A high-power short-pulse laser for EUV source generation using laser produced plasma and achieving low cost of ownership

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ABSTRACT

Powerlase has made significant advances towards making the LPP EUV source the most likely choice for a full production EUV lithography machine. Our main achievement was enhancing the performance of the LPP driver and particularly increasing the average power per laser module. This was achieved by increasing the electrical to optical conversion efficiency of our gain modules. In order to increase the conversion efficiency of the in-band EUV, we are currently using cryogenic solid xenon, as well as other target materials. The combination of an efficient and cost effective laser driver with appropriate choice of target material significantly lowers the Cost of Ownership (CoO) of the LPP EUV source, including day to day running, making it comparable to the cost of Discharge Produced Plasma (DPP) sources.

1. INTRODUCTION

A laser-produced plasma (LPP) optimized for emission in the EUV spectral region offers a scalable route towards a production level light source for next generation lithography. Compared to competing technologies based on discharge-produced plasma (DPP) sources, LPP has a number of advantages including flexibility of dimensions, spatial stability, large solid angle of light collection and low debris, whilst maintaining a favorable cost of ownership.

This article provides an overview of the EUV source currently under development at Powerlase. Particular attention is given to the advanced high power laser driver, which recently has been significantly improved by increasing output power whilst maintaining the footprint and cost of the laser module. Before discussing this laser system, consideration is given to the optimum laser parameters required for efficient EUV generation.

2. HIGH POWER LASER DRIVER

2.1. Introduction

A key element in the design of an LPP source is the choice of laser driver parameters. Certain parameters, such as laser pulse energy, pulse duration and beam quality (as quantified by the M^2 parameter) must be chosen in order to optimize the conversion efficiency of laser radiation into in-band EUV radiation. The choice of target (particularly its initial size and composition) and knowledge of optimum plasma conditions must also be taken into account when choosing these parameters.

Other parameters, such as average output power and repetition rate, are chosen in order to satisfy the EUV output requirements specified by the lithography tool manufacturers. In the next sections these parameters are discussed in detail.

2.2. Laser parameters for efficient EUV generation

Physical arguments can be used to estimate the optimum values of those laser parameters influencing the conversion efficiency of laser radiation into in-band EUV radiation. The parameters should be chosen such that an optically thick plasma is formed and maintained at the correct temperature for EUV generation near the Planck limit.

The optimum plasma temperature can then be estimated from the simple formula $T \sim E_{ph}/3$, where E_{ph} is the photon energy associated with the wavelength of maximum emission. For EUV lithography the wavelength of interest is 13.5 nm, corresponding to $E_{ph} = 92.1$ eV and therefore an optimum temperature $T\sim 30$ eV.

Following this reasoning, the required focused laser intensity I [Wcm^{-2}] can be estimated by equating it to the emitted intensity of a Planckian radiator. This leads to the expression $I \sim \sigma T^4$, where σ is the Stefan-Boltzmann constant and T is the plasma temperature. For T~ 30 eV, this yields $I\sim 10^{11}$ Wcm^{-2}.

The laser pulse duration defines the plasma heating timescale and must be carefully chosen in order for deposited energy from the laser to be efficiently converted into EUV radiation. This is because there are other timescales associated with the evolution of the laser-produced plasma that dictate the choice of pulse duration.

For instance, there is a relaxation timescale corresponding to the time required for the plasma ionization (which can be regarded as an internal degree of freedom) to reach equilibrium: In the early stages of the interaction free electrons are produced via high-field ionization, after which laser energy is deposited primarily into the electrons through collisional absorption[1]. Further ionization occurs when energy is transferred from the electrons to the ions via inelastic collisions. This process continues until a steady ionization state is reached, at which point the plasma ionization and excitation are described by the Saha equations[2]. For temperatures of interest here, this timescale is ~0.5 ns[3].

Another timescale concerns the time taken for the expanding plasma to become optically thick to its own emitted radiation (which for $T \sim 30$ eV corresponds to EUV radiation). The optical thickness τ of the plasma can be estimated from the formula for the optical thickness of a Doppler broadened line[4],

$$\tau \sim 30\left(\frac{\lambda}{13nm}\right)\left(\frac{m}{131}\right)^{1/2}\left(\frac{30eV}{T}\right)^{1/2}\left(\frac{n_i}{10^{20}\,cm^{-3}}\right)\left(\frac{L}{10\mu m}\right)\left(\frac{f}{0.1}\right)$$

where λ is the emission wavelength of interest, m is the ion mass measured in atomic mass units, n_i is the ion density, L is the thickness of the plasma layer and f is the oscillator strength of the line.

The characteristic electron density of the plasma is of the order of the critical density $n_{cr}[cm^{-3}] \sim 10^{21}/\lambda_l^2[\mu m]$ (where λ_l is the laser wavelength), as the majority of the laser radiation is deposited in the region of the critical surface. For a laser wavelength $\lambda_l = 1.064$ μm (typically produced by solid state Nd: YAG lasers) and an average ion charge state $Z \sim 10$, the corresponding characteristic ion density $n_i \sim 10^{20}$ cm^{-3}.

The thickness of the plasma layer L as a function of time t can be estimated from $L \sim c_s t$, where c_s is the plasma sound speed given by $c_s = (ZkT/m_i)^{1/2}$. The physical thickness of the critical density plasma layer is required to evolve to the point where $\tau >> 1$. Taking $\lambda = 13$ nm, m=131 (for xenon), T=30eV, $n_i = 10^{20}$ cm^{-3}, $f = 0.1$, it follows that $\tau \sim 30$ for $L = 10$ μm. Using the sound speed formula, this occurs at $t \sim 1$ ns.

The two timescales discussed above determine the time taken to create the optimum plasma state for EUV emission, and therefore place a lower limit on the laser pulse duration. However, the optically thick, critical density plasma has a finite lifetime t_{max} due to hydrodynamic expansion, dependent on the initial size of the target, d. For times much larger than

t_{max}, the characteristic plasma density drops below critical density, and the laser energy is no longer efficient absorbed in the plasma. The timescale t_{max} therefore places an upper limit to the laser pulse duration, and can be estimated from the following expression[5],

$$t_{\max} \sim \left(\frac{n_{e0}}{n_{cr}}\right)^{1/3} \cdot \frac{d}{c_s}$$

where n_{e0} is the electron density of the initially unperturbed plasma and c_s is the plasma sound speed. The above expression can be re-written using characteristic values as follows: -

$$t_{\max} \sim 15\left(\frac{n_{eo}}{10^{23}\,cm^{-3}}\right)^{1/3}\left(\frac{10^{21}\,cm^{-3}}{n_{cr}}\right)^{1/3}\left(\frac{10}{Z}\right)^{1/2}\left(\frac{m}{131}\right)^{1/2}\left(\frac{30eV}{T}\right)^{1/2}\left(\frac{d}{50\mu m}\right)\ \mathrm{ns}$$

In the case of the high-density xenon filament target currently under development at Powerlase (discussed in a later section), $d \sim 50$ µm. Taking Z=10, m=131, T=30 eV, $n_{eo}=10^{23}$ cm^{-3}, and $n_{cr}=10^{21}$ cm^{-3}, the above expression gives $t_{max} \sim 15$ ns. It follows that the optimum pulse duration for EUV generation using this target is of the order of 10 ns.

The laser focal spot size is often dictated by the initial size of the target from which the plasma is formed. For targets with $d > 30$ µm, the beam quality specification of the laser can be relaxed as the laser is not required to be focused to a diffraction limit spot. The laser driver can then be designed to operate at a higher M^2 value, which has the advantage that stored energy can be more efficiently extracted from the gain modules containing the optical pumped Nd: YAG rods[6]. Larger targets are also favorable from the point of view of increasing EUV conversion efficiency, but this point must be balanced by the fact that debris production also increases with target size.

2.3. Powerlase Starlase Laser System

Having considered the optimum laser parameters for efficient EUV generation, the laser solution under development at Powerlase is now presented.

The Starlase range of lasers is based on completely solid-state technology that employs diode pumping of Nd: YAG rods in order to generate laser radiation at a wavelength of 1.064 µm. The system currently under development for EUV generation utilizes electro-optical (EO) switching to generate short laser pulses with 9 ns duration, and is therefore ideal for use with micron-scale, solid density targets. At the present time, the laser is capable of producing an average output power of up to 1 kW at a repetition rate of 3.5 kHz, and operates with a beam M^2 of 12.

One key feature of the laser technology is that excellent electrical to optical conversion efficiency has been achieved. This is a consequence of three important factors. Firstly, conversion efficiency of electrical power to optical power provided by the pump diodes is excellent at approximately 50%. Secondly, careful gain module design has been employed in order to optimize and homogenize the coupling of diode pump power to the Nd: YAG rod (Figure 1). Thirdly, continued development of the laser configuration and improved switching technologies allow power to be efficiently extracted from the gain modules. As mentioned earlier, by relaxing the beam quality requirement of the laser, the extraction efficiency of power from the gain modules can be further enhanced. Figure 1 also shows an example of beam quality data used to determine the M^2 parameter. This is done by scanning a CCD camera through the beam waist of the focused laser beam in order to measure beam size at a number of positions, and then fitting the points with a curve generated from Gaussian beam propagation theory[7].

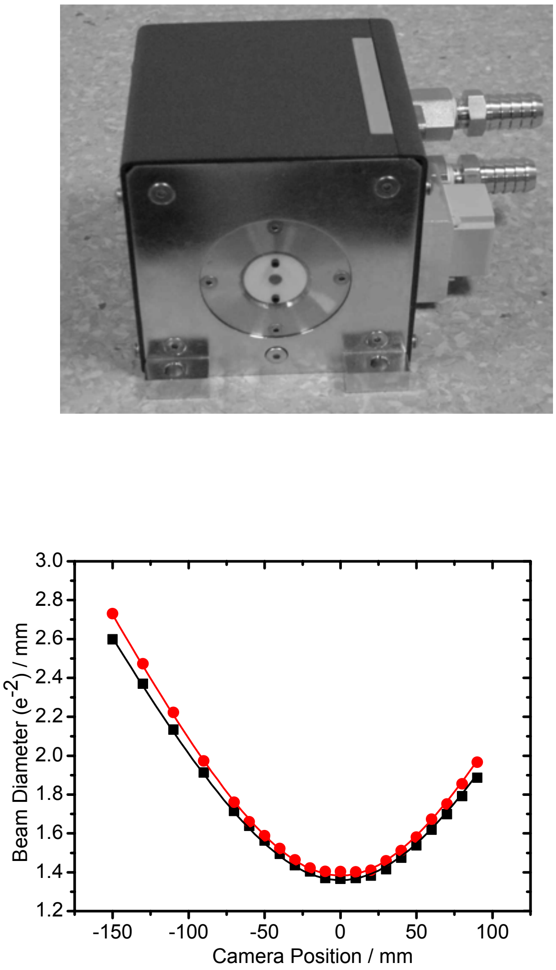

Figure 1: Powerlase gain module (top) and beam size data (bottom) used to infer beam quality (M^2 parameter).

Within the context of the complete EUV light source, a key efficiency factor is the conversion efficiency of laser energy into in-band EUV radiation. To date, we have measured an EUV conversion efficiency of 0.8%/2π sr/2%BW using the Starlase system to irradiate a jet of xenon clusters a short distance (~ 1mm) away from the gas supply nozzle. However, in order to reduce source-induced debris and increase conversion efficiency, work has begun on developing a high-density xenon filament as the next stage in LPP target development. This type of target has been shown[8] to exhibit an EUV conversion efficiency of up to 0.95%/2π sr/2%BW. We have so far demonstrated a conversion efficiency of up to 0.8%/2π sr/2%BW using a 50 μm diameter xenon filament. Figure 2 shows a section of the Powerlase EUV source roadmap, which was prepared in response to industry demands. This illustrates that advanced target and laser technology, both of which have already been demonstrated at the present time, can be combined to produce an EUV source capable of satisfying industrial requirements.

The current EUV source power requirement is 115W at the position of the intermediate focus (IF) following the collection optics. This requires 15-25kW of laser input power depending on the choice of target in the final stages of source development. In order to produce the required level of laser power and be able to deliver it to the LPP target, Powerlase is continuing to increase the output power of the EO-switched laser module whilst employing spatial multiplexing (discussed in the next section) to combine multiple beams on target. The output power of the laser module is scaled up using a combination of increased repetition rate along with enhancements to key laser components such as cavity, gain module and switch design.

	Oct-02	Today	End-2004	Future		
				05	Xe	Sn
Solid state laser driver (kW)	**0.450**	**1**	**3.6**	**8.5**	**25**	**15**
Net conversion efficiency (%)	**0.5**	**0.8**	**0.9**	**1**	**1.2**	**2.5**
EUV power (W/2π)	**2.25**	**8**	**32.5**	**85**	**300**	**375**
Collection angle (sr)	**5**	**5**	**5**	**5**	**5**	**5**
Collector Efficiency	**40%**	**40%**	**40%**	**45%**	**45%**	**45%**
EUV at IF (W)	**1**	**2.6**	**10.5**	**30**	**110**	**135**

Figure 2: Section of EUV source roadmap illustrating laser driver power requirements.

2.4. Spatial multiplexing

In spatial multiplexing schemes, several laser sources are spatially combined using mirrors and other optics in order to create a single effective laser source, which is then imaged onto the LPP target using a focusing optic (figure 3).

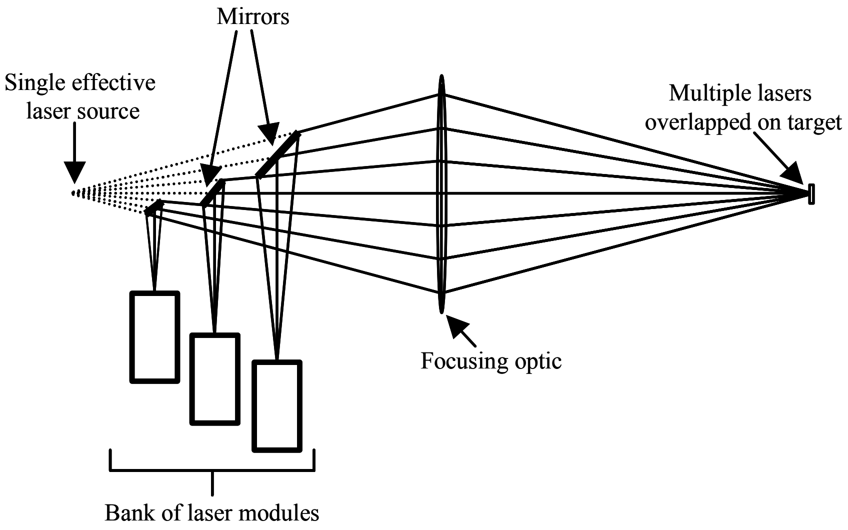

Figure 3:Principle of spatial multiplexing.

In order to account for differences in path lengths between the combined beams, conditioning optics (e.g. expanding telescopes) can be used to adjust beam divergence such that the corresponding focal spots are all equal in size. The effective focal spot can be monitored in real time by taking a small fraction of the laser light and focusing it onto a CCD camera (figure 4).

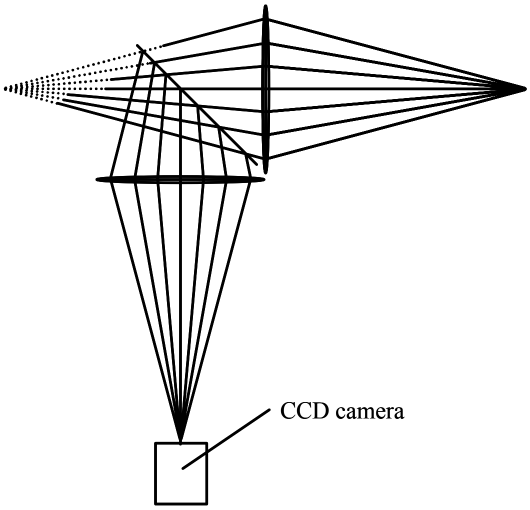

Figure 4: Use of CCD camera to monitor multiple beam overlap in real time.

Similarly, the lasers can be timed to arrive simultaneously on target using commercially available timing pulse generators to account for path length differences. However, it is also possible to temporally interleave the pulse trains of one or more lasers in order to increase the effective repetition rate of the system.

It can therefore be seen that spatial multiplexing of laser modules offers greater scale-up flexibility in comparison to LPP schemes that employ a single high power laser. Also, by sharing the power requirement over several laser modules, the power per module is reduced and the laser design can be simplified. Furthermore, spatial multiplexing has the advantage that in the event of failure of one of the laser modules, the EUV source can continue to operate albeit at a reduced output power.

This method of spatial multiplexing has previously been demonstrated successfully[9], when three 150W beams were spatially multiplexed on target in order to deliver 450W of laser power. Figure 5 illustrates the image recorded on the CCD alignment camera, showing three overlapping, equally sized focal spots.

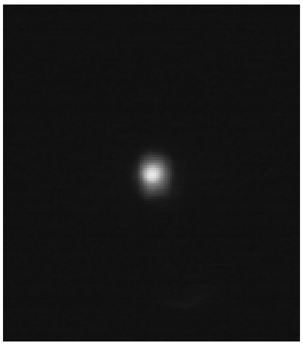

Figure 5: CCD image showing multiple overlapping beams.

	02	Today	End-04	05
Average power (kW)/module	**0.150**	**1**	**1.2**	**1.2**
Rep rate (kHz)	**3.5**	**3.5**	**6**	**6**
Number of multiplexed beams (n)	**3**	**1**	**3**	**7**
Total Average power for multiplexing (kW)	**0.450**	**1**	**3.6**	**8.4**

Figure 6: Laser power road map illustrating scale-up method using spatial multiplexing.

The next stage in the development of the LPP EUV source will be to spatially multiplex three 1.2kW Starlase systems (figure 6). When combined with a high-density xenon target (described in the next section), the EUV power at the IF is expected to be 10.5W (fig. 2).

3. TARGET DESIGN AND VACUUM ENVIRONMENT

3.1. High density xenon target

The principal objective of LPP target design is to create a localized region of high-density material such that laser absorption is maximized, whilst absorption of the generated EUV radiation in the chamber environment is minimized. If a nozzle is used to deliver the target material, the plasma must be created far enough away from the nozzle that nozzle debris does not limit the lifetime of the collection optics.

The target should be refreshable and able to support the high repetition rates (> 3.5 kHz) that are produced by the Starlase range of lasers, and are required for optimum EUV dose control during the lithographic process. The source environment must also be debris free and hydrocarbon and water levels must not exceed specified limits.

A promising method of achieving these requirements is provided by a cryogenic, high-density xenon filament target. In the system currently under development at Powerlase, a high-density xenon filament with diameter of 50 μm is injected into the vacuum system shown in figure 7. This system uses two 3000 ls^{-1} turbo pumps to achieve an ultimate pressure of 5x10^{-10} mbar and a background pressure of 5x10^{-4}mbar when operating the xenon target.

The xenon is recycled in a closed loop employing continuous gas filtration in order to achieve extremely low levels of contamination. Residual Gas Analyzer (RGA) measurements indicate hydrocarbon levels of ≤5x10^{-10}mbar (for molecular masses Σ45-200) and a water level of ~10^{-9} mbar, both of which constitute acceptable levels of contamination according to EUVL stepper manufacturer requirements. The recycling system is capable of delivering a stable xenon pressure of up to 50 bar at the nozzle inlet.

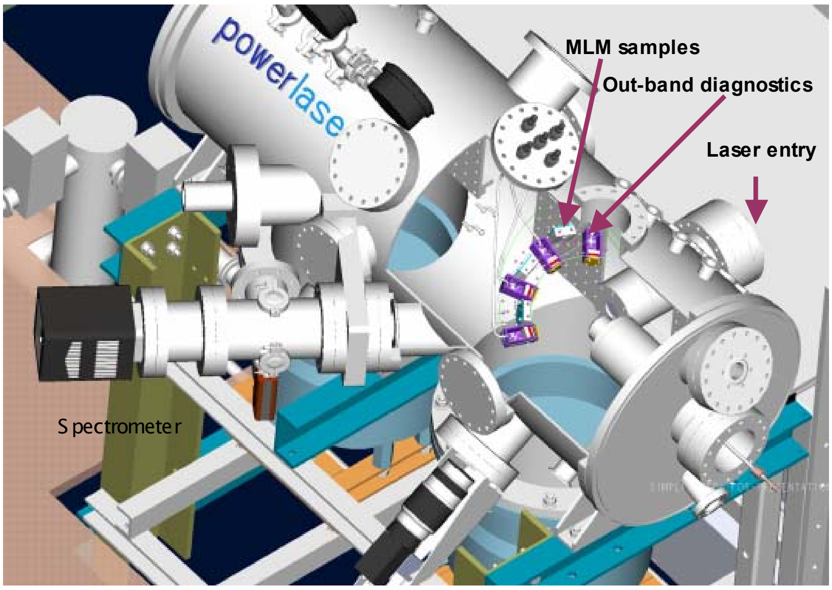

Figure 7: EUV source chamber showing pumps and plasma diagnostics.

Figure 8 shows some images of the xenon filament. The main issue currently being addressed is the stability of the target[10], as changes in the filament direction can lead to substantial variations in the EUV output. However, several strategies exist which circumvent this problem and are currently being investigated.

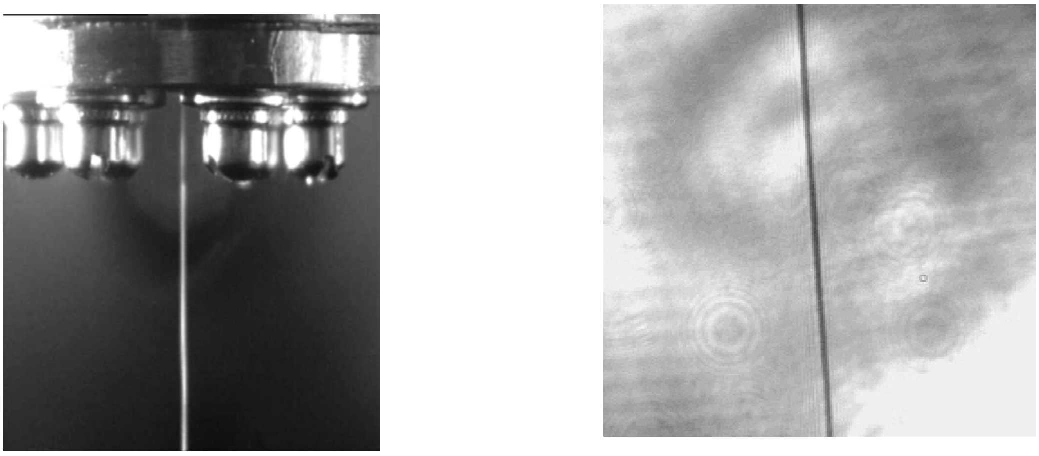

Figure 8: Images of the xenon filament target taken using CCD camera with zoom lens (left) and shadowgram produced using a low power, 10 ns pulse duration laser as the illumination source (right).

3.2. Tin target

Tin is an alternative target material that offers a higher EUV conversion efficiency in comparison to xenon targets. A typical EUV emission spectrum for tin is shown in figure 9. We have demonstrated a conversion efficiency of 1.5%/2π sr/2% BW, although theoretical modeling suggests that with further optimization, conversion efficiencies approaching 3 %/2π sr/2% BW can be obtained[11].

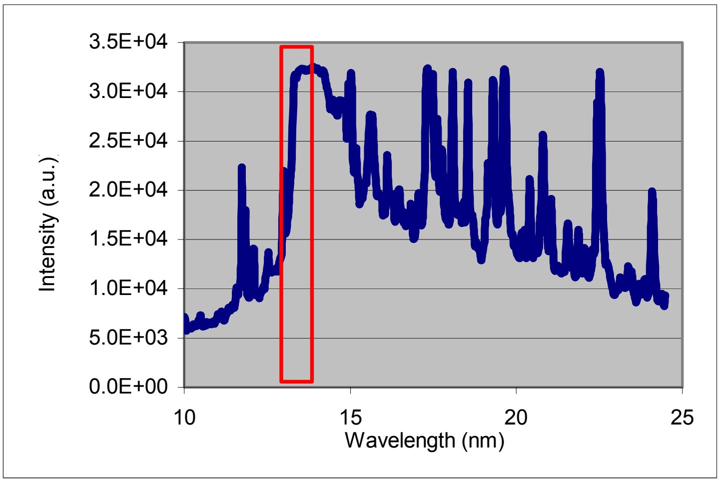

Figure 9: Tin spectrum taken using flat field spectrometer (FFS). The marked lines indicate the wavelength band of interest.

However, macroscopic tin targets are difficult to implement in high repetition rate EUV sources because of the need to refresh the target and more importantly, the high level of debris produced. One proposed solution[12] uses tin-doped droplets with diameter of 35μm in order to make use of the EUV emission characteristics of tin, whilst minimizing the quantity of debris produced and simplifying management of the target material. This method supports laser repetition rates in the range 20-100 kHz and therefore provides a promising alternative to xenon targets.

4. COST OF OWNERSHIP

In order to demonstrate the commercial viability of the LPP EUV source, a cost of ownership model was prepared[13]. This is summarized in figure 10, where available EUV source output power (into 2π sr) and corresponding source capital cost are plotted over the next few years.

These projections are based on the cost of laser diodes, laser design and choice of target. Note that a production level source using xenon will be available by the end of 2006, at a cost of approximately US$4M. If tin target technology can be introduced in order to dramatically improve the EUV conversion efficiency (figure 2), the cost of the EUV source can be reduced. With continued development work, we estimate that the source cost in the EUV production tool will be approximately US$2.5M. Improvements in others influencing factors, such as efficiency of the EUV collection optics and photoresist exposure requirements, will help to further drive down the cost of ownership.

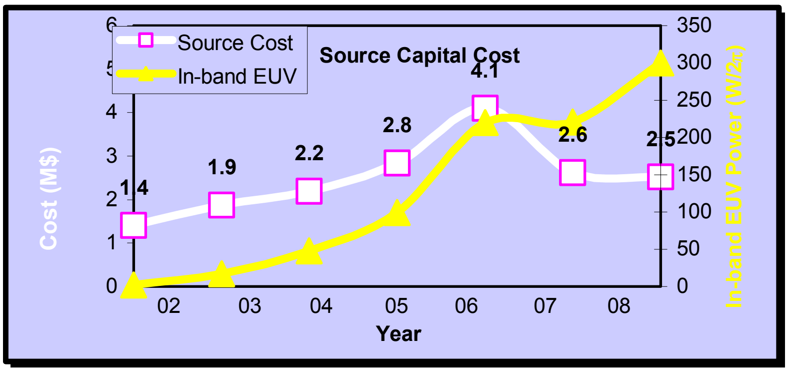

Figure 10: Source capital costs.

5. CONCLUSION

Laser produced plasmas provide a flexible and scalable route towards a production level EUV source for lithography. The key technological components of the EUV source, namely the target and most importantly the laser driver solution, have already been demonstrated to be technically viable. In addition, cost of ownership calculations indicate that the LPP source is a commercially viable solution that will satisfy the requirements specified by EUV stepper manufacturers.

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