EUV lithography : historical perspective and road ahead

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Inaugural lecture
Prof. Vadim Banine
September 19, 2014

/ Department of Applied Physics

Technische Universiteit
Eindhoven
University of Technology

EUV Lithography

Historical perspective and road ahead

Where innovation starts

Inaugural lecture prof. Vadim Banine

EUV Lithography

Historical perspective and road ahead

Presented on September 19, 2014
at Eindhoven University of Technology

Introduction

“Any sufficiently advanced technology is indistinguishable from magic”
Third law of Arthur C. Clarke

Ladies and gentlemen,
The main topic of my lecture will be the physics and technology of nano-lithography and extreme ultraviolet lithography(EUVL) in particular. Looking from a historical perspective I will attempt to sketch possible trends and opportunities for scientific advancement in the chosen area and share my experience of co-operation between industry and scientific institutes as well as the lessons I learned from it.

In my presentation I will refer frequently to the empirical laws, such as Moore’s or Koomey’s, which are mostly governed by economic developments without going into details of economics due to a lack of any thorough economic knowledge and leaving this subject to the specialists such as Adam Smith, Karl Marx, Alan Greenspan and Francis Fukuyama.

I will also use statistical material, knowing all too well the scientific ambiguity of such an approach based on uncertainty of both data collection and the data interpretation. Thus statistical material will be used for illustration purposes only.

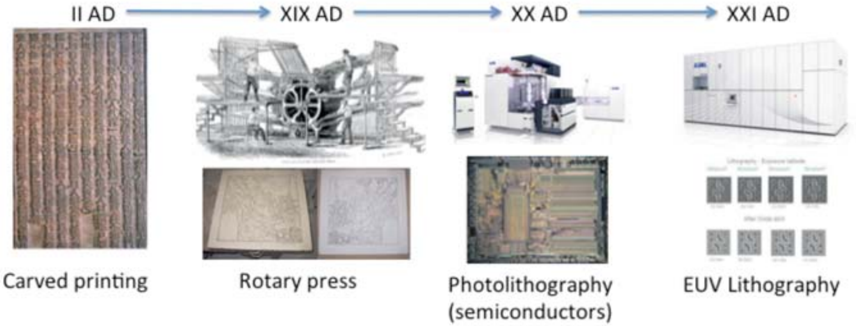

Figure 1

From carved printing [1] through rotary press [2] to Photolithography and EUVL [3], [4], [5] Lithography in the form of the carved type printing can be dated as far back as the 3rd century AD.

Starting from the 19th century lithography played a major role as the basis for dissemination and preservation of the knowledge in the form of printed books, maps, newspapers etc. In the mid 20th century, with the invention of the micro- and nano-electronics, it took on a new meaning and became the basis for the patterning solutions of the modern day semiconductor industry. This by itself increased the creation and dissemination of knowledge exponentially, which in its turn fuels further progress in technology.

For 50 years the progress of semiconductor industry and thus lithography was governed by the law named after a founder of Fairchild Semiconductors and later co-founder of Intel, G. Moore.

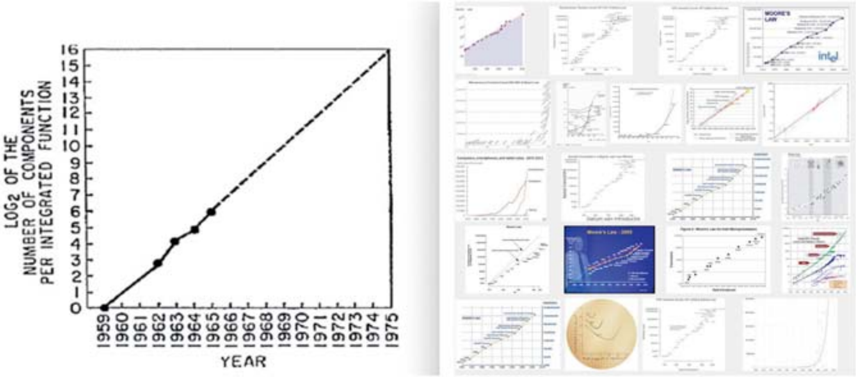

Figure 2

Left in the figure is the famous publication of the graph, which is later became known as Moore's law [6]; Right in the figure is a picture of several out of thousands of Moore's law representations on Google search in 2014

Though it has been reformulated several times, Moore's law basically states that the number of transistors on integrated circuit doubles every 1.5-2 years. Though it is not an exact law as, for example the 2nd law of Newton, and at best can be called an economic law or a conjecture, based on a couple of points over a period of 6 years (see Figure 2), the prediction of Moore has proved to be true for the last 50 years.

Almost every year prominent technologists and scientists come up with a prediction concerning the end of the Moore’s law. Quoting the NY Times in 1997: “… the question keeps arising of whether Moore’s law will lapse in the next decade or so, ending the era of explosive growth.” A similar article appeared in the NY Times in 2003. In 2005 L. Penenberg in Slate wrote: “Unless chip manufacturers figure out some new techniques the march to miniaturization could stall”. Similar claims came in 2008 and in 2014 at SPIE conferences. Though it is difficult to imagine that such aggressive scaling will continue indefinitely, one cannot but think about the 1st law established by Arthur C. Clarke:

“When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong.”

Although the past track of a development is no insurance for its continuation in the future, it is worthwhile mentioning that it is possible to extend the exponential trend of Moore retrospectively back to 1900 as was done by Ray Kurzweil [7].

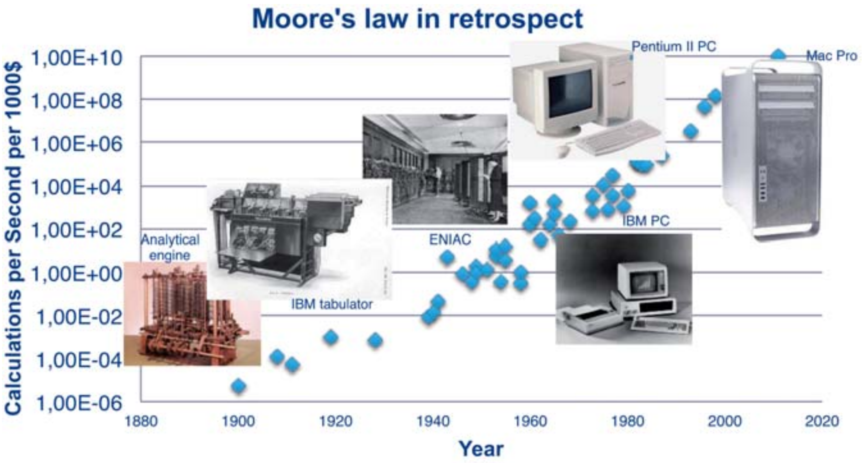

Figure 3

Trend of the technological advances of computers according to R. Kurzweil in calculations per s per 1000$ (data are taken from [7])

Looking around, everyone can see the technological change our society has experienced in the last 50 years due to the industry driving and competing along the road set by Moore. We have seen a significant paradigm shift of employment of technology from:

- connecting different locations e.g. land-line telephones, to
- connecting individuals e.g. mobile phones and to
- connecting smart things and devices in the near future e.g. automotive, home appliances, medical etc. (or as it called nowadays: “internet of things”)

This is nicely illustrated in [8].

Another trend, which governs semiconductor progress, is related to power consumption.

The more computational technology embedded in our society, the higher the percentage of power consumption is dedicated to it. Till 2005 making transistors smaller and at the same time increasing the clock speed (so-called Dennard scaling) went hand in hand. This simultaneously allowed a decrease in the chip cost and a rather straightforward increase of computer performance. In 2005 this type of scaling came to an end. One of the contributing factors to this was the

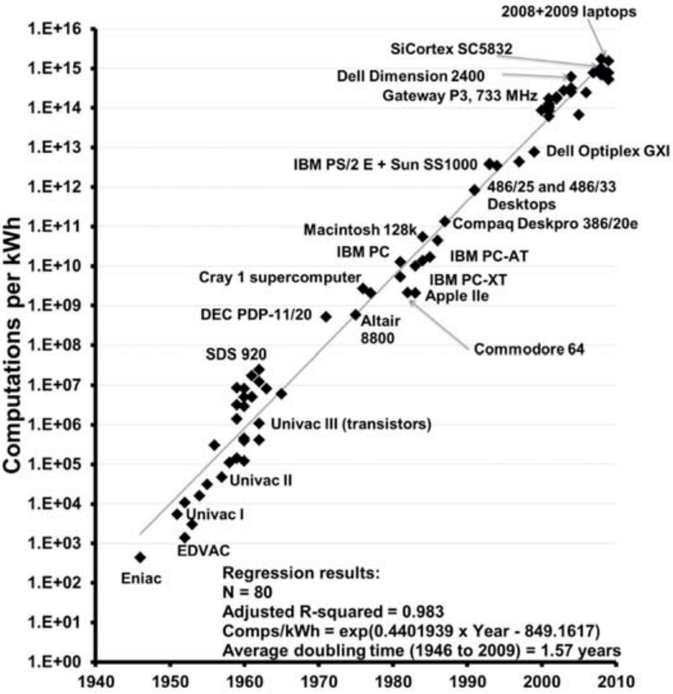

Figure 4

Koomey’s-Moore’s law for computation per kWatt [10] excessive power requirement of the computer chips while the wide spread use of mobile devices prompted another push for more power-efficient technologies.

One more fact, related to power consumption, has to be taken into account as well. Though evaluations differ, currently server farms alone already account for at least a couple of percent of the electrical power consumption in the US [9, 10].

Thus scalability of the power efficiency of computations becomes a significant additional driver for Moore’s law. As has been shown in [10] the dependence of computations per kWh as a function of time have a familiar Moore’s like behavior, which is sometimes called Koomey’s law, see Figure 4.

Place of lithography in semiconductor technology

As has been stated above lithography is one of the most important components of the progress of semiconductor technology. Figure 5 is a sketch of the semiconductor process with the end product a working chip. It starts with manufacturing of a silicon wafer, whose diameter has changed over the years from 100 mm in 1975 to 150 mm in 1980 and 200 mm 1990 to the current size of 300 mm. The next step after wafer polishing, is depositing a certain material on the wafer, which is coated with a photosensitive photoresist layer. During the lithography step a pattern, printed on the mask (or reticle), is projected onto the photoresist of the wafer. This process may be familiar to some of the older people in the audience: before the era of digital photography and printers, photos were made using of an optical enlarger in a dark room. While an optical enlarger magnifies the pattern on a film in order to produce larger pictures, the optical lithography systems nowadays de-magnify the pattern by a factor of 4. Similar to the "dark room" process the photosensitive layer is developed after exposure. Then an etch or implantation step is performed.

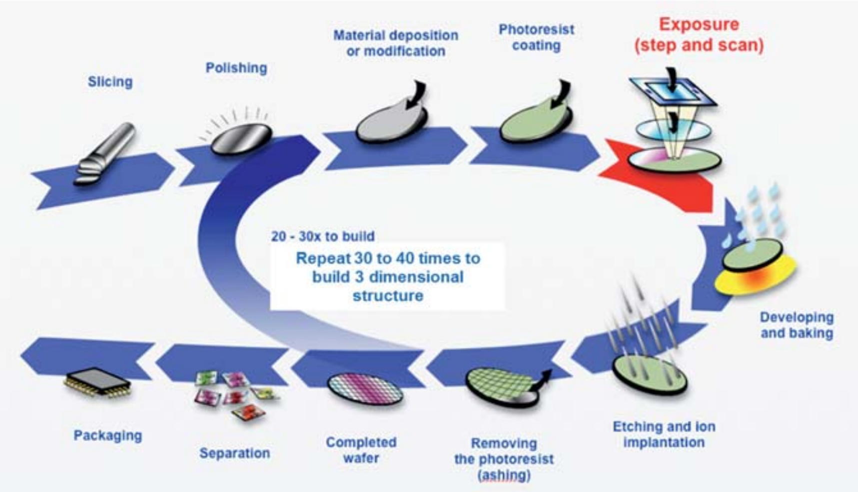

Figure 5

Lithography is at the heart of chip manufacturing

This process, repeated 30-50 times in a layer by layer way, builds up the 3D structure of a chip, Figure 6.

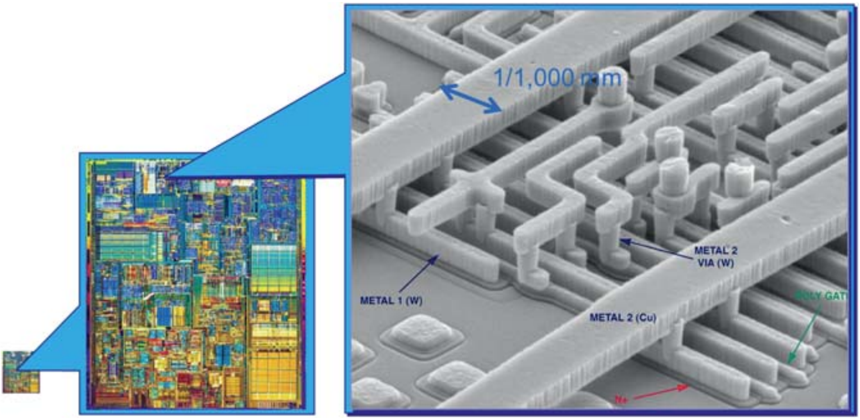

Figure 6

A chip under the microscope

Extreme Ultra-violet Lithography

New challenges to further scale down the critical dimension of semiconductor devices in the 21st century attracted the close attention of both high-tech companies and scientific institutes to extreme ultra-violet lithography (EUVL).

The number of publications devoted to a certain technological problem by the scientific community can be considered as a sign of this community's interest in that particular problem. At the same time, the absolute number of publications does not directly correspond to the problem's significance. In order to illustrate this one can apply a uniform search on the Web of Science (WoS) for articles in the field of interest. As an example, the problem could have been significant enough, such as "Street Lighting" (Nobel Prize 1912), but has by now become quite

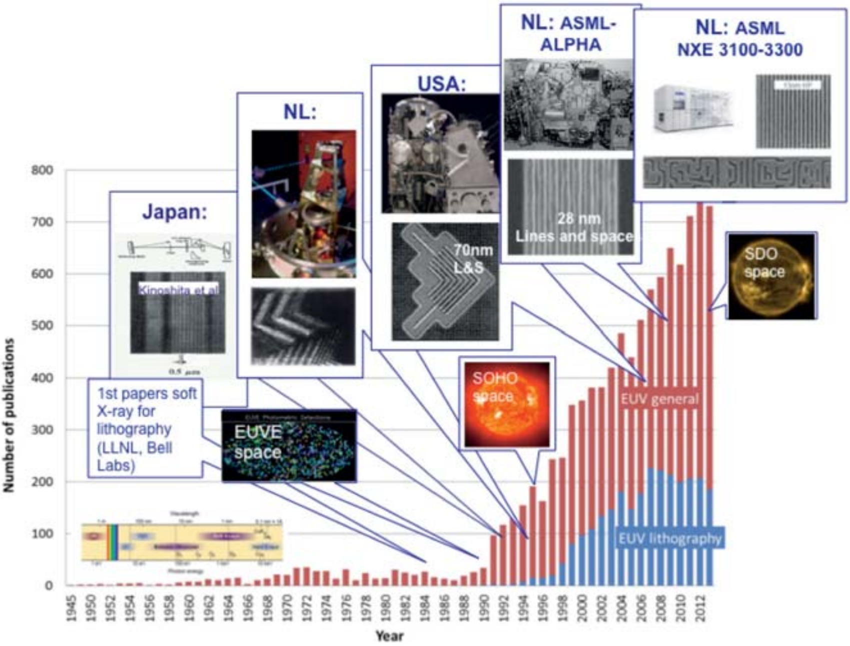

Figure 7

History of Extreme Ultraviolet Lithography (EUVL) [11], [12], [13] mundane and too developed to attract any significant attention: 785 publications over the last 69 years. It is almost equal in count to the search for the “Gravitational Wormhole”: 530 publications over the same period. One might argue that as exciting and futuristic as such a problem might be (Star Trek), it is very far from any practical application. A very popular subject and relatively close to application, however still far from becoming a real wide spread product, would be “Graphene” (Nobel Prize 2010): 56,889 hits on WoS. In this list “Extreme Ultraviolet” scores a decent 10,236 hits on WoS: already applied but still very interesting.

As indicated in [11], the region between ultraviolet and X-ray is one of the last regions of the electromagnetic spectrum to be developed and to find a practical application. As can be seen from the chart in figure 7, the number of published articles mentioning this part of the spectrum remained relatively low till the end of the 1980’s. Unlike EUV, both X-ray and ultraviolet have a significantly longer absorption length. EUV is absorbed in nanometers of any solid material and micrometers under normal conditions in gases. This defines a high threshold for technology, which one has to use in such an investigation (special multilayer reflective optics, high vacuum, hot 20-50 eV plasma or accelerator technology for production of EUV). At the same time, from the application point of view, interest has been very limited. That being said, one should mention that with the current technological achievements in the area opportunities for the investigation of materials in EUV might be quite promising, as is evident in the work of Weilun Chao et al on Soft X-ray microscopy [14]. Also investigation of the EUV spectrum of the sun is important for understanding the evolution of Earth’s ionosphere, predictions of communication system degradation (including GPS) and atmospheric heating.

As one can see, significant technological advances are needed in order to be able to exploit this part of the spectrum. Such opportunity presented itself at the end of the 1980’s in the form of a new application: EUV lithography. It led to an explosion of the number of publications at this point in history.

The first paper on the possible application of EUV, or as called at that time soft X-ray, for lithography was published by Bell Labs [15] in 1985. Already in 1989 Kinoshiba et al [16] demonstrated EUV imaging in resist with critical dimensions of ~ 0.5 µm, using Schwarzschild projection optics and synchrotron as a source. In 1991 EUV images were shown by prof. Bijkerk’s group [17]. A laser produced plasma (LPP) source was utilized in order to produce EUV radiation. CDs of

~60-80 nm were demonstrated in Japan [18] and in the US on an ETS tool [19] in 2000 and 2001 respectively. The EUV lithography program was launched at ASML in 1997. It resulted in the 2006 shipment of two Alpha Demo Tools to R&D facilities at IMEC (Belgium) and the University of Albany (NY, USA), which performed on the level of 28 nm for the critical dimension (CD) printing. This progressed further towards the shipment preproduction systems NXE:3100 and NXE:3300, see e.g. refs [20, 21].

Another interesting trend can be observed from figure 7: while the number of citations for EUV lithography peaked in 2007, the total amount of papers in scientific publications has continued its grow till now. This can be taken as a sign of the relevance and scientific value of the field of EUV.
In order to understand what drives the shift of lithography to EUV from the technological point of view, one should consider the formula for the resolution of optical lithography:

$$R = k_1 \lambda / NA,$$

where λ is the wavelength of light, k_1 is a coefficient and NA is the numerical aperture of the lens [22]. One can easily see that scaling wavelength is instrumental in the improvement of the optical resolution. The evolution of lithographic wavelengths has gone from 436 nm (aka g-line) to 365 nm (aka i-line) to 248 nm (aka KrF) to 193 nm (aka ArF) and finally to 13.5 nm (aka EUV). As an

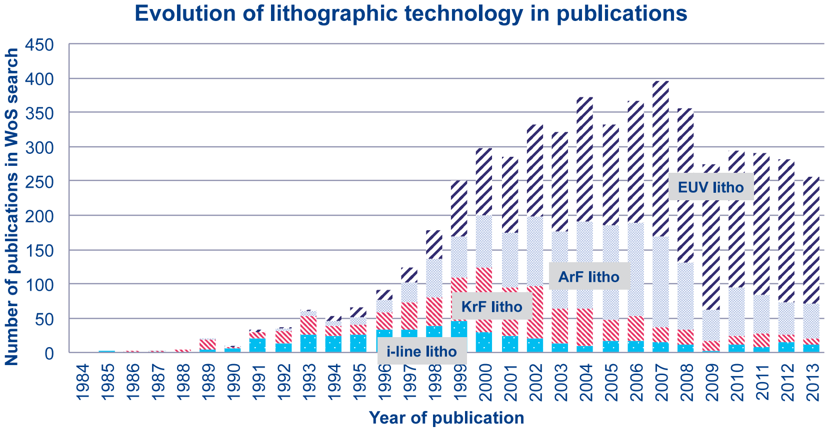

Figure 8

Number of articles found in WoS on lithography made with 365 nm(aka i-line) to 248 nm(aka KrF) to 193 nm (aka ArF) and finally to 13.5 nm (aka EUV).

example, for 13.5 nm wavelength, NA of 0.6 and an equal-lines-and-spaces pattern, the minimum feature size would correspond to k_1 of 0.25 and be equal to ~6 nm. This is a significant step down “Moore’s alley”.

Figure 8 describes the evolution of lithographic technology with the wavelength applied (i-line: 365 nm; KrF: 248 nm; ArF: 193 nm and EUV: 13.5 nm) in the context of the scientific material, dedicated to each of the technologies, which can be found at WoS. As one can see, each step forward produced both higher peaks in the number of articles in the scientific literature and in their total amount than at each step before. It can be used as an illustration of increased technological challenges as well as investment in the solutions for which scientific methods are needed. One can argue that it shows a shift from the technological approach in the form of a craft to scientific one.

With the printed feature size of the semiconductors continuously decreasing and now shifting from the 22 nm to 14 nm node, double patterning (DP) lithography based on 193 nm deep ultraviolet (DUV) systems is being employed [5]. The next step towards extreme ultraviolet lithography (EUVL) is seen as a logical one with respect to cost reduction in equipment space as well as a carrier for further feature downscaling [6].

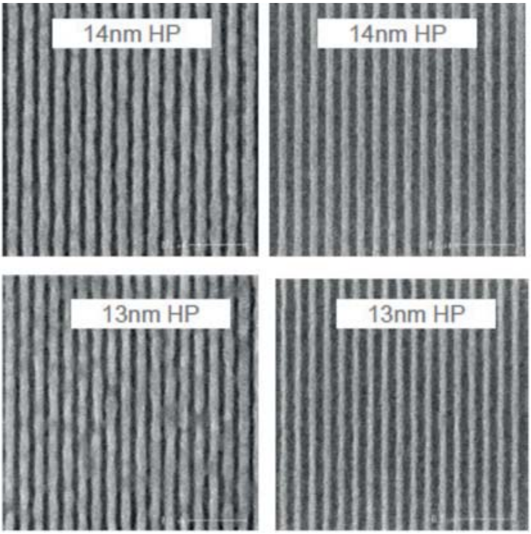

Figure 9

Single exposure lines and spaces structure at 13 and 14 nm in various resists: Chemically amplified resist (left) and Inpria resist (right) [24]

Though this step is economically logical major technological developments are needed in order to realize it and with it comes extremely exciting science.

EUV lithography already now produces stunning images of a single step exposure, see e.g. [23] and [24]

A major technology change and the realization of hundreds of inventions were needed in order to achieve this result.

The three main important differences between EUV and DUV lithography are:
- Reflective multilayer (Bragg type) optics instead of refractive optics
- Plasma source (laser produced plasma and discharge produced plasma) sources instead of UV laser
- High level of contamination control at the mask as well as in a high-vacuum environment (instead of normal pressure in DUV)

Reflective optics of EUV

Due to the fact that EUV is already being absorbed in a very thin layer, it is not possible to use refractive optics for this wavelength. Furthermore, the reflectivity of EUV from any surface at normal incidence is quite low (<< 1%). In order to realize an optical system with EUV at 13.5 nm one has to use interference coatings consistent with 40-60 Mo-Si pares of layers with a thickness per pair equal to about 6.7 nm, see Figure 10.

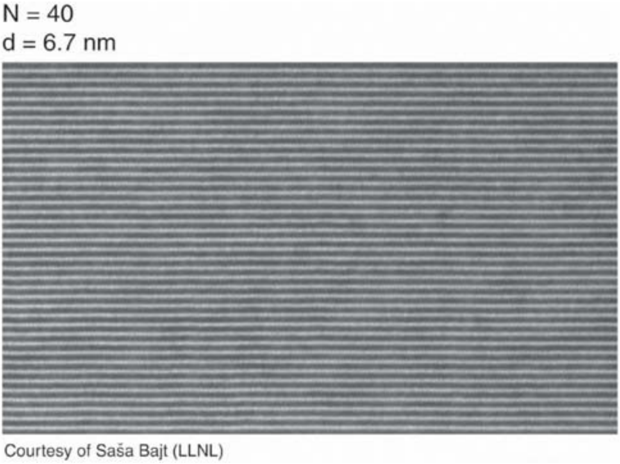

Figure 10

TEM picture of a cross-section of multilayer (Molybdenum-Silicon; MoSi) coating [26]

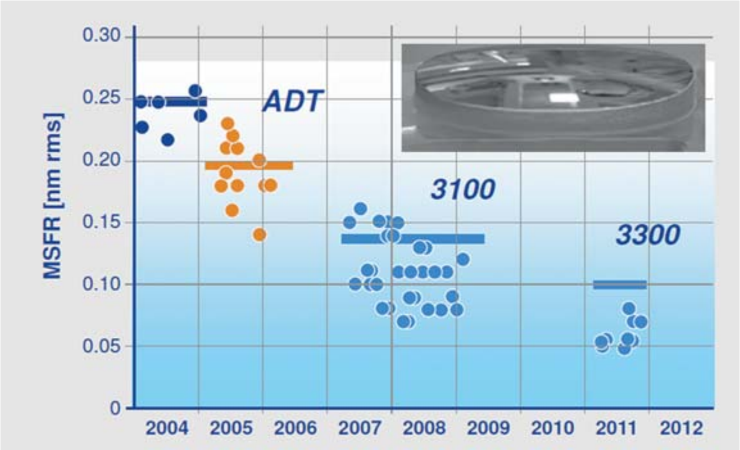

Figure 11

Roughness results and target levels for mirrors of different EUVL tool generations and coated mirror for the NXE:3300B generation.

Furthermore in order to have a good reflection of about 68-70% as well as imaging, the surface of the aspherical mirrors, used in the optical system for the scanner, has to be polished very accurately. For example looking at the performance of the multilayer Optics [25] in Figure 11, one can see the improvement of the achieved mirror roughness from 0.25 nm rms in 2004 to 0.05 nm rms now. These values are at the level of a single atom!

EUV Source

At the same time a number of challenges proved to need more attention than originally envisioned. One of those is the EUVL source, see figure 12.

The whole history of the source development can be divided into the main four “ages”:

- **Age of choice**. During this period starting from 1998 till roughly 2001-2002 the main understanding of the EUVL system was developed. This age also produced the understanding of the source requirements, in particular the desired power. At the same time a number of EUV production options was investigated [27], such as accelerator technology based [11], laser produced plasma [28, 29, 30, 31, 32, 33] and different types of discharge produced plasma sources [34, 35, 36, 37, 38, 39, 40, 41]. The level of the power demonstrated at that time was ~ 0.1 W.

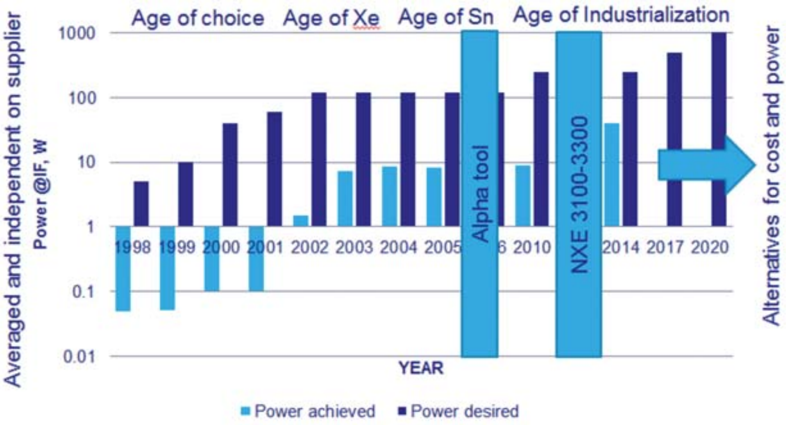

Figure 12

History of the source development: power requirements and achievements specified as watts at intermediate focus (focal point of collector after all debris mitigation apparatus, spectrally pure) [12].

- **Age of Xe (Xenon)**. While the understanding of the EUV source requirements matured, the list of candidates for the sources narrowed down to Xe laser produced plasma [31] and discharge pinch plasma sources [34, 36]. The achieved level of power with Xe source in this period of time (till 2003) was of the order of watts. At the end of this period it also became clear that due to a low conversion efficiency (CE) of Xe plasma (< 1% in 2π in 2%-band) the chance for these sources to achieve 100 W of EUV clean photons after collection (at intermediate focus (IF) [42] is not high. Thus the necessity of change to a different EUV “fuel”, namely Sn, was formulated and investigated during this period [42]
- **Age of Sn (Tin)**. Age of Sn or switch of multiple suppliers to the Sn fuel started in 2003 [32, 33, 35, 37, 41]. The best powers achieved in IF increased by a factor of 5 mainly due to conversion efficiency (CE) increase to the value of 5-6% for Sn [41, 43, 44, 45, 46, 47, 48]. The switch to Sn did not only have advantages. In comparison to Xe, Sn is a rather “dirty” EUV fuel. Thus additional measures had to be taken while dealing with a decrease in the lifetime of the collector optics.
- **Age of industrialization**. Right now we are living in the age of industrialization. It started with the delivery of 2 ADT tools with EUV sources based on Sn DPP and proceeded with NXE-3100 and later with NXE-3300 machines. NXE-3100 was delivered both with Sn DPP and Sn LPP sources and NXE-3300 with a Sn LPP source. While peak performances of those sources achieved almost 100 W level [49] the average power and utilization are still a challenge. As can be seen from

Figure 12 the power delivered at IF experiences a steady though slower than desired growth. At the same time the industry remains power hungry and future requirements exceeding the 250 W can be expected. In order to make a next step in this direction significant and sometimes pioneering research is needed. I will come back to this topic later in this lecture.

Defect control at EUV mask

Unlike DUV systems, until recently EUV did not use pellicle for the mask protection. The contaminating particles of the size close to critical dimension (CD), if they reach the reticle (mask), might be imaged on the wafer, producing defective chips. Two main courses of action have been pursued in order to resolve this problem: contamination control of the mask and the manufacturing of ultra-thin (< 100 nm) free standing membranes for EUV pellicle.

Reticle contamination control in recent years has advanced significantly [7]. At the same time, thin-membrane manufacturing has shown significant progress. It originated as an idea from the membranes proposed and manufactured for the EUV spectral purity filter, see [50]. The first prototype of a full-size free-standing pSi pellicle has recently been fabricated [51], see Figure 13.

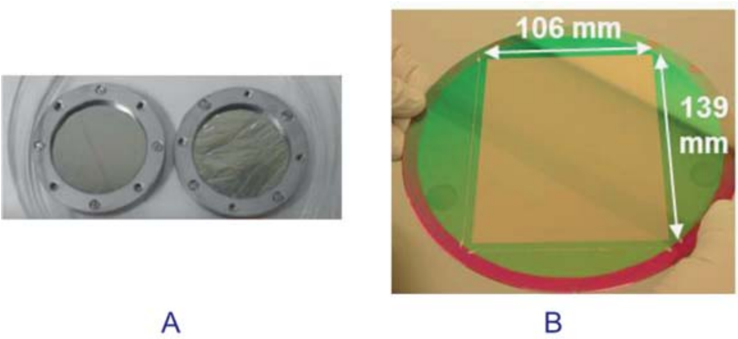

Figure 13

A. Free standing membranes for spectral purity filter (SPF) [50] and B. Example of 70 nm thick poly-silicon (pSi) pellicles obtained based on 200mm silicon wafer fabrication process [51]

Further improvement in mask contamination control would suggest the need for research into new materials and understanding of the contaminations processes in the tool environment.

Contamination and erosion control of optics

As stated above while DUV lithography machines work at normal pressure the optical path of EUVL apparatus is placed in a high quality vacuum. The reason for this is twofold: high absorption of EUV in any material including gases (e.g. already at 10 mbar 30% of radiation will be lost after 2 m of optical path) and possible contamination or erosion of optical surfaces (e.g. already 1 nm of carbon deposition on each optical surface in the exposure tool will lead to an EUV loss of ~10%). In order to put it into perspective the required lifetime of the optical components in future generation EUV lithography tools is specified at 30,000 illumination hours. Solutions already provided in the tool, as well as data of the existing ASML tools at customers, show that the methods used in order to maintain a high quality vacuum have a positive effect on the lifetime of optics [52]. On the other hand because it is not feasible to perform lifetime tests of such long duration, fundamental understanding of the processes that limit the lifetime is required. Here is where applied scientific research can be fruitful for the industry.

Future of EUVL

Now I want to try and sketch some emerging challenges of EUV lithography as well as the possible next steps in its development. I will also attempt to put this in the long-term perspective of the scientific research needed to fulfill the industry needs as well as provide you with some examples of it.

The future technological advancement can be looked at from two different perspectives: the scaling of the current EUV lithography at the same wavelength of 13.5 nm and going beyond EUV (BEUV) to the next wavelength, as has happened a number of times in the development of lithography.

The technological and concurrent scientific challenges of the “conventional” 13.5 nm EUVL include:

- Technologically: higher throughput of the system by achieving more of effective EUV power from the source and on the other side of the “power duality”, maintaining resist sensitivity growth under control. Scientifically it will mean: understanding of and pushing on the physical limits of the current sources, looking for alternatives and understanding and developing new resists;
- Technologically: tighter control of mask contamination and thus scientifically: better understanding of the mask contamination processes as well as looking for new possible solutions;
- Technologically: maintain long optical lifetime at higher powers and scientifically: establish scaling laws of the very long (almost decade) optical degradation and finding solutions for it if necessary;
- Technologically: decreasing printable critical dimension by increasing numerical aperture of optics and scientifically: investigating new optical schemes and increasing quality of the multilayer optics even further

I want to provide the audience with three examples of interesting science, which can impact the future development the EUVL technology.

Example 1. Further study on contamination and erosion control of optics

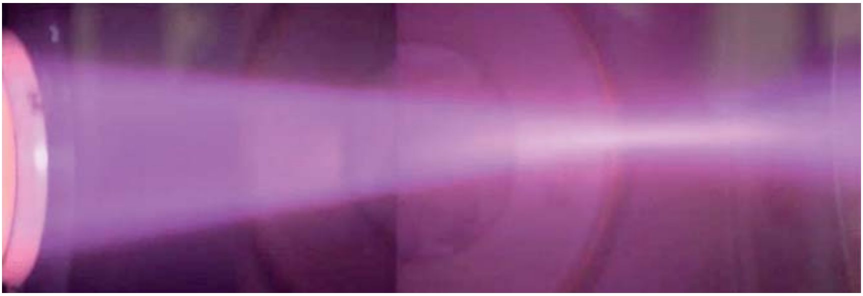

Figure 14

Plasma created in the EUV converging beam in rest Ar gas.

In 2002, while performing an alignment of the EUV optics, John de Kuster, Luc Stevens and I observed an effect as depicted in figure 14, namely a plume of light generated in the converging EUV beam in the residual argon gas, something that has been observed later in other gases as well.

By itself the plasma created under the conditions of EUVL is an interesting object of scientific study. It is created without any discharge, whether optical or electrical, under low pressure and characterized by low density and temperature on the one hand, and is visually localized on the other hand. Plasmas, produced in such a way, are not very well investigated outside EUV studies.

The existence of light by itself does not cause any significant effect onto the performance of the EUV system. The plasma created in EUV might on the other hand have an impact on the surface processes as well as processes in the bulk of the machine [53]. The effects and characteristics of plasma are described briefly in [54], where it has been demonstrated that in the long term it might have a beneficial self-cleaning effect for EUVL optics. Due to the very long lifetimes (about 7 years) required by the optics, as mentioned before, direct experiments are virtually impossible. Thus scaling laws have to be established in order to predict the impact of some subtle effects for very long exposures, hardly measurable in relatively short experiments. This study is being performed in the cooperation between ASML, prof. F. Bijkerk's group at the University of Twente, the group of prof. G. Kroesen at TU/e and a group of prof. K. Koshelev at ISAN. Another effect of EUV induced plasma on tool performance is the creation and behavior of particles in the tool, which is relevant for the study of defectivity, as mentioned above. This is now being investigated by the group of prof. G. Kroesen at TU/e .

Example 2. Further study on EUV sources

The main path for the EUV source development is LPP. High, close to theoretical, CE has already been shown in the low repetition rate systems [45-48]. Also the development of the high power CO_2 lasers proved to be an achievable target and lasers already installed in the field are operating at 22 kW [24]. The intermediate path lies along achieving stable operation in industrial installations with proven parameters or being optimized in low power laboratory experiments. In the somewhat distant future, possibly beyond this decennium, even high power requirements should be fulfilled. The sources for those power requirements could be in the modifications of existing industrial solutions with more effective lasers and target shaping or completely different types of sources. Let us consider one of those: free electron laser in a “shoe box”. While Free Electron Lasers (FEL) have been considered for EUVL application for the last 10 years [55, 56, 57] it remains both a potentially promising yet a very large and expensive machine. Recently a number of articles appeared that exploited the principles of micro-fabricated dielectric laser accelerators or laser wake field acceleration of a tabletop size, which might in the distant future substitute the lengthy accelerators [58], [59]. Alternative FEL mechanisms have also been proposed in [60] and further investigated in [61]. Though those techniques signify only the first steps, the future of those might be very exciting both scientifically and technologically.

Example 3. Beyond-EUV

Adaption of the current system to the new wavelength forms a technological and scientific challenge whereby the wavelength choice is dictated by the available reflective multilayer optics and source.

If looking at scaling beyond 7 nm node and 2020 another wavelength of around 6.7-6.8 nm can be considered [27]. Using the same formula as before for the resolution of optical lithography, one can conclude that the corresponding best achievable resolution for 6.7 nm wavelength is ~ 3 nm.
At the same time, the development of such a system meets significant challenges compared to the existing 13.5 nm, as mentioned in [27]:

- New multilayer material process with e.g. La and B pairs and larger number of pairs (~200 vs 60 for 13.5nm)
- Significantly better ($\sim\lambda^2$) polishing of the substrates to reduce stray light
- Dealing with a narrower spectral bandwidth (~0.5% vs 2% for 13.5 nm) both for high angular spread mirrors and an effective EUV radiation coupling of the source
- New “fuel” for the source management, e.g. gadolinium (Gd) or new source

In the initial experiments by IPM/Phystex a single mirror reflectivity of ~ 44% was achieved against the theoretically achievable ~ 80%. For comparison the achieved values for 13.5 nm multilayer are ~72-73%. The theoretical value for 6.x multilayers exceeds this of “13.5 nm” but the actual achieved value at that time was significantly lower. The work of multiple groups in recent years has managed to narrow this gap, see figure 15. By 2012 the reflectivity achieved in the group of prof. Fred Bijkerk of the University of Twente was ~50% [62]. Lately another significant step in this direction has been made by the same group, which exceeded the reflectivity barrier of 60% [63]. Nevertheless, further effort to bridge the gap is needed.

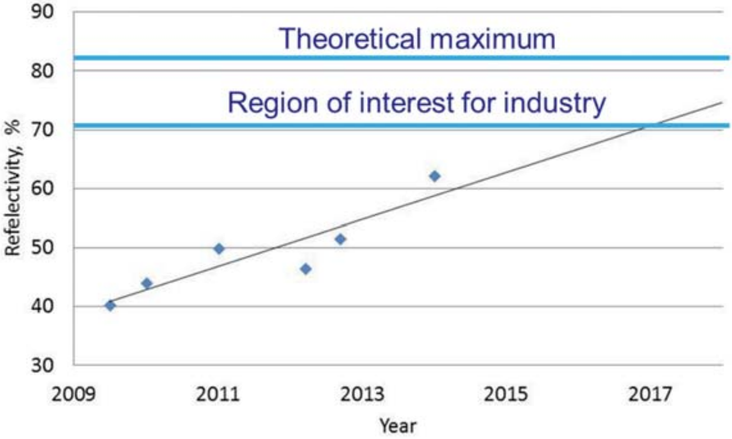

Figure 15

Achievements of reflectivity for 6.x nm ML mirror. Summary of groups of IPM/Phystex, the University of Twente and Rigaku [62, 63]

As shown in [23], the highest conversion efficiency in-band (CE) achieved for the Gd fuel for LPP by ISAN is ~1.8%. That is already a significant value but an improvement has to be made to reach the best value of CE for Sn of 5-6%, see above. Another possibility here is to use FEL techniques mentioned above. Looking at the graph of publications with respect to BEUV lithography with the uniform search in WoS for both 13.x and 6.x nm one can see that 6.x nm is at the beginning of its scientific period in comparison with 13.x nm, see figure 16. It is worthwhile mentioning that these analyses have an indicative value only, and are not scientifically accurate.

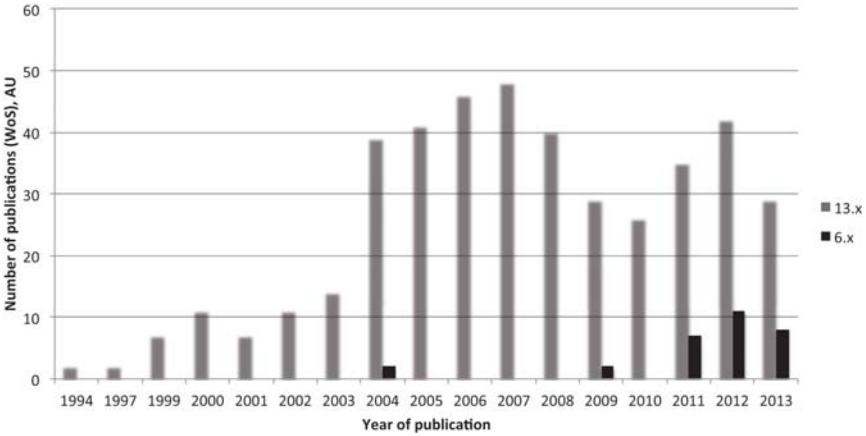

Figure 16

Relative amount of publications per year in 13.x and 6.x nm as a possibility for lithographic application

Working together: Universities and Industry

In the last 17 years working at ASML in co-operation with scientific universities and institutions I have learned a number of valuable lessons on the efficiency of research and technology project settings.

1. Research in EUV lithography requires a massive amount of investment. EUV photons are very expensive. This means that it is difficult for one university or laboratory to perform such investigation without significant backing from government and industry (e.g. EUV LLC). On the other hand there is an extensive list of successful co-operations, where different universities and institutes combine their expertise and infrastructure for EUV. Here are just a few of them:
    a. So called “Flying circus” cross-measurement of EUV sources in the early days of EUVL has been performed in close co-operation between ASML, FOM Institute of Rijnhuizen and Philips Research with the aid of Carl Zeiss LLNL and Bessy, see e.g. [64].
    b. Co-operation between ASML, TU/e and ISAN on the EUV sources, see e.g. [65]
    c. Co-operation between FOM Institute Differ, ISAN and MESA+ of the University of Twente on EUV induced plasma, [54].

2. From my point of view, the most useful research work on EUVL, which can be found at a later stage in the technological applications, occurs in close co-operation with the industry. Such co-operations are most fruitful, when a number of (PhD) students and scientists of a particular research institute or university are located (at least part time) in industry laboratories. This allows for a clear setting of the purpose of a research study, preserving the scientific value of it. Examples are:
    a. Long-term cooperation between TU/e and ASML, which has produced highly valuable work by the PhD students:
        i. E. Kieft (cum laude)
        ii. K. Gielissen
        iii. M. van der Velden
        iv. N. Lammers and currently

        v. R. van der Horst
        vi. F. van de Wettering and many others
    b. CP3E FOM IPP project between ASML, Carl Zeiss, Differ/ FOM Rijnhuizen, and ISAN as well as many years of co-operation between those groups before and after CP3E in the form of “Focus group” during which a number (6-8) of students were located at ASML’s premises.
    c. 14 year cooperation between ASML and ISAN, with frequent exchange of students and scientists.

   Again, the list of such cooperations is much more extensive than the list of examples above.

3. Every manager can lead a limited amount of projects, whether small or large, with sufficient quality (law of Benschop). Due to the fact that small projects take about the same time to manage as the large ones, it is important to find partners able solve a substantial part of the problem on their own and, if needed, with a large number of scientists and at separate locations. This usually contradicts the tendency of a scientific institute to think in terms of small (1-2 PhDs) projects, often confined to a group in a faculty, while the industry has to take care of the coherence and synergy of those multiple projects.
   Still it is not an impossible task to find such parties. An example of such successful cooperations is that between ASML, Carl Zeiss and FOM Rijnhuizen or ASML and ISAN. Also recently ARCNL, which will follow along this road, has been found.

4. Ease of cooperation, in my experience, is a threshold function of geographical distance between the cooperating parties (or, in other words the possibility to meet at very short notice). If the travel time between the parties exceeds 1 hour, the co-operation is not much easier than when it is 5 hours or more, but it is significantly easier when it is 20 minutes or less.
   This should not stand in the way of approaching remote institutes with a relevant competence. The time lag can be mitigated by regular exchange of researchers between the parties involved.

5. It is my observation that technological development in a company does not follow the same lines academic-research. Technological development relies much more on craft and not always on deep understanding of the matter. Also the best exciting scientific solution cannot always be implemented in the application due to engineering or the business limitations of a complete

system. This has to be understood and permanently calibrated by the co-operating parties. On the other hand if successful, it often brings both technological success and scientific advancement; see point 2 and 3 above. It is also worth mentioning that sometimes a scientific finding, which looks ridiculous from the common sense point of view, still find a way at a certain moment into technology if the need is high enough, e.g. [50]. Some patience is advisable from both sides in such cases.

6. The speed of development in the industry is sometimes much higher than that at a scientific institute mostly due to the amount of resources that the industry can focus on a solution of a certain prevailing problem. This is why it is advisable from the beginning for the scientific institution to select a research topic that preferably has a horizon of approximately ten years, is out of the scope of the immediate attention of industry but will contribute to its future.

I want to finish with another quote of Arthur C. Clarke (the 2nd law of AC):

“The only way of discovering the limits of the possible is to venture a little way past them into the impossible.”

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Curriculum Vitae

Prof. Vadim Banine was appointed part-time professor of Physics and Technology of EUV Lithography in the Department of Applied Physics at Eindhoven University of Technology (TU/e) on April 1, 2013.

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