Next Generation 193 nm Laser for sub-100 nm Lithography

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ABSTRACT

The next generation 193 nm (ArF) laser has been designed and developed for high-volume production lithography. The NanoLith™ 7000, offering 20 Watts average output power at 4 kHz repetition rates is designed to support the highest exposure tool scan speeds for maximum productivity and wafer throughput. Fundamental design changes made to the laser core technologies are described. These advancements in core technology support the delivery of highly line-narrowed light with ≤ 0.35 pm FWHM and ≤ 0.95 pm at 95% included energy integral, enabling high contrast imaging from exposure tools with lens NA exceeding 0.75. The system has been designed to support production lithography, meeting specifications for bandwidth, dose stability (± 0.3% in 20 ms window) and wavelength stability (± 0.05 pm average line center error in 20 ms window) across 2-4 kHz repetition rates. Improvements in optical materials and coatings have led to increased lifetime of optics modules. Optimization of the discharge electrode design has increased chamber lifetime. Early life-testing indicates that the NanoLith™ core technologies have the potential for 400% reduction of cost of consumables as compared to its predecessor, the ELX-5000A and has been discussed elsewhere.[1]

Keywords: excimer laser, ArF, 193 nm, lithography, 4 kHz, high repetition rate, narrow bandwidth, wavelength control

1. INTRODUCTION

From the first applications of optical lithography to the manufacture of semiconductor chips, shrinking the critical dimension (CD) has been one of the paramount goals of chipmakers. One of the three critical parameters used to accomplish the "shrink" has consistently been the reduction of the exposure wavelength. Over the past three years, excimer lasers at 248 nm have emerged as the preferred light source for leading edge production lithography. As chip features continue to shrink, the need for new leading-edge exposure tools becomes more urgent. Though the near term imaging requirements for the majority of critical layers will likely use extended 248 nm technology, some processes will depend exclusively on the availability of 193 nm solutions. Fundamental limitations at 248 nm along with the high costs and design complexity associated with phase shifting mask technology spur a demand for 193 nm at the leading edge of chip fabrication. The next critical transition in exposure wavelength—from 248 nm to 193 nm—is upon us. 193 nm DUV exposure tools, driven by argon fluoride (ArF) excimer lasers will be used to image features of 100 nm CD and below.

2. SYSTEM CONFIGURATION

Following the successful early development of high repetition rate ArF lasers[2], numerous advancements in core technologies have been incorporated into the NanoLith™ 7000. Broadly speaking, these changes fall into three categories: 1) changes that directly support 4 kHz operation, 2) changes that indirectly support 4 kHz operation (i.e. improved thermal management), 3) changes to improve performance in support of tightened product specifications. Modifications are summarized on a module-by-module basis in the proceeding subsections.

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Table 1 Critical Specifications of the NanoLith™ 7000

Key Specification	
Maximum Repetition Rate	4000 Hz
Nominal Pulse Energy	5 mJ
Output Power	20 Watts
Spectral Bandwidth	≤ 0.35 pm FWHM ≤ 0.95 pm E 95%
Dose Error (99.7% of bursts)	≤ ± 0.3%

2.1 Discharge Chamber

The 7000 discharge chamber is a fundamental redesign of previous Cymer discharge chambers. The gas flow loop and tangential fan design have been optimized to support higher gas velocities while avoiding higher fan speeds (rpm) that would limit bearing life. The improved flow loop also yields better flow stability and uniformity. Additional heat exchangers have been added to maintain gas temperatures under the increased thermal load of 4 kHz, high duty cycle operation. Various changes to internal structures have been implemented which improve uniformity of gain and energy stability across all repetition rates. Finally, a novel electrode design results in better efficiency and stability, as well as extended electrode life. The flow loop redesign dictated a significant increase in the chamber size and weight; one consequence is that the volume per refill is increased by 2.2X. This increased volume provides a benefit by helping to extend gas life to 100 million shots.

2.2 Pulse Power System

The power systems modules have also undergone major changes from previous designs. Most evident of these is the addition of a new module, the resonant charger, as an intermediary between the high voltage power supply and the commutator. Traditionally, lithography lasers have used a relatively complex high voltage supply to energize the commutator's first capacitor bank (henceforth referred to as C_0). Such a supply accepts a command signal from the laser control system specifying the desired voltage on C_0, followed by a trigger; the supply responds by providing constant current to C_0 until the command voltage is achieved. The resonant charger topology works very differently. The high voltage power supply now operates at a single voltage, and charges a large (relative to C_0) capacitor in the resonant charger, termed C_{-1}. C_0 (in the commutator) is charged from C_{-1} via a charging inductor in the resonant charger. The time for maximum energy transfer is determined by the resonance frequency of the combined LC tank circuit defined by the charging inductor, and the series combination of C_0 and C_{-1}. For the case of $C_0 << C_{-1}$, the peak voltage on C_0 approaches twice that on C_{-1}. In Cymer's resonant charger approach, proprietary technology within the resonant charger module permits precision regulation of the final voltage on C_0 to intermediate voltages. The primary advantage to this technology is its scalability to higher repetition rates. With increasing repetition rates, the time between laser pulses — and hence the time permitted for charging C_0— decreases. (In fact, the allotted charging time decreases faster than the interpulse time because some interpulse time must be reserved for tasks such as: measuring energy and executing the energy control algorithm.) In the traditional, charge-on-command scheme the need for faster charging must be met by redesign of the supply for faster charging or ganging several supplies. In the resonant charger approach, faster charging can be accomplished by reducing the charging inductor and increasing the peak current of the simpler DC supply.

The NanoLith™ 7000 commutator and compression head are similar in concept to previous Cymer designs but with reduced rise time in each stage resulting in improved energy stability and efficiency. All pulse power modules employ direct water cooling—that is, heat-dissipating components within the modules are mounted on cold plates. This approach permits the power system to occupy ~1.5X the volume of that used in Cymer's 6000 series lasers, despite having twice the average power dissipation, thereby reducing overall system footprint.

2.3 Optical Modules

The NanoLith™ 7000's line-narrowing module (LNM) contains three major enhancements. First, the optical design has been revised to produce higher dispersion to meet the stringent bandwidth requirements. Second, the housing has been redesigned to accommodate the new discharge chamber and to provide uniform bandwidth at varying duty cycles. Finally, this module incorporates a fast, high precision tuning element to supplement the stepper motor used in prior designs. These two act as a woofer/tweeter combination in the laser's wavelength control servo loop, providing greatly improved line center stability.

The complement to the LNM is the wavelength stabilization module, which supplies on-board metrology of pulse energy, center wavelength and FWHM bandwidth. To exploit the improved tuning capabilities of the LNM, it is necessary for this stabilization to provide wavelength data on each pulse. Meeting this requirement at 4 kHz operation drove a complete redesign of the electronics assemblies within the stabilization package. Drive electronics and a new wavelength-control algorithm were added to support the high-speed tuning element in the LNM. Improved algorithms for calculating wavelength combined with a more accurate calibration procedure yields a significant improvement in wavelength tuning accuracy for the system. The optical design of this package is substantially the same as in the 5000A series, although a number of engineering improvements improving module life have been included.

At the system level, optical modules and interfaces have been redesigned to produce a tightly sealed beamline, based on designs originally developed for Cymer's ELX-6000F2 157 nm laser.[3] Residual O2 levels of <20 ppm in high-fluence regions of the beamline are achievable with this technology. A further improvement in purge purity has been produced by elimination of elastomers in the purge-gas delivery system.

2.4 Enclosure

The space requirement of new semiconductor equipment is usually an important figure in the budget planning and operating cost analysis for new wafer Fabs. With the NanoLith™ 7000 Cymer has been able to double the system performance without a significant increase in its footprint or service area compared to today's ELS-6000 lasers. Effectively, the footprint is unchanged while the height has been increased by 7" to accommodate the improved pulsed power module technology. Convenient door panels provide easy service access and "quick view" windows allow the monitor of key support modules without powering the laser off. New safety guidelines as SEMI S2-0200 have been taken into account with NanoLith™ 7000 design.

3. SYSTEM PERFORMANCE

3.1 Energy Stability

In recent years, manufacturers of laser lithography tools have altered their utilization of the light source, tailoring the laser's pulse energy and repetition rate for each lithography process. It is thus incumbent on the laser designer to ensure that the laser's performance meets specifications at all repetition rates. Various phenomena within the laser system can produce degradations in performance at some repetition rates. The NanoLith™ 7000 has been designed to minimize such effects.

Figure 1 depicts a scan of repetition rates spanning 1 kHz to 4 kHz with the laser operating at constant high voltage. Data were collected at repetition rates spaced by 4 Hz, five bursts taken at each repetition rate. Average power and 3-sigma energy stability at the end of a 500-pulse burst are graphed. In this way, the system's intrinsic stability is charted. The overall system efficiency shows excellent linearity, with no rolloff in power at 4 kHz. Peaks in the energy stability curve show residual effects of resonances; however, the laser's stability meets the target of $3\sigma < 12\%$ across the entire range.

As noted above, Figure 1 illustrates the laser's intrinsic performance in constant voltage mode. Of greater interest in lithography applications is the dose stability when the laser is operated in energy-controlled mode. Figure 2 provides this data for 5 mJ pulse energy operation. The laser was run at approximately 30% duty cycle for 1000 bursts at each repetition rate. For each burst, the largest dose error in a 20 ms trapezoidal window was recorded and graphed. Figure 2 shows all data; however, the 99.7% level specification permits discarding the three worst doses. By this criterion, the data shown meets the ± 0.3% specification. A noteworthy characteristic revealed in Figure 2 is the improvement in dose stability with repetition rate. This can be attributed to the increasing number of pulses within the 20 ms window as repetition rate increases: typically, for a fixed repetition rate the dose error decreases inversely with the window size in pulses. As seen in Figure 1, the intrinsic energy stability degrades slightly with increasing repetition rate; the dose stability improvement with repetition rate increase demonstrates that the larger pulse window more than compensates the intrinsic stability degradation.

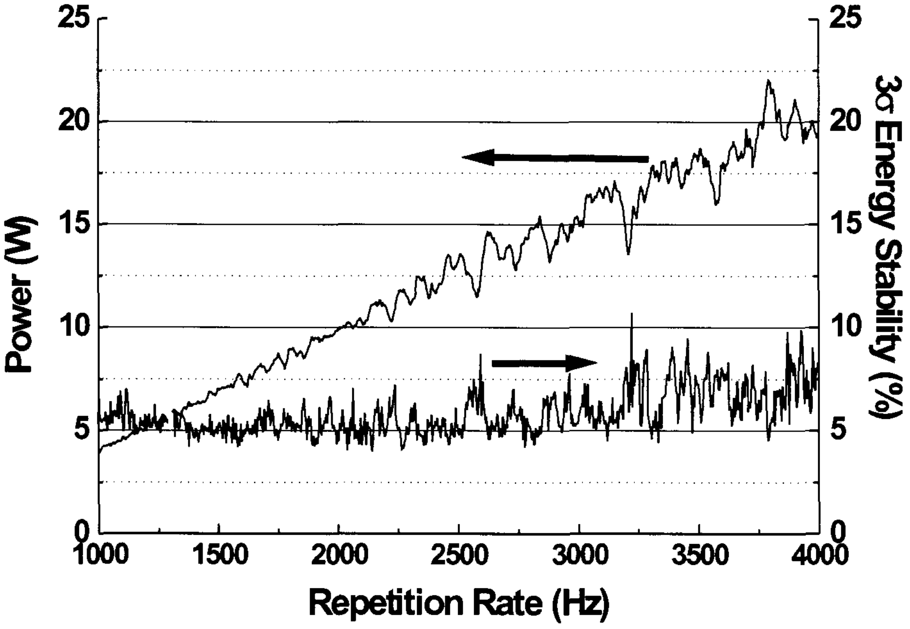

Figure 1. Power and energy stability measured at constant high voltage operation from 1 to 4 kHz. Operating voltage was 950 V, chosen to produce 5 mJ at 4 kHz operation.

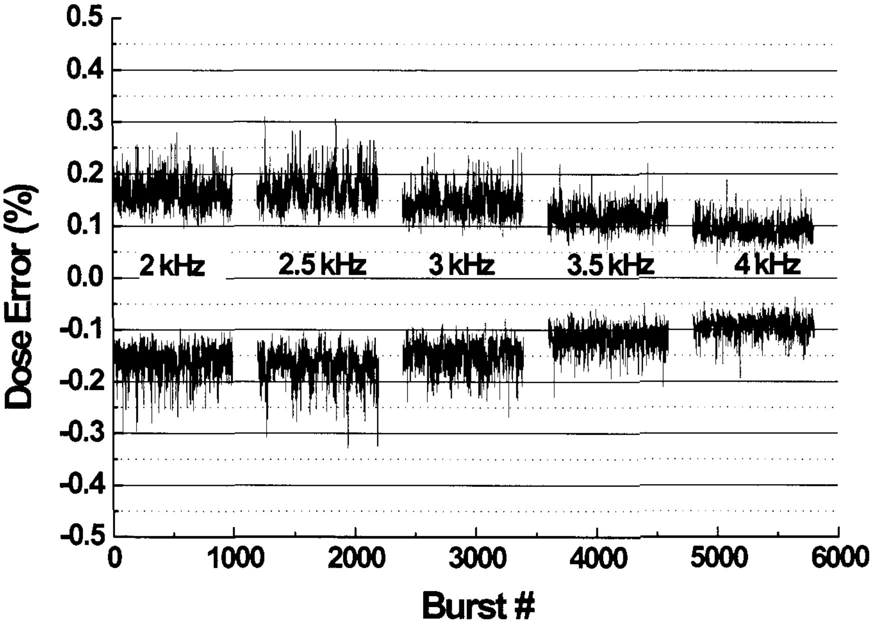

Figure 2. Dose stability at repetition rates from 2-4 kHz. 5 mJ operation, ~30% duty cycle at 4 kHz. Data shows worst dose error from each burst of 1000 bursts at each repetition rate.

3.2 Spectrum

As projection lens designs push to ever higher NA values, the requirement for narrower bandwidths becomes more critical. Furthermore, the wide range of resist sensitivities envisioned for 193 nm lithography (5-15 mJ/cm^2), combined with a desire to maximize throughput, requires consistent delivery of narrowband light at both low and high duty cycles. Figures 3 and 4 depict spectra taken with a double-pass grating spectrometer (instrument function: 0.10 pm FWHM, 0.28 pm 95% energy included integral) with the NanoLith™ 7000 operating at 4 kHz, 5 mJ/pulse at 11% and 75% duty cycle.

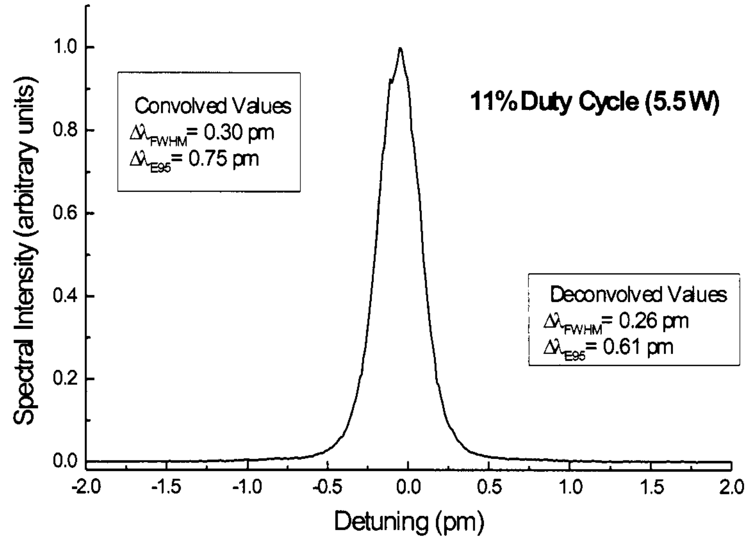

Figure 3. Spectral profile, 40 pulses/burst, 0.3 s interburst (11% duty cycle) at 5 mJ, 4 kHz.

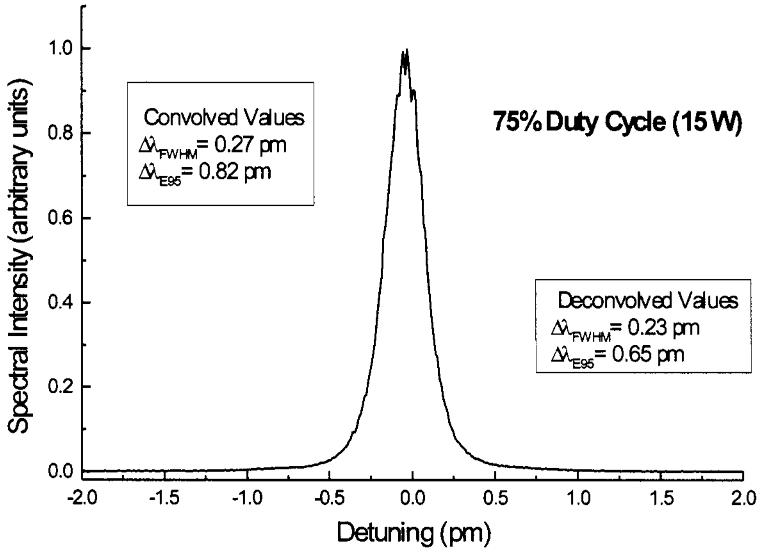

Figure 4. Spectal profile, 1200 pulses/burst, 0.1 s interburst (75% duty cyle) at 5 mJ, 4 kHz.

3.3 Wavelength Stability

Center wavelength stability is a specification of increasing interest as focus budgets are reduced. As with dose stability, this is a specification which must be met over a wide range of repetition rates. Robust and accurate wavelength control has been under aggressive development for the NanoLith™ 7000, both through reducing the sources of wavelength instability and improved wavelength correction strategies. Figure 5 shows a scan in which maximum and minimum line center errors within a 40-pulse moving window were recorded as the laser was operated at repetition rates spanning 2 to

4 kHz with a 4 Hz increment. The specification for this measurement is line center error < ±0.05 pm; the specification is met with nearly 50% margin.

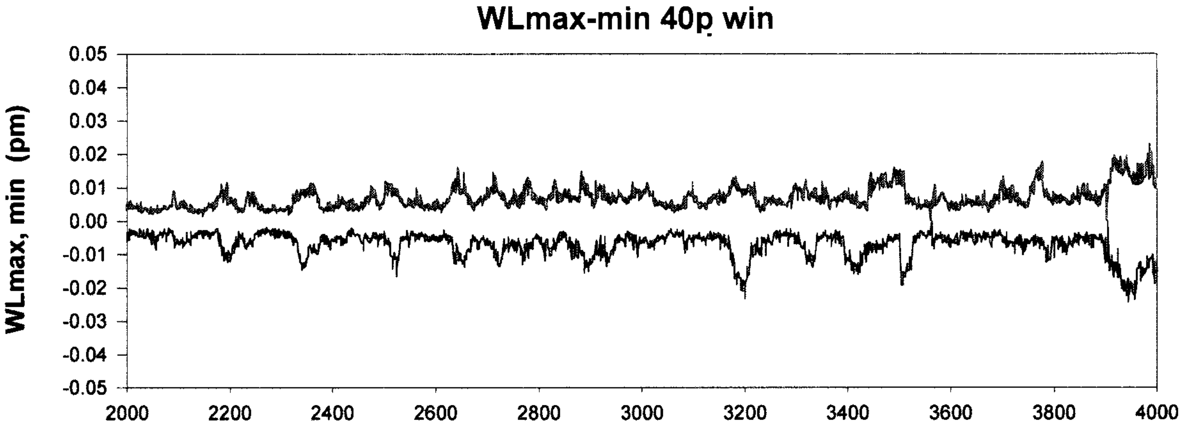

Figure 5. Line center error for a 40 pulse moving window average at repetition rates from 2-4 kHz.

3.4 Gas Life

Maintaining consistent performance throughout gas life is important in maintaining high yields without sacrificing throughput. With the NanoLith™ 7000, Cymer has extended its ArF gas life to 100 million pulses. Figure 6 displays the operating voltage and FWHM bandwidth measured on a 5 minute interval throughout a 82 million shot run at 5 mJ, 4 kHz, 33% duty cycle. The oscillations in the operating voltage reflect the depletion of fluorine as the laser is fired (gradual voltage rise) followed by an automatic injection of fluorine by the laser's gas-handling system (sharp voltage drop). Note that the bandwidth is virtually unchanged through this depletion/replenishment cycle; thus ensuring consistent contrast throughout a prolonged exposure run.

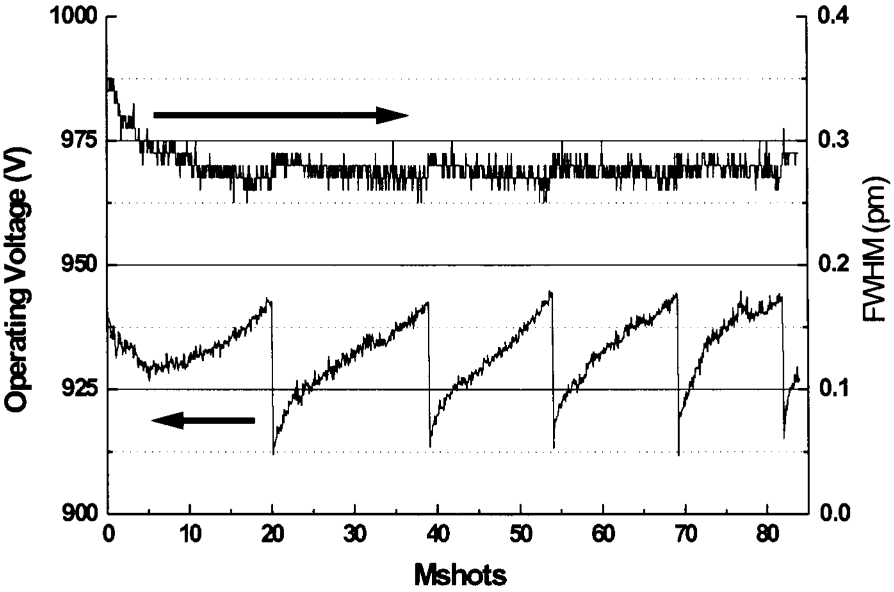

Figure 6. Operating voltage and FWHM bandwidth for 82 Mshot gas run.

4. CONCLUSION

The next critical transition in exposure wavelength used to drive advanced microlithography is upon us. Starting in 2001, 193 nm DUV exposure tools powered by ArF excimer lasers will be used to image features of 100 nm CD and below. In an effort to support the semiconductor industry, Cymer has designed and developed a new high performance, 4 kHz repetition rate 193 nm laser. The NanoLith™ 7000 is designed to successfully support production lithography at this critical node. Offering 20 Watts of average output power, the NanoLith™ 7000 is well matched to the next-generation of leading edge exposure tools supporting the highest scanning speeds for maximum productivity and throughput. This fact becomes increasingly important as the industry also switches to 300 mm wafers. Advancements in core technology development enable the delivery of highly line-narrowed light essential for high contrast imaging at lens NA's exceeding 0.75. Further, improvements in optical materials and coatings have led to greatly increased lifetimes of optics modules which greatly reduces the cost of consumables when compared to previous 193 nm sources.

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[1] P. O'Keeffe et al., "Development of a Production Worthy 4 kHz 193 nm Laser for sub-100 nm Lithography," SEMI Technology Symposium 00, 2000.

[2] J. M. Hueber et al., "Performance of Very High Repetition Rate ArF Lasers," SPIE Microlithography, 2000.

[3] G. M. Blumenstock, T. P. Duffey, E. Onkels, R. Sandstrom, "F2 (157 nm) Laser for VUV Microlithography," SEMI Technology Symposium 99, 1999.