High Power Low Cost Drive Laser for LPP Source

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ABSTRACT

We report on the approach for a high-power high-beam-quality drive laser system that is used for a laser-produced-plasma (LPP) EUV source. Cymer has conducted research on a number of solutions for a multi-kW drive laser system that satisfy high volume production requirements. Types of lasers to be presented include XeF at 351 nm and CO_2 at 10.6 micron. We report on a high efficiency XeF amplifier with a 3rd harmonic Nd:YLF master oscillator operated in the 6 to 8 kHz range and a CO_2 laser system with Q-switched cavity dumped master oscillator and RF pumped fast axial flow amplifiers operated in the 10 to 100 kHz range. CO_2 laser short pulse gain and optical isolation techniques are reported. Optical performance data and design features of the drive laser system are discussed, as well as a path to achieve output power scaling to meet high volume manufacturing (HVM) requirements and beyond. Additionally, the electrical efficiency as a component of cost of operation is presented. Development of a drive laser with sufficient output power, high beam quality, and economical cost of operation is critical to the successful implementation of a laser-produced-plasma (LPP) EUV source for HVM applications. Cymer has conducted research on a number of solutions to this critical need. We report our progress on development of a high power system with two gas-discharge power amplifiers to produce high output power with high beam quality. We provide optical performance data and design features of the drive laser as well as a path to output power scaling to meet HVM requirements. Development of a drive laser for LPP EUV source is a challenging task. It requires multi-kW laser output power with short pulse duration and diffraction limited beam quality. In addition, this system needs to be very reliable and cost-efficient to satisfy industry requirements for high volume integrated circuit manufacturing. Feasibility studies of high power laser solutions that utilize proven laser technologies in high power optical gain modules and deliver required beam properties have been performed and are reported.

Keywords: EUV source, laser-produced plasma, XeF power amplifier, Nd:YLF seed, CO_2 laser amplifier

1. INTRODUCTION

Extreme Ultra-Violet (EUV) lithography is currently slated to be used in production of integrated circuits below 32nm critical dimension on the international technology roadmap for semiconductors (ITRS) in 2013. EUV light sources based on laser produced plasma (LPP) technology are being developed to meet high volume manufacturing joint requirements as set by leading lithography scanner manufacturers[1]. LPP EUV lithography light sources generate the required 13.5 nm radiation by depositing laser energy into a source element, such as xenon (Xe), tin (Sn) or lithium (Li); creating a highly ionized plasma with electron temperatures of several 10's of eV. The energetic radiation created by the recombination of these ions is emitted into all directions, is collected by a near-normal-incidence mirror (collector) inside a ultra-high vacuum (UHV) chamber, and focused to an intermediate point from where it is relayed to the scanner optics and ultimately to the wafer. The UHV source chamber containing the collector and intermediate focus (IF) aperture is shown in Figure 1. Conversion efficiency (CE) of the laser energy into EUV energy is critical to meeting the required powers. Several combinations of laser wavelength and source element CE are discussed. The drive laser for LPP must be of high power with good beam quality and has to meet targets for initial cost and cost of operation. Three major laser technologies have been investigated and are reported: Excimer at a wavelength of 351 nm, Solid State at a wavelength of 1064nm, and CO_2 at a wavelength of 10.6 micron. To a large degree the energy conversion efficiency (CE) is determined by the combination of laser wavelength as well as source element. The CE capability is used to determine the necessary output power of the drive laser for initial introduction and product enhancement during the life cycle of the technology. CE values for the three laser wavelengths stated above with Xe, Sn, an Li are shown in Table 1. The ability of the laser technology to achieve the necessary output power is determined by extraction efficiency and

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gain through the length of the lasing media. Extraction efficiency and gain are reported in section 3 for 10.6 micron laser radiation. Finally the cost for electricity and overall cost of operation is estimated.

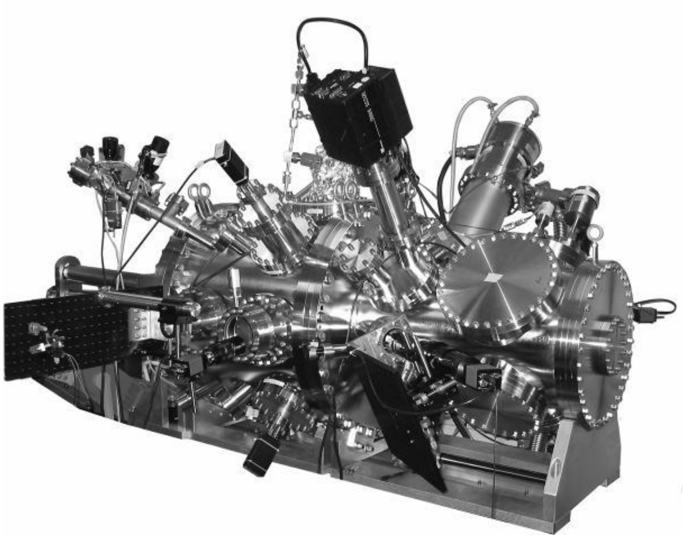


Figure 1: EUV Source UHV Plasma Chamber

	Xe	Sn	Li
Excimer/YAG (351nm/355nm)	TBD	0.5-1.0%	2.0-2.5%
Solid State (1.06µ)	0.5-1.0%	2.0-2.5%	2.0-2.5%
CO_2 (10.6 µ)	0.5-1.0%	3.5-4.0%	1.0-1.5%

Table 1: CE of various combinations of wavelength and source element.

2. XeF LASER TECHNOLOGY

The concept of a laser consisting of XeF power amplifiers and a Nd:YLF master oscillator was first described in ref.[2]. It is based on a single-frame two-channel hybrid system that utilizes Cymer's XLA MOPA universal platform. In this approach two gas discharge XeF gain modules are seeded by a high repetition rate solid state laser master oscillator (MO) with a near diffraction limited beam.

A diode pumped 3rd harmonic Nd:YLF laser system serves as MO. The MO generates two output beams that are synchronized with the XeF power gain modules and seed them in sequential order. The repetition rate of the MO is adjustable. For the current configuration it can be set between 8 and 12 kHz (4-6 kHz per each MO output). Both MO channels are identical with a beam quality M^2 better than 1.5. Figure 2 shows that the averaged temporal pulse shape of the MO pulses is ~ 9.3 ns at FWHM and ~ 15.9 ns at $FW1/e^2$.

With 30A drive current applied to the 40A pump diodes bars, the MO output energy is about 1.2 mJ per pulse at 4 kHz. An optimized design of the Nd:YLF power amplifiers in the system would generate 2 mJ output pluses at a repetition rate of 6 kHz at the same optical pump power[3].

Another important feature of the Nd:YLF MO is that its operating wavelength is tuned towards a longer wavelength compared to a free-running 3rd harmonic Nd:YLF laser[2]. This is necessary in order to create spectral overlap between the MO output and the XeF gain spectrum for efficient amplification of the MO beam in XeF laser active media. The gain spectrum of XeF module and the MO output spectrum are shown in Figure 3 and illustrate conditions when the MO wavelength is tuned to overlap with the 351.1nm XeF emission line. Technically, all three wavelength regions in the vicinity of 351.1nm, 351.2 nm and 353.3 nm XeF, corresponding to different vibrational electronic transitions of XeF shown in the diagram in Figure 4 can be utilized. However, from practical standpoint only two XeF lines, 351.1 and 351.25 nm, can be amplified from a single 3rd harmonic Nd:YLF MO due to limited tunability and bandwidth of the Nd:YLF oscillator.

Energy extraction from the XeF power gain module, seeded with the tuned 3rd harmonic Nd:YLF MO was studied in a Master Oscillator-Power Oscillator (MOPO) configuration. For a Power Oscillator (PO) we used a production-grade Cymer gain module filled with a XeF gas mix and seeded with a beam from the solid state MO. For better PO extraction the 3rd harmonic Nd:YLF MO was shifted to slightly longer wavelengths in order to better overlap with the 351.25nm line. No line selective elements were used in the PO cavity. The test results are shown in the Figure 4. We observed that without seed input, the PO oscillates on all three lines with the 353 nm line contribution to the spectral integral being approximately 50%. Once the PO was seeded and the system operated as a MOPO the contribution from the 353 nm line dropped below 10%. Additional efforts on alignment optimization did not completely eliminate the 353 nm line.

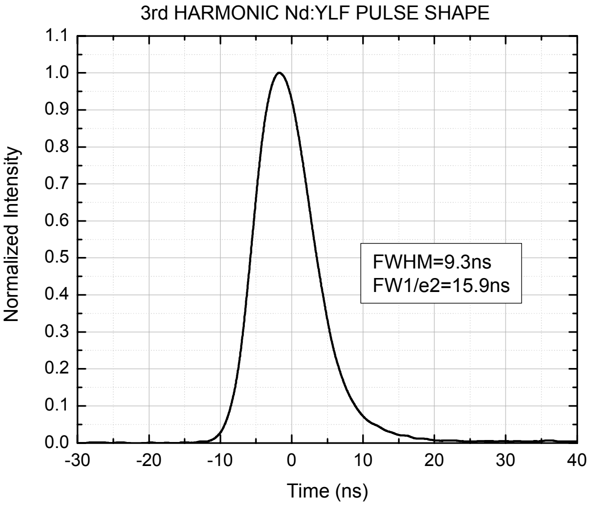


Figure 2: Pulse shape of Nd:YLF master oscillator at 351nm.

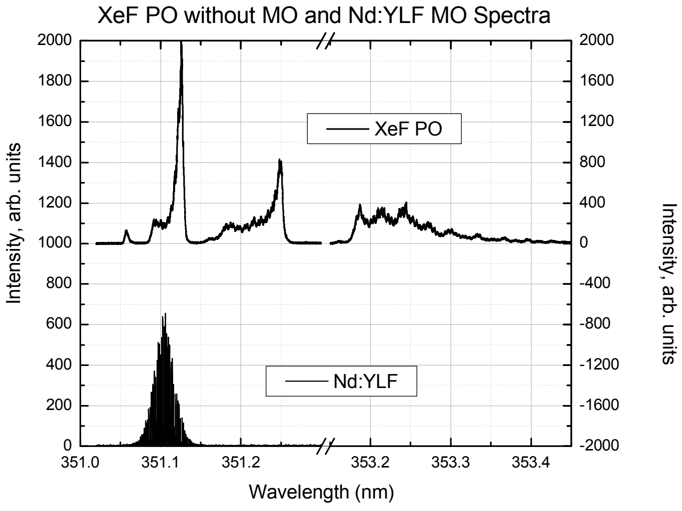


Figure 3: Spectra of Nd:YLF master oscillator (at 351nm) and XeF power amplifier operating without seed.

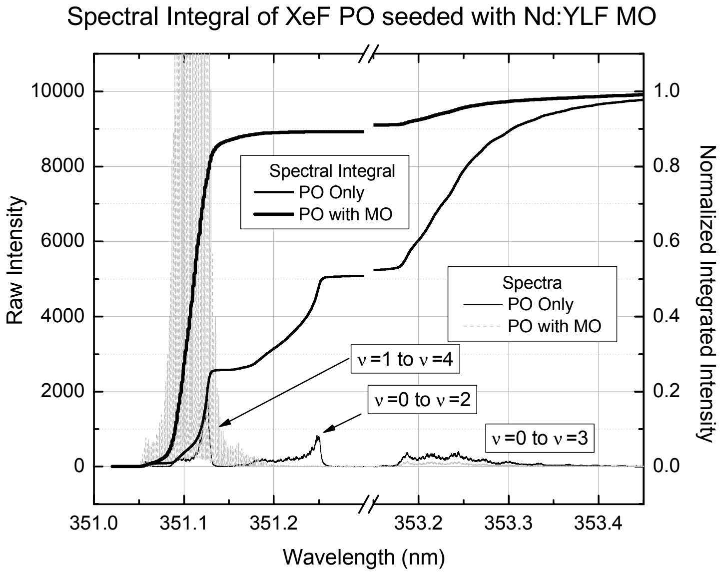


Figure 4: Spectra and spectral integrals of XeF power amplifier operating without seed and seeded with Nd:YLF master oscillator operating at 351nm. Energy in the seeded, line-selected regime is more than 90% of energy in multi-line regime without seed by master oscillator.

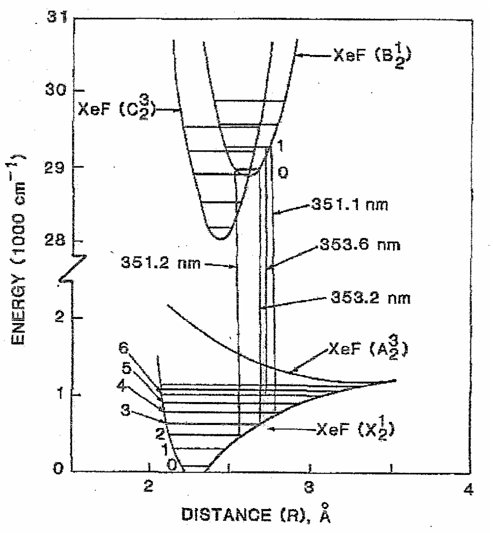


Figure 5: Energy level diagram for XeF, Ref.[4]

The optical performance of the XeF drive laser prototype is summarized in the Table 2. To date, 6 kHz operation of the XeF gain modules using an improved design of the discharge chamber and blower motors has been demonstrated.

Parameter	XeF Limit
Pulse Energy	200 mJ
Repetition Rate	8 kHz (per amp)
Pulse Width	16 ns
Energy Stability	1%
Pointing Stability	25 μRad
Beam Divergence	150 μRad
Wall-plug Efficiency	3.5%

Table 2: 351nm Excimer Laser Capability

The cost of operation of the excimer laser is determined by the cost of spare parts and consumables. Laser modules, electricity, gases, cooling water, and exhaust are all included for a complete cost model; however, several of these items are negligible in terms of dollars. Low power excimer lasers have been used in DUV lithography production for many years. Therefore, the cost of the laser modules is well understood and well documented. The cost of electricity for high power excimer lasers for use in an LPP system has been raised as an unknown factor and must be investigated. The electrical input power required is determined by the required output power and the electrical to optical conversion efficiency of the discharge cavity design plus the electrical usage of supporting modules. The overall efficiency of the broadband 351 nm XeF laser has been measured to be about 3%. This is about three times higher than existing highly line narrowed 248 nm DUV counterparts. The joint throughput model from leading scanner manufacturers estimates that production scanners will use the source at 25% duty cycle which is very close to how DUV sources are used today. The maximum utilization of the scanner in manufacturing over long periods of time is estimated to be 70%. The results of our calculation for the annual cost of electricity for the LPP laser are shown in Figure 6 and Table 3.

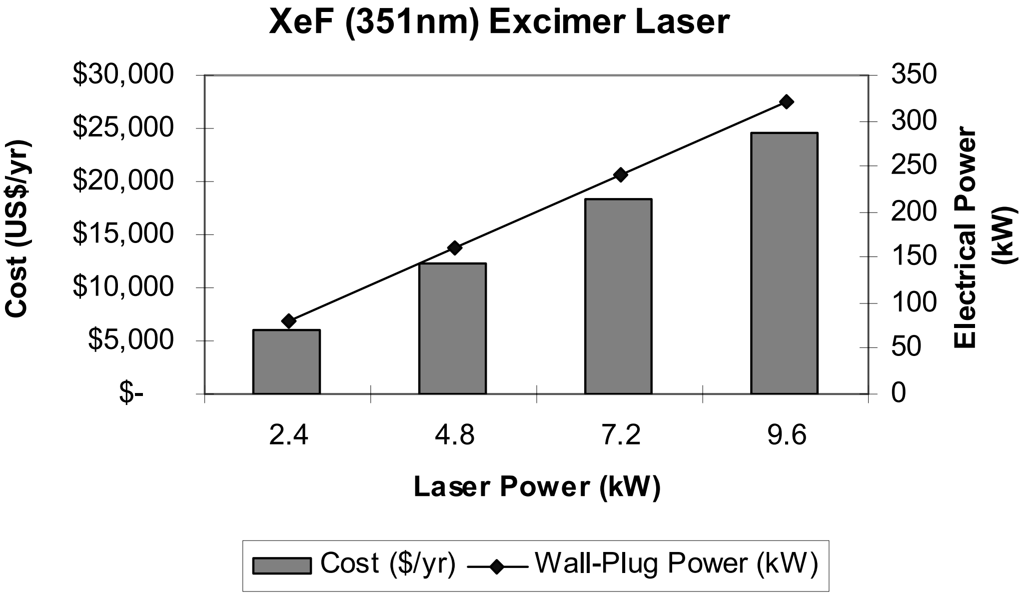


Figure 6: Estimate for cost of electricity for a XeF excimer laser.

Ave Laser Power (kW)	**2.4**	**4.8**	**7.2**	**9.6**
Ave Efficiency	3%	3%	3%	3%
Power Consumption (kW)	**80**	**160**	**240**	**320**
Duty cycle	25%	25%	25%	25%
Utilization	70%	70%	70%	70%
Electricity Cost ($/kWhr)*	0.05	0.05	0.05	0.05
Cost ($/yr)	**$ 6,132**	**$ 12,264**	**$ 18,396**	**$ 24,528**

* conservative estimate

Table 3: Estimate for cost of electricity for a XeF excimer laser.

3. CO_2 LASER TECHNOLOGY

Numerical modeling of 10.6 micron light incident on a Sn target has shown values of EUV CE as high as 4% into 2π sr, 2% bandwidth at 13.5nm. Given such a high theoretical CE, it is important to investigate such an advantageous target/laser combination. Some preliminary experiments were conducted using a Cymer excimer laser which had been converted to operate as a CO_2 laser in combination with planar Sn targets. The observed CE's were in the range of ~3 to 4%[5]. This value is similar to the CE with a XeF excimer laser on a Li target. Using 3% as the expected CE, the CO_2 drive laser power requirement is a modest 10 kW to get ~100W of EUV photons at the intermediate focus.

In this section we present one of the concepts for the LPP drive laser system that is currently under investigation. In the early 1990's several groups worked on the production of high peak intensity, high repetition rate CO_2 laser pulses[6-8]. The main approach was to use low pressure, fast axial flow, RF pumped laser modules either as Q-switched oscillators or amplifiers. A mechanically Q-switched oscillator 800 W average power was achieved at 8 kHz and 300 ns pulse width[8]. The same power was achieved in a MOPA configuration at 10 kHz and with a 35 ns pulsewidth[6]. If the pulse width was increased to 200 ns the system was capable of producing 2000 W at 7.7 kHz. Such a big difference in power can be explained by the limited rotational relaxation of vibrational levels during the laser pulse[9]. When the system was configured as a CW laser, it produced ~10 kW. It was noted that with optimization of pumping, optical isolation and repetition rate it would be possible to increase the average power to ~ 7 kW, keeping the pulse width in the range of several tens of ns. The most recent results obtained by investigation of a similar system demonstrated ~ 1 kW of average power at 100 kHz and 15 ns pulse width[10]. As illustrated in the Figure 7, the LPP drive laser concept is based on a master oscillator (MO) power amplifier (PA) architecture. A Q-switched, cavity dumped, RF pumped waveguide CO_2 laser is used as a master oscillator (MO) with three separate, fast axial flow RF pumped, CO_2 lasers as power amplifiers (PA). The pulse width of the MO is ~30ns (FWHM).

The repetition rate of the MO can be varied from 1 to 100 kHz and a continuous RF discharge is sustained in the PA's. Due to the low gain per length of the CO_2 gain media, three amplifiers are required to obtain the necessary gain length of ~20 meters. Using three amplifiers offers a number of advantages over just using a single amplifier of the equivalent length. First, the threshold for self-lasing through amplified spontaneous emission (ASE) can be made higher through the use of saturable absorbers and by increasing the optical path length between the amplifiers. Another advantage is the ability to optimize the RF power and gas mixture of each amplifier in the chain to achieve the maximum gain at the output. Figure 8 shows the power gain ratio of the first amplifier as a function of repetition rate. Note that the gain is essentially constant for repetition rates up to 100 kHz implying that the gain medium is not saturated. Figure 9 shows the amplification from a single amplifier as a function of the input pulse energy. The gain follows a classic saturation curve. Figure 10 shows the measured waveforms for input and amplified signal. The output signal is showing evidence of gain reduction during the pulse indicating that the gain media is becoming saturated. The gain reduction shows that the energy is extracted from the amplifier rather efficiently. The amplifier operates in a regime where there is a significant rotational relaxation and the energy is efficiently extracted from the vibrational band.

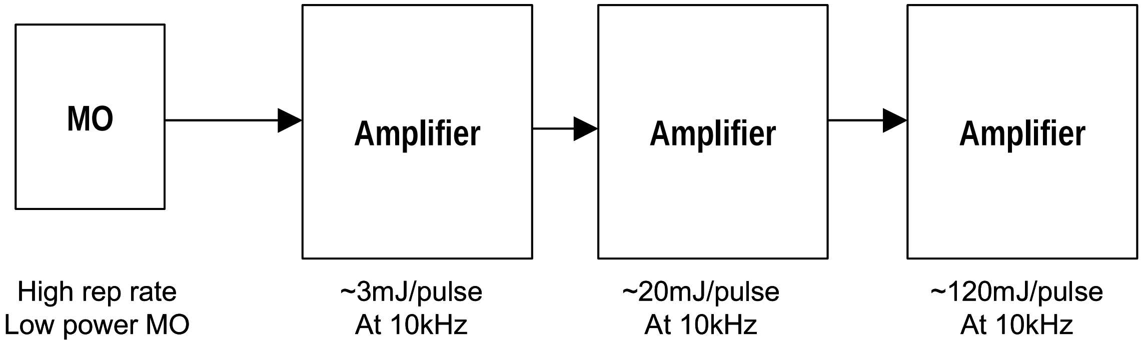
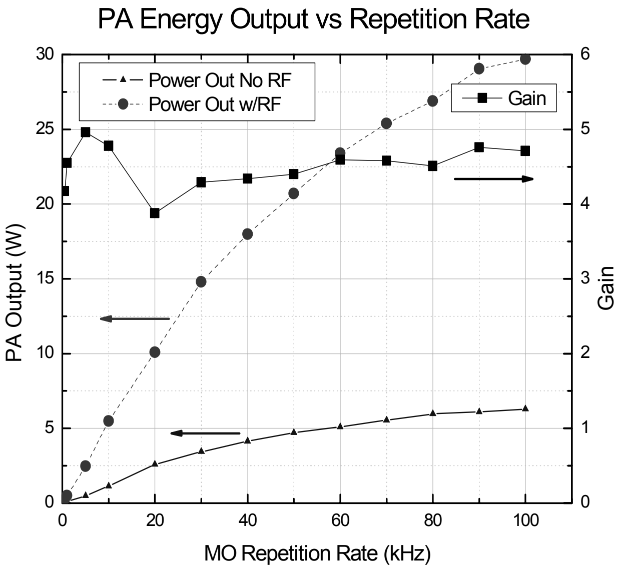


Figure 7: The current concept of the CO_2 drive laser system for the Cymer LPP EUV source: The MO is a high beam quality, high repetition rate q-switched CO_2 laser, and the power amplifiers are RF pumped fast axial flow modules.



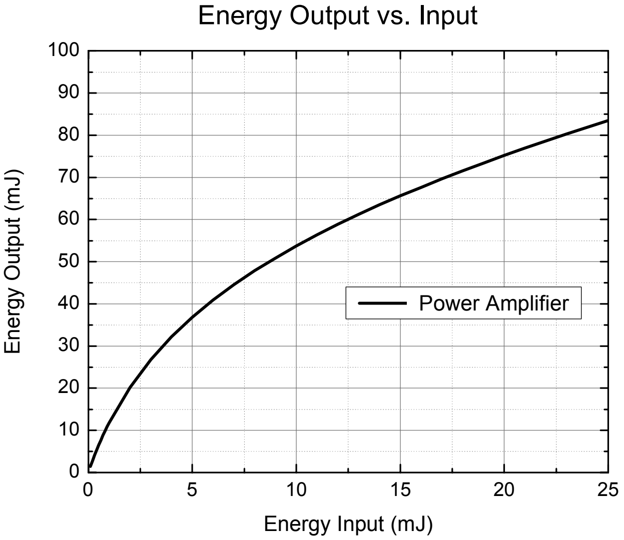


Figure 8: Measurement of the amplified and un-amplified output power as a function of the repetition rate. The power gain ratio is essentially constant as a function of repetition rate.

Figure 9: The CO_2 power amplifier gain as a function of the input pulse energy.

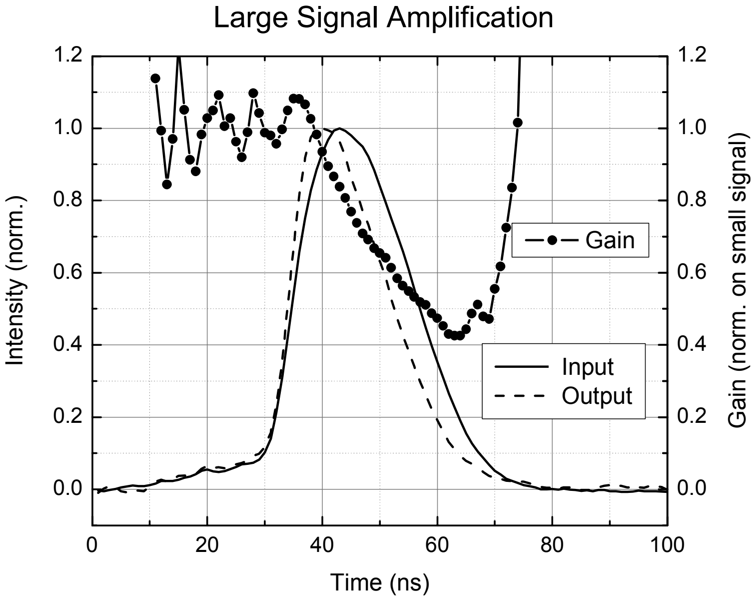


Figure 10: Pulse shapes of input pulse and amplified output pulse. The gain medium is showing evidence of saturation since the output pulse is undergoing gain reduction.

Cost is another very important factor for the selection of a drive laser[11]. Figure 11 shows our high and low estimate of the yearly cost of ownership for a CO_2 laser system. The price tag ranges from \$150k to \$300k with spare parts being the major cost driver. The laser gas category includes not only the cost of the gases used (especially helium), but also the possibility of using CO_2 recovery systems with scrubbers due to heightened environmental concerns. The optics category includes the possibility of having periodical replacements of the large ZnSe entrance windows due to either contamination from the tin target, or crystal defects from the long exposure to high intensity CO_2 light.

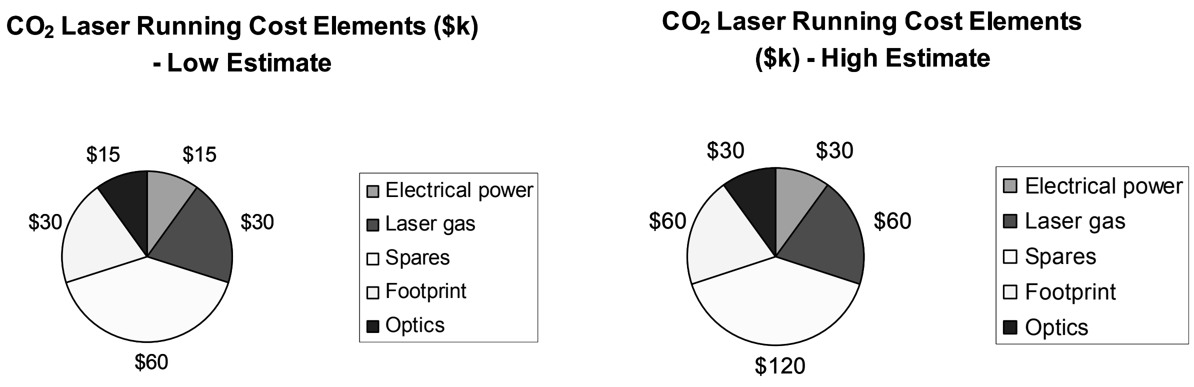


Figure 11: Projected high and low yearly cost of ownership estimate for our proposed CO_2 laser driver.

4. CONCLUSION

A comparison of the currently viable LPP EUV drive laser technologies is shown in Table 4. The table rates the various properties of the laser technologies relative to one another. Lasers based on excimer technology, specifically xenon fluoride excimers, have good beam quality, beam polarization, and pulse width (~15ns). They have good average wall plug efficiency (3.5%), available optical materials (fused silica, CaF_2, etc…), chip maker experience (a large install base already exists in manufacturing), initial system cost, cost of operation, and resist sensitivity to the excimer wavelength. Currently the available laser output power per module is limited to 2400 Watts. With the increase of the EUV power requirements at the intermediate focus, multiplexing of the modules will become necessary, driving the initial system as well as the recurring costs up for the excimer technology.

The strengths of the diode-pumped solid state laser technology include wall plug efficiency, beam quality, beam polarization, and pulse width. These lasers have average available optical materials and resist sensitivity. The chipmakers have relatively little experience with solid state lasers, the initial system cost is high (due to the high price of pumping diodes), and the cost of ownership is high due to the relatively short lifetime of the diodes.

The CO_2 laser is a mature technology with readily available high power and high repetition rate lasers, high reliability, with high wall plug efficiency as well as good beam quality. The available optical materials are expensive, the system cost is comparable to the excimer based lasers, and the resist is insensitive to the wavelength, but heating of the mask and wafer have to be carefully considered. The available pulse widths are either too long or too short, thus requiring developmental work to produce the desired pulse width, and the factories have little or no experience with their use.

In summary, all three laser technologies discussed here have their own weaknesses and strengths, and other factors (cost, EUV conversion efficiency, target material and delivery system) will have a contributing impact on the final choice of the drive laser for a laser produced plasma source.

	XeF	CO_2 - TEA	CO_2 - LP	DPSS
Laser Efficiency	3.5%	10-20%	10-20%	10-50%
Repetition Rate (max)	8kHz	~10kHz	30 - 100 kHz	30 – 100 kHz
Pulse Width (ns)	~ 15	50 - 150	15 - 150	5 - 50
Beam Quality	M^2 ~ 10	M^2 ~ 2-5	M^2 ~ 1.5	M^2 ~ 1 - 15
Power (kW)	1.6	1.5	10	0.1 – 0.6
10kW Cost CoO	Medium – High Medium	Medium Medium	Medium Low	High High

Table 4: Summary of capabilities of the different laser technologies.

Laser Type	λ (nm)	Power & effcy	Beam Quality	Optical Matls	Polar- zation	Pulse width	Fab Exp.	System Cost	CoO	Resist sens.
XeF	351	😐	☺	😐	☺	☺	😐	😐	😐	😐
DPSS	1064	☺	☺	😐	☺	☺	☹	☹	☹	😐
CO_2	10600	☺	😐	😐	☺	☹	☹	😐	☺	😐

Table 5: Summary of advantages and disadvantages of the different laser technologies.

REFERENCES

1. K. Ota, Y. Watanabe, H. Franken, V. Banin, in: Proc. Int. Sematech EUV Source Workshop, Santa Clara (22 Feb. 2004).
2. V.B. Fleurov, P.C. Oh, T.D. Steiger, I. V. Fomenkov and W. N. Partlo: Development in gas-discharge drive lasers for LPP EUV sources, in: Proc. of SPIE Vol. 5751, Emerging Lithographic Technologies IX, R. S. Mackay, Ed., 874-884 (2005).
3. A. Dergachev, P. Moulton, "Short-pulse, high repetition rate, high power Nd:YLF MOPA system," publication by Q-peak, http://www.qpeak.com/Papers/ASSP04/ASSP-2004-MOPA.pdf.
4. J.A. Blauer, T.T. Yang, C.E. Turner, Jr., and D.A. Copeland, "Excimer Kinetics and Multiline Model for the Electron Beam Pumped XeF(B-X) Laser, Appl. Optics 23, 4352-4367 (1984).
5. B. A. M. Hansson, I. V. Fomenkov, N. R. Böwering, A. I. Ershov, W. N. Partlo, D. W. Myers, O. V. Khodykin, A. N. Bykanov, C. L. Rettig, J. R. Hoffman, E. Vargas L., R. D. Simmons, J. A. Chavez, W. F. Marx, D. C. Brandt, in: *These Proceedings of SPIE Vol.* ***6151****, Emerging Lithographic Technologies X,* (2006).
6. U. Bielesch, M. Budde, M. Fischbach, B. Freisinger, J. H. Schaefer, J. Uhlenbusch, and W. Vioel, "Q-switched multikilowatt CO_2 laser system excited by microwaves", Proc. SPIE 1810, 57 (1993).
7. Naoya Hamada and Tatsuhiko Sakai, "High-power Q-switched CO_2 laser based on a fast axial gas flow system", Proc. SPIE 1810, 53 (1993)
8. Werner Fuss, Peter Loosen, Otto Maerten, and W. E. Schmid, "Scaling of high-repetition-rate Q-switched CO_2 lasers for industrial applications", Proc. SPIE 1810, 79 (1993).
9. J.W. Witteman, "The CO_2" laser", Springer series in optical sciences", Springer –Verlag, (1987).
10. Tatsuya Ariga, Hideo Hoshino, Taisuke Miura, and Akira Endo, "High power and short pulse RF-excited CO_2 laser MOPA system for LLP EUV light source", Proc. SPIE 6101, 61011N (2006).
11. Einar Ronander and Erich G. Rohwer, "Multikilowatt TEA-CO_2 laser system for molecular laser isotope separation", Proc. SPIE 1810, 49 (1993).