Update of Development Progress of the High Power LPP-EUV Light Source Using a Magnetic Field

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Gigaphoton Inc. has been developing a CO₂-Sn-LPP (LPP: Laser Produced Plasma) extreme ultraviolet (EUV) light source system for high-volume manufacturing (HVM) semiconductor lithography. Key components of the source include a high-power CO₂ laser with 15 ns pulse duration and 100 kHz repetition frequency, a solid-state pre-pulse laser with 10 ps pulse duration, a high speed Sn-droplet generator, a high-speed and high accuracy shooting system, and a magnetic field debris mitigation system. To achieve an in-band power of 330 W with long collector mirror lifetime and stable output, we improved the performance of key system components. We achieved an in-band power of 250 W under DC operation and demonstrated a power scalability up to 330 W. This paper presents the key technology update of our EUV light source.

Keywords: EUV light source, EUV lithography, Laser produced plasma, Debris mitigation

1. Introduction
The extreme ultraviolet lithography is the most promising technology for a production of next generation semiconductor devices [1,2]. The dimensions of transistor get progressively smaller each year to realize higher speed, lower power consumption and larger memory capacity. The current process of semiconductor lithography uses the wavelength of 193 nm 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 extends the process of shrinking the device dimensions further. However, the multi patterning leads to higher production costs due to a necessity for many lithographic and etching processes per wafer. EUV lithography uses 13.5 nm wavelength of EUV light that is >10× shorter than that of ArF excimer laser. This enables the production of devices with 7 nm and 5 nm feature sizes without a need for multi patterning technologies. Therefore, the next generation of highly integrated semiconductor devices can be produced at lower cost by EUV lithography. Several tens of EUV lithography tools have already been shipped and installed in advanced semiconductor factories in worldwide. The maximum power of the currently available EUV sources on the installed tools is up to 250 W, which is still insufficient to support HVM. A power of more than 330 W is required for mass production of the next 7 nm node size generation and 500 W is required for the 5 nm generation.

Gigaphoton Inc. (GPI) has been developing the LPP-EUV light source since 2002 [3-7]. The LPP-EUV light source is the most promising solution as the high-power light source for HVM semiconductor lithography because of its high efficiency, power scalability, and spatial freedom around plasma. The source produces 13.5 nm wavelength EUV light from the Sn plasma, which is generated by irradiating a Sn droplet with a high-power pulsed CO₂ laser. The combination of Sn and 10.6 μm CO₂ laser is a most effective method to generate EUV light for several reasons.
In addition, for a long collector mirror lifetime, controlling the source debris is an important aspect of the LPP source design. Sn debris deposition can be mitigated by optimum hydrogen (H₂) pressure and flow in the vessel. However, increasing the H₂ flow for higher EUV power decreases the droplet stability due to H₂ gas heating effects. To solve this situation, we developed the debris mitigation technology with a magnetic field [9-13], which reduces H₂ flow to a minimum and efficiently trap Sn ions and exhaust them from the EUV chamber. This paper presents the key technology update of our EUV light source.

2. Gigaphoton LPP-EUV light source system

Figure 1 shows the schematic diagram of our LPP-EUV light source system, which consists of several main key technologies:

a) Minimum-mass target supply technology for reducing debris generation
b) Pre-pulse technology for high conversion efficiency (CE) and high ionization rate
c) Debris mitigation technology with a strong magnetic field and with an optimized H₂ gas flow
d) Spatial and temporal shooting control technology between the droplets and the lasers

The CO₂ laser and the pre-pulse laser beam are combined at the combiner unit and the two laser beams are guided to the Sn droplet at the plasma point through the focus unit inside the EUV chamber system. The droplet-laser shooting maintains synchronization and optimal performance with several control loops. The EUV radiation from the Sn plasma is collected and introduced to the exposure apparatus by the collector mirror. Superconductive magnets installed outside of the EUV chamber produces a strong magnetic field inside the EUV chamber. A strong magnetic field protects the collector mirror from high speed Sn ions produced by the plasma.

To realize our EUV light source system, we have been operating three prototypes of EUV light source; Proto#1, Proto#2, and Pilot#1. As shown in Table 1, major difference between three systems is CO₂ laser power and output angle, other specification and concept is essentially identical.

3. Droplet generator for minimum-mass target supply

In fundamental research of laser produced plasma, it was confirmed that a minimum-mass target substantially reduces debris and out-of-band radiation [14-18]. The optimum size of the droplet is determined by the minimum number of Sn atoms that can obtain the required EUV radiation energy and avoid generation of unnecessary debris. Our droplet generator provides a stream of 20 μm diameter (minimum mass). Sn droplets at 100 kHz repetition frequency into the plasma point located in the primary focal point of the collector mirror. Enough position stability of the droplet is required to obtain stable EUV radiation. The plasma generates a kind of shock wave in the EUV chamber that disturbs the position of subsequent droplets.

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

<table>
<thead>
<tr>
<th>Target</th>
<th>EUV Power</th>
<th>Performance CE</th>
<th>Technology</th>
<th>Droplet Generator</th>
<th>CO₂ Laser</th>
<th>Pre-pulse Laser</th>
<th>Chamber cooling and flow</th>
<th>Collector Mirror Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>25W</td>
<td>3.0%</td>
<td>20 - 25μm</td>
<td>5kW</td>
<td>picosecond</td>
<td>25W level</td>
<td>Use as development</td>
<td>10 days</td>
</tr>
<tr>
<td>Proto#1</td>
<td>&gt;100W</td>
<td>4.0%</td>
<td>20μm</td>
<td>20kW</td>
<td>picosecond</td>
<td>125W level</td>
<td>development</td>
<td>&gt;3 months</td>
</tr>
<tr>
<td>Proto#2</td>
<td>250W</td>
<td>5.0%</td>
<td>20μm</td>
<td>26kW</td>
<td>picosecond</td>
<td>330W level</td>
<td>platform</td>
<td></td>
</tr>
<tr>
<td>Pilot#1</td>
<td>330W</td>
<td>6.0%</td>
<td>20μm</td>
<td>26kW</td>
<td>picosecond</td>
<td>330W level</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
droplets. This disturbance of the droplet position significantly affects the EUV radiation stability. We confirmed that >1000 μm spacing between the droplets is required to avoid droplet disturbance. To realize >1000 μm spacing for a stable EUV radiation at 100 kHz operation, we developed a high-speed droplet generator capable of >100 m/s droplet velocity.

4. Hybrid CO2 laser system and beam transfer system (BTS)

The CO2 laser driver must generate pulses of duration <20 ns required for best efficiency of the pre-pulse irradiation LPP scheme and must deliver 260 mJ of energy per pulse at a repetition rate of 100 kHz. The only way to meet this 26 kW 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 CO2 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.

As mentioned above, we developed a 26 kW CO2 driver laser system for Pilot#1 in 2016. However, as shown in Table 2, there are some topics that become more severe with higher CO2 laser output, due to the increase of optical mirror deformation due to thermal effects, or the effects of the increase of laser gain and intensity, and so on. Hence, we solved each matter that power loss of CO2 laser energy in optical pass, decrease of CE, and damage of optical mirrors or isolators.

If the beam size of the CO2 laser at an optical mirror becomes too large, a power loss of CO2 laser transmittance will be occurred by vignetting. On the other hand, a too small beam size causes optical damage by exceeding the damage threshold. For CO2 laser beam size control, we therefore installed a high-speed Beam Expander (BEX) control system. This system uses the feedback information of the CO2 laser beam size, detected at CO2 laser spot profile monitors. Figure 2 shows the result of a control test in Pilot#1 which demonstrates that this system is suitable to avoid the problems mentioned above.

Astigmatism occurs at some types of optical mirrors and at the BEX, which causes a difference of the focal position between two perpendicular planes. If astigmatism remains at the plasma point, the CO2 laser spot profile is distorted as ellipsoid and causes a decrease in CE. Figure 3 shows the CO2 laser spot profile at the plasma point; left one is Pilot#1 data before countermeasure, right one is small EUV light source experimental device (test bench) data. As countermeasure, for Pilot#1, we redesigned the combination of optical mirrors and BEX, to finally compensate the astigmatism (i.e. to obtain an axially symmetric CO2 laser spot profile) at the plasma point.

Table 2. List of several topics with CO2 laser operation.

<table>
<thead>
<tr>
<th>Mirror</th>
<th>Details</th>
<th>Matters</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 laser</td>
<td>beam is expanding due to thermal deformation of optical mirrors.</td>
<td>Decrease CO2 laser transmittance (Power loss)</td>
</tr>
<tr>
<td>CO2 laser</td>
<td>spot profile at plasma point is distorted as ellipsoid.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scattered or distrected CO2 laser beam is amplified inside the amplifiers, which</td>
<td></td>
</tr>
<tr>
<td></td>
<td>self-oscillation generate an oscillation state and back reflection by itself. A part of the CO2 laser beam that has reached at plasma point is reflected by droplets, and returned to oscillators and amplifiers.</td>
<td>Damage of optical mirrors or isolators</td>
</tr>
</tbody>
</table>

Fig. 2. Result of CO2 laser beam size control and CO2 laser beam profile in BTS, (a) initial beam profile, (b) the profile after 2 seconds without beam size control, and (c) the profile after 2 seconds with beam size control.

Fig. 3. Example of CO2 laser spot profile in Pilot#1 and Test Bench.
To reduce self-oscillation and back reflection, we redesigned the internal structure of the pre-amplifier with Mitsubishi Electric Corp. and changed operation parameters of pre-amplifier and main amplifiers. Figure 4 shows the result of the test in Pilot#1, before and after the countermeasure for back reflection. This graph shows that back reflection decreased to one third, which is enough to not exceed the damage threshold of optical mirrors or isolators at 26 kW CO2 laser output.

Fig. 4. Result of the test in Pilot#1, before and after countermeasure for back reflection.

5. Pre-pulse technology for high CE, high ionization and high-power demonstration

Pre-pulse laser technology is one of the key technologies for producing high CE. As mentioned above, our minimum-mass liquid Sn droplet target is of 20 μm diameter. The CO2 laser spot diameter, on the other hand, is at least several hundred μm to obtain optimal CO2 laser intensity for high CE at high pulse energy (i.e. HVM light source for EUV lithography). The 20 μm diameter droplet is too small to be irradiated by the CO2 laser with a spot diameter of several hundred μm. To solve this mismatch between the droplet size and the CO2 laser spot size, the droplet must be expanded prior to CO2 laser irradiation.

Physical key points of high CE plasma generation are optimization of target density distribution and extension of the laser absorption length. A liquid (solid) Sn target has the potential to produce a high CE but strong self-absorption of the in-band radiation due to an optically thick plasma can drastically reduce the CE [19,20]. The CO2 laser is an optimum driver laser [20-22], because Sn plasma produced by CO2 laser is optically thin for the in-band radiation i.e. self-absorption in the plasma is negligible [19]. The reason is that the critical plasma density depends on the drive laser wavelength. For example, the critical density at 10 μm laser produced plasma is two orders smaller compared to a 1 μm laser produced plasma [23].

In a previous study, the application of appropriate pre-pulse prior to the CO2 laser irradiation highly improved the CE. The droplet is crushed into a mist of sub-micron particles by pre-pulse laser irradiation. As a result, the ratio of surface area to the volume of the target increases significantly and the atomization by the CO2 laser proceeds more efficiently. Furthermore, we confirmed that the CE is further improved by using pre-pulse with picosecond (ps) duration as compared to nanosecond (ns) one [24]. Figure 5 shows Sn mist shapes after 10 ns (a) and 10 ps (b) pre-pulse laser irradiation before CO2 laser irradiation. Figure 5 (c) shows the EUV light radiation image just after CO2 laser irradiation using 10 ps pre-pulse laser. In the case of ns pre-pulse, the droplet is transformed into a high-density disk, whereas in the case of ps pre-pulse, the droplet expands and takes a dome-like shape of significantly low-density. This dome-like target, close to optimum target (low-density and long-scale length), produces the high CE by long-scale length EUV radiation shown in Fig. 5 (c). The CE of ns and ps pre-pulse obtained in test bench exceeded 2.5% and 4.5%, respectively. And, in the case of ps pre-pulse irradiation, the ionization rate is over 98% [25].

Fig. 5. Sn mist (a) with 1 μm -10 ns pre-pulse laser, (b) with 1 μm -10 ps pre-pulse laser, and (c) image of EUV radiation after CO2 laser irradiation with 10 ps pre-pulse laser.

We developed CE using a fundamental experiment with data taken at about 100 mJ CO2 laser energy. However, to achieve 330 W, we need to re-optimize plasma-related parameters (CO2...
Figure 6 (a) shows the result of the latest CE improvement research done at test bench. We optimize the plasma-related parameters and CO₂ laser energy. Optimized plasma-related parameters “Condition B” improved CE around 5% to 6%. With extrapolating this result, CO₂ laser power of 18 kW would be necessary to obtain 330 W in-band EUV power in Pilot#1. To apply “Condition B” for Pilot#1, we redesign system components, for example CO₂ laser BTS as we mentioned above.

Figure 6 (b) shows the latest result of high in-band EUV power and CE improvement done in Pilot#1. We optimized plasma-related parameters and varying CO₂ laser power from 4 kW up to 26.5 kW. We could confirm CE from 4.7% to 5.2%, and a maximum in-band power up to 330 W at CO₂ laser power of 26.5 kW. Non-linear behavior between CE, in-band power and CO₂ laser energy is coming from complex dynamics of droplet ablation, plasma generation and shooting method etc. We continue to investigate further improvement of CE.

6. Debris mitigation technology

The debris from the laser produced Sn plasma consists of energetic Sn ions, neutrals, and fragments. These factors cause coating sputtering, Sn implantation into the coating, deposition on the coating surface of the collector mirror, resulting in a reduction in the reflectivity of the EUV collector mirror. Especially, the allowance amount of Sn deposition on the collector mirror is very small. A deposited Sn thickness of around 1 nm, i.e. only several atomic layers, reduces the collector mirror reflectivity by 10% which is commonly regarded as the collector mirror lifetime specification. To realize the EUV collector mirror lifetime required for production-scale light source, GPI has been developing and optimizing a minimum-mass Sn droplet target, a pre-pulse irradiation scheme, and a Sn debris mitigation technology combining a magnetic field and H₂ gas flow.

In practice, not all Sn atoms supplied to the plasma generation point can be trapped by this magnetic mitigation system. Some fraction of the Sn atoms remains neutral or quickly recombines and cannot be guided by the magnetic field. The Sn atoms that deposit on the collector mirror can be removed chemically by etching, i.e. stannane gas (SnH₄) that is generated by an interaction of H₂ gas

Fig. 6. (a) Result of optimization of plasma-related parameters for higher CE with a test bench and (b) result of optimization of plasma-related parameters for higher CE with proof of principle system.

Fig. 7. Reflectivity measurement of actual collector mirror.
and EUV light inside the chamber. The dissociation of SnH\textsubscript{4} gas is a secondary debris source. SnH\textsubscript{4} dissociation takes place due to energy transfer when it collides on the collector mirror surface. The Sn atom then adheres to the collector mirror surface. If the amount of reattached Sn exceeds the Sn etching rate, Sn will remain on the collector mirror surface. Therefore, it is necessary to efficiently exhaust the generated SnH\textsubscript{4} gas from the vacuum chamber. In addition, the thermal dissociation of SnH\textsubscript{4} gas changes with the catalytic effect of the surface material. Hence, selecting a coating material with large activation energy for dissociation Sn deposition can be prevented.

To exhaust all Sn atoms from the EUV chamber efficiently, we optimized the flow of H\textsubscript{2} gas inside the chamber. In this concept, the H\textsubscript{2} gas flow and the chamber pressure can be minimized because almost all Sn debris can be trapped as Sn ions by the magnetic field. Figure 7 shows the degradation of the reflectance of actual collector mirrors under various conditions. The best collector mirror degradation rate is -0.5%/Gpls. According to the analysis of that experiment, the main limitation of this degradation rate is the dissociation of SnH\textsubscript{4} gas. The coating sputtering and the Sn implantation are sufficiently suppressed, i.e. they are well below -0.05%/Gpls due the magnetic field. To achieve further improvement for the 330 W HVM target above -0.05%/Gpls, we plan to redesign the EUV chamber in order to optimize the H\textsubscript{2} gas flow for improved reduction of the SnH\textsubscript{4} gas density over the whole surface of the collector mirror. In addition, optimization of the collector mirror coating will assist the formation of SnH\textsubscript{4} gas by catalysis.

7. Control technology

Several key technologies must be well controlled for EUV dose stability. To achieve enough performance, our system has several shooting controls loops to ensure a spatial and temporal shooting accuracy between the droplets and the lasers synchronization of \(\mu\text{m}\) and ns order. These control loops include droplets position control, laser beam axis control and timing control.

If the shooting control between droplet and lasers is insufficient, a part of the target droplet remains as fragments, which deposit on the collector mirror. Fragments, however, are difficult to displace by H\textsubscript{2} etching, therefore it is important to suppress the generation of them. Our previous studies on test bench have shown that the generation of fragments can be drastically suppressed by less than 10 \(\mu\text{m}\) accuracy of shooting control [26].

To realize that accuracy, we developed a high-speed laser beam axis control system (beam control frequency 20 Hz \(\Rightarrow 1\) kHz). The droplet shift is tracked with a high-speed actuator, using EUV energy information. Figure 8 shows the result of a shooting performance test with and without the high-speed laser beam axis control. During the initial few 10 ms, the droplet shift caused by H\textsubscript{2} gas flow and shooting is over ±40 \(\mu\text{m}\), the EUV energy therefore drops to zero without the high-speed laser beam axis control. On the other hand, with the high-speed laser beam axis control, the EUV energy is kept at the initial level.

![Fig. 8. Result of shooting performance test with and without a high-speed laser beam axis control.](image-url)
8. EUV light source system performance

Figure 9 shows dose control 250 W operation result conducted at 100 kHz and 100% duty cycle for 10 Bpls with Pilot#1 after upgrading shooting system with adapting a high-speed laser beam axis control system, suppression of back reflation, 1 kHz beam control system, optimized plasma related parameters and debris mitigation system.

We are continuously improving enhanced droplet formation, applying high-speed laser beam axis control technology and debris mitigation system in Pilot#1. With these technologies, it is possible to further suppress fragments, and extend lifetime of collector mirror.

9. Conclusion

The current status of key components has been presented for our high-power EUV light source Pilot#1 with unique debris mitigation system. We have upgraded EUV light source with the shooting system with adapting the high-speed laser beam axis control system, suppression of back reflation, 1 kHz beam control system, debris-mitigation system and optimized plasma related parameters. EUV light source system demonstrated 250 W DC with dose control at 100 kHz operation for 10 Bpls. And, in-band power of 330 W was demonstrated under burst mode operation.

We plan to improve following items to realize 330 W DC operation with long collector mirror lifetime and stable dose performance:

1) The CE higher than 6% via optimization of plasma-related parameters in Pilot#1.
2) Further reduction of the dose error and small Sn debris via application of the high-speed laser beam axis control and development of enhanced droplet formation in Pilot#1.
3) The reflectivity degradation rate to -0.05%/Gpls via optimization of the H\textsubscript{2} gas flow, optimization of the collector mirror coating material and redesign of the EUV chamber structure.

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