The microchip industry is trying to create ever-smaller structures on its products. Smaller and smaller circuits mean faster processors, more memory capacity and more efficient computers. Current production methods use light to write structures on microchips. As the structures get smaller, the wavelength of the light must be reduced also. According to the rules of optics the smallest structural dimension is related to the wavelength of the light used to create it. Microchip manufacturers already use light with a wavelength of 193 nanometres (visible light lies in the region of between 400 and 700 nanometre).

Microchips are getting more complicated by the day and future generations will feature even more intricate circuit patterns. The lithographic process that is used to project these circuits onto silicon currently still requires lenses. After 2010 however, the feature density on the chips will have grown so far that extreme ultraviolet light with a wavelength of 13nm will have to be used and the lenses will have to be replaced by mirrors. To measure these with the high accuracies required, Luke Krieg developed an absolute interferometer. This top view of his measurement set-up shows the light from an optical fibre shining through the central hole of a mirror being tested.

Lithographic mirrors measured with sub-nanometre accuracy

The absolute interferometer for extreme ultraviolet optics

Future generations of microchips will probably be produced using extreme ultraviolet light with a wavelength of thirteen nanometres. Optical lenses will no longer be suitable for the manufacturing process because they absorb the light at such short wavelengths. Mirrors will have to be used instead. Currently the main problem is the required precision to accurately determine the curvature of the mirror down to the nanometre. Researchers at TU Delft have built a new measurement system that promises to achieve just such a precision: an absolute interferometer. This new measurement system offers many advantages over competing methods.

by Bennie Mols
According to Moore’s Law the capacity of microchips will double every eighteen months. Although the American Gordon Moore, initially opted for a period of one year in 1965, and later changed his mind to two years, his final choice of eighteen months has yet to be proven wrong. The first lithographic processes used 436 nm light to create electrical connections 5 microns (1/200 mm) wide. The current generation of equipment uses 193 nm light and can make connections only 100 nanometres wide. Within a matter of years lithography is expected to use 137 nanometre light, although sceptics think this step will be skipped to pass directly to 13 nanometre technology.

Electromagnetic radiation affects our daily lives in many ways, in both positive and negative senses. Radio waves enable us to watch television, use mobile phones and cook in a microwave oven. Infrared offers us heat, night-vision goggles and remote control devices. Visible light, which is responsible for the wide range of colours we can see, covers only a small part of the electromagnetic spectrum. Although generally speaking the high-energy radiation outside the visible range, i.e. UV, extreme UV, X-rays and gamma rays, can be harmful to living organisms, it is also used in medical applications, astronomy and the semiconductor industry. The current lithography systems are limited to light of wavelengths longer than those of extreme UV, because this light would be absorbed by the lenses in the equipment. The only way to write microchips with this type of light is to use mirrors.

Test set-up of an extreme UV exposure system developed by Sandia National Laboratories. The heavy stainless steel structure is needed to ensure sufficient stability of the writing system and structural integrity for working in vacuum.

Four different methods of writing patterns onto silicon chips. Although visible-light lithography and UV lithography are limited by the wavelength of the light being used, these techniques can be readily scaled and they are easy and fast to use. Even finer patterns can be made using electron or ion beam lithography, but for the time being these techniques remain slow, expensive and prone to teething problems. X-ray lithography also has its drawbacks, in particular regarding construction and maintenance. The mask needs to be practically in contact with the surface being written on and no practical photo resist has yet been discovered for use with X-rays.

Microchip manufacturers are planning to create microchip structures smaller than 35 nanometres by the beginning of the next decade. This can only be done using extreme ultraviolet light. The problem with this is that the manufacturers will no longer be able to use optical lenses, as at such short wavelengths these absorb all the light, so no light would pass through them. The solution is to use mirrors, because such short-wavelength light can still be reflected. The wavelength of the preferred light is 13 nanometre, an extremely short wavelength, strongly absorbs at these wavelengths, but since the reflective coatings made of silicon are very thin, this absorption has only a small effect. The main complication when using mirrors is the need for them to be very accurately shaped, down to one-tenth of a nanometre, which is about the diameter of a single hydrogen atom. Is there a measuring principle that can offer such precision, is not too expensive and can be used in a conventional optical workshop? Quite a challenge, but even so researchers at the TU Delft have managed to come up with just such a measuring method.

Continuing from the preliminary theoretical work of doctorate student René Klaver, another doctorate student, Luke Krieg managed to build a measurement system that promises to achieve the required accuracy. Note the ‘promises’ in the previous sentence. Krieg has not quite been successful yet, but he is convinced that he will be so very soon. He works at the Optics section of Professor Joseph Braat at the faculty of Applied Physics at TU Delft. The research is supported by optical systems manufacturer Carl Zeiss, lithographic equipment manufacturer ASML, the research establishment TNO-TPD and the Netherlands Technology Foundation STW.

**Absolute interferometry** The system devised and constructed by Krieg is an absolute interferometer. The interferometer uses two interfering beams of light to measure the almost spherical shape of the concave mirrors. One beam falls on the mirror surface, where it is reflected before hitting a sensor, while the other beam of light reaches the sensor unobstructed. The word “absolute” refers to the fact that the only difference between the two beams of light is that one hits the mirror while the other one does not - there are no additional optical elements present. All competing interferometers are non-absolute, in that they use one or several intermediate optical elements, such as lenses, fibre surfaces, gratings and prisms. Because these elements are never entirely perfect, they introduce additional errors of their own which destroy the accuracy of the measurements.

“Our idea was to create an interferometer that did not use any other optical...
elements to measure the mirror surface,” explains Krieg about the measuring set-up. “It was to be a completely new type of interferometer.”

On paper, the final setup appears very simple, but in practice, things are much more complicated. The interferometer can be divided up into four major sub-components: the light source, the interferometer frame, the sensor and finally an algorithm to turn the complicated readings from the sensor into the shape of the mirror.

Krieg: “Each component was a separate challenge. I spent about a year on each of them.”

First however, he had to deal with the difficult concept of absolute interferometry. “The ultra-precise measurement of optical surfaces is essentially a chicken-and-egg problem”, Krieg explains. “The shape of the surfaces is measured using a verified length standard – the wavelength of light from a stabilized Helium Neon laser. There is no question whatsoever about the accuracy of this length standard. The problem is in the path that this light takes through the measurement setup. If we place any optical elements, like lenses, in our light beam, we disturb its path. The only way to make an accurate measurement is to know this path exactly, for which we need to know the shape of the intermediate optics with the same accuracy as we need to know the shape of our mirror. To measure these we would need exactly the type of setup we’re trying to build in the first place!”

Imperfect optics And then there is another problem. The shape of the optical elements can change with time. Krieg: “If we were to measure the shape today and then calibrate the entire system for that shape, we would not be able to repeat the measurement next week. The temperature might be slightly different, which would affect the shape of the lenses, so we would have to recalibrate all over again. Also, a surface may change after some time due to ‘wear’. If all optics were perfect, it would be simpler to use optical elements in the measuring set-up, but they are not.

The only way to get an absolute measurement is to make sure the beam of light does not have to pass through any optical element. This makes for tough design specifications.”

Krieg shows the mirror he used for his preliminary measurements, now safely packed away in a box. It has a diameter of twenty centimetres and it is transparent and yellowish in colour. The price of such a prototype is at least a million euros. Although the shape of the concave mirror appears to be perfectly spherical, it is ever so slightly off, in the order of a few micrometers, which is intentional. The mirror consists of a glasslike substrate that expands and contracts as little as possible with changing temperatures. The substrate will eventually be coated with approximately one hundred extremely thin layers to

The light exits the optical block through a pair of glass fibres. The light from one of the fibres is reflected by the mirror and focused between the two optical fibres before hitting the sensor, where it interferes with the light coming from the other fibre. The continuously changing interference pattern is recorded by the sensor. The measured data is processed using an Inverse Propagation Algorithm (IPA) developed by Krieg, which enables the shape of the mirror to be calculated down to sub-nanometre level.

The task of the interferometer’s suspension is to ensure that the relative position of the optical fibres, the sensor and the mirror remain constant within a few millionths of a millimetre. The structure is made from a special alloy with a thermal expansion coefficient one-tenth that of stainless steel. The mirror being measured (not shown) is placed on the ring at the top of the instrument, which is designed to ensure that the mirror always settles in exactly the same position every time it is inserted.

This schematic diagram of the light source shows the path travelled by the laser beams. The source produces lights of both 633 and 637 nanometres.
Precision mirrors for astronomers, physicists and biologists

Microchip manufacturers are not the only people looking for extremely accurate curved mirrors. Astronomers measuring in the extreme ultraviolet light range (usually between 5 and 30 nanometres) also need them. Extreme ultraviolet radiation is produced by gases with temperatures of at least one million degrees. The Sun’s corona and the direct vicinity of black holes can produce this type of radiation. Extremely short-wavelength light is also released when stars explode. Physicists analysing the conditions inside a plasma (a mix of free electrons and ions of the type produced inside nuclear fusion reactors) also have to work with extremely short-wavelength light for which optical lenses are useless. Biologists studying minute structures inside living cells also use increasingly short wavelengths. Under normal conditions, water absorbs very strongly at these short wavelengths, which would result in very low contrasts. However, there is a very small wavelength region where no absorption occurs in water, known as the water window. Biologists are now looking for ways of harnessing this light. Normal optical elements can no longer be used and mirror-based microscopes will have to be developed.

As in lithography, shorter wavelengths mean higher resolutions for microscopy. In ‘in-vitro’ biological applications very short wavelengths can be a problem however, since water absorbs most of this light. There is only a small wavelength range around 3 nanometres, the water window, in which the absorption by water is less than that by materials of interest such as proteins. Again, mirrors with extreme accuracy will be needed to achieve the desired resolution.

Active stabilisation No commercially available light source could produce an ultra stable wavelength different from but still close to 633 nanometres. So the research team had to make their own.

“We started with a standard tunable diode laser,” Krieg explains, “the wavelength of which can be adjusted. However, we have actively stabilised it to produce only light of 637 nanometres.”

The interference pattern produced between the beam reflected by the mirror and the direct reference beam hits a CCD sensor. The sensor currently used by Krieg is ten years old and lacks the required accuracy.

“As part of the same research project, the faculty of Electrical Engineering, Mathematics and Computer Science at Delft University is currently developing a completely new type of sensor that meets the specifications of our absolute interferometer. The sensor is being specially developed for our test system, but unfortunately it is not ready yet. The project started later because it proved difficult to find a suitable doctorate candidate.”

In its current incarnation, the Delft interferometer can determine the shape of the mirror down to four nanometres, whereas the requirement is one-tenth of a nanometre.

Trick & helium The trick used by Krieg to achieve absolute interference relies on the special properties of optical fibres. An optical fibre is placed near the centre of curvature of the mirror. The fibre has to be close to the centre of curvature, but not too close, or the light will be reflected back onto the tip of the fibre, which must be avoided. The fibre core conducting the beam of light measures only three micrometres in diameter. The laser light entering the fibre at the light source exits at the fibre tip as a perfect spherical wave, propagating radially in all directions like an expanding sphere. The spherical wave then strikes the mirror where it is reflected onto a light-sensitive sensor. On the other side of the centre of curvature of the mirror is the tip of a reference fibre. This also emits a spherical wave, but this one hits the sensor directly. The reflected light and the reference light interfere with each other, and the sensor registers the interference pattern.

“In fact, we are comparing light reflected by our mirror with light that passes unobstructed,” Krieg says. “Any difference is entirely the result of the shape of the mirror. This means we only have to calibrate the system once, unlike other methods.”

Since air also acts as an optical element with a certain refractive index, an absolute interferometer cannot operate in air. One solution would be to put the set-up in a vacuum, but this is far from simple. It is much easier to cover the measurement system with a cylinder and flush the air out, to fill the cylinder with helium gas instead.

Krieg, lifting the cylinder off the optical bench: “The refractive index of helium is practically the same as that of a vacuum. It is much easier to supply a bottle of helium gas with our system than to have users supply their own vacuum system.”

Lines, rings & chaos On a computer display, Krieg shows the resulting interference pattern. It looks much more complicated than the usual interference patterns of lines and rings. In fact, it’s chaos. Krieg also knows that the number of interference lines exceeds the number of pixels in the sensor measuring the interference pattern. This means that the sensor’s resolution is too low to see the full interference pattern.

Krieg: “Any scientists working in interferometry when presented with a pattern like this will say it’s no use to them. Nevertheless, we managed to solve the interpretation problem.”

Krieg uses two interference patterns, produced by using light with two slightly different wavelengths. He starts with a standard helium-neon laser with a wavelength of 633 nanometres and then uses a 637 nanometre laser light source. Both are in the visible part of the spectrum and both produce an interference pattern, but the patterns differ slightly from each other.

“By subtracting one pattern from the other,” Krieg says, “we get a new interference pattern, which we can interpret.”

Lithografic mirrors measured with sub-nanometre accuracy

The Chandra space telescope launched in 1999 by NASA to detect novas, pulsars and other high-energy sources already uses mirrors for the X-ray range. Improved measuring methods will help to greatly enhance the resolution of such telescopes.
“Even so,” says Krieg, “the sensor we are currently using is the main bottleneck. The fact that we can get an accuracy of four nanometres using this old sensor is a good indication that the new sensor being developed by times will enable us to achieve the one-tenth nanometre requirement. I am convinced we will get there, since all the other parts of the system satisfy the accuracy requirements.” Note that a dimensional accuracy of one-tenth of a nanometre does not mean that the position of each atom on the mirror’s surface has been measured. It simply means that the overall shape of the mirror will be measured within one-tenth of a nanometre. The system does not look at small local deformations. Other methods already exist to measure those in a statistical sense.

Countless benefits In addition to the great benefit that the absolute interferometer does not introduce systemic errors caused by the effects of optical elements along the route, the system offers other benefits. “Our system can handle much greater deviations from a perfect sphere than other interferometers can,” says Krieg. “Other interferometers always have problems measuring deviations from a perfect sphere, and as the deviation increases, the problems increase. The lithographic industry alone will need many differently shaped mirrors. Some will deviate more from the perfect sphere, others less. Since we are using two different wavelengths, there are practically no restrictions. This increases the general applicability of the absolute interferometer. On top of that, our system could be extended to measure lenses as well.”

There is yet another advantage. Many mirrors contain holes or consist of strange shapes, dictated by their application. Along the edges of a hole or any other discontinuity, light is diffracted. This effect introduces undesirable disruptions in the interference pattern, which seriously affect the accuracy of measurements at sub-nanometre levels.

Krieg: “Other methods measure only mirrors without sharp edges, and if the mirror does have them, they stay clear of the edges. Such methods cannot cope with diffraction. Our method is capable of compensating for diffraction.”

First, the resulting interference pattern is reduced from a very chaotic pattern to something that lends itself to interpretation. Next, the disruptive diffraction effect is subtracted. Finally, the measurement system represents the shape of the mirror as a series of at least six hundred numbers, each of which provides information about which corrections are required at which location on the mirror. Each of these interpretation steps requires quite a bit of mathematics.

Competition The main competition for the absolute interferometer developed by the group at TU Delft is the Sommargren interferometer developed by the Lawrence Livermore National Laboratories in collaboration with the National Institute or Standards & Technology (NIST) in the U.S.

Krieg: “As early as 1999 Gary Sommargren said that he had an absolute interferometer, but that was not the case. His first models still used a lens right in front of the sensor, but that has now been removed. Even so, his system still provides sufficient information to calculate the shape of the mirror. The synthetic interference pattern, measured using two different wavelengths, shows less variation than the pattern produced by a single wavelength.”

The measurement data obtained by Krieg’s interferometer forms a chaotic interference pattern. The pattern contains more oscillations than the number of pixels in the measuring sensor. Hence additional information is needed to enable the pattern to be unambiguously interpreted nonetheless. This information is supplied by a second interference pattern produced by a different wavelength.

The region in the centre of the image represents the area of the mirror with the hole in it. The pattern there is irregular because there is almost no light present. This area is not included in the measurement.

Physically speaking, this restored pattern is identical to the chaotic pattern produced by the first wavelength, but it uses the information contained in the more ordered synthetic interference pattern shown in the previous illustration. Only after this restoration procedure does the interference pattern provide sufficient information to calculate the shape of the mirror.

Competing nano lithographic methods for microchips of the future

In the race to establish the standard method for the production of the next generation of microchips, writing with extreme ultraviolet light (EUVL) is currently the most promising candidate. It is the subject of research projects in Europe as well as the U.S. and Japan. The International Semiconductor Roadmap describes EUVL as a potential solution for the future of microchip manufacture. Large companies such as ASML, Intel, IBM and Motorola are working on it, as are a number of large research establishments such as the Lawrence Livermore National Laboratory, the Berkeley National Laboratory and the Sandia National Laboratories. Even so it is far from certain that EUVL will become the next method of choice. Critics are of the opinion that the system requires a level of accuracy that is not feasible. One of the main obstacles to commercial use is the accuracy of the mirrors needed. The key question is whether the method will be sufficiently cost-effective. This has yet to be determined.

Another possibility, though often considered a second choice, is to write the patterns using electrons (Electron Beam Projection Lithography, EPL). The wavelength of electrons is one-thousandth of a nanometre, which is much less than the size of an atom. A beam of electrons can easily be focused into a point with a diameter of one nanometre.

However, the benefits of the small wavelength are offset by several major problems. The production speed of the writing technique is far too low for use in mass production. Also, the resolution is limited by the dispersion of electrons in various steps of the writing process on the chip and includes dispersion by the chip’s photosensitive layer. Other existing methods include X-ray lithography and ion beam projection lithography. X-ray lithography works with a very expensive (synchrotron that supplies X-rays with wavelengths of approximately one nanometre. A one-on-one mask then projects the radiation onto the chip wafer. To avoid high absorption rates, most of the installation has to be in a vacuum. X-ray masks are fragile and expensive to make and have remained a major obstacle to the commercial use of X-ray lithography. Ion beam projection lithography uses hydrogen or helium atoms. Complementary stencil masks are used to build up the image, which is then reduced by means of electrostatic lenses. The production of masks, the design of an ion imaging system, the fitting together of complementary masks and finding a suitable balance between sharpness and production speed remain the major problems with this method of writing microchips.
Ironically, the otherwise disruptive diffraction phenomenon also gives this interferometer its uncanny accuracy. Diffraction very rapidly changes the wave front of light coming from a small point (e.g. the tip of a glass fibre) into a perfectly spherical shape, even though the original wave front is irregular.

The Sommargren interferometer is also based on glass fibres, but unlike the interferometer developed by Krieg it uses optical elements between the fibres and the optics being tested.

The Sommargren interferometer is also based on glass fibres, but unlike the interferometer developed by Krieg it uses optical elements between the fibres and the optics being tested.

The light coming from the optical fibre in a Sommargren interferometer is reflected by the mirror being tested, back to the fibre, where the light is reflected under a different angle. It reaches the CCD, where it interferes with the rest of the light from the fibre. The reflecting surface of the fibre and the optics just before the CCD are optical elements. Just like the elements in a Fizeau interferometer they must be accurately measured as they may become distorted over time. This is why the Sommargren interferometer cannot be called an absolute interferometer.

Lithography from Delft — the Mapper

In July 2000 Prof. Dr. ir. Pieter Kruit established the Mapper Lithography company, as a spin-off project from his academic work at TU Delft. Mapper is developing an alternative lithography method in addition to the methods currently receiving most of the world’s attention: Extreme Ultraviolet Lithography (EUVL) and Electron Beam Projection Lithography (EPL). Mapper combines simultaneous writing using 13,000 electron beams with superfast optical data transport methods as used in the telecommunication industry. A single electron beam is split into 13,000 separate electron beams. Electrostatic lenses are then used to focus each of these beams onto the surface being written (the chip wafer). In a single scan, a wafer image field of 26x33 millimetres is exposed. The electron beams are switched on and off by 13,000 light beams, one for each electron beam. The light beams are generated by a data system containing information about what the required chip pattern looks like. Mapper’s aim is to both write wafers rapidly (more than ten per hour) and achieve a high resolution (less than 45 nanometres). The method is currently in the developmental stage.

Lithographic mirrors measured with sub-nanometre accuracy is not absolute. The fibre he uses to direct the light onto the mirror also serves as a reflective surface for the light returning from the mirror. Only then does it hit the sensor. The surface of the fibre can never be perfect and it is also prone to change with time. This makes his method less than absolute. He claims to be able to measure down to 0.25 nanometre, but that accuracy is not reproducible. If he were to repeat his measurement a week later, the outcome could be very different, even though the surface of the mirror under test hasn’t changed.

In addition, our system enables us to measure much larger mirrors in one go than the Sommargren interferometer can.” Other systems than Sommargren’s use even more optics, which puts them that much farther from being absolute interferometers.

“Whether our absolute interferometer will eventually be developed for commercial use depends on many other factors,” Krieg says. “The most important factor is the commercial feasibility of the proposed microchip production process.” Although the microchip industry remains the driving force behind the precision measurement systems for mirrors, the invention may also benefit biologists, physicists and astronomers. These scientists are increasingly involved in experiments requiring short-wavelength light and consequently mirrors with nano-precision shapes. The principle of the absolute interferometer developed at TU Delft is now protected by patent. Krieg will remain with the Optics section until the end of 2004. He hopes that the new sensor will become available before that time and that he will be able to use it to provide conclusive evidence that his absolute interferometer can measure the curvature of a mirror to an accuracy of one-tenth of a nanometre. Krieg has no doubt that the new sensor design will bring the system up to scratch. With a bit of luck he will be able to demonstrate this himself, but if not, his successors will have their work cut out for them. Krieg has now completed his research and was awarded his doctorate on 30 November 2004.

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