# High Power Short Pulse Laser Modules for Laser Produced Plasma EUV Source

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## Abstract

We have recently made significant steps forward in the performance of our laser driver module employed in our laser-produced plasma (LPP) EUV source. We have increased the average power output from the laser whilst minimising the overall Cost of Ownership (CoO) and footprint of the system. In addition to minimising the CoO of the laser solution, it is necessary to choose an appropriate target that can attain the overall requirements of EUVL. We are currently investigating solid xenon jets, as well as other target materials, in order to increase the conversion efficiency of the source and therefore further drive down its CoO. We have prepared a source roadmap in response to industry demands, and it shows that the combination of our demonstrated laser technology with available targets will meet the requirements for a production level source.

## 1. Introduction

EUV Lithography is considered to be one of the most attractive candidates to succeed conventional optical lithography in the coming years. This will permit reduction of structure sizes in semiconductor devices to less than 50nm. To enable this technology, a light source is required that emits in the spectral range around 13nm. The LPP EUV source has great potential to be the future source for EUV lithography, and offers several advantages over discharge-based EUV sources. These advantages can be summarised as power scalability through tuning of lasers parameters, low debris, pulse-to-pulse stability (optimum dose control), flexibility in dimensions, spatial stability, minimal heat load and large solid angle of collection **[1].**

The main objective of the EUV programme in Powerlase is to develop a high power, cost effective source able to deliver enough useable power for use in the microlithography process. We have successfully generated EUV radiation using a laser-produced plasma (LPP). In this scheme, we spatially multiplex (combine) several of our lasers and focus them onto a xenon target. To achieve this, Powerlase has successfully developed a laser suitable for generating efficient EUV emitting plasmas, such that the EUV source can be incorporated into the lithography tool. Powerlase has already demonstrated that our lasers are the most efficient high power lasers available **[2]**.

In addition to sustained laser development, we are taking the responsibility of developing an appropriate target to achieve what we have projected in our EUV development source roadmap **[3]**. The target development is not restricted to Xe solid jets but other targets materials are also investigated in order to increase the in-band EUV conversion efficiency (CE). The combination of highly efficient lasers and high CE of the in-band EUV through target development drives down the CoO of the EUV source. We believe that the CoO of the LPP source is comparable to the DPP source, and this will position Powerlase as a major competitor to the DPP source suppliers in terms of both capital and daily running costs of the EUV source.

## 2. Laser system

Our lasers are built to perform a variety of applications in a wide range of industrial sectors. One of these applications is the use of high power laser as a driver for the generation of LPP EUV sources.

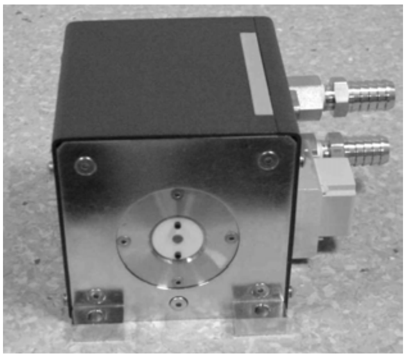

Figure 1a Gain module

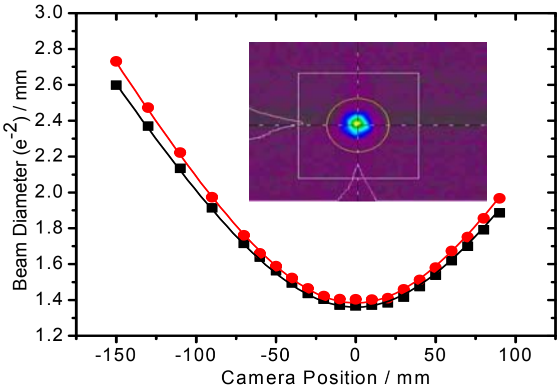

Figure 1b $M^2$ at power of 700Watt

The gain modules used in the LPP driver are extremely efficient and this is of course critical in order to maintain high overall efficiency of the EUV system. This in turn minimises the overall CoO and particularly the daily running cost. Figure 1a shows our gain module. An electrical to optical CE was measured to be 18% with room for further improvement. This is due to an excellent coupling between the laser crystal and diode pump power. The beam properties of the LPP driver were kept almost constant while increasing the output power. This has direct impact on the conversion efficiency and the stability of the EUV source. Beam quality of our laser beam was measured and a typical $M^2$ measurement is shown in figure 1b. It is also important to mention that our laser pulse duration is 9ns, and this has two important roles. One is purely technical which is to maintain the critical value of the peak intensity on target in order achieve the optimal CE. Also the hydrodynamic time scale of the specified temperature for 13.5nm lines for Xe is around 10ns, therefore, having a longer pulse duration will not enhance the CE because on longer timescales energy coupling becomes increasingly inefficient. The other important point is that from a commercial point of view, longer pulses require more lasers in order to reach the peak intensity required on target, leading to an increase in the cost of ownership (CoO) **[4]**.

The average laser power on target was achieved by spatially multiplexing a number of laser beams. Spatial multiplexing is based on a straightforward and easily scalable architecture. One laser is able to generate plasma for alignment purposes and laser energy from several lasers is added in order to achieve the required peak intensity for optimum EUV CE. The overlapping of the laser beams on target was monitored continuously. Previous measurements demonstrated the precision of this technique, such as the pulse-to-pulse stability of the EUV source, which was shown to be 3% and is a good indicator of how beams are overlapping [**5**].

Combining multiple lasers using the spatial multiplexing method offers several advantages over using a single high power laser as an LPP driver. Firstly, greater flexibility is offered in terms of scalability. Secondly, if a fault occurs on one of the multiplexed modules, the EUV system can continue to run (albeit at slightly reduced output power). This is in contrast to the single laser solution in which a laser fault would lead to shutdown of the complete EUV system.

## 3. EUV targets

In addition to laser development, Powerlase is engaged in LPP target development. The target we currently use is Xe. The vacuum system is capable of achieving an ultimate pressure of $5\times10^{-10}$ mbar. This is achieved using two 3000l/s turbo pumps. The working background pressure when Xe is injected is around $10^{-3}$ mbar, which minimizes the in-band EUV absorption to less that 10%. The Xe used is recycled in a closed loop thereby dramatically reducing the cost of the gas management system. Furthermore, the recycling system has a small footprint and employs continuous gas filtration, which strongly reduces contamination introduced by the ingress of moisture from vacuum components. From RGA spectra we have measured a hydrocarbon level of $\Sigma 45\text{-}200 \leq 5\times10^{-10}$mbar, and water level (peak 18)~ $10^{-9}$ mbar. These are acceptable levels of contamination according to EUVL stepper manufacturers requirements. The high-pressure Xe recycling system is capable of safely supplying up to 50bar at the nozzle inlet at a constant flow rate, which is crucial for providing an acceptable EUV source pulse-to pulse stability. However, the target was evaluated against certain criteria to match the requirements of EUVL. These criteria include high CE with minimum target-induced debris, low level of hydrocarbon and water from the target, refreshable and stable target, the target can be recycled, and most importantly can be efficiently pumped to minimize the EUV absorption in background gas. A Xe target in the form of a cluster gas jet was tested here and high CE was achieved, but this did not satisfy the induced debris criterion on account of plasma-induced nozzle erosion. A typical spectrum of Xe is shown in figure 2. The spectrum shows clearly the peak at 13.5nm and this is due to efficient pumping throughput and minimization of background pressure.

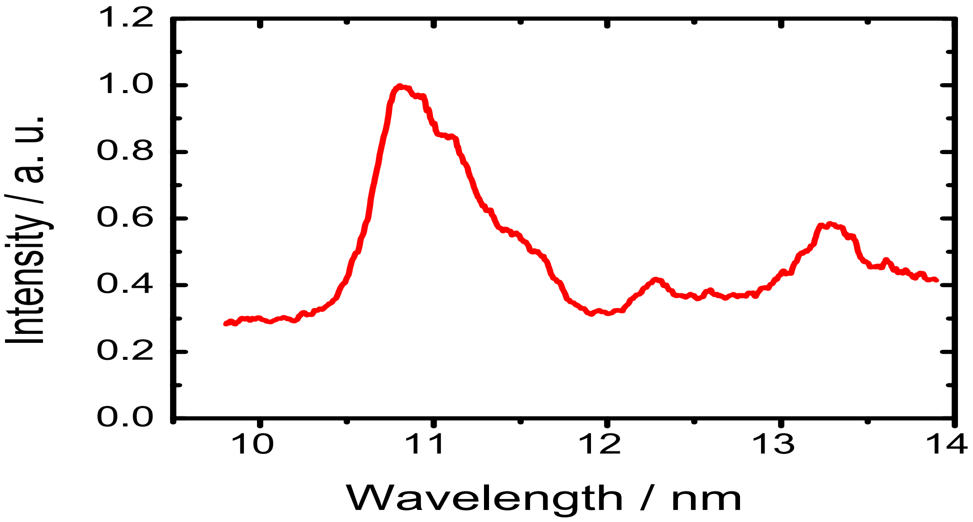

Figure 2 Xe spectrum was taken using transmission grating spectrometer (TGS)

In order to increase the CE and minimize the contamination effect associated with the gas nozzle we are currently using a solid Xe jet and working towards achieving 1% CE in 2π steredians. The plasma is placed around 25mm from the tip of the nozzle. A picture of the Xe solid jet is shown in figure 3. Fast Xe ion debris, which is associated with this target, is being addressed and countermeasures are under investigation in order to minimize their effect on the first optic and surrounding hardware.

Figure 3 Solid Xe jet

Achieving a higher CE and maintaining the cleanliness of the EUV photons will provide us with great opportunity to reduce the CoO even further.

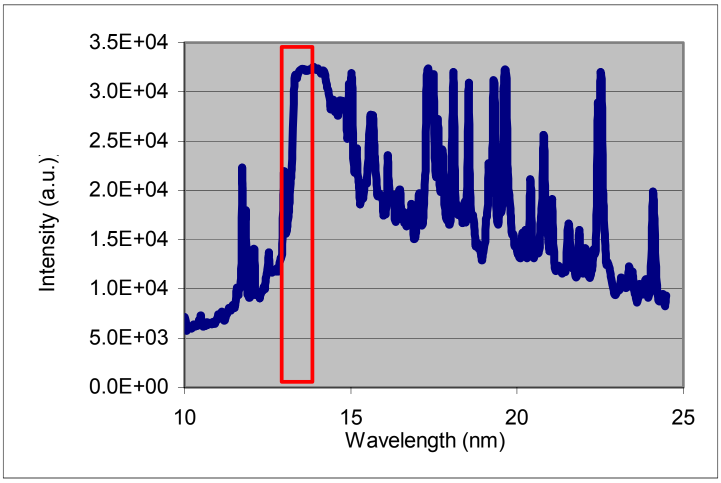

Figure 4 Sn spectrum taken using flat field spectrometer (FFS)

Alternative targets were considered with a view to increasing conversion efficiency. Tin (Sn) has already demonstrated higher CE, for instance 1.5%CE in $2\pi$sr was achieved. A typical spectrum of Sn is shown in figure 4.

We are proceeding carefully before introducing tin to our system due to the potential for target induced contamination and target additive ions contamination. However, as a high power laser manufacturer we always welcome new approaches to enhance the EUV conversion efficiency. We believe that with further engineering and more research Sn could be the target of choice for future EUV LPP sources. Discharge produced plasma (DPP) sources, on the other hand, face severe technical difficulties regarding the introduction of tin into gas discharge schemes.

In order to determine the angular distribution and the out-band radiation we have assembled a photodiode array at a distance of 110mm from the EUV source. The diode assembly is also equipped with multi layer mirror (MLM) samples to study debris induced from the source. A cross section of our vacuum chamber illustrating these diagnostics is shown in figure 5.

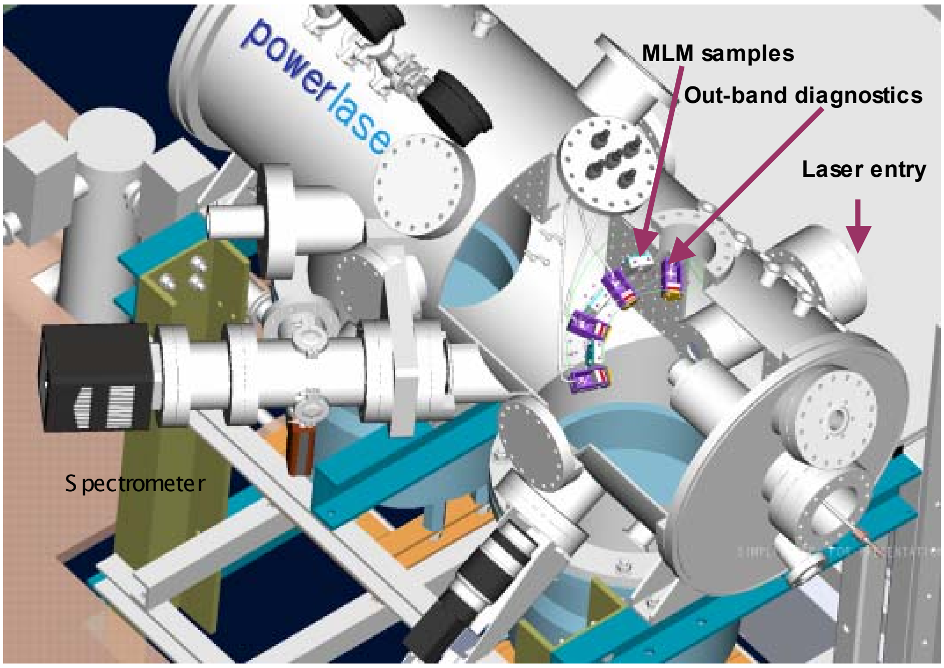

Figure 5 EUV vacuum chamber.

Out-band measurements using a Xe target showed that almost 60% of the emitted plasma radiation is in the region 5-20nm. Angular distribution measurements, shown in figure 6, exhibit less than 10% variation of the EUV intensity.

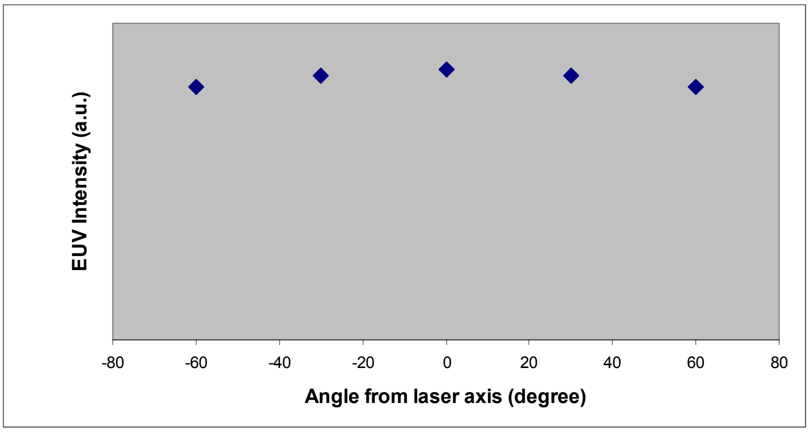

Figure 6 Angular distribution of the EUV source

## 4. Cost of Ownership

The stepper manufacturers' requirement for the EUV source power at the intermediate focus is 110W. We believe that LPP source technology has the upper hand in providing this level of power for production tools, but CoO is a critical consideration. Capital and running costs are critical to LPP source commercialization and integration with the EUV lithography tool. Powerlase has projected the cost of the LPP source and found it to compare favorably with the DPP source in terms of capital and daily running costs. Figure 7 shows Powerlase EUV roadmap and the capital cost of the source for each year. As a high power laser manufacturer, it is important for us to adhere to what we have predicted here. This projection represents our best estimate of the true cost of the LPP source.

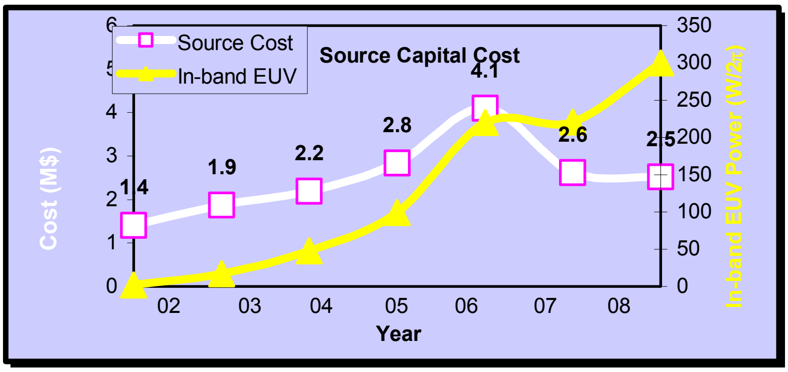

Figure 7 Source capital costs.

The projected CoO model is based on cost of the laser diodes, laser design and EUV target used. However, further reduction in cost can be achieved by addressing the following:

1. Laser diode costs
2. Solid state laser efficiency
3. EUV conversion efficiency and target commercialization
4. Collector efficiency
5. Photoresist exposure requirements.

Figure 7 above also shows that the EUV power will be available for use by the end of 2006 at a price of around US$4M using Xe target. Moreover, if a target such as tin is mature enough by 2006 the cost of the source will be even lower. With time and progress we estimate that the EUV source used in the EUV tool will cost around US$2.5M.
In figure 8 we show our progress from 2002 to date. We can see clearly that the cost per watt has reduced dramatically, and by 2008 the cost of 1 EUV watt will be approximately US$8,000. Note that it is most important to compare LPP to DPP in the final stages approaching large-scale production, as this is where the superior scalability of LPP technology will be decisive.

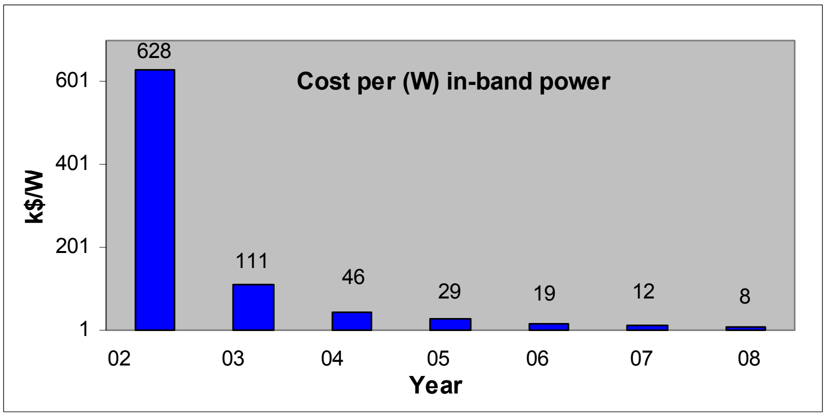

Figure 8 The EUV cost per watt.

## 5. Conclusion

In conclusion, Powerlase has made major steps forward towards the development of the EUV LPP source. We have proven the ability of our core laser technology and delivered a viable roadmap with attainable goals and a realistic projection of Cost of Ownership. We have shown that LPP is comparable in cost to DPP in the production phase and has a number of technical advantages.

### Acknowledgment

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