Extreme Ultraviolet Lithography (EUV)

By

Group 3

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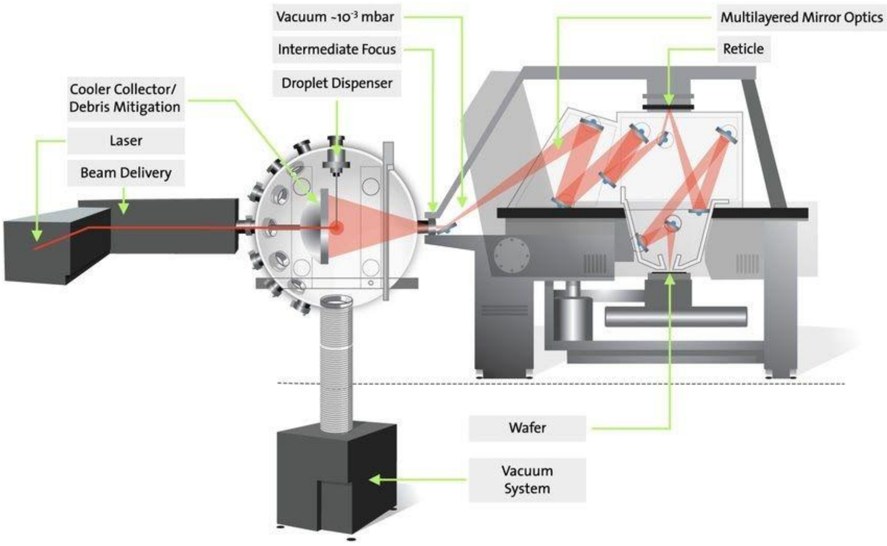
A Brief Introduction

For our report on a modern technological development, we decided to cover the innovation that is Extreme Ultraviolet Lithography (which from here on will be referred to as EUV). It is arguably the most complex and intricate piece of machinery we have seen so far in integrated chip technology. We have chosen EUV as it is an ingenious piece of technology that has postponed the supposed deadline of Moore's Law by what could hopefully be many years. This report seeks to explore numerous aspects of EUV, from its conception in 1986, the theory behind its operation, and the history of its development all the way up to its recent implementation in modern society. Lastly, we will discuss what this groundbreaking innovation will mean for the future of our technology.

What is EUV?

Extreme Ultraviolet Lithography is a process in chip production based on photolithography and is currently employed by Dutch company ASML, one of the leading semiconductor suppliers in the industry. ASML and their tools are essential to producing the chips for massive companies such as Intel and Samsung. On ASML's webpage there is a link to a video they made in collaboration with YouTube channel Seeker, a channel dedicated to keeping viewers informed and up to date with the latest science and technology news. The video in question explains what exactly EUV is, highlights the process that the EUV tool executes when ingraining a pattern on a silicon wafer, and features interviews with experts from ASML and Intel on EUV and the theory surrounding it. This video will serve as a basis and a reference for the majority of the information documented in this report.

The process EUV entails is complex but very clever. A mask, which can be thought of as a blueprint, is etched into the surface of a silicon wafer using light. The light source used is produced when a miniscule droplet of tin, that is fired across the vessel and is intercepted by not one, but two high power pulse laser beams that are created from gas compounds such as carbon dioxide or argon fluoride. For a long time, ASML found that they were not meeting anywhere near the required power for the machine to work with just one pulse laser beam. That was until 2015, when they discovered that they could time it precisely so that a second pulse laser beam could intercept the previously excited tin droplet to give it the boost in power it needed to form the plasma that emits the EUV light. The plasma produced will then be bounced off several mirrors and the mask, and then targeted at the wafer. You can see an illustration of the process in the diagram on the next page. Just imagining the intricacy of this system that allows it to be so accurate enables us to visualize how complex this system truly is.



Source : https://www.researchgate.net/figure/Schematic-of-a-laser-produced-plasma-EUV-scanner_fig1_244994879

The objective of pursuing innovations like EUV is to shorten the wavelength of the light towards the right of the electromagnetic spectrum pictured below, as the shorter the wavelength, the finer the imprints created will become. Finer imprints allow for more compact semiconductor chip designs in accordance with Moore's Law, as more transistors can be crammed onto the chip. Over the years, the wavelength has been cut from 365nm, to 248nm, to 193nm. Previously an attempt was made at 157nm, but it failed, costing the industry dearly and progress stagnated. Now, with the implementation of EUV we have hit wavelengths as short as 13.5nm. That is almost 15 times shorter!

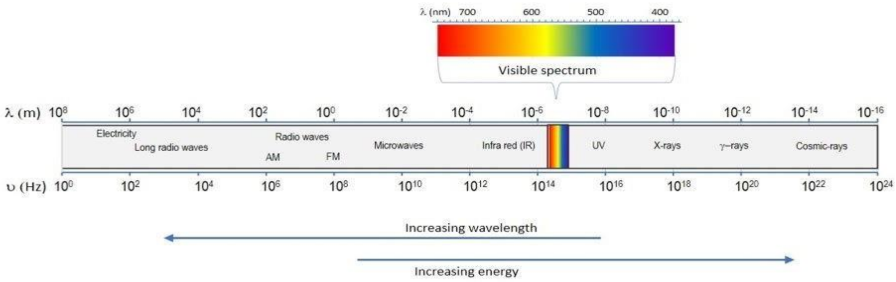


Image courtesy of https://www.engineeringtoolbox.com/electromagnetic-spectrum-d_1929.html

The Physics Behind EUV

The key theory behind the operation of EUV lies in the physics of waves. Waves have the simple function of transporting energy. There are many different types of waves but in relation to EUV we are only concerned with one type of wave: Electromagnetic waves. The light that allows you to read this is an electromagnetic wave. Other examples would include radio waves, the waves in your microwave, and x-rays. Two of the key properties of these waves that are utilized by EUV are their ability to reflect off surfaces and refract. I already mentioned how the reflection works. The EUV light reflects off several mirrors and the photomask before finally etching the contents of the mask onto the silicon wafer. The light travels in straight lines, as such it is necessary to direct the light using mirrors so that it can be targeted at the wafer

Before EUV, Argon Fluoride (ArF) gas was used to produce the light used in lithography. ArF produced a wavelength of about 193nm. In Physics, it is known that the wavelength of an electromagnetic wave is proportional to its frequency. (Wavelength = (Speed of light/frequency)). What this means is that as the frequency of the wave increases, the wavelength will decrease as a consequence. That poses the question “How do we increase the frequency?” and the answer to that is that we need more energy. This is illuminated by the relationship between energy and frequency of an electromagnetic wave. (Frequency = (Energy / Planck’s constant))

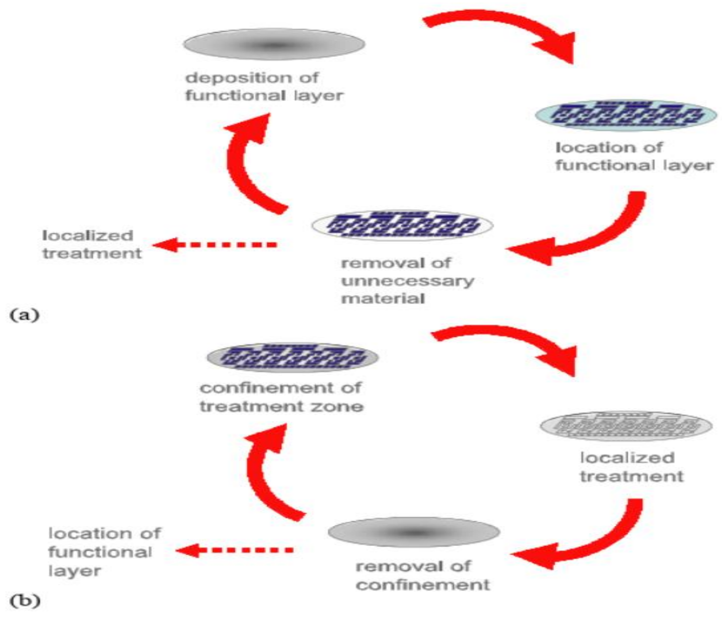
Knowing that, we can now deduce that to shorten the wavelength of the light used in lithography, we need to supply more energy. In other words, we need more power. This deduction is evidenced by the EUV machine’s massive Megawatt power consumption. A large percentage of that power is dedicated to the numerous components inside the EUV tool.

According to Gigaphoton, Sematech Symposium Japan, 532 Kilowatts of that power consumption is expended by producing the high energy lasers that are used to create the EUV emitting plasma. This is more than 10 times the power consumption of the 49-Kilowatt ArF lasers used prior. As such, we can understand how we managed to achieve a new wavelength that is almost 15 times shorter than the previous shortest wavelength

The history of EUV

EUV (Extreme Ultraviolet Lithography) is a branch of Lithography which was first invented around 1796 by a Bavarian playwright Alois Senefelder in Germany who found he could duplicate the scripts he wrote by writing on them in greasy crayon on limestone and then printing them in ink [1]. This concept developed overtime from the reproduction of texts to the reproduction of pictures. A major challenge to this method was the issue of faithfully reproducing halftones (the process of using many dots of different shapes and sizes to produce a gradient like effect to create images). This issue was solved in 1884 by Meisenbach who invented the linear screen which was used to smoothen the granular nature of photosensitive emulsions (liquids that don't mix, coming from the Latin word "To milk" with milk being an emulsion of fat and water) and so produce a clearer, more high quality image[1]. The images these screens produce are actually optical illusions. Due to improvements in this technique, it is actually impossible for the human eye to see the dots used by the printing screens to produce the image making the printing and copying of images a reality.

Lithography has survived the test of time, going beyond its old domains of printed texts and macro imagery (close up, detailed images) and jumping into the 20th century where in 1958 American Jack Kilby invented the very first printed circuit[1], one of the main sources of the production of the electronic chips we see in all out personal computers, tablets etc in the world of today. With Moore's law at the heart of this success pushing chip producers to double the density of the chips they produce with the process of Lithography being used to great effect in this area, with Optical lithography being the most used production choice currently. This process involves depositing a polymer layer of photosensitive resist onto a wafer and then exposed to wavelengths of a light source. This resist is then removed from the wafer at the conclusion of the process[1]. This process is repeated several times in a cycle as you can see from the below image.



A process of lithography in chip production by either removing non-functional material (Subtractive, A) or by forcing local treatment of the wafer where needed (Additive, B).
(Lithography main techniques, edited by Stefan Landis, page xix, Figure 1.1)

Major Improvements were made to decrease the exposure wavelength all the way back in the 1980's where tools started using different forms of radiation from a mercury lamp from 436nm to 405nm and then to 365nm. However, the first real transition came in the 1990's with the switch from mercury lamps to deep ultraviolet lasers starting with 248nm with a KrF laser (Krypton fluoride laser) and then 193 with an Arf laser (Argon fluoride laser)[1]. There was great investment into the reduction of this wavelength by many big named companies such as Sony and Intel. The next big attempt was to reduce the size down to 157nm with F2 lasers[1]. However there were several issues with this laser such as its bi-refringence which means the light passing through the lasers optics was being disrupted, changing its state reducing the quality of the image[1]. This ended up being a major failure. Seemingly disproving Moore's law, ending the efficiency streak and costing the industry millions.

Which brings us back to the modern era and onto EUV (Extreme Ultraviolet Lithography). EUV (or EUVL) was first proposed back in the 1980's as the next bold step in chip manufacturing[3], one which would change the lights wavelength of the currently established 248nm and 193nm all the way down to 13.5nm wavelength (being almost as small as x-rays [3]) . These reductions would save so much space on chips and allow for much more transistors to be fitted onto chips allowing for them to be faster, smaller yet cheaper (due to the reduction in materials required) with them nowadays being 22nm, 14nm or even 10nm in size[3]. Even more impressively, the development of this technology could kickstart Moore's law again which was long since considered invalid.

It has seen very intensive development worldwide, being strongly developed from 1997 in the United States and then through European and Japanese development programmes with prototypes emerging in 2006 by the company ASML located in the Netherlands[2]. However despite the effort, progress and success that has been had with EUV over the last 10 to 20 years, the technologies of today are holding back progress including issues such as a powerful enough power source required to run the EUV scanner in an efficient and cost worthy manner as well as the inability of industry facilities to produce flawless mask's to use for printing. The research into these issues has costed several billions worth of US Dollars. As can be seen from the below table EUV is very much a new process with many more variables to account for compared to the current 193nm and 248nm optical lithography used by current KrF and ArF lasers of today[1].

Sub-systems	**193 nm and 248 nm optical lithography**	**EUV lithography**
Source	Monochromatic source: KrF (248 nm) or ArF (193 nm) laser	Non-directional plasma source emitting in a large spectral range. Collector: sub-system to collect a part of the radiation of a spatially-emitted source. Residue control: sub-system specific to the plasma sources and necessary in order to minimize light collector contamination.
Projection optics	Optical system mainly constituted of transmission lenses.	Optical system mainly constituted of mirrors made from interferential multilayer deposition.
Mask	Transmission mask, made with a silica substrate. Protection film to avoid particle contamination.	Reflection mask, made of a very low expansion coefficient substrate. No technical solution for the mask's protection.
Environment	Controlled atmosphere	Tool under vacuum at around 10^{-9} mbar

(Lithography main techniques, edited by Stefan Landis, page 43, table 2.1)

The Complexity of Lithography and specifically EUV has led to a significant cost increase from $50 million currently likely increasing to $100 million with the scanners and environments needed for EUV. However additional research is being undergone to move away from the current optical lithography to help reduce the costs of these devices such as the e beam created back in 1952 by DR. H.C. Karl-Heinz Steigerwald which has major advantages such as not requiring a mask, eliminating one of the current technical issues with EUV and also not being limited by wavelength or depth of field. However, there are disadvantages to this technology, the main one being that it can only print sequentially (pixel after pixel) which completely ruins any form of efficient productivity. However, it is still being considered of using many independently controlled beams (up to the tens of thousands) at the same time, leading to a major increase in productivity[1].

References

Lithography main techniques, Edited by Stefan Landis (Gluckman library) = 1

THE VIEWPOINT by Banqiu Wu & Ajay Kumar Extreme Ultraviolet Lithography: Towards the Next Generation of Integrated Circuits, "Extreme Ultraviolet Lithography: Towards the Next Generation of Integrated Circuits" = 2

ASML Webpage, the only provider of EUV equipment, https://www.asml.com/en/ = 3

Why Is EUV Important?

Thirty years of innovation in physics, chemistry and material science have led us to the periphery of a future where Extreme ultraviolet Lithography is feasible. The continued production of IOT devices, as well as the exponential growth of AI and autonomous driving technologies mean we must constantly strive for chips that are smaller, lighter, cheaper and have lower power consumption. The integrated circuit of the 20th century was arguably the spur that incited a technological revolution. Thus, it is justifiable to question where the next generation of integrated circuits will steer us and why they are important to the evolution of technology, other industries, and the global economy.

Direct Reasons

For the semiconductor industry EUV is Moore's laws savior, preventing it from having to spend billions on research in other means of creating smaller and more efficient integrated circuits. Additionally, since 1965 Moore's law has been a motivating force that has stimulated the cutting-edge innovation that we have experienced in the past 55 years.

Arguably, the biggest impact of EUV will be on the semiconductor industry. [1] Samsung was the first to claim it will produce chips for customers using EUV tools and in [2]2018 they announced that they finalized their process for EUV and that the international version of the Galaxy Note 10 launched with the Exynos 9825 processor which is Samsung's first product partially made with EUV. But GlobalFoundries, Taiwan semiconductor manufacturing Company and Intel were not far behind. [3] According to a report done by MarketsAndMarkets "The EUV lithography market (EUVL) is expected to increase from USD 1.24 billion in 2017 to USD 10.31 billion by 2023". Extreme Ultraviolet Lithography's reason for being so prominent in the semiconductor industry today is because it uses 13.5-nm light. With it, manufacturers can substantially reduce the number of lithography steps. [4] For example GlobalFoundries will replace 15 steps with just 5 for its 7-nm EUV process. This makes the work at 7nm considerably faster and cheaper. [5] Extreme Ultraviolet Lithography enables the use of only one mask exposure instead of multiexposure. [6]

Extreme Ultraviolet Lithography is important as it has more advantages over other optical lithography's. For one it is said to achieve more depth of focus and linearity for dense and isolated lines when compared to its counterparts. Additionally, the superior critical dimension control and image placement have been obtained as a result of the low thermal expansion substrates. It has also been shown that the existing DUV resists can be extended for use with Extreme Ultraviolet Lithography.

Indirect Reasons

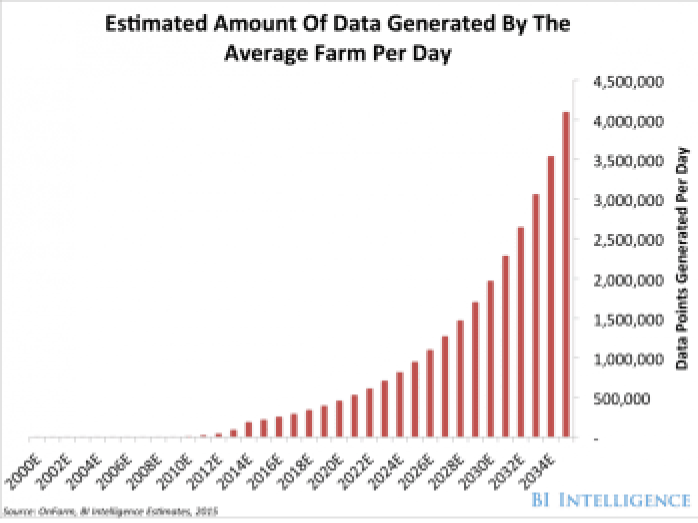
The technology industry has a major impact on many sectors. Therefore, it is certain that Extreme Ultraviolet lithography will play an influential role in the innovation of other sectors. The health care industry is one sector that will benefit from improvements in technology and therefore extreme ultraviolet lithography. According to Technavio, “The global digital healthcare market is poised to grow by USD 207.34 billion during 2020-2024”.

(Source: technavio.com – report - Digital Health Market by Application and Geography - Forecast and Analysis 2020-2024)

Other areas that are likely to benefit from more advanced integrated circuits and therefore Extreme Ultraviolet Lithography are sectors partaking in research that handles a large amount of data. [7] For example the next generation of particle accelerators are expected to generate trillions of events every second. Currently we do not have adequate equipment to make sense of that amount of data. We therefore need faster computers with larger data storage. Neither of which are possible without more advanced integrated circuits.

The global agriculture tech market is another sector primed for growth in the coming years. According to a BIS Research market intelligence report [8] the agriculture technology market is expected to generate 2.49 billion USD in revenue by 2024. The introduction of smart technologies into the farming workplace has been driven by the need for increased global food production. This demand for greater food production is expected to continually rise and thus a greater demand for more effective and efficient farming technology is likely to ensue. Similar to how a greater demand for medical technology will require more efficient integrated circuits, the farming sector will also require similar criteria. Therefore, Extreme Ultraviolet Lithography is vital to the advancement of our sectors as well as the expansion of our economy.

As well as there being faster, cheaper, and more efficient technology in the coming years there is expected to be an overall increase in the number of technological devices ergo an increase in the quantity of data generated by devices. Yet again, there is a need for a better generation of integrated circuits to handle these larger quantities of data. These more advanced circuits will most definitely require Extreme Ultraviolet Lithography to be manufactured.



(Source: BI Intelligence Estimated Amount of Data Generated by The Average Farm Per Day)

According to Energias Market Research "The Global Extreme Ultraviolet Lithography (EUVL) Market is expected to grow from USD 759.8 Million in 2017 to USD 1,453.06 Million in 2024 at a CAGR of 9.7% during the forecast period from 2018 to 2024". [9] The driving force behind this growth is expected to be the increasing demand for compact integrated circuits. More specifically, industries such as electronics and automotive are likely to claim great benefit from more compact and faster integrated circuits. This brings about another reason why Extreme Ultraviolet Lithography is important. Extreme Ultraviolet Lithography will create numerous jobs as a result of the industry growth in the coming years. This will also have beneficial implications for the global economy.

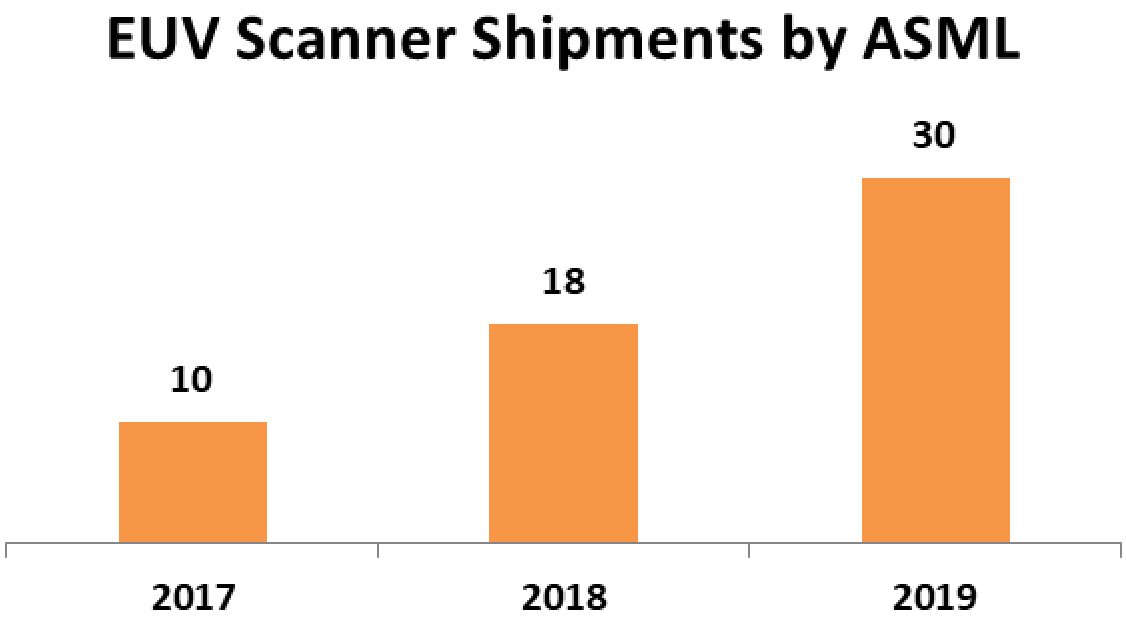
References

[1] ` EUV Lithography Finally Ready for Chip Manufacturing by Samuel K. Moore
[2] EUV: Lasers, plasma, and the sci-fi tech that will make chips faster by Engadget
[3] EUV Lithography Market (EUVL) by End User (Integrated Device Manufacturer (IDM) and Foundry Companies), Equipment (Qualitative), and Geography (The Americas and Asia Pacific) - Global Trend and Forecast to 2023 by MarketsAndMarkets
[4] EUV Lithography Finally Ready for Chip Manufacturing by Samuel K. Moore
[5] CMOS Past, Present and Future, 1st Edition. Authors: Henry Radamson Eddy Simoen Jun Luo Chao Zhao
[6] EUV lithography update, from oemagazine June 2002, by Charles Gwyn
[7] The Extreme Physics Pushing Moore's Law to the Next Level by Seeker
[8] Global Agriculture Technology-as-a-Service Market: Focus on Service Type (Software-as-a-Service, Equipment-as-a-Service), Technology (Data Analytics, Guidance, Sensing, Variable Rate), Application (Yield Mapping, Soil Management, Crop Health), Pricing Models, Break-Even Analysis – Analysis and Forecast, 2019-2024 by BIS Research
[9] Energias Market Research - Global Extreme Ultraviolet Lithography (EUVL) Market to Witness a CAGR of 9.7% During 2018 to 2024: Energias Market Research

The Future of EUV Technology

One of the great achievements of EUV is the revival of Moore's Law which kickstarts an exciting period for future technologies, Moore's law isn't the same as any other law as it's an observation made by Gordon Moore in 1965 and it states that, every two years the number of transistors on a chip doubles, which in simple terms means that the processing power of affordable computers will double every two years. Over the years Moore's Law gradually started to come to end, as scientists and engineers were no longer able to double the number of transistors on a chip every two years. However, with the development of EUV/EUVL, Moore's law still holds true. As the development of EUV continues it expected that, it will transform the production of semiconductors. The semiconductor industry as a whole is beginning to invest in EUV as it looks to transition high end technology production from 193Nm to EUV. In the next few years, the lithography market is expected to grow from USD 2.98 billion in 2018 to USD 10.31 billion by the end of 2020, at a CAGR (Compound Annual Growth Rate) of 28.16% [1].

The future for EUV seems to be bright with great investments from tech giants such as well-known Intel, Samsung, and many other huge firms. Intel on its own has committed over USD 4.1 billion with ASML, TSMC (Taiwanese Semiconductor Manufacturing Company) has invested another USD 1.4 billion while Samsung handed over USD 970 million. EUV is being funded by eleven different firm this includes Samsung, Intel, ASML, Toshiba and many more [2]. Thanks to these investments we are starting to see the first benefits from using this type of lithography, which is helping improve our current technology by making new products cheaper with the same capabilities and new more speedier components, for example in 2020 Samsung has reached a milestone in memory used for PC's, the Korean firm has released the first 10nm DDR4 DRAM which is based on EUV. Using this next-gen lithography technique will help RAM producers get past many barriers, which will allow for greater performance, decrease time of production and better yields which means that there will be a smaller amount of defective chips being manufactured. Also the tech giant is planning on starting the production of super-fast DDR5 RAM in 2021, which thanks to EUV will help bring computer memory to a completely new level when it comes to speed and efficiency, DDR5 RAM is being advertised to be 2x times faster than its predecessor which should be a major boost in performance. At the start of 2020 Samsung has also announced that the mass production of both 6nm and 7nm circuits will begin in Hwaseong, South Korea. TSMC is also predicted to begin the mass production of 7nm chips using EUVL and a new 5nm node technology is expected by 2021, these developments make TSMC the largest customer for ASML's EUV scanner [3]. We are also seeing production facilities which are based on EUVL and are being built by companies such as Intel, Hynix, and other tech giants. Intel will need EUV tools as it expands its fabs in Oregon, Israel, and Ireland. Besides, the chipmaker will need EUV scanners to equip its Fab 42 in Arizona. These factories will be used to produce chips using Intel's 7 nm fabrication process. SK Hynix will need EUV tools for its new fab near Icheon, South Korea [5].



The above image is showing and increased demand in EUV scanners which are produced by ASML.
Source : https://medium.com/@gaurav.k_57188/euv-lithography-future-of-lithography-8717acc78f80

Challenges Ahead of EUV Lithography

Despite many of its advantages, EUV still is not perfect and faces many challenges which ASML must overcome if they want to be the leading manufacturers of semi-conductors. One of the major challenges associated with EUV is the need of a high-power light source. The failure to produce a light source with sufficient power does not allow an EUV scanner to go fast enough, this has been causing major delays which pushed EUV from one node to the next. Successful production of high-power light would help improve the reliability of EUV and in turn make it more economically feasible.

Another very big roadblock for EUV lithography which slows down the technology from achieving its full potential and becoming successful in the field is the strong absorption of EUV radiation by all the materials that are used in an EUV scanner. Resists must be sensitive enough to capture the image, but at the same time high aspect ratio wafer structures require longer etch times and therefore better etch resistance from the photoresist. Thin resist layers are preferable because tall, narrow resist pillars tend to simply fall over. The downside is that thinner resists capture fewer photons and are more susceptible to erosion during the etch [4]. This means that both scientists and engineers need to consider alternatives for the materials that currently are in use. Current resists are chemically amplified and in turn each incident photon may generate photoacid materials. Each photoacid molecule, in turn, “deprotects” a resist polymer molecule, rendering it soluble in developer. The “sensitivity” of the resist is a measure of the number of photoacid molecules generated by each photon. Diffusion of photoacid molecules is key for successful amplification however, this can also cause image blur when diffusion occurs outside of the exposed area.

The sheer size of EUV scanners is another factor which can be challenging for ASML, their scanners are said to be the size of a school bus (in reality they weight around 180 tons), this makes transport very troubling it takes 40 freight containers, 20 trucks and 3 cargo planes to ship just one scanner to chip manufacturers. Required utility resources for EUV are also very large and the required resources are 1500 L/min of cooling water, 532kW of electrical power and 6 gas lines for one 200W output[6], once these requirements aren't met the productivity of the scanner begins to fall.
Due to many of the challenges that EUVL is tied with and being arguably the most complex piece of machinery in the industry, the technology has not yet been extremely successful. Each year we are seeing a continuous growth in the sale of scanners manufactured by ASML and the tide is beginning to slowly turn for the technology. Many large IDM'S (Integrated Device Managers) such as Intel, Samsung, TSMC and so on have seen potential in the technique which is being perfected by ASML and invested huge money into this specific lithography technique which forecasts a bright future for the technology. Hopefully, larger IDM's will decide join Samsung and TSMC to begin mass production of circuits with the use of EUV after they begin to see the successes of the technology.

References

[1]https://www.marketsandmarkets.com/PressReleases/extreme-ultraviolet-lithography.asp

[2] https://www.forbes.com/sites/jimhandy/2012/08/27/whys-everyone-investing-in-asml/#974bf7435737

[3] https://medium.com/@gaurav.k_57188/euv-lithography-future-of-lithography-8717acc78f80

[4] https://semiengineering.com/euv-finally-arrives-now-what/

[5] https://www.anandtech.com/show/13904/asml-to-ship-30-euv-scanners-in-2019

[6] Gigaphoton, Sematech Symposium Japan, September 15, 2010