Free Electron Lasers for EUV Lithography

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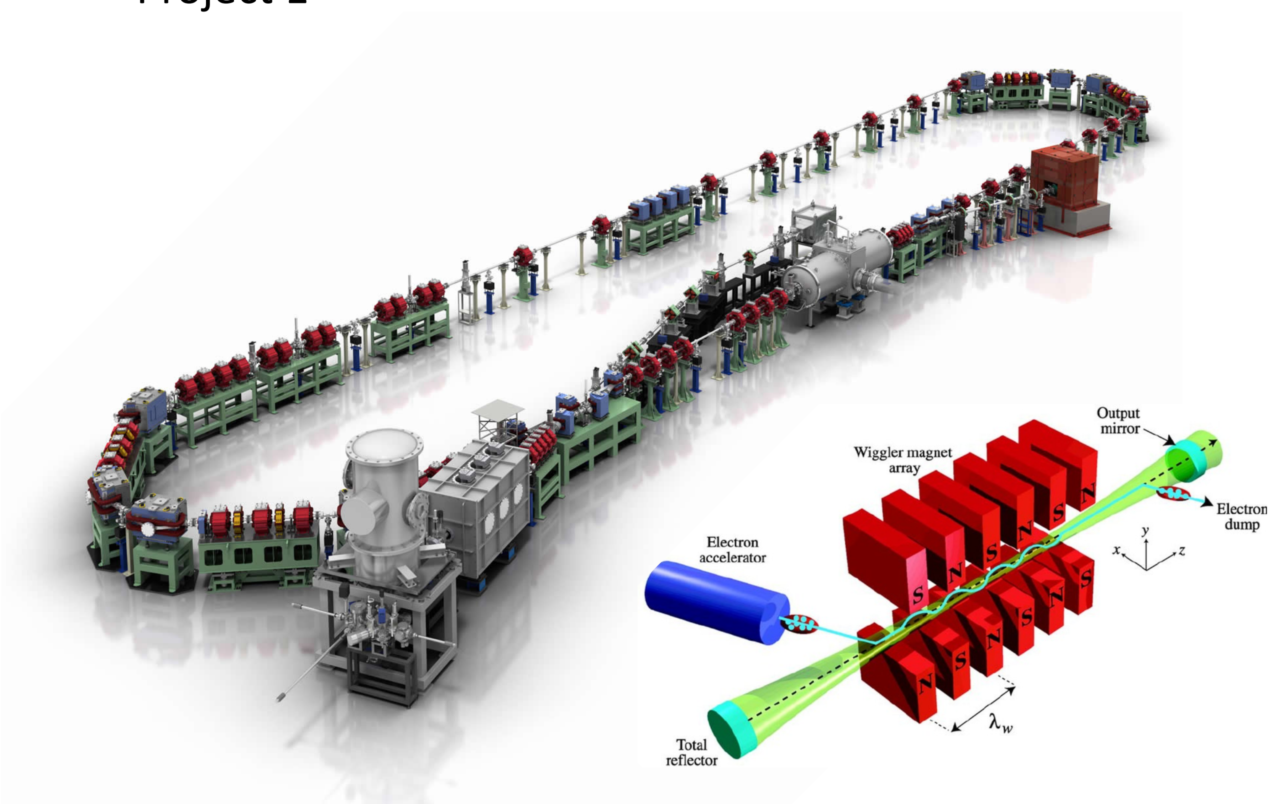
ENGN2920G
Project 1



Scenario

This report is written from the perspective of an advisor to the director of the Department tof Energy. It presents a technical analysis on the potential use of free electron lasers (FELs) as a light source for extreme-ultraviolet (EUV) lithography, as well as relevant market considerations.

Executive Summary

Recommendation:

EUV-FELs provide an avenue for competing with or even surpassing ASML's EUV capabilities. The EUV market is large enough to justify the cost of development. However, the intellectual property landscape is unfavorable to any potential ASML competitor, and a more thorough legal analysis will be necessary to make an ultimate determination.

Todays most advanced chips are made by EUV lithography (EUVL). Most of them are made by a single company in Taiwan, ASMC, and the systems that make the chips are all made by a single Dutch company, ASML. **The market for EUVL systems is expected to surpass $25 billion within 5 years**, so a domestic EUV program could have significant economic benefit. Advanced computing has become integrated with every facet of modern life, especially so in the defense arena. **Developing a domestic EUV ecosystem is therefore a matter of national security.**

ASML has succeeded in developing EUV systems which use a laser-produced plasma (LPP) light source. These are beginning to run into limitations in output power and system uptime that will be difficult to overcome**. Rather than spend years catching up to where ASML is now, it may be necessary to leapfrog the current state-of-the-art and develop a next-gen EUV lithography system based on a free electron laser (FEL) light source.**

FELs offer **three primary advantages** over LPPs:
1. Higher output powers
2. Tunable wavelength
3. Parallelizability

However, they also suffer from **two significant disadvantages**:
1. High upfront cost (~$250M)
2. Earlier stage of technology development (TRL-4)

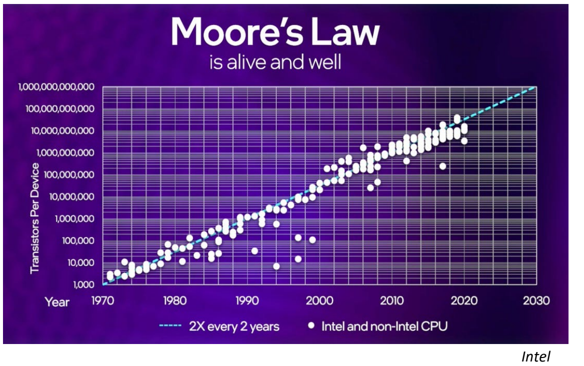
The high cost could be significantly reduced by leveraging previously existing FELs operated by the DOE. Experts suggest that a redundant system having two 20kW EUV-FELs of the energy-recovery linac (ERL) type would be most cost-effective and guarantee 100% fab uptime, significantly improving throughput.

A major hurdle to the development of a domestic EUV-FEL program would be possible infringement of ASML's intellectual property rights. **ASML and its primary optics supplier, Zeiss, hold the majority of patents in the EUV-FEL space**. While research and development may be able to proceed in a limited way without any licensing agreements, it is unlikely that the technology could be commercialized by a domestic company without significant legal costs.

Background

Moore's Law

Moore's law states that **the number of transistors on a computer chip doubles roughly every two years.** It is an empirical statement rather than a scientific fact, and its continuing validity depends on the steady advancement of chip fabrication technology. Moore's law has served the computer industry as a constant moving goalpost, motivating the ever-increasing computing power that every consumer benefits from.



Intel

Figure 1: Moore's law over 5 decades

Photolithography

Computer chips are made by a technique called photolithography. It works similarly to how film is developed in photography. A light is used to project a pattern on the surface of a silicon wafer through a mask. The illumination chemically modifies a photoresist, allowing it to be washed away in the development stage. The exposed substrate is then chemically etched, producing the desired features.

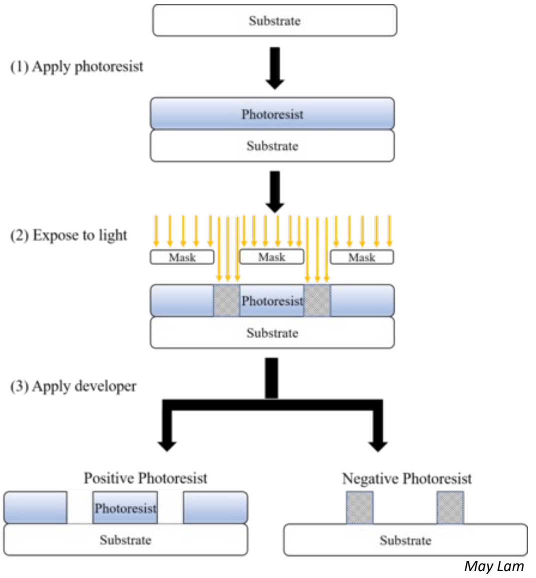


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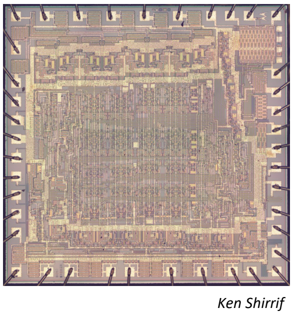
Figure 2: The photolithography process

Smaller transistors need smaller light!

To meet the demands of Moore's law, chip manufacturers have had to manufacture ever smaller transistors. The first integrated circuits featured transistors that were 10s of micrometers in size. By the 1990s, they had shrunk to sizes comparable to the wavelength of light, running into fundamental physical limits. As a result, the wavelengths used in photolithography have had to constantly shrink to make the smaller transistors. The first transistors were made using 365 nm light. **Today, the most advanced chips are made with extreme ultraviolet (EUV) light at 13.5 nm.**

Figure 3: High resolution die image of a Motorola 6820 chip from 1974 containing 4000 transistors. Todays most advanced chips contain as many as 1 trillion transistors.



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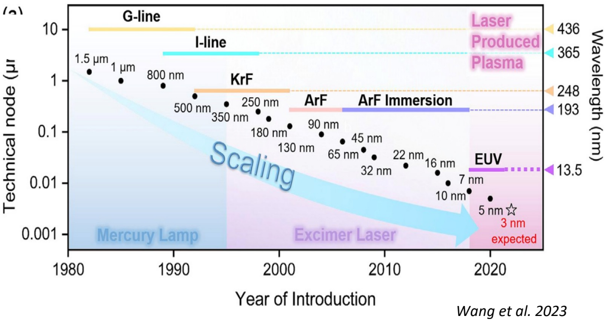

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Figure 4: Reduction in lithography wavelength over time

EUV Lithography

EUV comes with unique challenges

Unlike visible and near-UV light, **EUV is quickly absorbed by virtually every material**. So traditional light sources, optics, and photoresists used for other photolithography wavelengths do not work at EUV wavelengths. **Every part of the lithography process had to be completely reimagined**.

- **Light sources**

  EUV lithography systems typically use Laser Produced Plasma (LPP) light sources. They use a high power CO_2 laser which is fired at microscopic droplets of molten tin, turning them into a plasma. A second pulse of laser light then highly charges the tin ions, resulting in high energy electronic transitions that emit 13.5 nm photons.

- **Optics**

  EUV light is absorbed by virtually every material, so traditional refractive lenses don't work. Instead, EUV light can be focused using curved multilayer mirrors, typically made of alternating layers of molybdenum and silicon. The small amount of light reflected from each layer constructively interferes with the light reflected from each other layer due to Bragg diffraction, creating a high reflectivity meta-material.

- **Photoresists**

  Because of the limited power of EUV illumination, EUV photoresists must be very sensitive. Chemically amplified resists (CARs) are typically used. They consist of a polymer matrix, a photoacid generator (PAG), a base quencher, and a solvent. Exposure causes the PAG to generate acid which diffuses through the resist and increases its solubility in the exposed region so that it can be washed away, leaving the desired pattern behind.

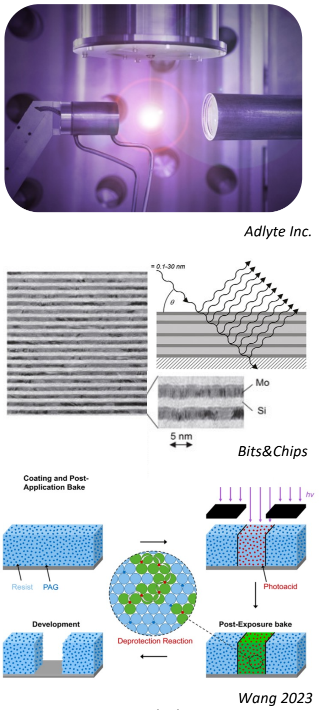


Figure 5: LPP light source, multilayer mirror, and PAG resist

The EUV ecosystem is dominated by ASML

EUV lithography systems are arguably the most complex machines humans have ever built. **A single EUVL system contains over 100,000 unique components,** all of which need to be made to exacting specifications. Only the Dutch company ASML has been able to manage the logistical complexities necessary to bring an EUVL system to market, earning them a complete monopoly. This poses economic as well as national security concerns. The United States is totally reliant on ASML and the international fabs (most notably TSMC in Taiwan) that use ASML's systems to make our most advanced chips, including those used for military purposes. There is therefore a significant national security interest to develop a domestic EUV ecosystem. **It will not be possible for domestic EUV companies to compete with ASML *in the short term***. But it may be possible to compete in the long term by developing an entirely different approach to the challenges of EUVL. There is a lot of ongoing development in EUV optics and photoresists and improving existing LPP light sources, but **there is very little ongoing development of alternative light sources.**

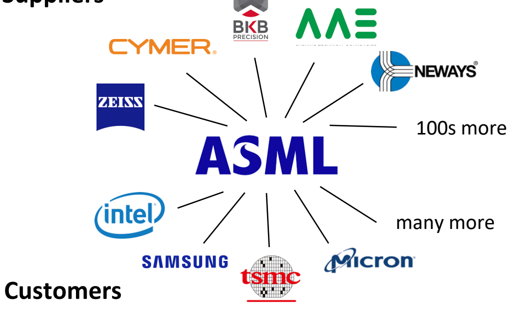


Figure 6: The EUV ecosystem

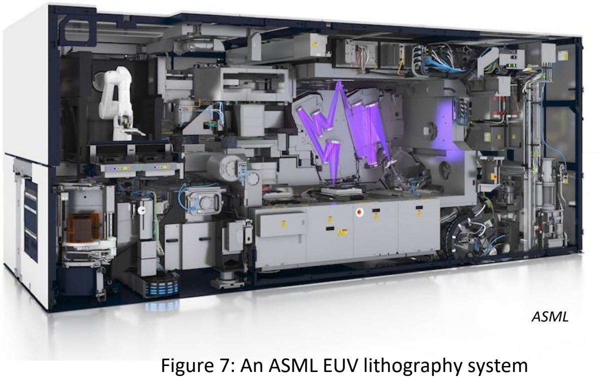


Figure 7: An ASML EUV lithography system

What’s wrong with LPP light sources?

Low power limits throughput

The typical optics stack in an EUV system consists of 11 mirrors. Each mirror has a reflectance of about 70%, so the total transmission through the optics stack is around 2%. To make up for this extreme inefficiency in the optics, the power leaving the light source must be very high. The EUV industry is now moving towards high numerical aperture (NA) EUV systems, which will require even higher powers than today’s 0.33 NA systems.

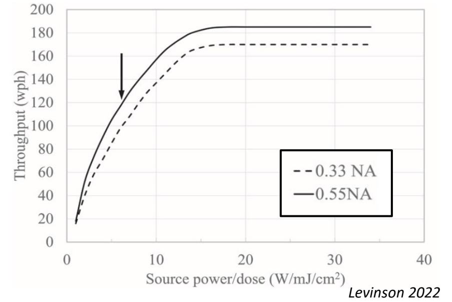


Figure 8: throughput vs illumination power

Customers want the highest possible throughput (wafers/hour) to make their substantial investment into an EUV system worth it. The maximum throughput is currently limited by the source brightness. An output power of 1.3 kW will be needed to achieve the maximum possible throughput given mechanical constraints, but typical LPP sources used in commercial EUV systems have output powers of around 250 Watts. LPP sources with output powers as high as 500 W have been demonstrated in the lab, but have yet to be integrated into a commercial instrument Achieving output powers greater than 1 kW in an LPP source is remains a difficult challenge which will require significant R&D costs to overcome.

Shot noise

An issue related to the power limitations is shot noise. Because of the particulate nature of light and matter, each pulse of light that illuminates a photoresist has a finite number of photons striking a finite number of photoresist molecules. As the illumination power decreases, the probability that any given photoresist molecule is not struck by a single photon increases. This leads to so-called shot noise or stochastic related defects. These defects are often in the form of microbridges that form between features, causing short-circuits.

Tin contaminates optics

A major challenge confronting further LPP development is the generation of tin debris that contaminates the light source’s collection mirror. The tin plasma creates high energy ions which can slam into the mirror’s surface and adhere to it. Their high kinetic energy makes them difficult to stop by conventional methods. As the output power of the LPP increases, more high energy tin ions are generated, exacerbating the problem.

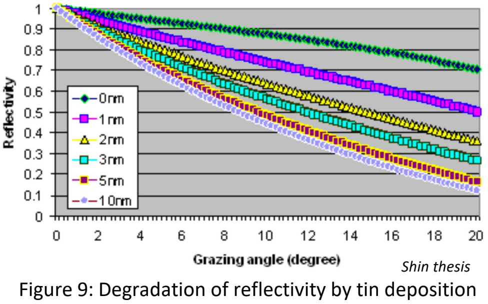


Figure 9: Degradation of reflectivity by tin deposition

The collection of tin on the collection mirror reduces its reflectance. **This necessitates regular and costly maintenance to restore the mirror surface, resulting in significant downtime which slows production.** While many mitigation strategies have been developed, none have been able to entirely avoid costly downtime due to tin contamination

Fixed wavelength

Because LPPs rely on electronic transitions of certain highly charged ions, the wavelength options are limited by the spectra of those ions. Additionally, complicated spectra prevent the isolated emission of wavelengths significantly smaller than 13 nm, **preventing further reductions in wavelength for future technology nodes.**

Free electron lasers: An alternative to LPP sources

How do they work?

Free electron lasers (FELs) generate light by accelerating electrons to relativistic speeds then wiggling them with a series of alternating magnets. The electrons then emit light at a wavelength proportional to the wiggling frequency. With the appropriate choice of electron energy and magnet spacing, high power EUV light can be generated.

Free electron lasers consist of 3 key components:

1. **Electron gun** – produces the electrons that generate the light
2. **Accelerator** – accelerates the electrons to a desired energy
3. **Undulator** – series of alternating magnets that wiggles the electrons to generate light

Design considerations

Free electron lasers are large and complex scientific instruments. Designs vary, but **all FELs share similar requirements that contribute to their costs: a large footprint, radiation management systems, cryogenic systems, and vacuum systems.** Under these constraints, there have been many clever design ideas to maximize output power while minimizing footprint and energy costs**. A particularly promising design idea is the multipass energy recovery linac FEL (ERL-FEL)**, in which spent packets of electrons are decelerated and their energy is used to propel unspent electron packets, recirculating and conserving energy. This both reduces the footprint and reduces energy costs.

For integration into a fab facility, experts have suggested using **a redundant design with 2 duplicate FELs to ensure 100% uptime**. Given an output power of >20kV, **each FEL could provide light to around 10 lithography systems in parallel.**

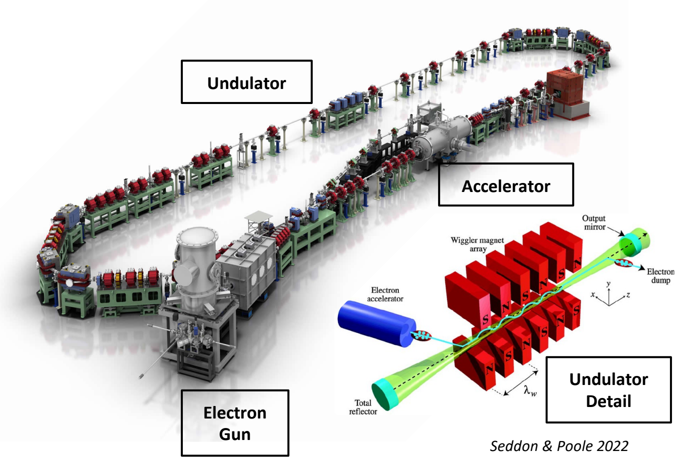


Figure 10: Free electron laser

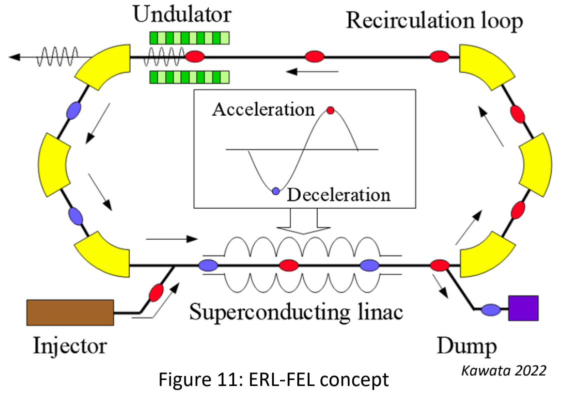


Figure 11: ERL-FEL concept

Advantages	Disadvantages
Can achieve powers >20 kW	Massive footprint (50m x 20m for more compact designs)
Can feed multiple lithography systems in parallel	High up front cost
Can be easily adapted to generate smaller wavelengths for future technology nodes	High radiation management costs
Can eliminate downtime by having two redundant EUV-FELs per fab	Produces coherent light, which is bad for photolithography
Large pre-existing knowledge base in accelerator scientist communities	

EUV-FELs: Bibliometric and Patent analysis

Technology Readiness level

Today, EUV-FELs are at a technology readiness level of about 4. The principles of free electron lasing were demonstrated decades ago. Papers on FELs began to appear in the 1960s. Papers on FELs for generating EUV light started appearing in the early 1990s and by the mid 2010s were making up about 20% of all papers being published on FELs. Several FELs have been built and are running in labs around the world, and **the necessary capabilities for an EUV-FEL light source for lithography (>1kW power, EUV generation, precise system control) have already been separately demonstrated.** Now a platform that integrates these capabilities in a single device is needed to demonstrate its potential for EUV lithography.

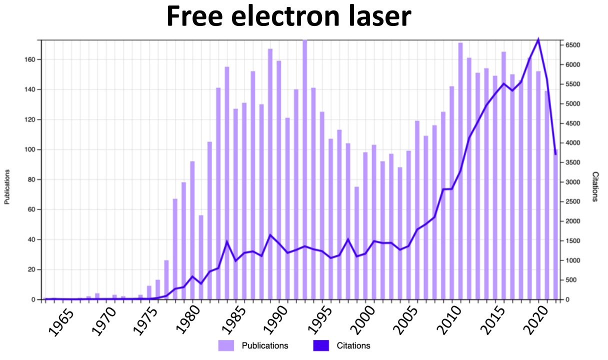


Figure 12: Free electron laser bibliometrics

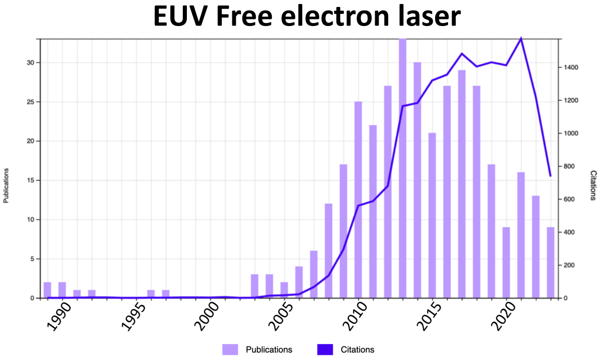
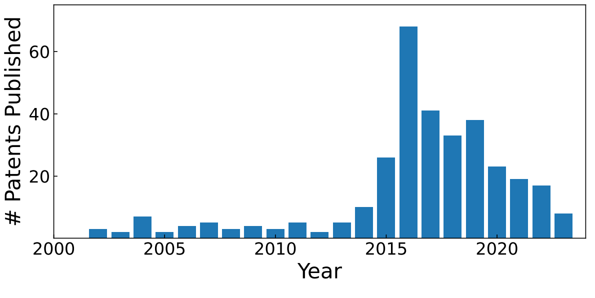


Figure 13: EUV free electron laser bibliometrics

Patent landscape

There are about 125 currently active patents covering EUV-FEL technology. As shown below, 85% of the patents are held by private corporations. The majority of patents in the field were published in the past decade. **ASML and their primary optics supplier, Zeiss, hold 57% of the patents in this field.** While ASML has not publicly announced an intention of developing EUV-FEL light sources, they are clearly aware of and prepared for the potential disruption that a high power EUV-FEL would cause.



The US government combined with domestic universities and private companies hold a relatively small number of patents compared with ASML. They are also generally more limited in scope, for example covering a particular way to focus the electron beam in a FEL. **This will make it difficult to compete with ASML on EUV-FELs from an intellectual property perspective.**

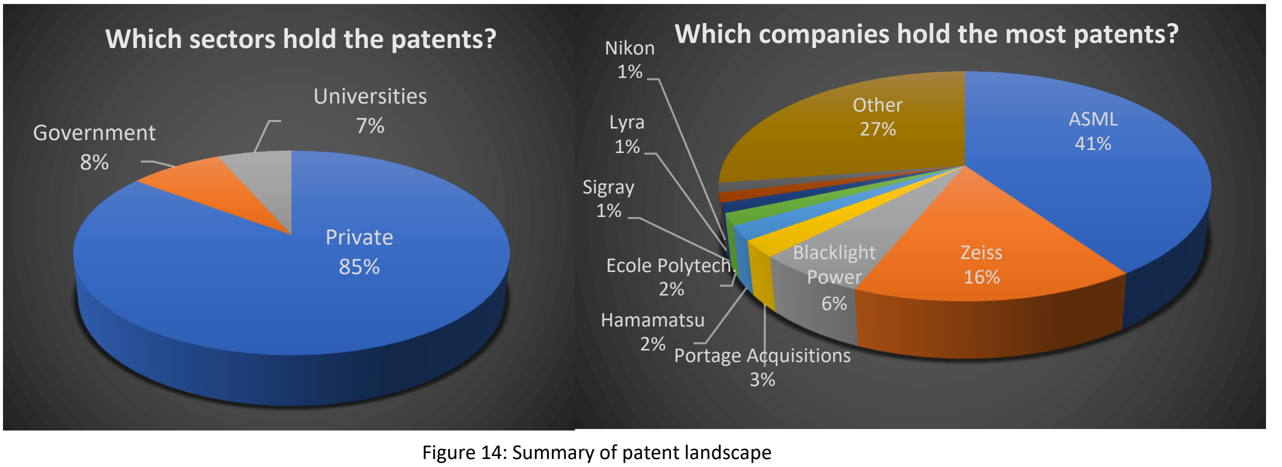


Figure 14: Summary of patent landscape

Economic analysis

EUV Market

Although they only became available in the last decade, the market for EUV systems is already valued at $10 billion and expected to continue its exponential growth trajectory for several years to come. **Experts predict that the EUVL market will grow to around $25 billion in the next 5 years** as the demand for more advanced chips continues to increase. The large market size justifies significant investment in any advance that would significantly increase throughput. **The US government recently committed $280 billion to boost the domestic chip industry through the CHIPS act, much of which is administered by the DOE.**

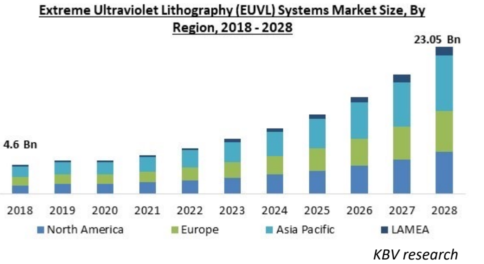


Figure 15: EUV market projections

Cost of EUV-FEL Development

A group from MIT and GlobalFoundries, an American semiconductor manufacturer, published a study in 2015 in which they estimated the cost of building an EUV-FEL light source for a lithography facility. They determined that the radiation vault housing the accelerator makes up a large fraction of the overall cost, so **minimizing the footprint of the FEL is critical to keeping costs down**. The authors opted for a redundant pair of 20 kW ERL-FELs based on Jefferson Labs' proposed JLAMP design, which they determined would provide the clearest path to industrialization at the lowest cost. Their assessment is summarized in the tables below, **an upfront capital expenditure of $240M is expected along with yearly operational expenditures of $230M.** In addition, they estimated that this setup would have approximately **twice the throughput of comparable LPP powered EUV systems**.

Capital expenditures

Item	Cost ($M)
Building & facilities	50
Cryogenic plant	35
Electronics and softwawre	20
Undulators and Optics	25
Accelerator	100
Installation	10
Total	**240**

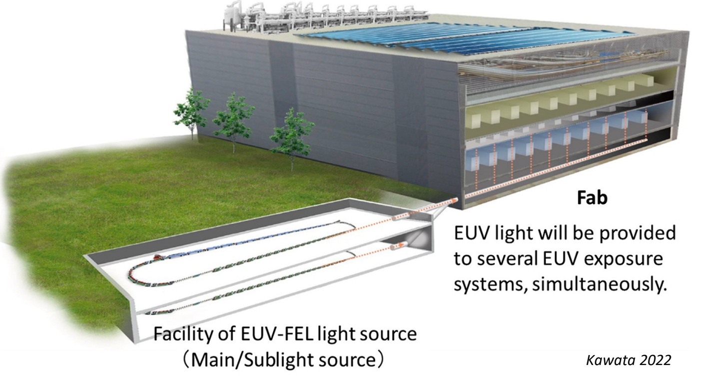


Figure 16: Proposed EUV-FEL powered fab layout

Operational expenditures

Item	Cost ($M/yr)
On-staff labor	5
Electrical power	7
Contract labor	5
Parts	4
Supplies	<1
Cryogenic plant operations	1
Total	**23**

DOE is uniquely positioned to cut development costs in half

There are a number of FELs currently in operation in the united states. The most advanced of these are likely the FEL program at Jefferson Lab or the LCHC at SLAC, both DOE affiliated labs**. The cost of developing an EUV-FEL could be substantially reduced by using these existing facilities.** EUV lithography using a FEL light source could then be demonstrated without needing to build a new accelerator or cryogenic plant, cutting the capital expenditure in half.

Conclusions

EUV lithography is a large and growing market, and its products are critical to every modern economy and military. Today, 100% of EUV lithography systems are made bv a single Dutch company, ASML, and more than half of the advanced chips are made by a single company in Taiwan, TSMC. It is therefore in the national interest of the United States to develop a domestic EUV ecosystem.

It will take several years and substantial investment to catch up to ASML's current capabilities, at which point they will have already progressed, making today's tech obsolete. It may therefore be necessary to leapfrog the current EUV technologies used by ASML and take an alternative approach to prepare for future trends in lithography. Further reductions in transistor size will require higher illumination powers and possibly shorter wavelengths than current EUV-LPP light sources. This makes free electron lasers an attractive avenue for development.

Free electron lasers have the advantage of being able to produce significantly higher output powers than LPPs, and they are also tunable in wavelength. However, they have an estimated upfront cost of $200-300 million, and still require substantial development before they are ready for commercialization. The cost could be reduced significantly during development by using existing DOE accelerator facilities at SLAC or Jefferson Lab. The cost of development could be justified given the $25 Billion projected EUV market size by 2028.

There are significant IP obstacles to the eventual commercialization of EUV-FELs. The majority of patents in the field are held by ASML and Zeiss, who may not be open to licensing out this potentially valuable technology. A more thorough legal analysis of the patent landscape would be needed before a final determination is made.

Methodology

EUV-FEL concept

The proposed EUV-FEL concept outlined in this report was put together form combining recommendations made in several research papers published in peer reviewed journals (refs 1-4). The cost estimate was provided in ref. 1, a review paper by lithography experts from GlobalFoundries and MIT.

Bibliometrics

Bibliometric analysis was preformed using the Web of Science database. The presented data on page 7 are the results of the following searches:

- TI = Free electron laser
- TI = Free electron laser AND (ALL = EUV OR ALL = extreme ultraviolet OR ALL = 13 nm)

Patent analysis

Patent analysis was carried out using data from the Patentscout database which was processed in python. Patents relating to EUV-FELs were found using the search: *("free electron laser" OR FEL) AND (EUV OR "extreme ultraviolet").* The data was exported from Patentscout as csv files, which were then analyzed in Python using the Pandas package.

References

1. Hosler, E. R., Wood, O. R., Barletta, W. A., Mangat, P. J., & Preil, M. E. (2015). Considerations for a free-electron laser-based extreme-ultraviolet lithography program. *SPIE Proceedings*. https://doi.org/10.1117/12.2085538
2. Kawata, H., Nakamura, N., Sakai, H., Kato, R., & Hajima, R. (2022). High power light source for future extreme ultraviolet lithography based on energy-recovery linac free-electron laser. Journal of Micro/Nanopatterning, Materials, and Metrology, 21(02). https://doi.org/10.1117/1.jmm.21.2.021210
3. Hosler, E. R., Wood, O. R., & Barletta, W. A. (2017). Free-electron laser emission architecture impact on EUV lithography. *Proceedings of SPIE*. https://doi.org/10.1117/12.2260452
4. Lee, J., Jang, G., Kim, J., Oh, B., Kim, D., Lee, S., Kim, J., Ko, J. H., Min, C., & Shin, S. (2020). Demonstration of a ring-FEL as an EUV lithography tool. *Journal of Synchrotron Radiation*, *27*(4), 864–869. https://doi.org/10.1107/s1600577520005676
5. De Bisschop, P., & Hendrickx, E. (2019). Stochastic printing failures in EUV lithography. SPIE Advanced Lithography. https://doi.org/10.1117/12.2515082
6. Feng, C., Deng, H., Zhang, M., Wang, X., Chen, S., Liu, T., Zhou, K., Gu, D., Wang, Z., Jiang, Z., Li, X., Wang, B., Zhang, W., Lan, T., Feng, L., Liu, B., Gu, Q., Leng, Y., Yin, L., . . . Xiang, D. (2019). Coherent extreme ultraviolet free-electron laser with echo-enabled harmonic generation. Physical Review Accelerators and Beams, 22(5). https://doi.org/10.1103/physrevaccelbeams.22.050703
7. Ding, Y., Wei, D., Huang, Q., Song, Y., Wu, J., Li, W., Wang, Z., Tang, X., Xu, H., Liu, S., & Chen, G. (2022). The development of laser-produced plasma EUV light source. Chip, 1(3), 100019. https://doi.org/10.1016/j.chip.2022.100019
8. Shin, Hyung Joo. Cleaning of tin debris by reactive ion etching in a discharge-produced EUV plasma source. University of Illinois at Urbana-Champaign, 2009.
9. Wang, X., Tao, P., Wang, Q., Zhao, R., Liu, T., Hu, Y., Hu, Z., Wang, Y., Wang, J., Tang, Y., Xu, H., & He, X. (2023). Trends in photoresist materials for extreme ultraviolet lithography: A review. Materials Today, 67, 299–319. https://doi.org/10.1016/j.mattod.2023.05.027
10. Mayer, P., Brandt, D. C., Fomenkov, I. F., Purvis, M., & Brown, D. J. (2021). Laser produced plasma EUV sources for N5 HVM and beyond: performance, availability and technology innovation. SPIE Advanced Lithography. https://doi.org/10.1117/12.2584407
11. Jaramillo, E. (2023, August 6). Beijing wants its own EUV light source, a key part of the chip supply chain. The China Project. https://thechinaproject.com/2023/08/03/beijing-pushes-china-to-develop-its-own-euv-light-source-a-key-part-of-chip-making-tech/
12. Ting-Fang, C. (2023, June 27). ASML says decoupling chip supply chain is practically impossible. Financial Times. https://www.ft.com/content/317be8b3-48d9-411e-b763-261a179c9d0d
13. Research infrastructure initiatives in the CHIPS and Science Act - AIP.ORG. (2023). AIP. https://ww2.aip.org/fyi/2022/research-infrastructure-initiatives-chips-and-science-act
14. FACT SHEET: CHIPS and Science Act will lower costs, create jobs, strengthen supply chains, and counter China. (2023). The White House. https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/
15. A next generation photon science facility at Jefferson Lab. (n.d.). Thomas Jefferson National Accelerator Facility. https://www.jlab.org/accelerator/FEL/jlamp
16. Miller, C. (2022, October 5). The chips that make Taiwan the center of the world. Time. https://time.com/6219318/tsmc-taiwan-the-center-of-the-world/
17. Miller, C. (2022a). Chip war: The Fight for the World's Most Critical Technology. Simon and Schuster.