Key components development progress updates of the 250W high power LPP-EUV light source

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ABSTRACT
Gigaphoton Inc. is developing a CO₂-Sn-LPP EUV light source based on unique and original technologies including a high power CO₂ laser with 15 nanosecond pulse duration, a solid-state pre-pulse laser with 10 picosecond pulse duration, a highly stabilized droplet generator, a precise laser-droplet shooting control system and a debris mitigation system using a magnetic field. In this paper, an update of the development progress of our 250W CO₂-Sn-LPP EUV light source and of the key components is presented.

Keywords: EUV light source, EUV lithography, Laser produced plasma, Tin, CO₂ laser, Droplet generator, Collector mirror, Debris mitigation

1. INTRODUCTION

The extreme ultraviolet (EUV) lithography is the most promising technology for a production of next generation semiconductor devices1,2). The dimensions of a transistor get progressively smaller each year to enable higher speed, lower power consumption and larger memory capacity. The current process of semiconductor lithography uses the 193nm wavelength produced by Argon Fluoride (ArF) excimer laser. The latest semiconductor devices are produced using techniques of resolution enhancement such as phase shift illumination, source mask optimization, and optical proximity correction and immersion lithography. The multi patterning technology (double, triple and quadruple patterning) extends the process of shrinking the device dimensions further. Semiconductor devices with node size of 14nm are already in mass production. However, the multi patterning leads to higher production costs due to a necessity for many lithographic and etching processes per wafer. The shrinkage of device size using excimer laser sources and resolution enhancement techniques is therefore approaching fundamental and economic limitations. EUV lithography uses 13.5nm wavelength of EUV light that is >10x shorter than that of ArF excimer laser. This enables the production of devices with 7nm and 5nm feature sizes without a need for multi patterning technologies. Therefore the next generation of highly integrated semiconductor devices can be produced at lower cost and EUV lithography equipment and EUV lithography processes are being developed for this reason. Already, several tens of EUV light sources and EUV lithography tools were shipped and installed in advanced semiconductor factories worldwide. The efforts aimed at productivity and yield improvements are underway. However, the maximum power of EUV sources currently available on the installed machines is around 100W, which is still insufficient to support high-volume-manufacturing (HVM). 250W is required for the mass production of next generation 7nm node size devices and 500W is required for 5nm ones.

Gigaphoton has been developing the laser-produced-plasma EUV light source since 20023-7). The source produces 13.5nm wavelength EUV light from the tin plasma, which is generated by irradiating a tin droplet with a high power, pulsed CO₂ laser. The combination of tin and 10.6um wavelength CO₂ laser is a most effective method to generate EUV light for a number of reasons8). Recently we found that an irradiation of the target, prior to CO₂ laser irradiation, with a pre-pulse of appropriately chosen parameters leads to a dramatic improvement of conversion efficiency (CE). This year we achieved >250W EUV output with 4.7% CE. We have also achieved 119 hours continuous operation with more than 130W EUV output. Furthermore, Pilot # 1 achieved 143 hours of operation at 110W EUV power with 5% average CE. This paper presents the key technology update of the Gigaphoton EUV light source.
2. GIGAPHOTON LPP EUV LIGHT SOURCE SYSTEM

Figure 1 shows the concept of Gigaphoton's high-volume-manufacturing (HVM) EUV light source, which consist of five key technologies:

1) Hybrid CO₂ laser system with solid-state-seeded, multi-line oscillator and fast gas flow amplifiers.
2) Pre-pulse technology for high CE and high ionization rate.
3) Shooting control technology of laser beam position and droplet position.
4) Tin debris mitigation technology exploiting ion guiding with strong magnetic field produced by a superconductive magnet.
5) Collector mirror with a grating structure that is highly efficient at reducing an out-of-band light.

The details of each key technology are mentioned in the following sections.

Table 1 Specifications of Proto#1, #2 and Pilot#1 system

<table>
<thead>
<tr>
<th></th>
<th>Proto#1 Proof of Concept</th>
<th>Proto#2 Key Technology</th>
<th>Pilot#1 HVM Ready</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target</strong></td>
<td>EUV Power 25W</td>
<td>&gt;100W</td>
<td>250W</td>
</tr>
<tr>
<td><strong>CE</strong></td>
<td>3.0%</td>
<td>4.0%</td>
<td>5.0%</td>
</tr>
<tr>
<td><strong>Pulse Rate</strong></td>
<td>100kHz</td>
<td>100kHz</td>
<td>100kHz</td>
</tr>
<tr>
<td><strong>Output Angle</strong></td>
<td>Horizontal 62° upper</td>
<td>62° upper</td>
<td>&gt;75%</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>~ 1 week</td>
<td>~ 1 week</td>
<td></td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Droplet Generator</td>
<td>20-25um</td>
<td>20um</td>
<td>20um</td>
</tr>
<tr>
<td>CO₂ Laser</td>
<td>5kW</td>
<td>20kW</td>
<td>27kW</td>
</tr>
<tr>
<td>Pre-pulse Laser</td>
<td>picosecond</td>
<td>picosecond</td>
<td>picosecond</td>
</tr>
<tr>
<td>Collector Mirror Lifetime</td>
<td>Used as development platform</td>
<td>10 days</td>
<td>&gt;3 months</td>
</tr>
</tbody>
</table>

Figure 1 Concept of Gigaphoton HVM EUV light source system

In our R&D facility, we have been operating three prototypes of EUV light source that are called Proto#1, Proto#2 and Pilot#1. As shown in Table 1, Proto#1 was designed as a proof of concept with a focus on the debris mitigation technique. Proto #2 served as a platform for system control development and CE optimization. Pilot#1 in turn was designed with a thought for a commercial application in a semiconductor fab supporting HVM, and Figure 2 shows system overview of Pilot#1.
3. DROPLET GENERATOR

The droplet generator emits a stream of 20um diameter droplets of tin at 100 kHz repetition frequency into the plasma point located in the center of the EUV chamber. Sufficient position stability of the droplet is required to obtain stable tin plasma and stable EUV emission. The plasma generates the shock wave in the EUV chamber that disturbs the position of subsequent tin droplet. This disturbance of the droplet position significantly affects the EUV stability. We found that >900um spacing between the droplets is required to get around this problem. To cope with this issue, we developed a new, high-speed droplet generator capable of 90 m/s droplet velocity. This means that even at 100 kHz operation, we can get 900um spacing required for a stable generation of EUV light. The progress of development of the droplet generator is shown in Table 2 and Figure 3.

Table 2 Progress of development of the droplet generator

<table>
<thead>
<tr>
<th>Unit</th>
<th>Proto #1</th>
<th>Proto #2 (~2014)</th>
<th>Proto #2, Pilot #1 (Present)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Droplet speed</td>
<td>45 m/s</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Back pressure</td>
<td>12 MPa</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Repetition rate limit</td>
<td>100 kHz</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Status</td>
<td>Proven</td>
<td>Proven</td>
<td>Proven</td>
</tr>
</tbody>
</table>

Figure 3 Improvement of droplet spacing of the new generator
4. HYBRID CO\textsubscript{2} LASER SYSTEM

The CO\textsubscript{2} laser driver must generate pulses of a duration <20ns required for best efficiency of the LPP process, and must deliver >200mJ of energy per pulse at a repetition rate of 100kHz. The only way to meet this >20kW average power requirement is to use master-oscillator-power-amplifier (MOPA) approach. It is well known that an amplification of pulses with duration comparable to the relaxation dynamics of the CO\textsubscript{2} medium is significantly less efficient as compared to a CW operation. For this reason we have developed a multi-line capable master oscillator that can ameliorate the problem of reduced efficiency of pulsed amplification.

The configuration of high power, pulsed CO\textsubscript{2} laser system is presented in Figure 4.

![Figure 4 System configuration of high power short pulsed CO\textsubscript{2} laser](image)

The multi-line oscillator was custom-designed at Gigaphoton especially to deliver the required pulse format. This innovative device combined the RF-discharge-excited, slab-waveguide CO\textsubscript{2} laser technology with the relatively recent, solid-state, quantum-cascade lasers (QCL) used as seeders\textsuperscript{9}). This marriage enabled a robust generation of pulses of excellent stability and duration adjustable within 15-35ns. The multi-line operation was also implemented by combining four QCLs addressing P-branch lines P18-P24 of regular band of CO\textsubscript{2} molecule (10.6 um). Our prior studies have shown that simultaneous amplification on these 4 strongest lines was expected to bring up to 20% energy improvement as compared to amplification on a single line only. The oscillator power was boosted to about 100W by a system of two, multi-pass amplifiers built also on RF-discharge-excited, slab-waveguide CO\textsubscript{2} lasers. The diagram of the short pulse, multi-line oscillator is shown in Figure 5.

![Figure 5 Concept of short pulse, multi-line seeder of the CO\textsubscript{2} laser system](image)

The Gigaphoton’s proprietary master oscillator can work asynchronously with pulse repetition rate from zero to 100kHz, which is ideal for the synchronization between the droplet target and the plasma drive laser. The jitter of the master oscillator pulses was confirmed to be below 2ns, assuring good control accuracy.

The power amplifier stage of the MOPA system consisted of pre- and main amplifiers. The task of the power pre-amplifier was to boost 100W of master oscillator output to the level required for an efficient driving of power amplifier stages. The power stages employed multi-kW, commercial RF-discharge-excited, fast-flow CO\textsubscript{2} lasers. In the Proto systems, fast-axial-flow (FAF) lasers were used as main amplifiers. Recent developments in collaboration with
Mitsubishi Electric Co. have allowed us to use also the fast-transverse-flow (FTF) lasers, which have got a number of advantages over FAF ones\textsuperscript{10}, such as a possibility to arrange multi-passing. An effective preamplifier based on multi-passed FTF laser\textsuperscript{11} was first tested in Proto #2 system. Pilot #1 system in turn has the power side of MOPA built entirely on FTF CO\textsubscript{2} technology. Higher power output and slightly improved beam quality are expected from this system.

The detail of the FTF amplifier unit was shown by Mitsubishi Electric in the 2017 SPIE Advanced Lithography poster 11423-82.

A comparison of beam profiles produced by Proto#2 and Pilot#1 systems are shown in the Figure 6. The uniformity of the beam profiles is improved in the Pilot#1 system. We aim to obtain CE enhancement following the improvement of CO\textsubscript{2} laser beam profile.

![Figure 6 CO\textsubscript{2} laser profiles of Proto#2 and Pilot#1 system.](image)

5. PRE-PULSE TECHNOLOGY FOR HIGH CONVERSION EFFICIENCY

Figure 7 shows the concept of dual-pulse irradiation system.

An improvement of conversion efficiency from CO\textsubscript{2} laser energy to the EUV light energy is one of the most important issues for the development of 250W EUV light source. We found that the application of appropriate pre-pulse prior to the CO\textsubscript{2} laser irradiation highly improved the CE. The droplet is crushed into a mist of sub-micron particles by the shockwave of irradiation with the pre-pulse laser. Thanks to this, the ratio of surface area to the volume of the target increases significantly and the atomization by the CO\textsubscript{2} laser proceeds more efficiently. Furthermore, we found that the CE is further improved by using pre-pulse with picosecond duration as compared to nanosecond one. In Figure 8, the comparison of CE figures obtained with nanosecond and picosecond pre-pulse are presented.

Figure 9 shows the deformation forms of the tin droplet irradiated by picosecond and nanosecond pre-pulse. In the case of nanosecond pre-pulse, the droplet is transformed into a high-density disk, whereas in the case of the picosecond pre-pulse, the droplet expands and takes a dome-like shape of significantly smaller density. The CO\textsubscript{2} laser energy can more effectively penetrate the mist after the Pico second laser is applied, and the entire tin volume can be subject to ionization, which we believe contributes to the improvement of CE and reduced amount of debris.

We also found the pre-pulse conditions to realize 5.5% CE. In the figure 10, the experimental results are presented. These findings will be utilized in our future developments.
Figure 7 Concept of dual shooting and magnetic debris mitigation

Figure 8 Conversion Efficiency of nano-second and pico-second pre-pulse laser

Figure 9 Forming of tin mist of different pre-pulse laser
6. MITIGATION OF TIN DEBRIS

A mitigation of tin debris is important to raise the so-called availability of the EUV light source as a commercial product. With this in mind we developed the magnetic mitigation technology. The concept of this technique is shown in Figure 11.

The tin atoms undergo ionization by the high temperature plasma, become trapped by the strong magnetic field and then guided to the ion catcher. Unfortunately, not all tin can be captured by this magnetic mitigation system. Some fraction of the tin atoms remains neutral or quickly recombines and cannot be guided by the magnetic field away from the collector mirror. The tin atoms that attach to the surface of collector mirror can be removed chemically by stannane gas (SnH4) that is generated by an interaction of hydrogen and EUV light inside the chamber. The disassociation of stannane gas is a secondary source of atomic tin that can contribute to the pollution of the collector mirror. To prevent this, we have attempted to optimize the flow of gas inside the EUV chamber.

Figures 12 shows the distribution of tin deposition rate on collector mirror surface obtained in 2015 and 2017. This data were acquired from XRF analysis for multiple small test pieces attached on dummy collector mirror. Obviously, deposition rate was drastically reduced in these two years by optimizing various conditions inside chamber.

Figure 13 shows the decrease of the collector mirror reflectance versus pulse number. This data was obtained with real collector mirrors. After mitigation improvement, the decrease in reflectance is about 10% at 9.6 Bpl/s. In addition, it also shows measured images of the Far Field.
The mitigation improvement includes optimization of etching conditions, shooting control accuracy, and the like. With this improvement, we have the prospect of achieving a collector lifetime at the level applicable to semiconductor mass production factories. In the future, we will further improve mitigation and continue the evaluation with high EUV output and long operation times.

Figures 12 Improvement of debris mitigation of collector mirror (Sn deposition rate)

Figure 13 Transition of collector mirror reflectance (After/before improvement)
7. SYSTEM PERFORMANCE

We are conducting comprehensive testing of Proto#2 and Pilot#1 light sources. Here, we present long-term stability data of each light source. Furthermore, the EUV energy data by the latest control in Pilot #1 is also shown.

Figures 14 shows Proto#2 data of the dependency of EUV power and CE on CO2 laser power without dose control at 100 kHz pulse repetiton and 50% duty cycle. Previously we achieved a maximum EUV power of 268W with 3.5% CE at 22kW CO2 laser power. In the case of low CO2 laser power, we got >4.0% CE, however. As the CO2 laser output increases, CE decreases (On the left side of FIG. 4). Therefore, we improved the irradiation conditions. As a result, the drop in CE on the high CO2 laser output side was reduced and an EUV output of 302 W could be obtained.

Figure 15 shows data of a long term operation of Proto#2 system, under conditions of dose control realized by controlling the CO2 laser power. EUV power was 188W with dose stability (3sigma) below 0.3%. Operation time was 7 hours with average CE is 3.7% and about 15kW of CO2 laser power. As can be seen in figure 15, the EUV output is controlled to be almost constant. Although CE is declining, this is due to deterioration, and we will make improvements on CE drop.

Figures 14 Improvement of CE on high output side

Figure 15 High power long term operation data in Proto#2
Figure 16 shows the proto#2 data of 119Hours operation data with dose control at 132W condition.

![Figure 16 Long term operation data for 119hours in Proto#2 (Plot: continuously running or continuous operation)](image)

The left side of figures 17 shows recent test data of the pilot # 1 system with dose control feedback at 50kHz. The EUV output was 113W, the average of the dose stability (3 sigma) was below 0.04%, the average CE 5.3%. Continuous source operation lasted more than 143 hours. Sometimes the dose error increases because of an irradiation error. As a measure against that, we are considering a new control method. The right side of figures 17 shows 50,000 pulses of EUV energy, dose error and CE. It can be seen that stable EUV is generated during 50,000 pls.

We introduced a new control scheme to improve the energy control performance of Pilot#1. Figure 18 shows data of dose error before and after improvement. The dose error improves with the new method. Furthermore, we are developing new technologies for controlling the laser optical axis at high speed. This makes it possible to further improve dose error.

![Figures 17 Long term operation data for 143hours in Pilot#1](image)
8. CONCLUSION

The current status of key technology components has been presented for our 250W EUV light source. Gigaphoton’s EUV Proto#2 system achieved maximum 302W EUV power, and 119 hours continuous operation in a condition of 130W EUV power.

We also started operating the Pilot#1 HVM EUV light source system. The Pilot#1 achieved 113W EUV power, 143 hours operation with more than 5.0% conversion efficiency.

We plan to improve mainly the following in the future:
1) The power of CO2 laser driver will be increased up to 27kW.
2) Further improvement of the Sn etching conditions and of the collector mirror lifetime, i.e. to further reduce the decrease in the reflectance of the mirror
3) Introduction of high-speed control and improvement of irradiation accuracy. Thereby further reducing the dose error.

9. ACKNOWLEDGMENT

This work was partly supported by the New Energy and Industrial Technology Development Organization (NEDO), Japan. We acknowledge their continuous support. We acknowledge the following researchers and organizations; Plasma simulation was supported by Dr. Jun Sunahara, Dr. Katsunori Nishihara, Prof. Hiroaki Nishimura, and others in Osaka University; plasma diagnostics was provided by Dr. Kentaro Tomita, Prof. Kiichiro Uchino and others in Kyushu University; laser engineering was supported by Dr. Akira Endo of HiLase Project (Prague) and Prof. Masakazu Washio and others in Waseda University. We also acknowledge many companies and engineers; collaboration by EUV collector mirror suppliers; special thanks are due for the development of CO2 laser amplifiers carried out by a team at Mitsubishi Electric: Dr. Junichi Nishimae, Dr. Shuichi Fujikawa and others.

10. REFERENCES