New Paltz
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Department of Electrical and Computer Engineering

Semiconductor Characterization Fundamentals
EGE593

Extreme Ultraviolet Lithography
Term Paper

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Abstract

Since the development of the integrated circuit in the late 1950s and the advent of Moore's Law in the 1960s, the semiconductor industry has done everything it can to continue to pack more transistors into a single chip's area. The latest edition of this effort is that of Extreme Ultraviolet Lithography, or EUV. Through the use of EUV, the industry has made substantial gains in transistor density previously unattainable. This paper seeks to understand the industry before EUV which what led to its development, as well as how it functions, and the current state of EUV today and into the future.

Contents

The History of EUV-Lithography

Before delving into the world of Extreme Ultraviolet lithography, or EUV for short, one should familiarize themselves with the technology's predecessors and how EUV came to be. Furthermore, one should familiarize themselves with the Rayleigh criterion. In photolithography, the process used to manufacture semiconductors, there is the Rayleigh criterion which describes the minimum feature size obtained from the wavelength used, shown in Figure 1.

$$CD = k\frac{\lambda}{NA}$$

Figure 1. Rayleigh Criterion [1]

As seen in Figure 1, the critical dimension, *CD*, is the minimum feature size obtained. Within the criterion, *k* is a constant denoting post-process factors, *NA* is the numerical aperture of the lens for the light to pass through, and λ is the wavelength. Therefore, one can see how if all post process factors within the criterion cannot be changed, lowering the wavelength or aperture are the only ways to reduce the feature size.

Pre-EUV Semiconductor Fabrication: UHVML

From the inception of semiconductor manufacturing until the mid to late 1990s, the primary method of manufacturing was via light emitted from an ultra-high voltage mercury vapor lamp (UHVML). The voltage and composition of the lamp would be varied to produce different wavelengths of light [2]. Once the correct wavelength was emitted, through a lithographic process involving photoresist and optical masks, the semiconductors would be fabricated. Throughout the years, there were many iterations of this process, each with a different wavelength generated by such a lamp.

G-Line

Until the mid-1980s, the primary wavelength used to manufacture semiconductors was that of the "G-line," at 436nm. Through use of the G-line, manufacturers were able to generate features in the silicon wafers of as small as 1µm. The G-line gave way to the use of the I-line [2].

H-Line

Although H-line wavelengths of 405nm would be next after the G-line, the semiconductor industry instead decided to skip it in favor for the I-Line. It is difficult to find sources attesting to why the industry chose to not develop the H-line, so let us move to the I-line.

I-Line

From the mid-1980s until approximately 2000, manufacturers favored the wavelength of the "I-line," at 365nm. Using the I-line, they were able to generate features down to 0.25µm [2].

Following the ever-increasing need for decreased feature size governed by Moore's Law, the industry desire to double transistor count every two years, the G- and I-lines were soon found to no longer be capable of the feature sizes needed. Therefore, the industry switched from the mercury lamp of old, to the excimer laser of new.

Pre-EUV Semiconductor Fabrication: DUV

Following the inability of the UHVML to keep up with the expectation of Moore's Law, the excimer laser was deployed in the industry around 2000. An excimer laser is a type of laser light emitted by the combination and excitation of a noble gas with a reactive gas [3]. The wavelength of the laser can be adjusted by changing which gases are present. Typically emitting ultraviolet light at the far end of the spectrum, called deep ultraviolet (DUV), the excimer laser was the perfect candidate to further reduce the wavelength used for fabrication.

DUV: Wavelengths and Feature Sizes

Following the implementation of the excimer laser into the industry, several iterations using very different gas combinations have been used. Figure 2 shows a table of the most popular excimer laser configurations and their respective wavelengths.

Type	Wavelength
KrF	248nm
ArF	193nm
F_2	157nm
Ar_2	126nm

Figure 2. Excimer Laser Wavelengths

As seen in Figure 2, using the excimer laser the industry was able to bring their wavelength used down to 126nm. Using the standard lithographic process, the minimum feature size obtained with DUV was approximately 80nm. To keep up with Moore's Law however, something needed to be done to further reduce the transistor count. Therefore, the industry developed immersion lithography.

DUV: Immersion Lithography

In standard lithography, there is an air gap between the emission point of the laser and the wafer itself. By filling the air gap with something of a higher index of refraction, say water, then we can obtain a larger numerical aperture [4]. Figure 3 shows the equation for determining the numerical aperture and Figure 4 shows an example of immersion lithography.

$$NA = nsin\theta$$

Figure 3. Numerical Aperture Equation

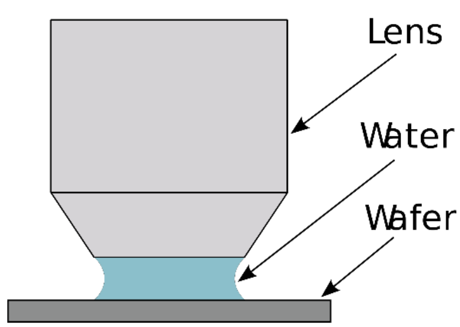

Figure 4. Immersion Lithography

As seen in Figure 3, the numerical aperture is determined by the index of refraction, *n*, and the maximal half angle of light entering/exiting the lens, θ [5]. Therefore, when the air gap is filled with water as shown in Figure 4, the feature size is decreased, since water has an *n=1.44* in respect to air *n=1.00* [5]. Throughout the refinement of DUV technology, the industry was able to reduce the maximum feature size down to 80nm. However, Moore's Law begged for more.

Theory and Development of EUV

Given the increasing demand for a reduction in size, the industry needed an even smaller wavelength than the excimer lasers were able to produce, enter EUV. First proposed in the 1980s, the technology laid dormant until its revival in the mid-2000s when DUV was approaching its limit for feature size. But what makes EUV so special? The technology behind EUV is vastly different than any of its predecessors and we will discuss those differences.

EUV Generation

The first major difference with EUV is how the light is generated in the first place. Figure 5 shows the electromagnetic spectrum with some relevant details.

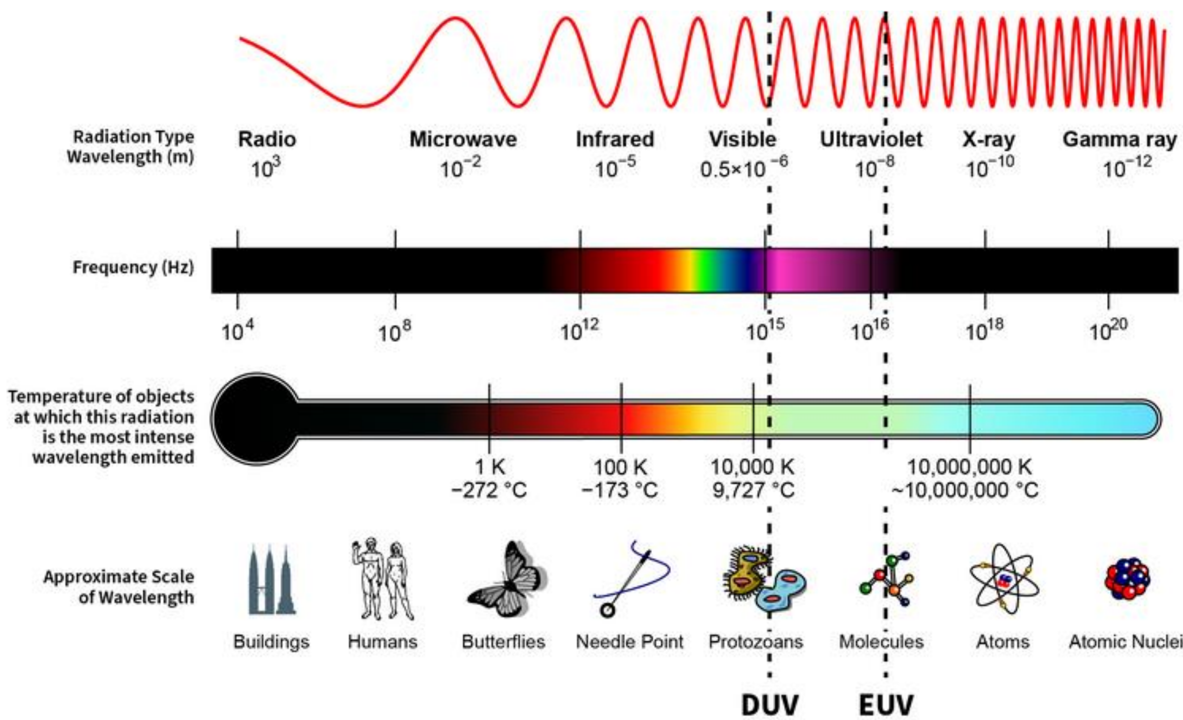

Figure 5. Electromagnetic Spectrum

As seen in Figure 5, the wavelength of EUV, residing at 13.5nm, is at the extreme end of the ultraviolet segment of the spectrum. Furthermore, to generate such wavelengths, objects need to be heated to extreme temperatures in the millions of Kelvins. To achieve this, EUV uses superheated Tin (Sn) plasma. Within the EUV machines, a tiny 0.25µm droplet of liquid Sn is hit by a high powered (20-60kW) laser multiple times. The first shot expands the droplet into a disc-like shape whilst removing 20 electrons from its valence shell. Following this expansion, a second shot is used to excite the now Sn20+ charged ions to a superheated state where it emits light at the 13.5nm wavelength [6]. Figure 6 shows a 3D model of such expansion while Figure 7 shows an experimental expansion and excitation resulting in emission.

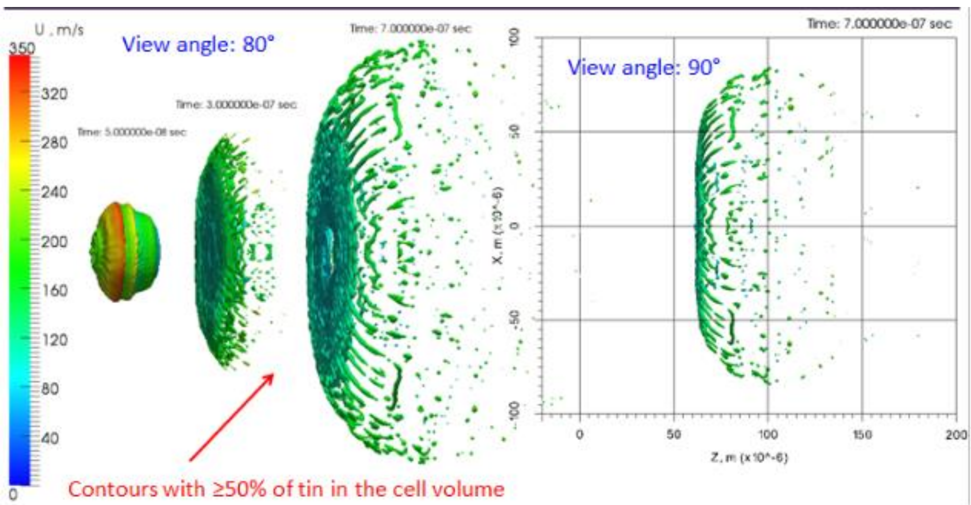

Figure 6. 3D Model of Sn Expansion

Figure 7. Expansion and Excitation

As seen in Figure 6, the Sn is expanded from its droplet into a disc. Furthermore, Figure 7 shows that disc being excited by the laser and resulting in the emission of EUV light. The EUV emitted is then collected and focused using mirrors.

Optical vs Reflective

Unlike previous technologies, EUV cannot use optics to focus the light into a concentrated area due to the materials used for said optics having a high absorption rate of EUV [6]. Therefore, a concave mirror is used to collect and focus the emitted light into a narrow field which is then sent forward through the process. Figure 8 shows an example of the EUV generation and focusing.

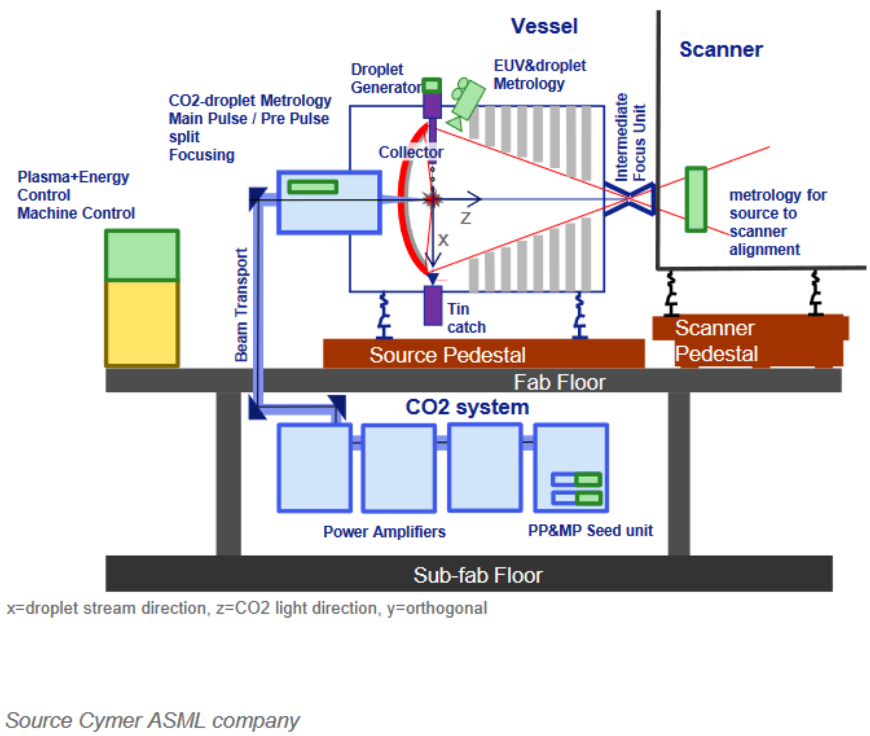

Figure 8. EUV Generation

As seen in Figure 8, the droplets of Sn are shot with the high-powered laser and the emitted light collected by a “collector” mirror which is then focused before entering the remainder of the fabrication machine.

Blanks

Unlike the photomasks of old, which had the designs printed onto a mask which blocked the light from printing onto the wafer, EUV technology relies on the absorption or reflection of the light to imprint onto the wafer. Therefore, EUV uses what are called blanks. A blank is a complex stack of multiple elements and can be seen in Figures 9 and 10.

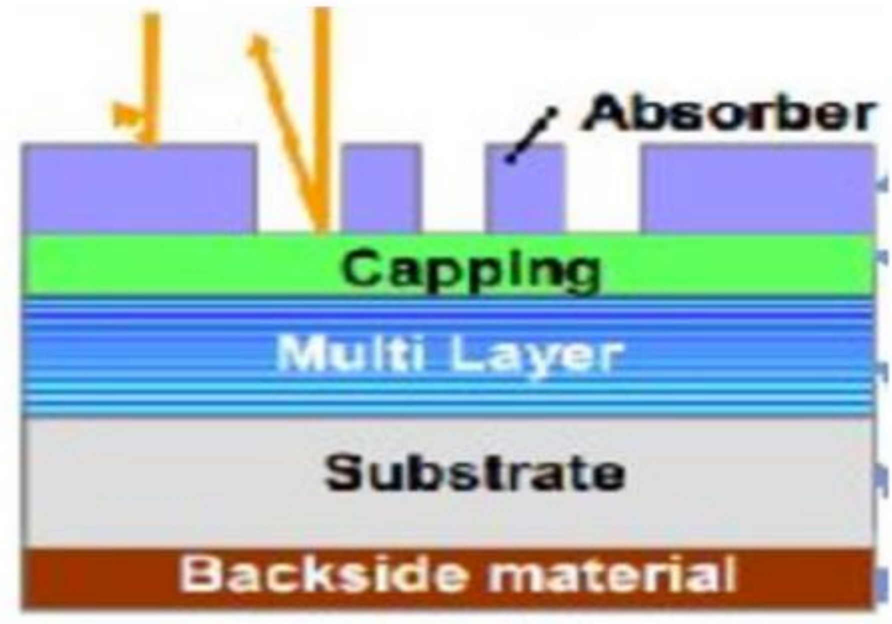

Figure 9. EUV Blank

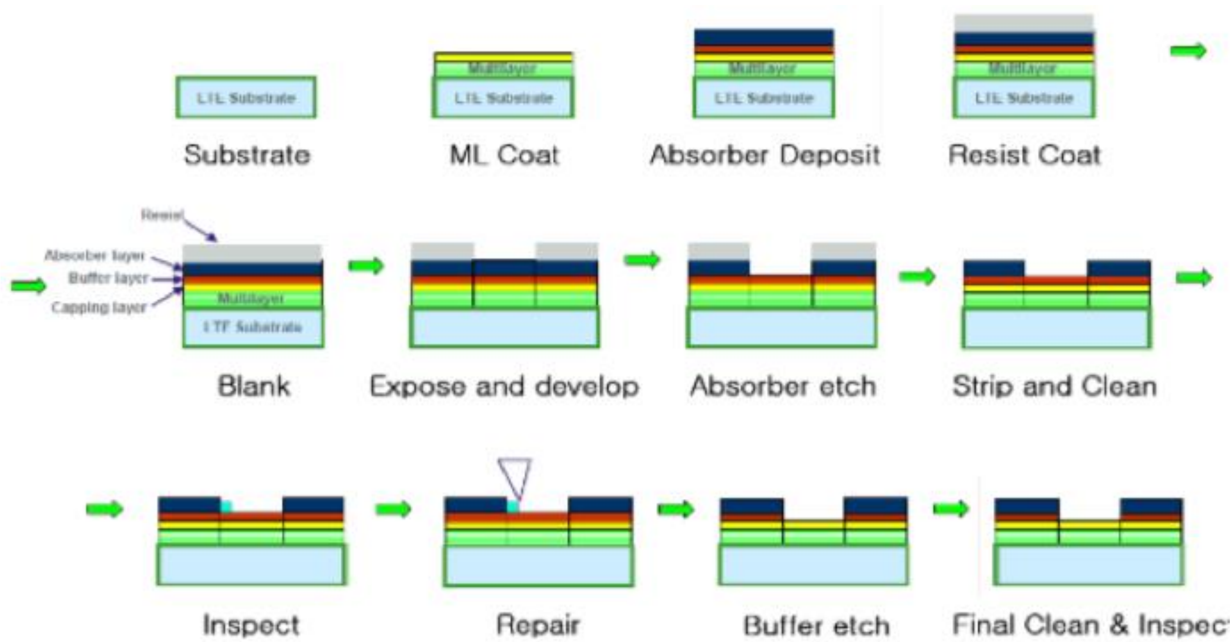

Figure 10. EUV Blank Creation

As seen in Figures 9 and 10, the blanks are comprised of five layers. The first layer is a low thermal expansion substrate used as a backing material. Next, silicon is deposited on top of the backing. Then, between forty to fifty layers of silicon and molybdenum are alternated above. After the multilayer, there is a buffer layer of silicon deposited on top. Following the completion of the main layers, a ruthenium capping layer, which reflects EUV, is deposited followed by a final absorber layer, which absorbs EUV, of tantalum [7]. Since there is so much involved in the creation of the blanks, they are very expensive. Industry grade blanks can fetch north of $100,000 a piece while research grade ones are around $10,000. The major difference between the two is quality. Industry grade blanks have defects on the order of single atoms, while research grade have many hundreds of defects. Now that we understand what the blank is and how it is created, how is it used?

Fabrication

Once the blank has been created and etched according to the design specifications, it is loaded into the fabricator. Figure 11 shows an example of the design scheme of an EUV fabricator.

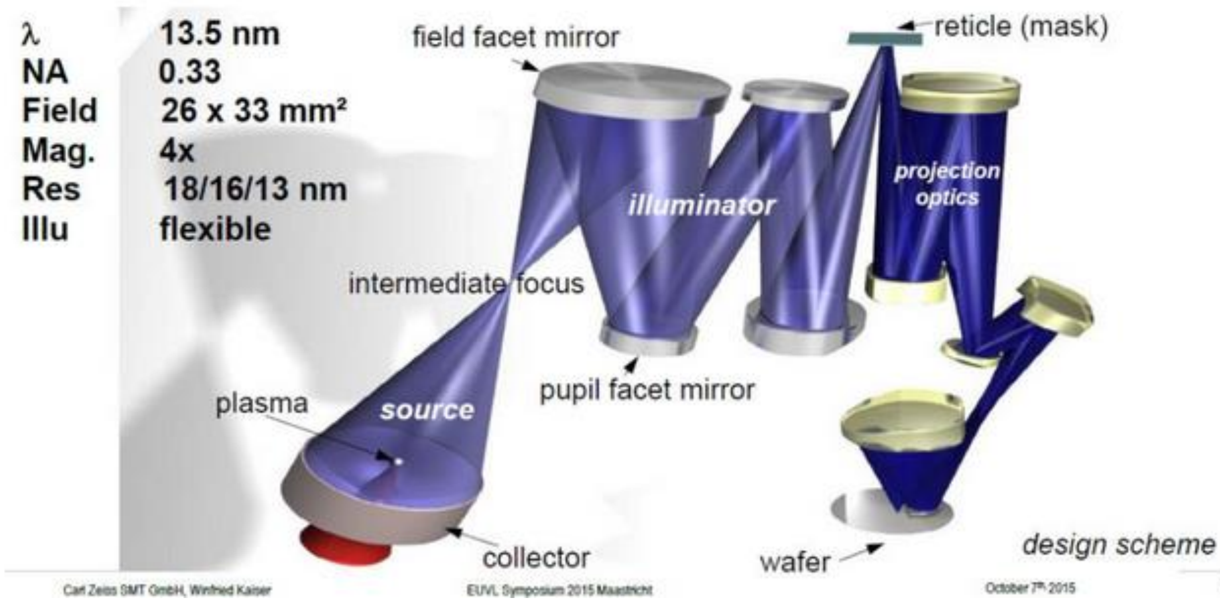

Figure 11. Fabricator Design Scheme

As seen in Figure 11, the EUV is generated by the plasma and focused by the collector. From there, the light is reflected into the blank (also called mask or reticle), and what is not absorbed (the design to be printed) is then reflected down onto the wafer surface. Although an extremely convoluted way of going from generation to wafer, the EUV fabricator has tremendous benefits compared to the older technologies.

Today's EUV

Now that we have explained how the EUV fabrication process operates, what are the advantages to this complex technology?

Benefits

Chief among the benefits to EUV lithography is that the first operational machines made by ASML (Advanced Semiconductor Materials Lithography), currently the sole manufacturer, were used by Samsung in 2020 for the fabrication of the 7nm node. Therefore, the industry was able to keep up with the expectations set by Moore's Law. Furthermore, 7nm is just the beginning of EUV use. If we compare the longevity of previous fabrication technologies and how they were adjusted for ever decreasing feature sizes, one could expect the same for EUV. In fact, TSMC

(Taiwan Semiconductor Manufacturing Company) and Intel plan on using EUV for the upcoming 5nm and beyond [6,8]. However, EUV is not without its limitations.

Limitations

Since the process used to generate EUV is comprised of essentially obliterating droplets of tin extreme temperatures, there are limitations. The first issue is that the collector mirror builds up a thin layer of debris from the tin obliterations, thus resulting in lowered efficiency and EUV output. Another issue is that the fabricators require time to cool components after being run for hours on end. Therefore, ASML recommends about seven hours downtime every two weeks [9]. If we use the current ASML specifications of 70-90 wafers per hour fabrication rate, this downtime results in a loss of 490-630 wafers every two weeks [9]. Additionally, the least expensive machine from ASML currently costs around $150 million. Therefore, it is understandable that smaller fabrication companies are hesitant to adopt the EUV technology until the downtime and cost can be improved.

The Future of EUV

Since EUV is such a new technology in the fabrication industry, there are many issues that need to be improved, such as cost and machine downtime, and ASML is currently working on these. Once these issues are resolved or improved, it is reasonable to think that EUV will have a more widespread footprint in the industry. Furthermore, although EUV helps conform to Moore’s Law, eventually it too will hit its minimum for feature size. Therefore, the next technology called Beyond EUV (BEUV) is already in the earliest stages of development.

Conclusions

Throughout the lifetime of the semiconductor fabrication industry, various methods have been used to continually decrease the feature size for the next technology node. These range from the original UHVMLs, to the DUV of excimer lasers, and to the latest EUV lithography. By having a firm understanding of the EUV technology, we are poised to understand the next great leap in semiconductor fabrication.

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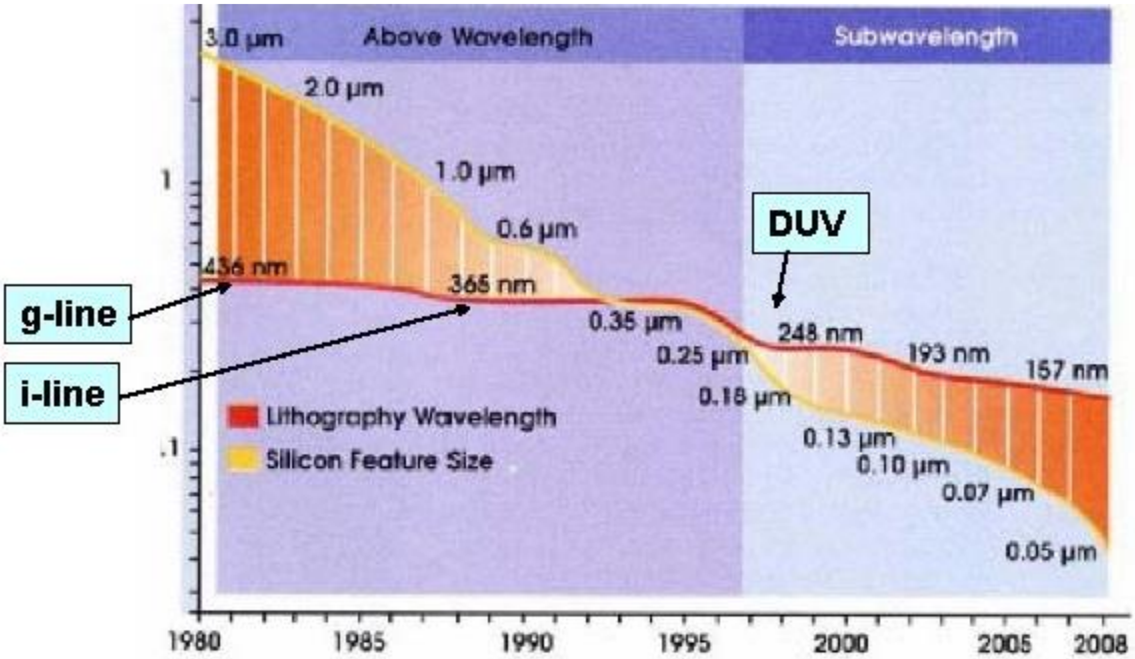
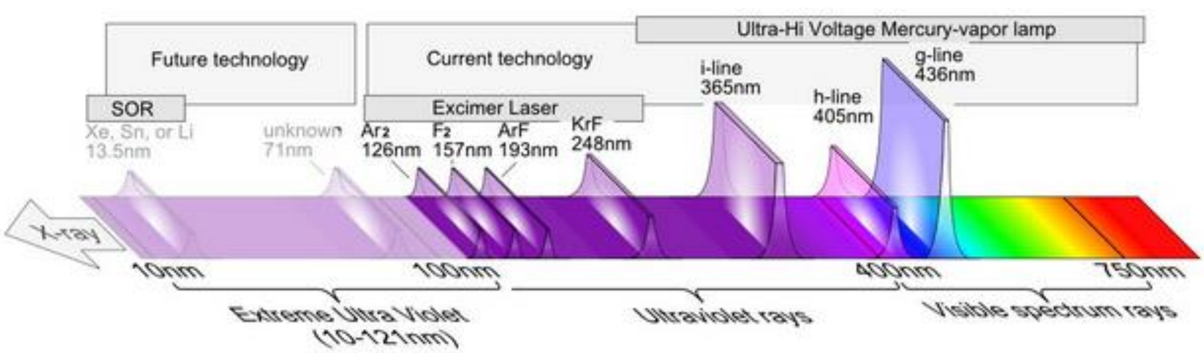
Appendix

Here you will find graphs and figures otherwise not used in the paper but are a good reference.



Appendix 1. Lithography Technology Timeline



Appendix 2. Wavelengths and Technology Type