Development of a Short Pulse High Power Laser for the Production of Extreme Ultraviolet Radiation

Final Report
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by
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EE402

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Senior Design Coordinator
ABSTRACT

The increasing need for extreme ultraviolet laser technologies has presented itself in the last several years. These shorter wavelengths, 5-50 nm, are required in the manufacturing processes and analysis of new nanotechnologies, such as EUV lithography to manufacture the next generation of computer chips. Currently EUV light sources are large and extremely expensive and therefore only available in large national laboratory settings. One of the goals of the current research being done at the Engineering Research Center is to develop small, cost effective EUV light sources that will be widely available to smaller labs. With the knowledge that is gained from experiments with these new laser sources, new cutting-edge solutions can be provided to help solve the problems associated with nano-science and nanotechnologies.

I have been working with a team of graduate students towards upgrading the power output of one of the labs current table top EUV lasers. This entails work in a broad range of areas. The original Ti:Sapphire crystal used as a gain medium to amplify the laser was increased in size to allow for a much higher gain. For this increased gain to occur the power of the pumping lasers used to create a population inversion in the material also had to be increased. Next a cooling system was developed to remove the heat introduced into the crystal by the pumping lasers. The new laser will also require larger optics and vacuum boxes to enclose them.

The new pumping lasers are setup and ready to be aligned with the new crystal. A cooling system has been built and tested for leaks. The new optics and the holders required to mount them to the table are currently being manufactured. All the required vacuum chambers have been assembled and tested for leaks. Once all the components have been manufactured and proved reliable, the entire system can be integrated and tested. The primary goal in the assembly of the overall system is to minimize downtime. Once assembled, aligned, tested, and working properly, experiments with EUV light can be performed. These experiments will hopefully lead to applications such as high resolution imaging and nano-fabrication.
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INTRODUCTION

For the last 40 years computer chips have been manufactured using optical methods such as photolithography. In photolithography, light is shown on a mask to create the complex structures that make up the transistors on a chip. Decreasing the size of these features allows for much more of them to fit in the same area, thus increasing performance and decreasing cost. The size of computer chips and their components has been decreasing by about a factor of 2 every two and a half years. Due to the long wavelengths of UV light, the current photolithography process is reaching its limitations. To overcome the current limitations, new light sources, multilayer optics, and lithography techniques must be developed. One solution is to create light sources with much shorter wavelengths, in the extreme ultraviolet region, so the features on computer chips can continue to decrease in size and subsequently increase in performance.

There are many other applications, other than nano-fabrication, of EUV light sources. These include ultra-high resolution microscopes, nano-scale imaging, and spectroscopy. Because of the size and competitiveness of the semiconductor industry it is arguably the most important reason for the advancement of EUV technologies.

Because of the importance in developing these new technologies, the National Science Foundation created the Center for Extreme Ultraviolet Science and Technology. This engineering research center is a partnership of four institutions: Colorado State University, the University of Colorado at Boulder, the University of California at Berkley, and the Lawrence Berkeley National Laboratory. Currently EUV light sources are large and extremely expensive and therefore only available in large national facilities. The overall goal of these four institutions is to create EUV light sources that are much smaller and more cost effective, so that they are readily available to smaller laboratories. With the development of cheaper light sources, EUV applications, and the advances in optics gained from the research at these facilities, these technologies will become more practical for commercial use. The previous work accomplished by these institutions will be discussed further in the following section.

Currently table-top lasers causing the emission of extreme ultraviolet light in the 14 nm range have been demonstrated. The next step, and focus of this report, is to
increase the power output of the EUV light source. The EUV light in the current setup is created by heating plasma, an ionized gas, using high energy pulses from a laser. This stimulates energy transitions in the ions which causes the emission EUV photons. Therefore by increasing the power of the laser incident on the plasma, the number of excited ions and resulting emitted photons will increase, thus increasing the output of the EUV light.

Increasing the power of the laser exiting the plasma will be accomplished by increasing the size of the gain media used to amplify the laser. The material used as the gain medium is Titanium Sapphire, which has a broad bandwidth of about 400nm which allows for ultra short pulses. The old crystal, which is about 2.5 cm in diameter, is being replaced with a crystal that is about 10 cm in diameter and much thicker. Increasing the size of the gain medium also requires an increase the energy required to pump the medium.

Pumping is the creation of a population inversion in a material. By introducing energy into a medium, atoms are excited to an upper level, where they remain for a short period of time before decaying to a lower energy state via spontaneous or stimulated emission. As the atoms decay to a lower state, energy is released in the form of a photon. When a photon is emitted due to stimulated emission it has the same frequency, phase, polarization, and direction of propagation as the inducing photon. Since stimulated emission depends on the density of the atoms in the excited state, an increase in pumping energy increases stimulated emission. Because of this, the number of photons created due to the laser passing through the medium is increased, and thus the laser output is increased.

For Ti:Sapphire the range of wavelengths that can be used to pump the material is between 400 nm and 600 nm. Because of this the crystal can be effectively pumped using an Argon Ion laser, or a frequency doubled Neodymium YAG laser. In the upgraded system, two 15 J lasers will be used to pump the new crystal. This amount of energy will create a substantial amount of heat in the crystal which will need to be removed by a cooling system to prevent damage or cracking. The expected increase in output power of the laser using the new pumping lasers and Ti:Sapphire crystal is about 10 fold.
With the increased power output and shape of the beam of the laser, new optics will be required to align and split the beam before it can be used to create the plasma. Since the plasma and the resulting EUV light must be created in a vacuum, some of the optics will be need to be computer controlled from outside the vacuum box. A computer will be used to control 15 small motors inside the alignment chamber that are connected to a step mirror. The step mirror is used for wave-front compensation and increases the instantaneous power incident on a target where the plasma is created. These motors will allow the user to maximize the laser power without opening the vacuum chamber. Because of the increased size of the optics and the addition of the computer controlled alignment, new vacuum boxes were designed to replace the older smaller boxes.

Once assembled the new EUV light source can be used in experiments to further the knowledge in the areas of lasers, optics, and plasma physics. With this increased knowledge, cutting edge solutions can be provided to help solve the problems in the semiconductor industry associated with nano-fabrication. Other applications for EUV light sources can then be tested and developed further for commercial use.
SUMMARY OF PREVIOUS WORK

Through a combined effort between the four institutions that make up the Center for Extreme Ultraviolet Science and Technologies, many advances have been made in the field of extreme ultraviolet sources and technologies. Several methods have been developed to produce EUV radiation. One of the methods, which is used in the laser I have been working on, is the laser-induced plasma source, which was discussed earlier. Another method that has been developed is called high harmonic generation. HHG occurs when high intensity lasers, greater than $10^{13}$ watts/cm$^2$, are used to excite a gas causing it to emit radiation at frequencies that are multiples of the lasers frequency, also called harmonics. Under certain conditions very high order harmonics can be achieved, and EUV radiation is generated. The third type of source that has been developed is called a capillary discharge system. In this setup, a hollow metal tube is filled with a gas and a large current is discharged across the tube emitting EUV radiation. An example of this is a several kilo-amp current discharged across a xenon filled alumina capillary.

The next area of development went into the new optics necessary for wavelengths in the extreme ultraviolet region. Most materials are extremely absorbent to EUV light, which poses a big problem for focusing or manipulating the light. New multilayer optics are being developed to solve this problem. These optics use many alternating layers of metal and silicon with thicknesses equal to half the wavelength of the light, creating constructive interference in the layers. Using this technique, reflectivities of up to fifty percent have been achieved. Another problem is the lifetime expectancy of multilayer optics. Carbon growth and oxidation can limit the lifetime of these optics. Several solutions have been developed to solve this problem, such as protective layers and cleaning techniques.

With the advancement in EUV sources and optics new applications could be developed. These include, but are not limited to, ultra-high resolution microscopes, nanoscale imaging, nanocluster spectroscopy, and nanofabrication. As discussed earlier nanofabrication using EUV lithography has been the major reason for the increased interest in this research over the past several years.
CURRENT WORK

Currently, I am working with a team of graduate students in the development of a more powerful laser used to create and heat a plasma to emit EUV radiation. As discussed earlier, there are many aspects of the laser that need to be upgraded to produce the higher output. To achieve a higher output using the same source laser, a larger gain media must be used. Using a larger Ti:Sapphire crystal requires larger lasers to create the necessary population inversion for the gain to occur. The new pumping lasers are on a separate optical table that must be secured to the adjacent tables to ensure they are level and aligned. Increasing the pumping power also requires a method to rid the sapphire of unwanted heat. Lastly, larger optics to handle the increased power, and vacuum boxes to store the optics were designed and manufactured. In the following sections I will go into each of these aspects into more detail.

**Ti:Sapphire Crystal:**

At a cost of almost sixty thousand dollars and a year to receive once ordered, this is the heart of the upgrade. The much larger gain achieved with this crystal is how the power output will be increased by about 10. There is a holder that was also manufactured for the crystal with an inlet and outlet so that a coolant can flow around the outside edge of the crystal. These ports are where the cooling system will be connected. Lastly, it is important that the crystal be at the correct height, so the laser aligns perfectly with the optics inside the vacuum boxes.

**Ti:Sapphire Crystal Riser:**

Once the height of the crystal was determined, I had to manufacture a riser that attaches to the base of the crystal holder and can be mounted to the optical table. I milled the piece out of aluminum with a height of 4.45 in. It has tapped holes in the top to secure it to the crystal holder, and places at the base where a clamp can be attached. This was manufactured out of a piece of scrap aluminum that was purchased for another project.
Cooling System:

Next I designed and built a cooling system to remove excess heat from the crystal when the system is being run. The system is housed in a metal enclosure, and contains a pump, reservoir, and heat exchanger. I installed quick connect bulkheads on the outside of the enclosure so the system can easily be disconnected from the buildings water supply. The heat exchange’s cold water supply and return are connected to the bulkheads on the inside of the case. Lines are run from the quick connects, on the outside of the case, to the buildings cold water supply and waste. The reservoir is connected to the inlet on the pump, which circulates the water out of the enclosure, through the crystal holder, back to the enclosure, through the heat exchange, and back to the reservoir. I made the reservoir using a water tight container that I drilled two holes in for the inlet and outlet. The fittings for the reservoir have o-rings to seal the holes. This is a closed loop system, currently filled with distilled water. Heat from the closed loop system is removed as it passes through the heat exchange. The enclosure will be mounted under the optical table, near the crystal, on a hanging shelf that I would have to make. The overall cost of the cooling system with a new pump, reservoir, and fittings while reusing an old heat exchanger and enclosure was about 350 dollars.

Cooling System Shelf:

I made the shelf out of a ¼ in. aluminum plate and 4 ¾ in. diameter aluminum rods. The rods are tapped at both ends, so the shelf can be connected to the bottom with a screw, and the top can be hung under the table with a threaded rod. The bottom of the optical table will need to be tapped before the shelf can be put in place. I faced the four rods so they would be exactly the same length, and the shelf would hang level. I got the materials for this project from the supply room and they were put on the account without knowing the exact costs.

Pumping Lasers:

The upgraded pumping method uses two 15 J lasers to create the population inversion in the new crystal. This system was setup by several of the graduate students before I joined the project and sits on a separate optical table. For these lasers to
effectively pump the crystal they need to be aligned properly. This will require that the optical table be connected to the adjacent table with a plate.

**Table Plate:**

Using a ¾ in. steal plate, I drilled and counterbored a pattern of holes that lines up with the holes in the tops of both optical tables. Next I drilled 4 large holes down the center of the plate which will have large bolts running to steal beams under the tables. When the plate it secured to the tops of the tables and the beams are secured under the tables, the tables will stay aligned with each other. Holes to attach the optics on the pumping laser table that overlap the location of the plate were then drilled and tapped using the CNC (computer controlled milling machine). The plate was then sandblasted to get rid of any rust and oil, and then painted. The optics that overlap the location of the plate are now raised ¾ in. and need to be redesigned to still line up with the rest of the optics on the table.

**Redesigned Mirror Mounts:**

The mirror mounts consist of two parts, the mirror holder and the mount. Since the mirror is not being changed the mirror holder doesn’t have to be changed, but the mount will need to be ¾ in. shorter due to the steal plate connecting the two tables. The holes for the two pieces also need to line up, so the ¾ in. of material had to be removed from the bottom part of the holder. After removing the necessary material, the mirror holder was in contact with the mount which would not allow the mirror to be aligned. To solve this, the base was thinned by 0.1 in. Another problem that arose from shortening the mount was the room for clamping and securing the base to the optical table was eliminated. The first idea to fix this problem was to counterbore the slot for the screw that connects the mount to the table. This wouldn’t work because the slot would have to be counterbored almost the entire thickness of the material, and it would be susceptible to bending. Instead the screw slot was moved closer to the mount allowing the head of the screw to fit in between the mount and the mirror holder. Also, some material was removed from the back and sides of the mount to allow for clamps to be attached. This mount was designed using a 3D modeling program and then converted into 2D sketches.
so it can be manufactured. These mounts were manufactured on the CNC and then anodized. These drawings are attached at the end of the report and labeled in the list of figures.

**Optic Holders/Mounts:**

The larger optics that are necessary for the increased power output all have holders and mounts that were already designed. The 3D models of all of these assemblies needed to be turned into 2D drawings before they could be sent off for manufacturing. I worked for several weeks converting many of these drawings. The rest of the drawings were done by the other graduate students working on the project. The 3D and 2D drawings of these assemblies are attached at the end of the report and are labeled in the list of figures. These holders and mounts were then milled on the CNC and sent to be anodized.

**Vacuum Boxes:**

Although there are only three new vacuum boxes being used on this project, there are five in total between this and another project underway. I have worked for the last four months preparing and assembling these boxes. The frames are built in a machine shop in the lab, while the walls and legs were sent to another company to make. When the steal frames are made, they have welds that must be sanded smooth so that an airtight seal is made along the o-ring between the frame and the sides. Next the o-ring grooves in the aluminum walls must be sanded smooth for the same reason. After the pieces are sanded they are rinsed well with soap and water to get as much of the debris off as possible. Then every hole, groove, and surface is meticulously cleaned with methanol and cotton swabs. All the particles and oils must be removed so they do not contaminate the optics inside the vacuum once it is assembled. Once all the pieces were cleaned, they were assembled and tested for leaks.

The boxes are pumped using a turbovac pump until they reach pressures in the box on the order of $10^{-6}$. If this couldn’t be achieved, which happened on several of the boxes, the box was tested for leaks by releasing helium around the seams and using a residual gas analyzer to detect extremely small amounts of helium. This method
pinpointed the leaks and allowed us to fix them. Currently, all five boxes have been completed and tested for leaks. Four of the five boxes meet the required pressures necessary for our applications. A solution to fix the fifth box is currently being discussed and possibly includes adding some bolts on the top to reduce the bending from the extremely high pressures inside the chamber.

The cost of materials and labor to produce these boxes depends on the size. The largest box was about $10,000, and the turbovac pump required to pump the boxes also cost around $10,000. I estimate the total cost for the three vacuum boxes that will be used on this project plus the turbovac pump to be around $30,000 to $35,000.

**Computer Controlled Mirrors:**

This laser system will utilize an optical system that doesn’t require the vacuum boxes to be opened for the power to be maximized at the target. There are fifteen motors that control the five mirrors in a step mirror. These motors will be controlled by a user via a computer which plugs into a port on the side of the vacuum chamber. This setup was designed and built by another project group, and is currently in the final testing phase.

**Overall Assembly:**

The assembly of the upgraded laser will start when all the components of the new laser system have been built and tested. Testing all the components individually before the overall system is assembled will greatly reduce the downtime of the current laser setup. The final installation and testing of the overall assembly will probably take place over the summer. Once the system is installed, the painstaking task of aligning all the optics will begin. On the following page is a model of the vacuum boxes and the laser beam path through the boxes once the system is fully assembled.
CONCLUSIONS AND FUTURE WORK

Much of this year was spent preparing for the laser to be assembled. Since the optics take awhile to manufacture, they were the priority in the beginning of the project. After finalizing all the drawings for the mounts, the mounts and optics were sent to the machine shop to be manufactured on the CNC. The several months it will take to get all the optics manufactured, allowed us to finish much of the other components. Ensuring that everything is built, tested, and working properly before the system is integrated into the old system, will save time during the assembly process. The following is a list of what was accomplished this year:

- Built and Tested 5 Vacuum Boxes
- Riser Piece for Ti:Sapphire Holder
- Cooling System for Ti:Sapphire Crystal
- Hole Pattern in the Table Plate to Secure the two Optical Tables
- Shorter Mirror Mount Designed to sit on the Table Plate
- 3D Models of Mounts Converted to 2D Drawings for Manufacturability

Over the summer, I will continue to work on all the aspects of the laser that haven’t been finished. I will need to fix the leaks on the final vacuum chamber. Once all three of the vacuum boxes are working properly they will need to be moved and installed in the lab that will be using them. After the boxes are setup in their appropriate places, the optics can be installed and the computer control system setup. The table with pumping lasers can then be linked to the rest of the optical tables. Then the new crystal can replace the old one and be hooked to the new cooling system. Once the major pieces are in place the long process of aligning all the optics will start.

Most of the optics involved in the pumping lasers will have to be realigned since four of them will be moved when the plate linking the tables is installed. After these are aligned the two pumping lasers will have to be aligned with the new crystal. The source laser will also have to be aligned. This will ensure the laser is aligned with the vacuum box input. Next the optics inside, the vacuum boxes, can be aligned using a computer
connected to a port on the side of the vacuum box. Once the system is completely setup and aligned, it can be tested.

After thoroughly testing the system, it can be used to perform experiments. At this time, I am not sure what kind of experiments will be performed with this system, but I should find out when the laser is closer to completion.
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2. http://euverc.colostate.edu/


5. Lecture Notes, EE546 Optical Electronics, J. J. Rocca

3 corner holes Ø0.374 THRU

4 thru holes with 45 degree chamfer 0.05 deep Ø0.300

2.000

<COMPANY NAME>

DIMENSIONS ARE IN INCHES
TOLERANCES
TANGENT CIRCLE
ANGULAR MACh: BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
MATERIAL --
FINISH --
APPLICATION DO NOT SCALE DRAWING

PROPRIETARY AND CONFIDENTIAL
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3 0.25in radius Fillets
0.33in deep
R0.250
4 45deg chamfer
0.05in. deep
meant for 0.1in. dowel pin
all other counterbored holes

∅ 0.266 THRU
∅ 0.750 ± 0.200

4 holes along the center
∅ 0.750 THRU
∅ 1.500 ± 0.200
4 center holes
∅0.201 ∅0.500

10 45 degree chamfers
.05 deep
meant for 0.1 in. dowel pins

A (2:1)

<COMPANY NAME>

DIMENSIONS ARE IN INCHES
TOLERANCES:
FUNCTIONAL
ANGULAR MACH NEST
TWO PLACES DECIMAL:
THREE PLACES DECIMAL:
MATERIAL:
FINISH:
APPLIC.:
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10 0.3in. diameter thru holes with 45 degree chamfer 0.05 deep
1 thru slot with radius 0.13in. and 0.26in counterbore with radius 0.2in

Note: Counterbore for the slot is on the back, counterbores for the thru holes are on the front.
3 0.125 in. radius fillets
0.33 in. deep

4 center holes
\( \phi 0.201 \pm 0.000 \)

3 corner thru holes
\( \phi 0.374 \)

12 45 degree chamfers
0.05 deep
meant for 0.1 in. dowel pins

A (2:1)

REV

ZONE

DESCRIPTION

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APPROVED

REVISIONS

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ANGLULAR MACHN. BEND 2
TWO PLACE DECIMAL 2
THREE PLACE DECIMAL 3

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REVISION SHEET 1 OF 1
12 0.3in. thru holes with 45 degree chamfer 0.06 deep
φ0.300
12 45 degree chamfers
0.5 deep
meant for 0.1 in. dowel pins
12 0.3in. diameter thru holes
with 45 degree chamfer 0.05 deep

<COMPANY NAME>
3.45 degree chamfers
0.05 in. deep
meant for 0.1 in. dowel pin

*R = 0.15 in. radius thru hole

3.45 degree chamfer
0.05 in. deep
meant for 0.1 in. dowel pin

<COMPANY NAME>
## APPENDIX A: ABBREVIATIONS

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<td>EUV, XUV</td>
<td>Extreme Ultraviolet</td>
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<td>UV</td>
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<td>HHG</td>
<td>High Harmonic Generation</td>
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<td>Ti:Sapphire</td>
<td>Titanium Doped Sapphire</td>
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<td>YAG</td>
<td>Yttrium Aluminum Garnet</td>
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