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Advanced Excimer Laser Technologies Enable Green Semiconductor Manufacturing

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ABSTRACT

"Green" has fast become an important and pervasive topic throughout many industries worldwide. Many companies, especially in the manufacturing industries, have taken steps to integrate green initiatives into their high-level corporate strategies. Governments have also been active in implementing various initiatives designed to increase corporate responsibility and accountability towards environmental issues. In the semiconductor manufacturing industry, there are growing concerns over future environmental impact as enormous fabs expand and new generation of equipments become larger and more powerful. To address these concerns, Gigaphoton has implemented various green initiatives for many years under the EcoPhoton™ program. The objective of this program is to drive innovations in technology and services that enable manufacturers to significantly reduce both the financial and environmental “green cost” of laser operations in high-volume manufacturing environment (HVM) – primarily focusing on electricity, gas and heat management costs. One example of such innovation is Gigaphoton’s Injection-Lock system, which reduces electricity and gas utilization costs of the laser by up to 50%. Furthermore, to support the industry’s transition from 300mm to the next generation 450mm wafers, technologies are being developed to create lasers that offer double the output power from 60W to 120W, but reducing electricity and gas consumption by another 50%. This means that the efficiency of lasers can be improve by up to 4 times in 450mm wafer production environments. Other future innovations include the introduction of totally Helium-free Excimer lasers that utilize Nitrogen gas as its replacement for optical module purging. This paper discusses these and other innovations by Gigaphoton to enable green manufacturing.

Keywords: Lithography, Green, Electricity, Neon gas, Helium gas, Excimer laser, ArF immersion, Injection-Lock system, eTGM, Hybrid laser

1. INTRODUCTION

In recent years, "green" has become a pervasive topic in virtually all industries worldwide. Green initiatives are now mandatory for many companies - requiring manufacturers to execute programs and initiatives that address corporate responsibility without negatively impacting their bottom line. This also impacts the semiconductor industry as a whole - both equipment manufacturers and users. Excimer lasers provide the necessary light for lithography processes used to produce semiconductors. In a semiconductor manufacturing factory or “fab,” the power consumption of Excimer lasers will continue to increase as high power lasers grow in demand. Fig.1 shows the estimated total electricity consumption of all existing ArF dry and ArF immersion laser system in the world for next 15 years.[1)] At this rate, electricity consumption could almost double in 10 years.

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Optical Microlithography XXVII, edited by Kafai Lai, Andreas Erdmann, Proc. of SPIE Vol. 9052, 90522J © 2014 SPIE · CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2054047

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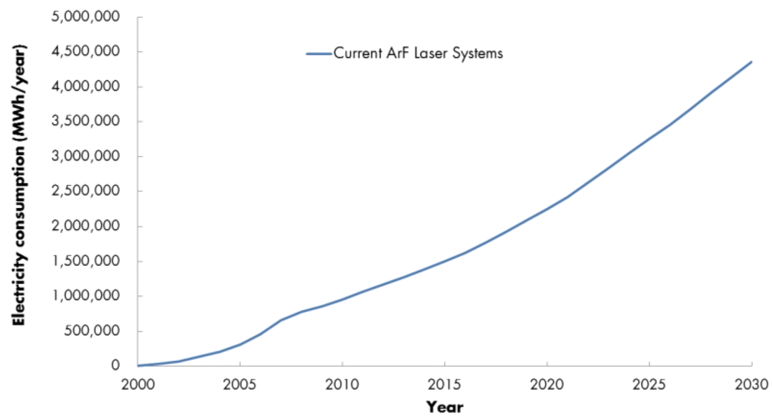

Fig.1 Electricity consumption

As a laser manufacturer, Gigaphoton has led the drive towards creating greener, more environmentally-friendly products for the semiconductor industry. Green has been an integral part of Gigaphoton's business and R&D strategies, focusing on delivering solutions for HVM – where the consideration of green is most critical. But green strategy is not only about conserving resources and eliminating waste. It is also about reducing total operational cost. Fig.2 illustrates that the estimated cost of utilities, including electricity consumption, gas consumption and heat management, is approximately 30% of the total cost of operating a laser. Gigaphoton will continue to innovate new technologies and services that reduce the overall cost of operations – including both cost of utilities and consumables – through the EcoPhoton™ program .

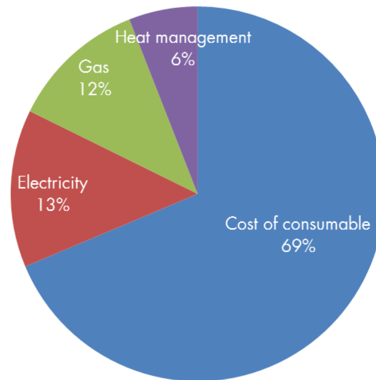

Fig.2 Breakdown of total cost of operation

2. LASER ARCHITECTURE FOR LITHOGRAPHIC ENGINE

In order to deliver the high throughput and resolution required by lithography scanners, Excimer laser light sources are required to produce both high power and narrow spectrum light. However, when power is increased, the spectrum width tends to widen. To overcome this challenge, Gigaphoton introduced the world's first GigaTwin™ platform based on Injection-Lock technology.

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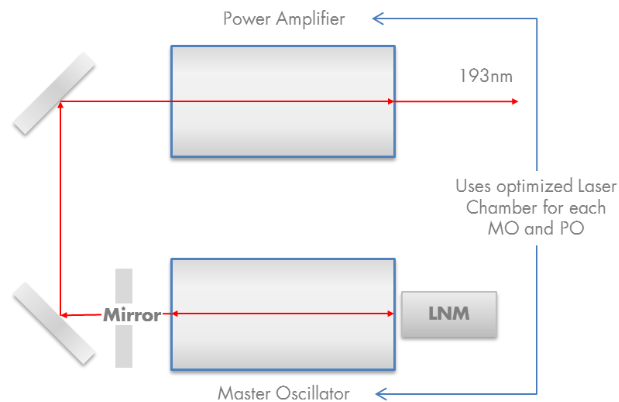
2.1 Master Oscillator and Power Amplifier systems

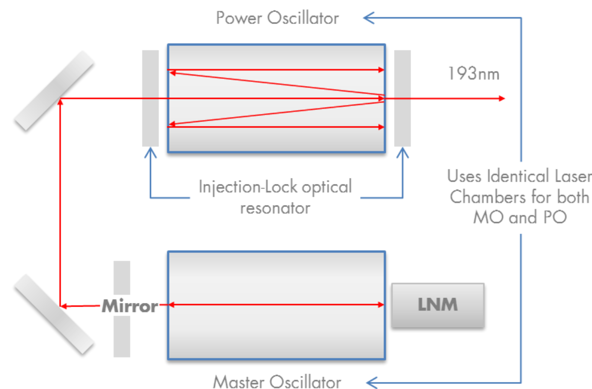
The Master Oscillator and Power Amplifier or "MOPA" system is widely used in lithography equipments. Fig.3 (a) shows the configuration of a MOPA system. The Master Oscillator laser chamber shown in the bottom position generates a narrow spectrum "seed" light through an optical resonator consisting of a Line Narrowing Module (LNM) and Mirror. This light is then fed into the Power Amplifier chamber shown in the top position, where the power is amplified through a single-pass or double-pass amplification process. Both the Master Oscillator and the Power Oscillator typically require laser chambers that are optimized for each purpose.

2.2 The Injection-Lock system

Fig.3 (b) shows the configuration of a GigaTwin™ platform with the Injection-Lock technology. The narrow-spectrum seed light is generated by the Master Oscillator using the same process and technology as the MOPA systems. This light is then fed into a Power Oscillator, as opposed to a Power Amplifier. The Injection-Lock in the Power Oscillator consists of an optical resonator that is able to amplify the light without affecting the width of the spectrum. The Injection-Lock laser system configuration is more complex in architecture than its counterpart MOPA system, but from an efficiency and scalability perspective, it is the most ideal solution for high power laser operations.



(a) Master Oscillator Power Amplifier



(b) Injection-Lock system

Fig.3 Laser architectures for lithography

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3. KEY PERFORMANCE OF THE INJECTION-LOCK LASER SYSTEM

This section explains the key output (Energy dose stability, Wavelength stability average and Spectral bandwidth E95) and reliability performance levels confirmed by Injection-Lock systems used in semiconductor manufacturing.

3.1 Output performance

Energy dose stability is an important property of laser output, because it affects critical dimension (CD) control. Fig.4 shows the trend of energy dose stability at 90W, 100W, 110W, 120W, and again at 90W. This data was calculated by integrating the energy over the specified moving window. The figure shows that there is virtually no difference from 90W through 120W operations.[2)]

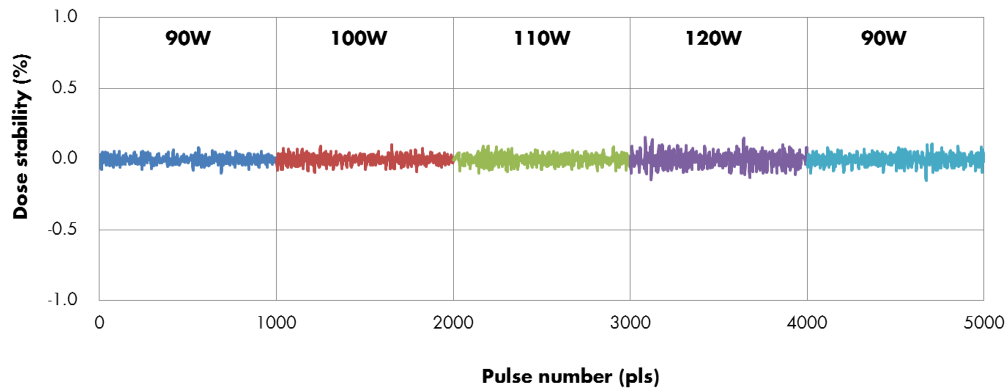

Fig.4 Energy dose stability under various power tuning

Wavelength stability is an important factor for focus control, because changes in wavelength can cause de-focusing. Fig.5 shows the dependency of wavelength error on wavelength control for various output power levels. This data was calculated by statistically treating the wavelength error averaged over the specified moving window. Wavelength control accuracy was stable and no change was seen from 90W through 120W operation.

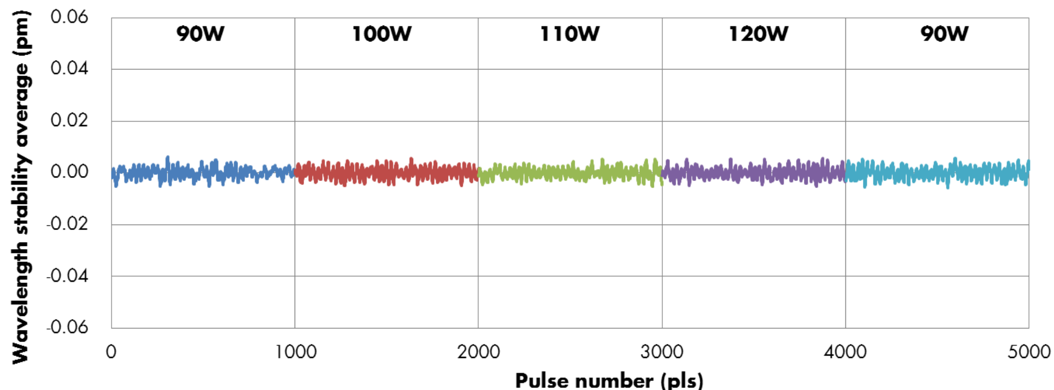

Fig.5 Wavelength stability error under various power tuning

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The spectral bandwidth of lasers is an important factor for imaging ability and CD control. Fig.6 shows the spectral bandwidth of 95% energy concentration (E95) set point at 0.3pm for various output power levels. The data shows that spectral bandwidth control accuracy is stable and no change was seen from 90W through 120W operation.

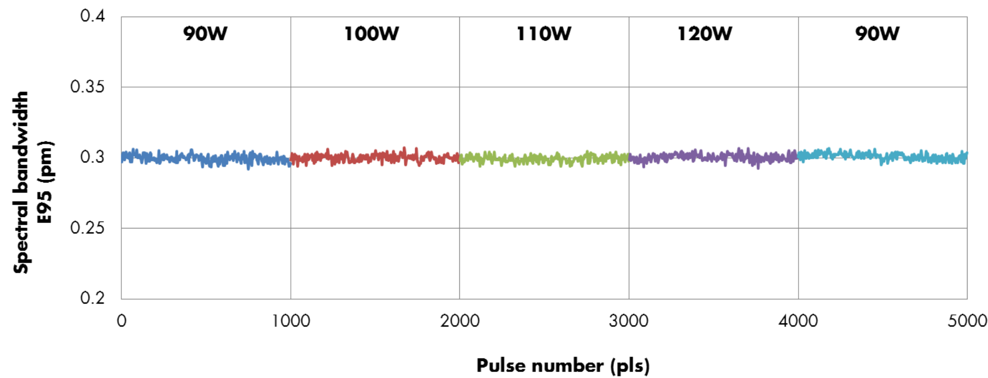

Fig.6 Spectral bandwidth under various power tuning

3.2 Reliability performance

As ArF immersion lithography moves into high volume production, the reliability of the laser becomes a common concern for industry. An important measure of reliability is the laser's "availability." Availability is defined as the percentage of the system's available time v.s. the total time. The equation is as follows.[3)]

$$Availability = \frac{Total\ hour\ of\ operation - (Scheduled\ Downtime + Unscheduled\ Downtime)}{Total\ hour\ of\ operation}$$

Gigaphoton has evaluated the reliability of 175 lasers based on the GigaTwin platform with Injection-Lock technology. Fig.7 shows availability of these lasers up to Q3 of 2013. The results show that the GigaTwin™ platform meets the industry's highest standards with average availability exceeding 99.5%. Various technologies used in the GigaTwin™ platform contribute to these results.

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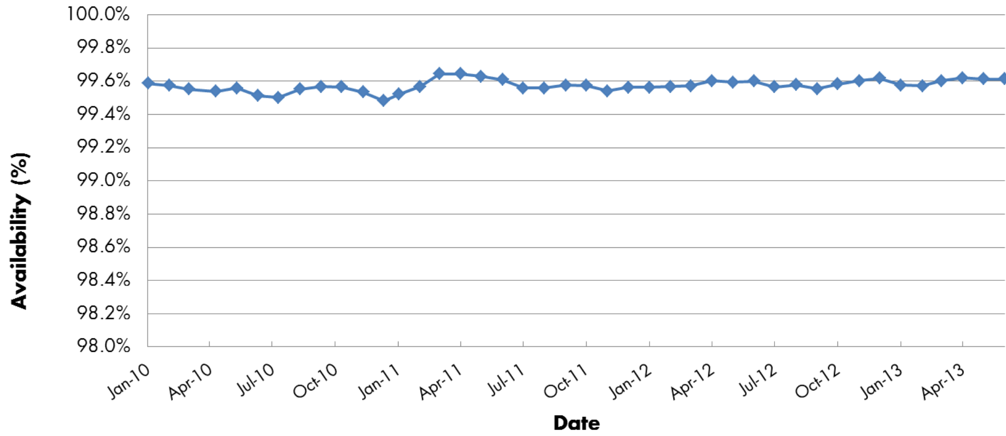

Fig.7 Availability of GigaTwin™ platform

The Mean Time Between Failures or "MTBF" is a measure of a laser's robustness. First the MTBF of each laser unit or "MTBFi" is calculated as follows.

$$MTBFi = \frac{Total\ hours\ of\ operation\ in\ 3\ months}{Number\ of\ error}$$

Note that if *number of errors* is zero, the MTBFi value is set as the total number of operational hours in a three-month period. The MTBF is calculated by averaging the MTBFi values across the total install base as follows.

$$MTBF = \frac{\sum MTBFi}{Number\ of\ install\ base}$$

Fig.8 shows the MTBF of a typical GigaTwin™ system installation. The data shows that the MTBF is steady around 2,200 hours – demonstrating that very few failures occurred and operation is very reliable.

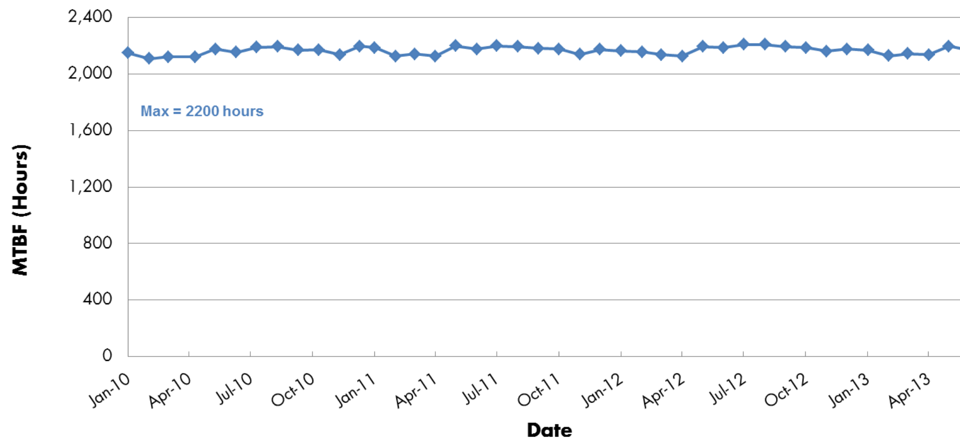

Fig.8 MTBF of the GigaTwin™ platform

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The key performances levels of the GigaTwin™ platform with Injection-Lock technology have been successfully confirmed. Both output performance and reliability performance demonstrate sufficient levels to meet the demands of the semiconductor manufacturing industry.

4. ELECTRICITY REDUCTION

4.1 Evaluation of electricity reduction

The next generation of process technologies, such as 450mm wafer production, will require higher throughput and greater output power from laser light sources. The simplest way to increase output power is to increase the input electricity. However, continuously increasing electricity consumption to generate more power is not a practical solution for HVM environments where both cost and environmental impact are critical control elements. Instead, technical innovations are required to maximize radiation efficiency to generate more power using less electricity. Gigaphoton has taken on this challenge to develop technologies that deliver the output power from 60W to 120W while reducing the input power by one half. If successful, the electrical efficiency of lasers will increases 4 times compared to current systems.

The first step was to further improve the efficiency of the current systems design. Today, higher output power can be achieved on a GigaTwin™ platform using less electricity. Survey data collected from actual customers production sites have indicated that the actual electricity consumption of Injection-Lock technology based systems were 30% less than that of MOPA systems. The second step will involve the integration of the new Hybrid laser technology.

The graph in Fig.9 shows the laser output power v.s. the laser input power. The laser input power is a measure the input power to the laser chambers. The blue line shows the relationship between the laser input and output powers for conventional laser systems that do not implement the Injection-Lock. The red line shows the same comparison with the Injection-Lock technology. [4)]

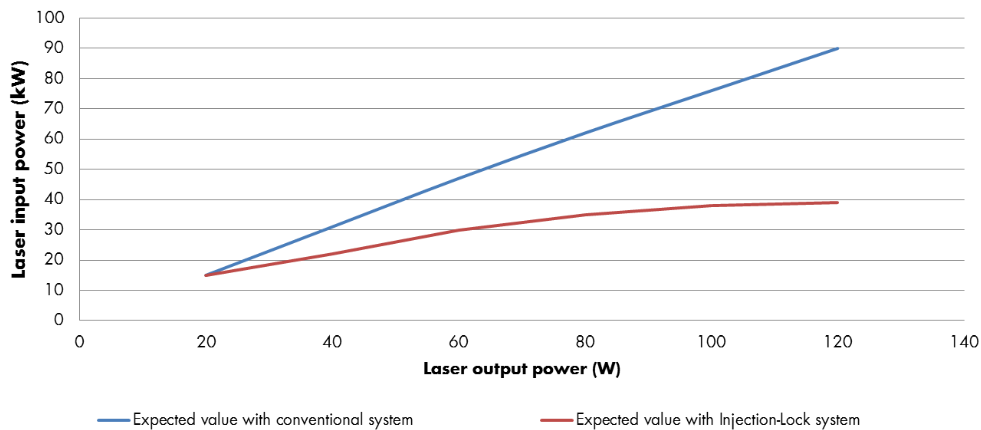

Fig.9 The trend of the electricity consumption of Injection-Lock system

This figure shows the following factors.

1) The advantages of the Injection-Lock laser systems compared to conventional lasers are clearly visible as output power increases
2) 120W laser systems with Injection-Lock technology require less than half of the electrical energy compared to a conventional laser system.

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This data is one of many examples that demonstrate the effectiveness of Gigaphoton's EcoPhoton™ program in creating innovations that reduce the overall green cost of operations. Gigaphoton will continue to drive the EcoPhoton™ program to the next level – creating new innovations such as the Hybrid laser systems to dramatically reduce energy consumption.

4.2 Hybrid Laser System

In order to further decrease the power consumption of lasers, Gigaphoton is developing the Hybrid laser system - consisting of a high coherence solid-state laser oscillator with wavelength converters to generate the initial 193nm laser pulse, and an ArF Excimer laser power oscillator. The current ArF immersion lasers with Injection-Lock technology can utilize the same laser chamber in both the Master Oscillator and Power Oscillator positions. The peak power consumption of a single ArF Excimer laser chamber is 30kW. Hence a today's GigaTwin™ ArF laser system can consume up to a peak total of 60kW. In contrast, the Hybrid laser system depicted in Fig.10 shows the same ArF Excimer laser chamber as the GigaTwin™ system used in the Power Oscillator position – thus consuming the same peak power of 30kW. However, a solid-state laser, which consumes a peak power of only 6kW, is used in the Master Oscillator position. Hence the total peak power consumption of a Hybrid laser can be reduced to 36kW, which amounts to approximately a 40% reduction compared to current Injection-Lock systems.

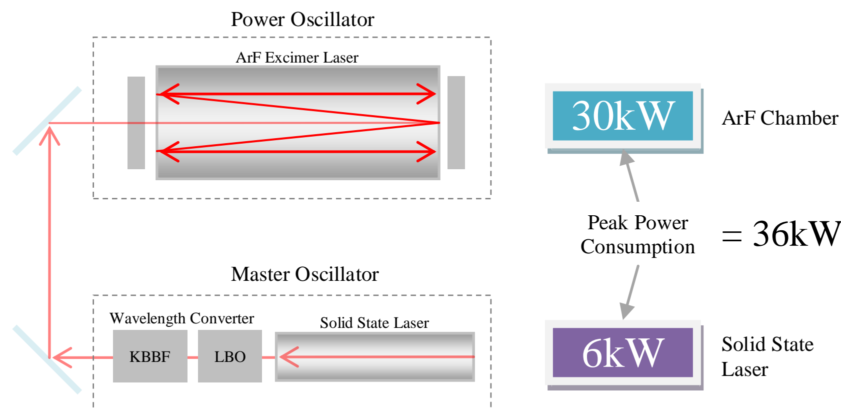

Fig.10 System architecture

The Master Oscillator in a Hybrid laser system will consists of a Ti:sapphire solid-state laser operating at 6kHz with LBO and KBBF non-linear crystals for converting wavelengths to 193nm. The KBBF crystal is capable of obtaining DUV light below 200nm by SHG and is known to have relatively high conversion efficiency for wavelengths in the vicinity of 193nm. Other advantages include transmittance down to 155nm and non-hygroscopicity. Fig.11 shows the photo of experimental system of solid-state laser oscillator. Gigaphoton has been working on experimental systems units to test and evaluate various wavelength conversion and solid state laser system overall with future plans to develop a prototype using an alternative seed laser system employing a Yb and Er fiber based laser to achieve stable, high coherent light with a small footprint.

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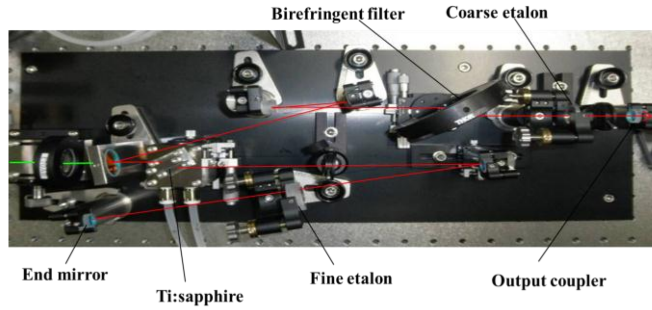
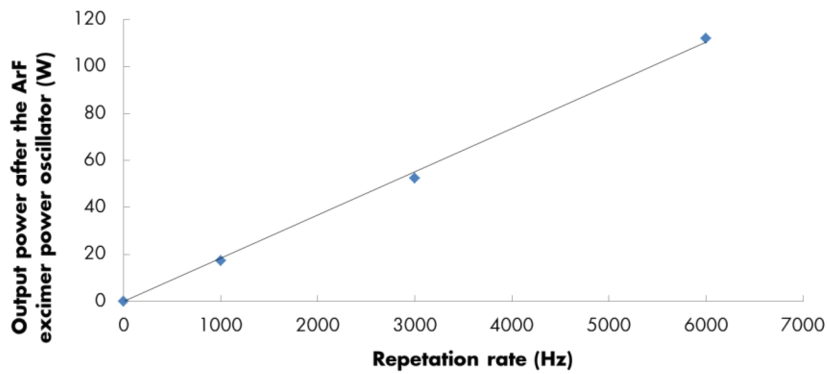
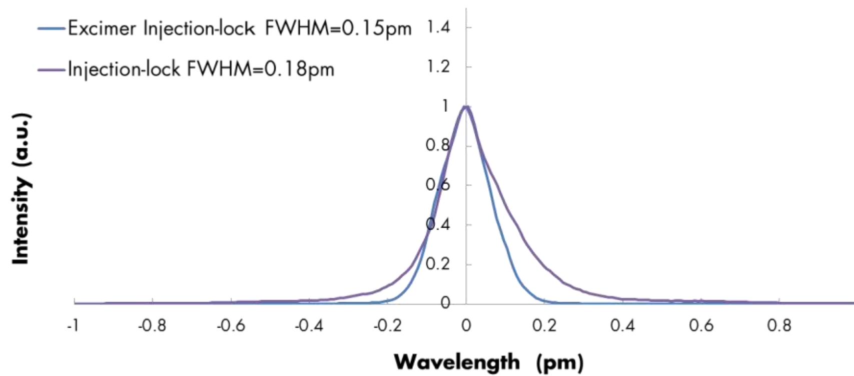


Fig. 11 Experimental system of solid-state laser oscillator

Fig.12 shows the initial experimental data using the Ti:sapphire laser and KBBF system. FIg.12 (a) shows that the output power levels of 118W at 6kHz has been successfully achieved. FIg.12 (b) shows that a spectral bandwidth of 0.18pm (FWHM) has been confirmed. These results are almost equal to that of our current ArF immersion lasers for microlithography.



(a) Output power of Hybrid Laser System



(b) Spectral profile of Hybrid laser system

Fig.12 Output power of the experimental system using Ti:sapphire laser and KBBF

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By developing the required high-efficient technologies that enable the Hybrid laser system, the target of achieving twice the output power from 60W to 120W while cutting the input power down to a half is likely to be achieved.

5. GAS USAGE REDUCTION

As the worldwide laser install base grows, so will the demand for rare natural resources to maintain them. When the supply of these rare resources becomes scarcer, prices could soar or in the worst case they could eventually dry up – causing huge turmoil in the industry. Measures need to be taken well ahead of time to prevent such a catastrophe. This section will briefly discuss effective technologies for reducing or eliminating the dependency of lasers on rare natural resources – in particular Helium and Neon gas.

One major component of an Excimer laser system is Neon. 193nm laser light is generated by a strong electrical discharge created inside a laser chamber filled with Neon gas. Each time the light is discharged, impurities are created within the chamber. As these impurities build up in the chamber they can eventually cause declination in energy due to absorption. Hence, the contaminated gas must be periodically exhausted and replaced with fresh Neon.

Helium is another gas widely used in ArF laser systems. Its properties – especially the thermal stability – make it an ideal gas for optics-based modules like the Line Narrowing Module or "LNM" to maintain spectrum and wavelength stability. However, the price of Helium has soared in the last few years and recently, there was an industry-wide concern regarding the possibility of a major shortage in the supply due to the planned shutdown of the US Federal Helium Reserve which provides a huge percentage of the world's Helium.

5.1 Neon gas usage reduction

The gases inside an ArF Excimer laser chamber are composed primarily of Neon gas combined with very small amount of Argon and Fluorine. The natural supply of Neon gas has started to diminish in recent years, prompting concerns in the industry, and reduction of its usage has become a critical challenge globally. Due to the high oscillation efficiency of the Injection-Lock technology, Gigaphoton has been able to reduce the usage of Neon gas to about one half compared to the MOPA systems. Today, Gigaphoton continues to develop advancement in gas control technology such as eTGM to reduce Neon gas usage even further.

The amount of Neon gas that needs to be injected will depend on the amount of impurities generated during the electrical discharge. The amount of impurities generated can be altered by accumulation of the laser pulses. Ideally, the laser changes the Neon injection volume by analyzing laser condition. However, fixed injection volumes and timing is used in conventional gas control systems.

The eTGM system employs new gas control algorithms that utilize laser parameters such as input power, gas pressure, output power, spectrum and wavelength stability information to determine the Neon injection parameters. By using this system, laser can automatically decide how much Neon to be injected. This allows greater accuracy in determining the level of impurities generated, that enables injection volume and timing of Neon gas to become more flexible. FIg.13 shows the comparison of Neon gas consumption between eTGM and conventional systems. This data indicates that the Neon consumption at 500 million pulses with eTGM is about one half compared to conventional systems. Assuming the laser shoots roughly 60 billion pulses in a year, eTGM can reduce Neon gas consumption by about 70K liters/year. This is equivalent to about 4% of the total running cost of an Excimer laser. As the need for reducing the consumption of Neon gas becomes stronger in the future, new innovations such as Neon recycling systems for lasers will be needed.

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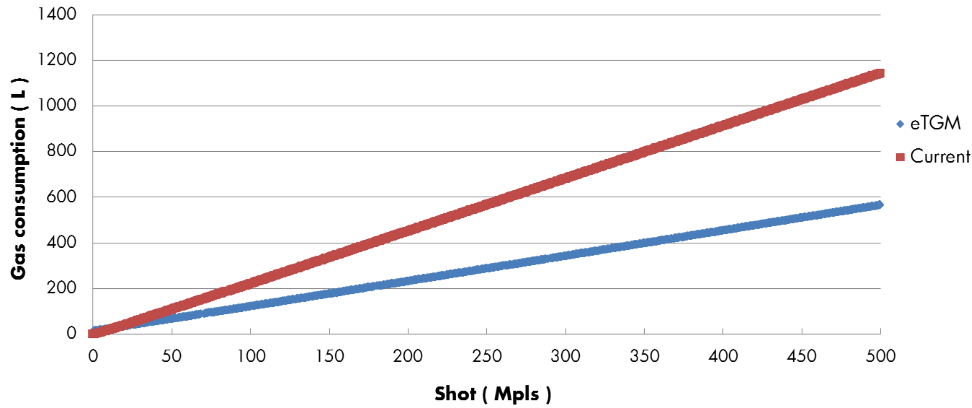

Fig.13 Comparison of gas consumption

5.2 Helium-free laser systems

A single ArF Excimer laser system consumes approximately 270M liters/year of Helium gas – primarily for LNM purging. The purpose of using Helium gas to purge the inside of an LNM is to stabilize the performance by eliminating the thermal effects generated during the exposure. However, due to future risks associated with the worldwide supply, it is desirable to eliminate dependency on Helium altogether. An alternative method for purging the gas inside of and LNM is to use Nitrogen instead of Helium. However, the refractive index differs between Helium and Nitrogen, so the wavelength and spectrum stability performance can be negatively affected by switching to Nitrogen. To verify this effect, Gigaphoton conducted an experiment comparing performance of the laser using Nitrogen purge with Helium purge. For spectrum stability, E95 was measured at duty cycles of 8.3%, 23.6% and 75.2%. For wavelength stability, maximum sigma was measured under repetition rates ranging from 2000Hz through 6000Hz and duty cycles from 8.3% through 75.2%. All the experiments are conducted with output power level at 60W.

Fig.14 shows the E95 measurements of Nitrogen purged LNMs under various duty cycles. It demonstrates that E95 varies linearly as duty cycle increases. Based on this data, under exposure mode where duty cycles are in the vicinity of 30% to 45% for general wafer production environments, Nitrogen purge can offer the same performance level as Helium purge. Further experiments will be conducted in cooperation with wafer manufacturers.

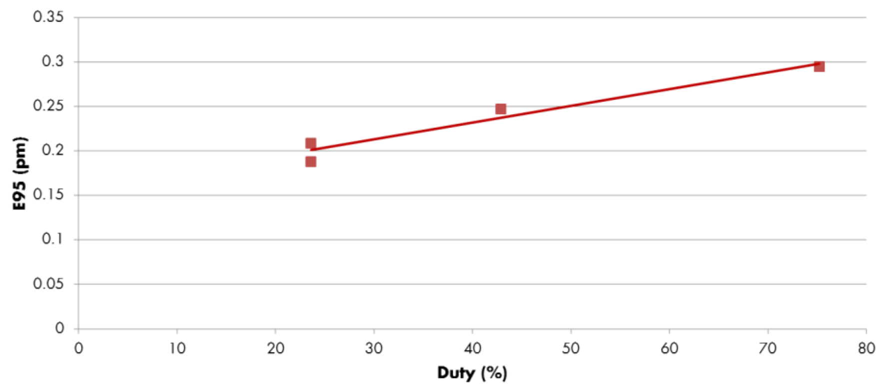

Fig.14 E95 of Nitrogen purge LNM under various duty cycle

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Fig. 15 shows the comparison of maximum sigma between Helium and Nitrogen purge under various exposure conditions. No major difference was found in the performance levels between the two gases.

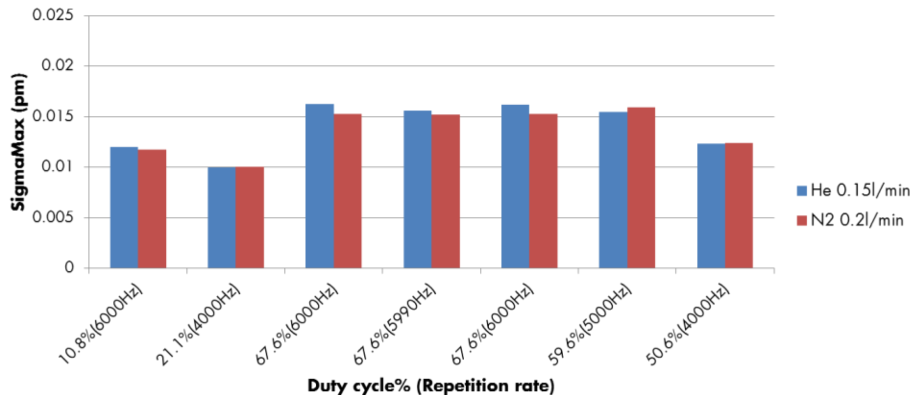

Fig.15 Wavelength stability of Nitrogen purge LNM

6. CONCLUSION

Gigaphoton has been developing green technologies through the EcoPhoton™ program to support the sustainability of HVM environments. The Injection-Lock technology is one of the key enabling technologies for green manufacturing. It continues to delivers performance levels that meet evolving design targets, and the industry's highest demand for reliability. It has been verified that the Injection-Lock technology can offer more than 50% savings in electrical energy, and in the future, an additional 50% reduction can be realized through the next generation Hybrid-laser systems, ultimately bringing the total electricity consumption down to 1/4 that of conventional systems. At the same time the output power is doubled from 60W to 120W, resulting in an 8X increase in overall efficiency levels. Furthermore, the Injection-Lock technology can reduce Neon gas consumption by 50%, and similarly, another 50% reduction can been achieved by employing new gas control systems such as eTGM. This also brings the total gas consumption levels down to 1/4 that of conventional systems. The EcoPhoton™ program extends its activity to eliminate usage of other noble gas such as Helium. A Helium-free laser system is being developed that utilize Nitrogen for gas purging in an LNM.

From the perspective of cost of ownership, the estimated cost of utilities including electricity, gas and heat management of a laser is approximately 30% of the total cost of operation. Gigaphoton's EcoPhoton™ program will continue to deliver new and innovative green technologies that help to minimize or eliminate the consumption of valuable natural resources, and while at the same time reducing the cost of operations. Gigaphoton has already begun working on next generation green technologies that not only enables reduction of natural resource consumption but also recycling them.

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