Kiril A. Pandelisev) very recently introduced, can handle heat dissipation, and enables crystals growth of any size with yields of 90% & purity of over 99.9999%. The new methods are also very relevant to other crystal types, like Barium Fluoride BaF_2, being considered for the 157nm microlithography tools.

Due to the advances in CaF2 - 193nm tools are readily growing in availability and in initial use by the industry.

157nm Lithography

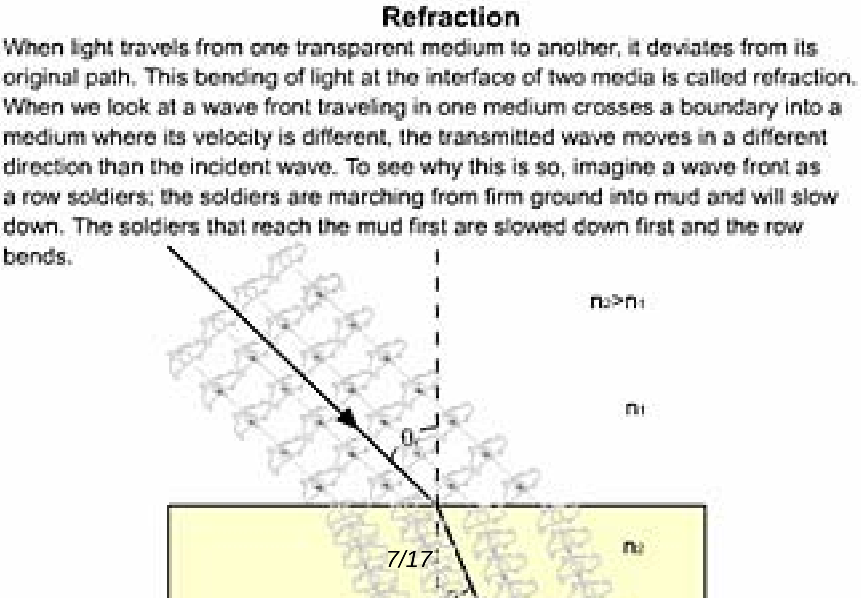


Reflection

When light strikes the surface of an object, some of the light is reflected. When a narrow beam of light strikes a flat surface we define the **angle of incidence**,θ_i, to be the angle an incident ray makes with the normal to the surface and the **angle of reflection**,θ_r, to be the angel the reflected ray makes with the normal. For flat surfaces, it is fount that the incident and the reflected rays lie in the same plane with the normal to the surface, and that the **angle of incidence equals the angle of reflection.**

We discussed the necessity of an optical material with high transmission (that will not absorb too much of our exposure light source energy) and with very low or no compaction (as not to change our refraction indices or lens thicknesses). CaF2 provides these requirements. With improved yields & purity of CaF2 material we can see advances already in that direction of 193nm wavelength utilization.

Are CaF2 optics compatible with 157nm wavelengths? Well, CaF2 provides the said solutions to compaction & transmission, but here comes the crunch: Birefringence. CaF2 suffers intrinsic birefringence (IBR) at 157nm wavelength. Birefringence is basically a phase difference caused by different directions of an object having different indices of refractions, which can be caused by stress or the way the object is made. It is also a function of the polarization of light. When left uncorrected, this will result in degraded image performance at high resolutions. Ordinarily, a crystal with a cubic structure such as calcium fluoride does not exhibit birefringence in stress-free material because of its high symmetry. However, when the wavelength of light is only a few hundred times the crystal interatomic spacing, the symmetry-breaking effect of the finite value of the photon wave vector starts to become significant and gives rise to the effect. Phew!



Refraction

When light travels from one transparent medium to another, it deviates from its original path. This bending of light at the interface of two media is called refraction. When we look at a wave front traveling in one medium crosses a boundary into a medium where its velocity is different, the transmitted wave moves in a different direction than the incident wave. To see why this is so, imagine a wave front as a row soldiers; the soldiers are marching from firm ground into mud and will slow down. The soldiers that reach the mud first are slowed down first and the row bends.

So, the future of 157nm processes relies on optical compensation ingenuity to overcome birefringence.

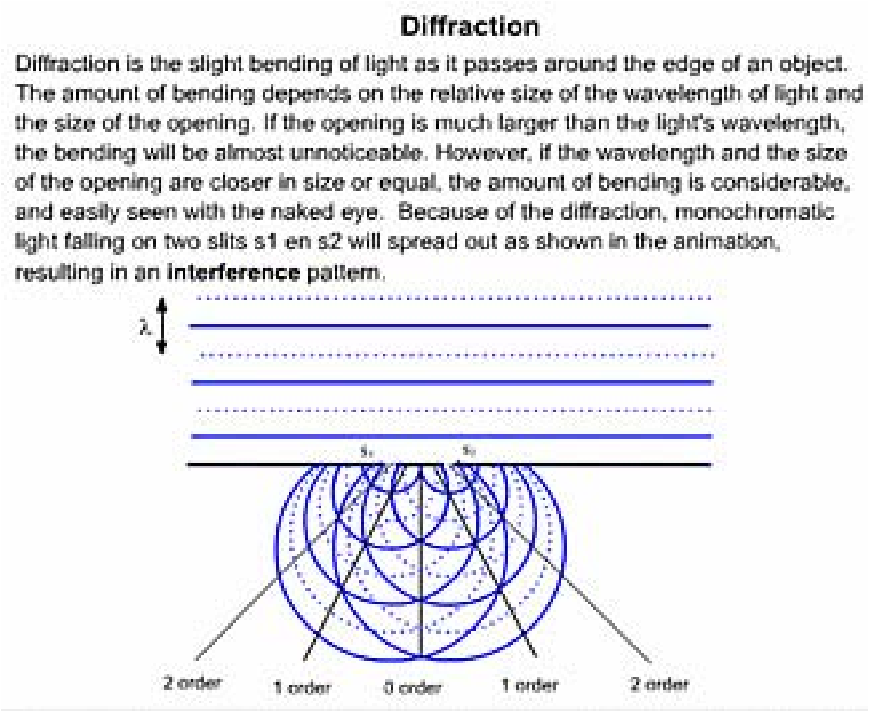
Proposed solutions:

- Optics Orienting. These solutions can reduce the consequences of the effect but cannot eliminate it totally. Also known as clocking. Clocking adjusts the lens elements in 60° angles in the horizontal plane. But clocking for IBR in the lens will remove the possibility of using clocking later to adjust for the inevitable imperfections in any lens element.

- Manufacturing mixed crystals (adding a barium fluoride or magnesium element to the lens design) which eliminates the effect entirely. This is possible in principle, although not yet achieved.

- Innovative catadioptric designs that use less CaF2 optical material projection systems, to further reduce the effect of IBR in sub-100nm lithography (read more on this later on).

Extreme Ultra Violet Lithography: EUVL



Diffraction

Diffraction is the slight bending of light as it passes around the edge of an object. The amount of bending depends on the relative size of the wavelength of light and the size of the opening. If the opening is much larger than the light's wavelength, the bending will be almost unnoticeable. However, if the wavelength and the size of the opening are closer in size or equal, the amount of bending is considerable, and easily seen with the naked eye. Because of the diffraction, monochromatic light falling on two slits s1 en s2 will spread out as shown in the animation, resulting in an **interference** pattern.

In the coming years chip makers plan to make chips with architectures measuring below 50nm. Deep Ultraviolet light of 248nm, 193nm or 157nm wavelengths will not be able to provide the means to do this. Smaller features require wavelengths in the extreme ultraviolet (EUV) range. Light at these wavelengths is absorbed instead of transmitted by conventional lenses. This will mean the death of Optical Microlithography as we know and love today :-(

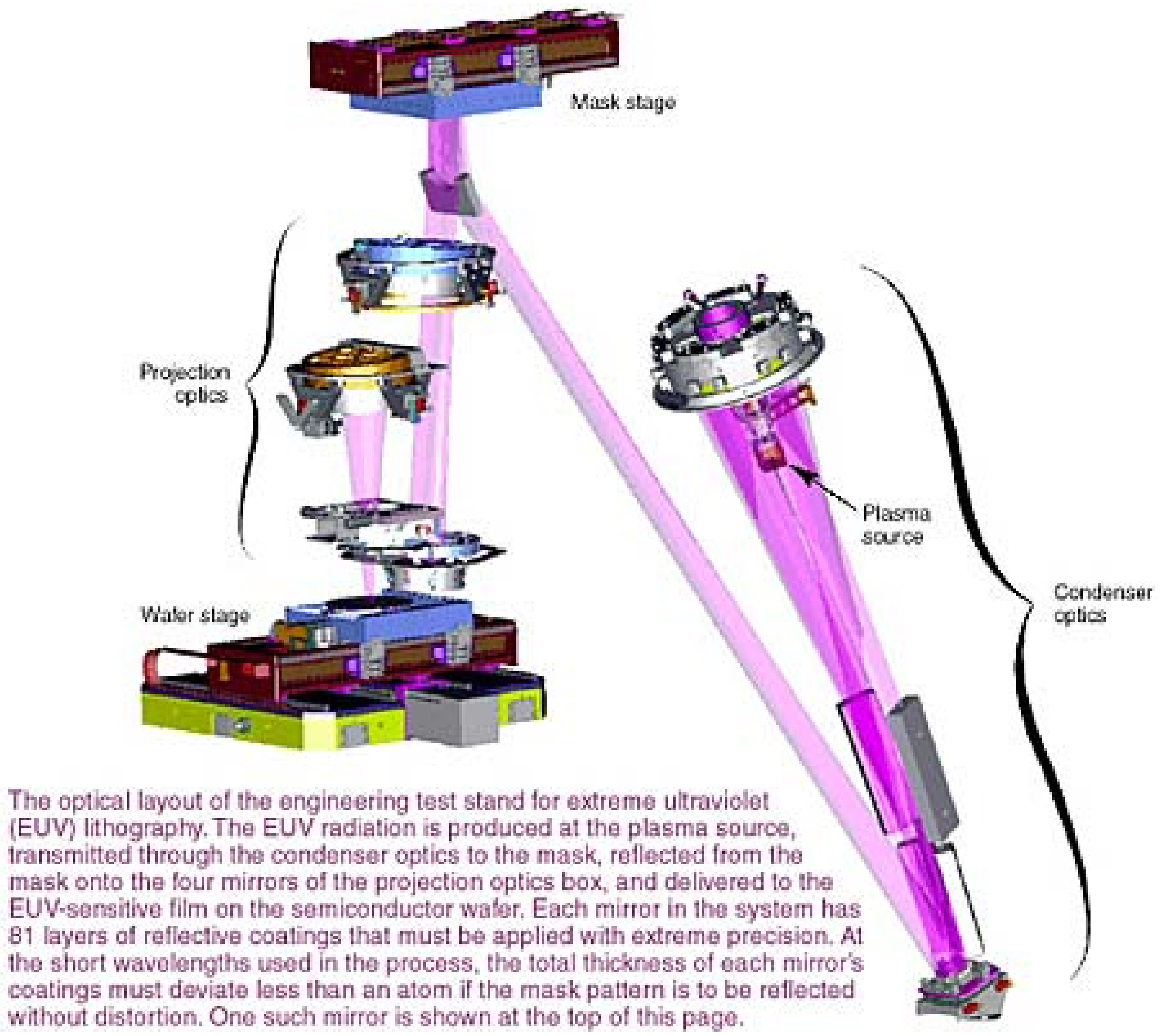
EUVL has been embraced by all three of the major lithography tool suppliers-ASML, Canon Inc. and Nikon Inc.-and industry research consortiums in North America, Europe and Japan. They have arrived at the conclusion that EUV is the primary next generation lithography solution for mass production of microchips.

There are still a lot of technical obstacles to cross. Many of these hurdles are associated with the mirrors and the exposure light source involved in EUVL. For example, each mirror in the series of mirrors used in EUVL in its current conception absorbs 30 percent of the 15nm to 14nm wavelength light used in the technology. This creates energy transmission problems that have to be solved.

Also we have a problem with suitable reticles. EUVL reticles will be constructed of as many as 40 layers of glass film. This all makes flaw inspection and repair extremely difficult. A key breakthrough in this area was the development of an Ultra Clean Ion Beam Sputter Deposition System. This method produces precise, uniform, highly reflective reticles with fewer defects or flaws than those produced by conventional physical deposition processes.

Researchers Lawrence Livermore and Lawrence Berkeley have made huge advances in producing the highly reflective multilayers that are used on the optical mirrors as well as on the reticle. They developed advanced multilayer coatings of molybdenum and silicon that can reflect nearly 70 percent of the EUV light at a wavelength of 13.4 nm.

A lot of additional R&D is taking place to solve these problems. Intel's recent press release regarding commitment to a major player to purchase beta EUVL machines proves the industry's seriousness and commitment to the EUVL solution.



The optical layout of the engineering test stand for extreme ultraviolet (EUV) lithography. The EUV radiation is produced at the plasma source, transmitted through the condenser optics to the mask, reflected from the mask onto the four mirrors of the projection optics box, and delivered to the EUV-sensitive film on the semiconductor wafer. Each mirror in the system has 81 layers of reflective coatings that must be applied with extreme precision. At the short wavelengths used in the process, the total thickness of each mirror's coatings must deviate less than an atom if the mask pattern is to be reflected without distortion. One such mirror is shown at the top of this page.

A proposed EUVL microlithographic system would use a laser-produced plasma to supply the EUV radiation source (80W-100W of power needed). The solutions to provide such an energy source are either huge magnetic field created currents or coupling the power of multiple lasers. These power sources will generate large amounts of heat with temperatures exceeding 1000°C.

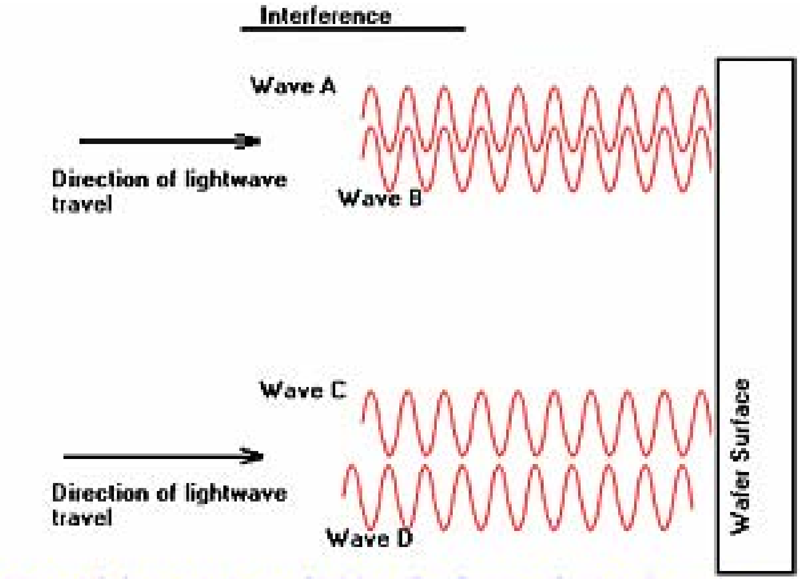
The radiation would travel through a complex condenser optics system before reflecting from a lithographic reticle. That image is then projected by the projection optics onto a silicon wafer. The wafer would reside on a typical wafer stage and the whole critical parts of the system would be isolated from the outside world in the traditional methods (see chapter 2).

The design is not so different or radically divergent from the methods used in a 248nm or 193nm system (see chapter 2), except that because of the short wavelength (14nm-15nm) of EUV all materials, including nitrogen and oxygen (used to cool & bathe the optics), absorb EUV, the system must operate in a vacuum and use reflective mirrors and reticles. The necessity of a vacuum sealed enclosure raises other issues regarding maintenance.

X Ray Lithography: XRL

Not much information is readily available regarding X-Ray Lithography. Once thought to be the NGL to inherit the DUV methods, but the past few years have shown more achievable results in the areas of EUV, partly because of huge advances in material, some of we mentioned earlier on in this article. It is rumored that XRL will only be really used in certain niche applications some of them military applications, micromachining and some directly related to the semiconductor industry - test contact probes, for instance, that need to be mechanically accurate and maintain spring properties.

X Ray light wavelengths are in the region of 1nm in length. They were discovered in 1895 by W.H. Roentgen while experimenting on the nature of cathodic rays.



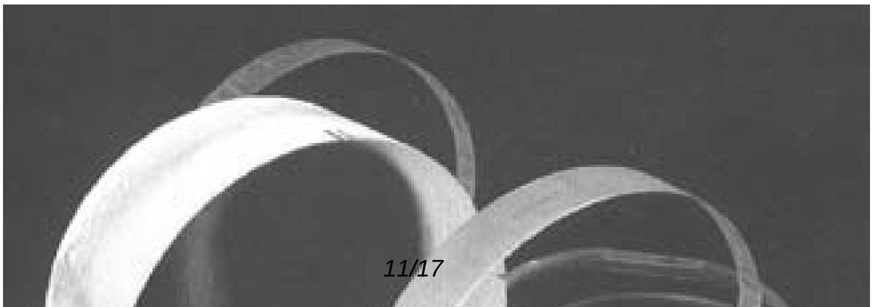
Wave A is in exact phase with Wave B = Constructive Interference.

Wave C has 180deg phase shift to Wave D = Destructive Interference.

The applications of X Rays in medicine and industrial inspection are well known, but why is this radiation of interest in lithography? In short, because of its ability to define very high resolution images in thick materials. The resolution comes from the extremely short wavelength, of the order of 0.01-1.0 nm, and the high penetration ability, arising from the transparency of most materials in this region of the spectrum.

In some ways an XRL microlithography tool should be less complex than an optical tool. This is because it does not need the large and complex imaging lens and because the reticle is held in close proximity of the wafer, making alignment between the reticle and wafer easier. A Helium (He) atmosphere is necessary in the region surrounding the exposure area. Similar to the EUVL necessity, this raises other problems.

Reflective vs. Refractive solutions



Microlithography manufacturers are busy looking at catadioptric designs (the combination of optical lenses with mirrors to minimize chromatic aberrations). Previous optical systems have been primarily refractive in design. If we were to replace certain lenses with mirrors we could minimize the need for CaF2 based lens materials. Designs using fewer optical elements is paramount (uses of multiple axes with beam splitters or mirrors etc.), but it will not decrease the necessary mechanical assembling and tuning methods in use for 'traditional' all-refractive optics.

Besides minimizing the use of CaF2, optical designers must now consider the orientation of the CaF2 crystals in their designs. Lithographers have been using lenses made with crystal orientations of [111]. Although clocking these crystals around the optical axis has been suggested as a way to mitigate the birefringence problem, it's not enough. Designs will have to combine [111] oriented crystals with CaF2 crystals of other orientations to solve the problem more effectively.

Advances in Reticle design and application

Reticles are an integral component in the lithographic process of semiconductor manufacturing. High-purity quartz or glass plates containing precise images of integrated circuit layer. Each layer of a microchip will require a different reticle containing the desired image. These images are optically transferred onto the silicon wafers as discussed previously in chapter 2.

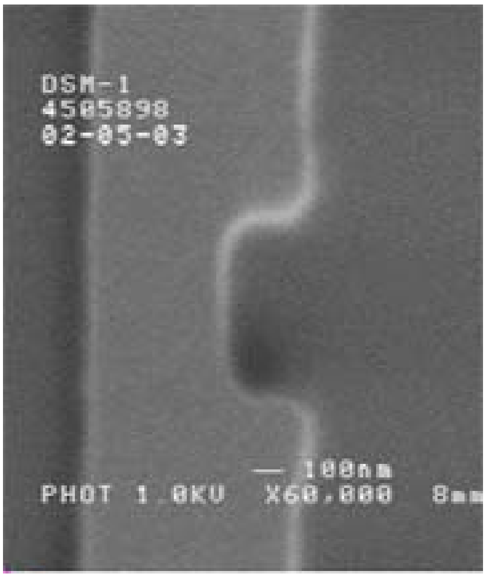
The conventional reticle, or the Binary reticle, is a stencil of the layer required. It is composed of clear and opaque elements which form one layer of a circuit pattern. Light passes through the clear elements, exposing a pattern on the wafer. but the limitations of exposure light sources and shrinking design rules driven by the (nearly insatiable) demand for more powerful, faster, lighter and cheaper devices, have rendered the reticle into a critical and key factor to technical advances in Microlithography. Although we can make the accurate pattern on ordinary binary masks, the lines blur together when reduced onto the wafer in a typical 4:1 lens reducing microlithography tool.

Advanced microchips are being built at the sub wavelength level. Sub wavelength manufacturing, requires advanced reticles because the circuit images transferred to the silicon wafer are in reality smaller than the wavelength of the lightsource used to expose the pattern. The solutions to actually achieving this successfully are:

-The Advanced Binary Reticle. The advanced binary reticle uses reticle enhancement techniques, such as optical proximity correction (OPC) and phase shift features (PSM).

- The Phase Shifting Mask/Reticle (PSM). Phase shift masks are capable of sharpening the light's effects on photo resist for sub-quarter micron designs far better than ordinary binary masks.

- Embedded Attenuated Phase Shift Masks (EAPSMs). These are similar to binary masks, in that they begin with a quartz substrate coated once with a material which the layer's design is then etched into. The most common material used in today's EAPSMs is molybdenum silicide. Unlike chrome, molybdenum silicide allows a small percentage of the light to pass through; however, the amount that passes through is "weak" and does not expose the resist on the wafer. Because it does pass through, the light is 180° out of phase compared with the light passing through the quartz alone. Therefore, where the material and the quartz meet, light interferes in such a way as to sharpen the edges of the design, producing a faithful reproduction in the resist.



When destructive interference occurs any time there is a change from the coating material to the glass. That is, at every edge the sharpening begins by essentially dragging down the light from the bright zone into the dark zone, enabling device shrinkage using currently available tools and technology.

- Alternating Aperture Phase Shift Masks. This is another method to produce reticles that engineer DUV destructive interference in order to print lines smaller than the wavelength of light. Going beyond the traditional chrome-on-glass approach, AAPSMs utilize selectively etched quartz areas.

To very simply summaries the above: Phase shift Reticles enhance contrast to expose the photo resist and print features at resolutions that binary masks are unable to achieve with today's exposure light sources and lenses.

Cost of Ownership (COO)

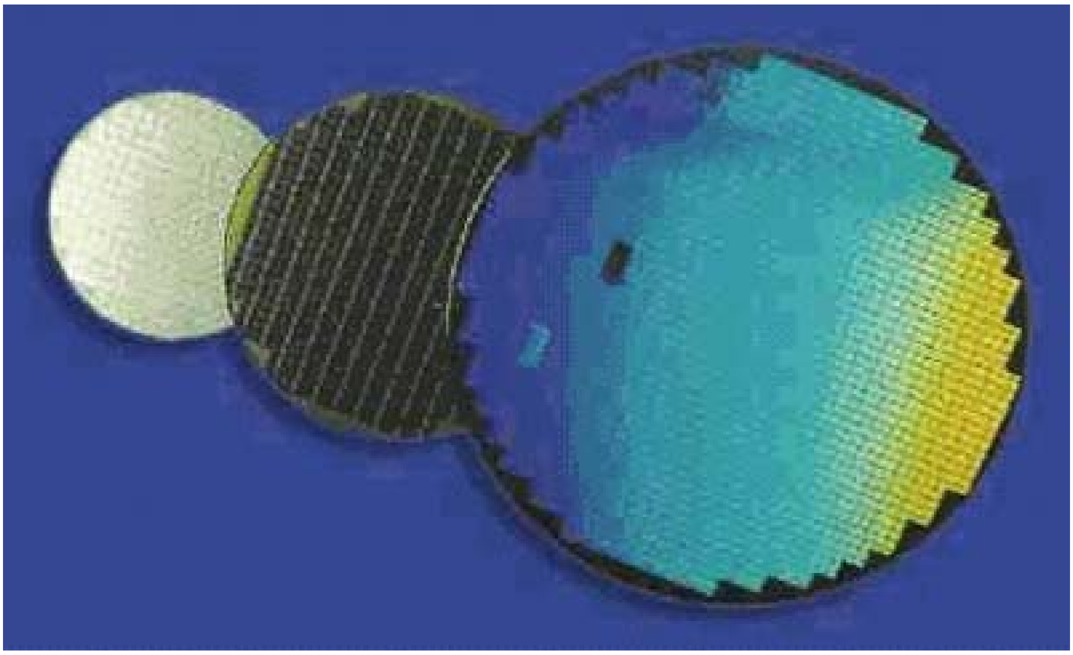
As usual one major deciding factor is the cost. Three aspects have to be looked upon to determine the COO:

- System costs
- Wafer/Material throughput.
- Operating costs

In general, on the production floor, the more advanced tools are used for the critical layers whilst the 'older' are used for non critical layers, this is to reduce costs of very expensive photoresists, reticles and other various tooling.

If a chip maker where to choose 193nm machines for his critical layers, he probably would complement his production needs with less costly 248nm (DUV) & 365nm (I-Line) machines and systems.

Material Size



The transition of material size from 200mm silicon wafers to 300mm is under way. Older fabrication plants may be upgraded, most new ones under planning or construction will be 300mm compatible. Why is this transition in material size needed? To allow a leap forward in productivity. The huge leaps taken in this industry over the last 5 years have doubled the productivity potentials, but material size has stayed the same 200mm size during this time frame. Economically speaking, the larger sized material will provide higher yields of good, fast microchips. This size of material transition requires larger tools and improved solutions to handle the new dimensions, we can safely say that the 300mm manufacturing obstacles have been overcome and production can commence.

Final Words

This article has taken a peek into the upcoming next 10 years of the microlithography aspects of the microchip manufacturing industry. Finally, it seems, we have reached the end of optical microlithography as we perceive it today. The optical lenses in use today are just not transmissive enough for the ultra low wavelengths of the future exposure light sources imperative to scale down the microchips structures below the 50nm range.

It may be assumed that main optical research efforts will be put into the identification and development of advanced mirror coating materials and the painstaking accuracy required to implement these solutions.

Consortiums, derived of the semiconductor industry major players, have decided on the roadmaps and timelines to adhere to in order to be ready in time to ensure that the manufacturing process in the industry will meet the demands and be in good position to supply the performance enhanced microchips of the future that the market will demand. Huge amounts of money are invested into research, research facilities, alpha and beta engineering tools. The brightest and most innovative minds at the universities across the globe are feverishly working out the kinks in the NGL.

Sadly, smallish sized industry leaders in the fields of optical microlithography have no longer the financial means to continue independently on their own and have been bought out by bigger and more financially robust companies. SVGL (previously Perkin Elmer) is one of these companies who no longer exist.

What remains to be seen are the solutions to the Next-NGL challenges of 25 -30 years ahead when the EUVL is drawing it's terminal breath.

Further interesting reading and information:

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