Feasibility study of 6 kHz ArF excimer laser

for 193 nm immersion lithography

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ABSTRACT

A feasibility study of next generation 6 kHz ArF laser for lithography is presented. High repetition rate operation of excimer lasers faces two technical challenges: 1) the occurrence of acoustic waves caused by the discharge in the laser chamber and 2) the huge energy consumption of the large gas flow fans. This paper describes our approach to dampen the acoustic waves. A computer simulation of acoustic wave generation inside the discharge chamber was done. The simulation correlates well with Schlieren photography measurements that visualized the acoustic waves. Based on these results, a chamber for 6 kHz repetition rate was newly designed. Measured spectral data (FHWM and E95) proved that the acoustic wave perturbation was remarkably reduced. A very efficient design method for high repetition rate laser chamber has therefore been established.

Keywords: ArF excimer laser, 6 kHz operation, immersion lithography, acoustic wave

1. INTRODUCTION

193 nm lithography tools equipped with ArF excimer laser light sources are used in leading edge semiconductor manufacturing. When 193 nm lithography was firstly introduced to industry, the design rule target was 130 nm, Half Pitch (HP). However, the rapid progress of 248 nm lithography has been driving the target resolution of 193 nm lithography to smaller values. Today the targeted design rule is below 90 nm. But immersion technology is considered as the key technology to enable a HP below 65nm with 193 nm lithography. Therefore, requirements for ArF excimer laser for lithography are getting stricter, especially the demand for a smaller design rule requires a narrower spectral bandwidth, and the demand for higher throughput requires a higher laser output power.

However, for a single laser chamber it is difficult to realize a very narrow spectrum and a high laser power at the same time. In this case the laser operation condition has reached a trade-off between small bandwidth and high output energy. In addition, it is increasingly difficult to extend the lifetime of the line-narrowing module, because the larger laser power causes an increased DUV optical load to all optics.

Therefore, a dual chamber system has been adapted[1)]. An oscillator laser (master, chamber 1) with low-output energy and extremely narrow-bandwidth is injected into an amplifier laser (chamber 2) that is synchronized with the master laser. The operating conditions of each chamber can be optimized for the various applications. The lower laser power of the oscillator improves the lifetime of the optical components. This dual chamber system surely enables higher power at narrower bandwidth that is essential for advanced exposure processes.

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2. REQUIRED SPECIFICATIONS

The output power of ArF lasers increased year by year. The target average power will be above 45 W. One of the most important technical issues for high power ArF lithography is the reduction of optical damage in both, the exposure tool and the laser. Since the excimer laser pulse duration is very short (~30 nsec) the peak power is high, which can easily damage the optical elements.

One method to reduce the optical damage is to decrease the laser pulse energy, which can be done by increasing the repetition rate. A laser operating at 4 kHz needs 15 mJ pulse energy for 60 W. However, in case of 6 kHz, a 10 mJ pulse energy is needed for 60 W. If the laser pulse energy decreases from 15 to 10 mJ, the damage to quartz by two photon excitation will be reduced by (10/15)^2 = (2/3)^2=40%.

Optical pulse stretch (OPS) is another method to reduce the laser peak power. In OPS, a part of the laser beam is first separated by a beam splitter and, after a delay path, recombined with the main beam. The delayed light overlaps with a later part of the main laser pulse, i.e. the shape of the laser pulse spreads and the peak power is reduced.

These two methods are not exclusive and there is a synergy effect if the two methods are combined. Especially the first method - high repetition rate laser – has a “low risk” [2].

Specifications for the next generation ArF excimer laser of Gigaphoton are shown in Table 1.

Table 1. Required specifications for 6 kHz ArF excimer laser

	6 kHz Laser	GT40A
Max Power	60 W	45 W
Rep.Rate	6000 Hz	4000 Hz
Spectrum (FWHM)	0.20 pm	0.20 pm
Spectrum(E95)	0.5 pm	0.5 pm
Pulse Duration	70ns	70ns

3. TECHNICAL ISSUES

One of the most important issues of high repetition rate laser development is the elimination of acoustic waves inside the discharge chamber[3]. The acoustic wave causes a fluctuation of the laser gas density at the discharge area, which deteriorates laser properties. The effect of the acoustic wave increases with increasing repetition rate. Hence, more sophisticated countermeasures are needed for a 6 kHz laser as compared with a 4 kHz laser.

The mechanism how acoustic waves influence the laser characteristics are explained as follows. The laser gas is excited via a discharge. This discharge is generated by applying a high voltage, ~30 kV, during several nano-seconds between two electrodes. During the short discharge period, a huge amount of energy is deposited in the laser gas inside the small discharge area, i.e. the temperature in this area rises quickly. This causes a large fluctuation of the gas density, which produces a shock wave, i.e. an acoustic wave. The acoustic wave propagates outside of the discharge area, and returns to the discharge area after being reflected by the chamber walls. The reflected wave causes a fluctuation of the gas density in the discharge area. If the discharge occurs in an area of fluctuating density, it will be unstable and therefore the laser performance too. An illustration of acoustic waves inside a laser chamber is shown in Figure 1.

Typically, acoustic waves cause a larger spectral bandwidth of the laser[4]. Experimental data of the spectral bandwidth versus repetition rate are shown in Figure 2. Note that this chamber is not optimized. The spectral line shapes were measured with the ELIAS spectrometer.

It can be clearly seen that extremely large spectral bandwidths are observed at some repetition rates. The time for an acoustic wave to return from the chamber wall depends on the chamber inner structure, and there are evidently certain

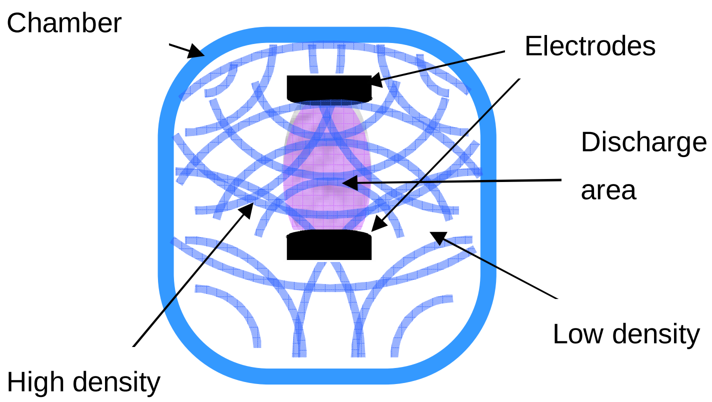


Fig. 1 Image of acoustic wave behavior in a laser chamber

repetition rates at which acoustic waves strongly interact. These repetition rates will limit the operation of exposure tools. Therefore damping of acoustic waves is needed in order to realize higher repetition rate laser.

Another major issue in the development of high repetition rate laser is the reduction of the electrical power consumption of the gas flow fan inside the discharge chamber. For a higher repetition rate laser operation, a faster gas circulation system is needed because less time remains to remove the gas between consecutive discharges. However, the electrical power to drive the motor increases with the third power of the revolution speed of the fan. Hence, a more efficient gas flow system is needed for the 6 kHz laser development.

As mentioned above, there are two major technical issues for the 6 kHz laser development. In this paper we discuss the acoustic wave damping.

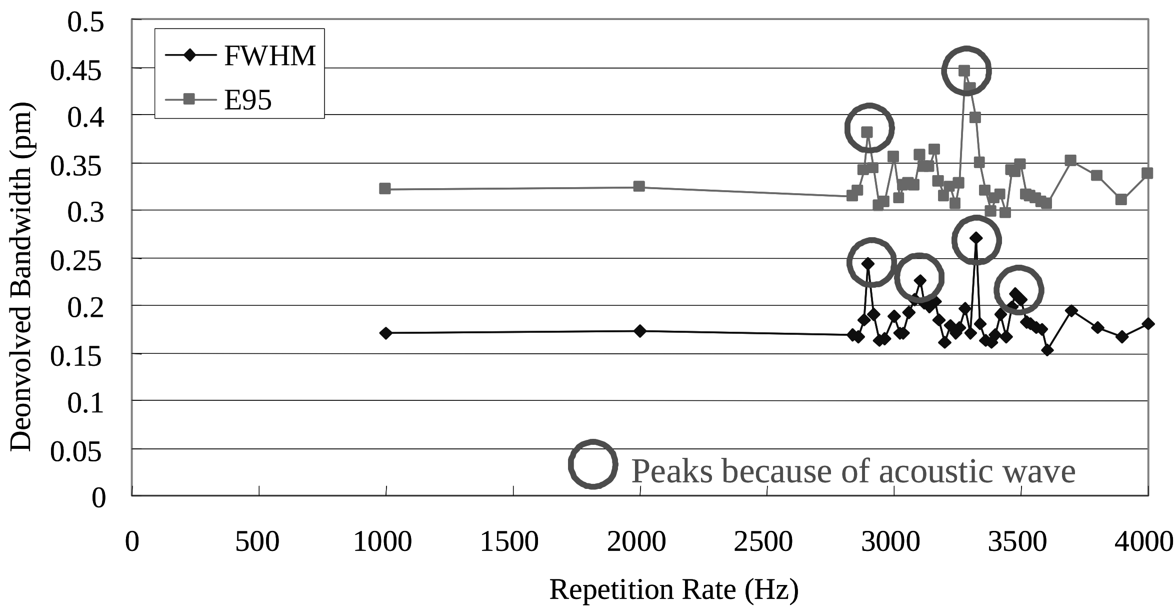


Fig. 2. Effect of acoustic wave on spectra bandwidth (non-ideal chamber)

4. ACOUSTIC WAVE SIMULATION

Several methods exist to minimize the effects of acoustic waves on the laser properties. Two major methods were used for the laser development. The first one is to place acoustic wave absorbers inside the chamber in order to reduce the intensity of the reflected wave. The second one is to remove the structures near the discharge area, which reflects the acoustic wave. In order to efficiently adapt these methods, it is important to investigate the behavior of the acoustic wave inside the laser chamber. However, the behavior of acoustic waves inside the laser chamber is very complicated due to the complex inner structure of the laser chamber. Several parts inside the chamber, e.g. for electrical insulation and smooth gas flow, make the inner shape of the chamber very uneven and the prediction of acoustic wave behavior difficult.

It is therefore not an efficient way to use the trial and error method making actual lasers chamber and evaluating the acoustic wave effects. Computer simulation is here the more effective and time saving development method.

A wave equation is solved to investigate the wave behavior. Equation (1) is the basic equation. P is the sound pressure, c is the wave propagation speed, and x, y, z are the position coordinates.

$$\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}+\frac{\partial^2 P}{\partial z^2}-\frac{1}{c^2}\ddot{P}=0 \qquad (1)$$

The equation (1) is derived from two equations, continuity equation (2) and Euler's equation (3).

$$-\frac{1}{k}\frac{dP}{dt}=\mathrm{div}\left(\frac{d\vec{U}}{dt}\right) \qquad (2)$$

$$\vec{\nabla}P=-\rho\ddot{\vec{U}} \qquad (3)$$

Here, U is the particle displacement and ρ is the gas density. The calculated wave front pattern has been compared with the actual pattern.

To measure the actual pattern, the Schlieren method was used. The Schlieren method is a gas density measurement method that is based on the corresponding refractive index differences. The contrast ΔE due to a gas density change is given by equation (4). ΔE is the Schlieren image intensity. The Schlieren measurement system applied to the laser chamber is shown in Figure 3.

$$\Delta E=\frac{\partial^2 \rho}{\partial x^2}+\frac{\partial^2 \rho}{\partial y^2} \qquad (4)$$

The acoustic wave front in the discharge area was measured by this system. Two dimensional gas density changes were observed perpendicular to the laser beam propagation direction. Results are shown in Figures 4.

The temporal change of the wave pattern can be clearly seen. The computer simulation has been further optimized by comparison with the experimentally obtained images. Figures 5 show the images of the calculated wave fronts.

A main issue was the optimization of the initial condition of the sound source consisting of many frequencies. The frequency spectrum of the sound has therefore been measured and the result was used in the simulation code. Finally, the time and spatial resolution were also optimized, evidently with respect to the calculation time.

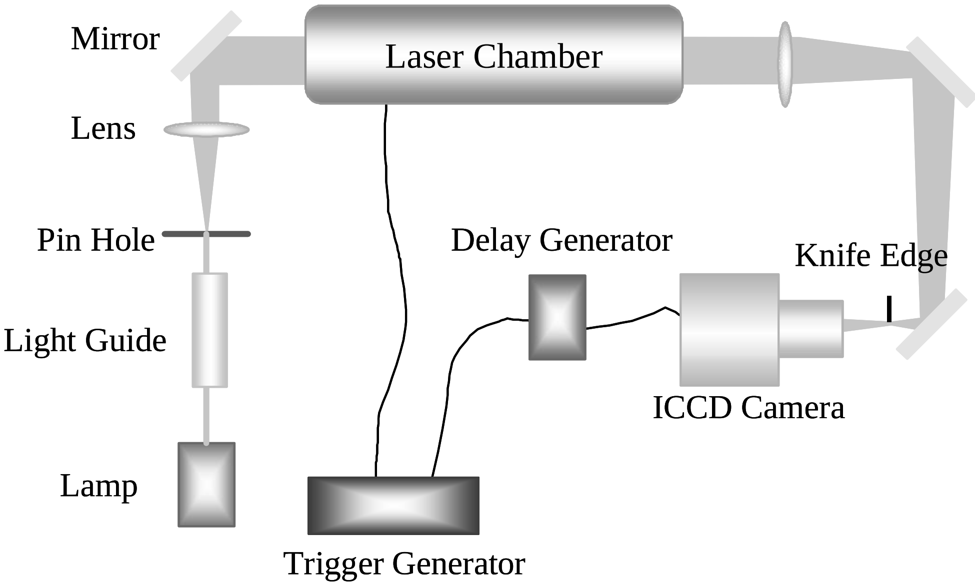
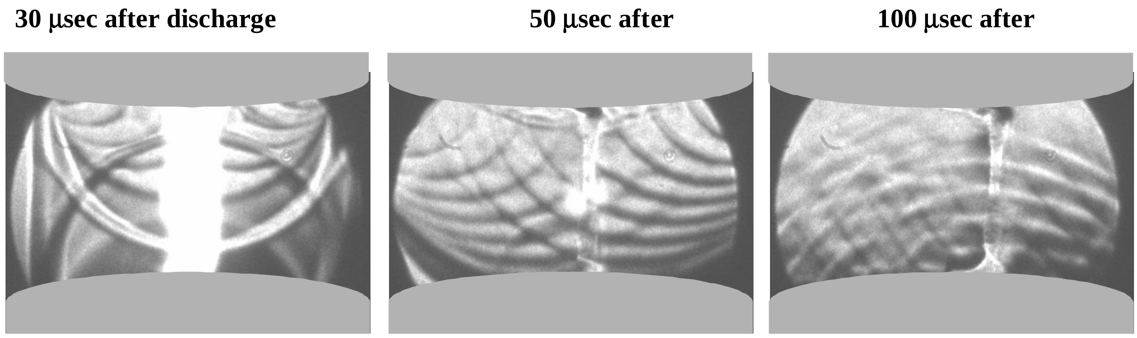
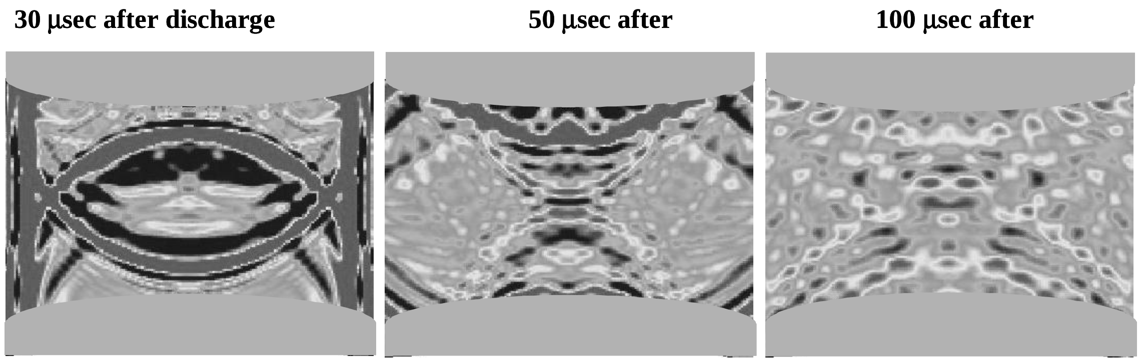


Fig. 3. Schlieren measurement system

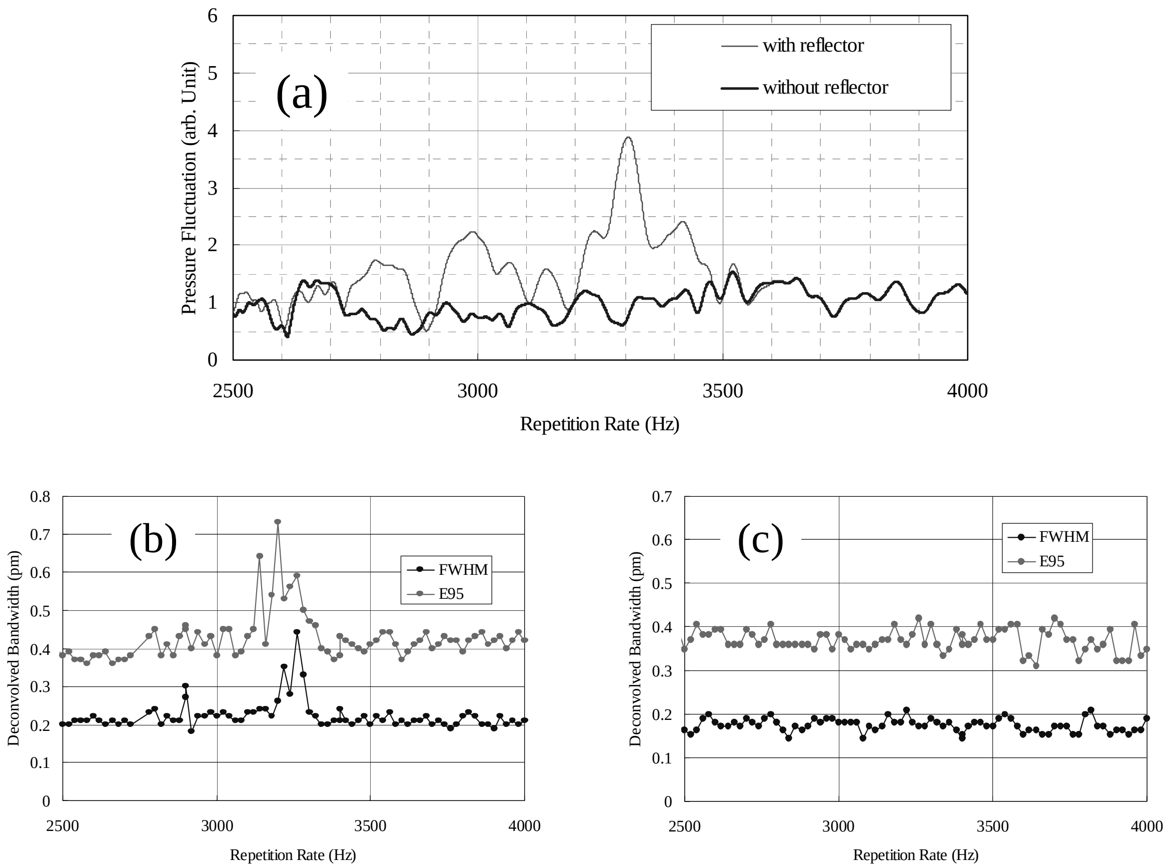


Figs 4. Visualized acoustic wave (measured by Schlieren method)



Figs 5. Calculated wave front (calculated by PC)

In a next step a quantitative analysis was done. The gas density fluctuation in the discharge area was the parameter selected to evaluate the acoustic wave effect on the laser bandwidth. Two different discharge chambers were compared. One chamber had a reflector placed near the discharge area whereas the chamber other had no reflector. Figures 6 show the calculated pressure fluctuation compared with the measured spectral laser bandwidth and purity.
In the case for the chamber with reflector the gas density fluctuation has peaks at certain repetition rates where also the spectral bandwidth has peak values. These peaks disappear for the chamber without reflector in both cases, calculation and actual measurement.
The developed computer simulation therefore accurately predicts the acoustic wave behavior and can be used for a new laser chamber design.



Figs 6. (a) Gas fluctuation calculation results
and spectral bandwidths measurements (b) with reflector and (c) without reflector

5. ACOUSTIC WAVE ANALYSIS FOR 6 kHz OPERATION

A computer simulation for a former laser chamber and a new design has been made. Figure 7 shows the calculated gas pressure fluctuation in the discharge area for the former laser chamber. The predicted gas pressure fluctuation at 6 kHz increases up to 50 % compared to the maximum fluctuation below 4 kHz for the former chamber.

Acoustic waves inside the new chamber have to be reduced in order to keep the pressure fluctuation level at least as low as in the old laser chamber at 4 kHz. The inner chamber structures were therefore especially designed to reduce acoustic wave propagation, and the layout of the acoustic wave absorbers was optimized. With these improvements, the effect of the acoustic wave at 6 kHz was reduced to the same level as at 4 kHz. An actual laser chamber was produced and was

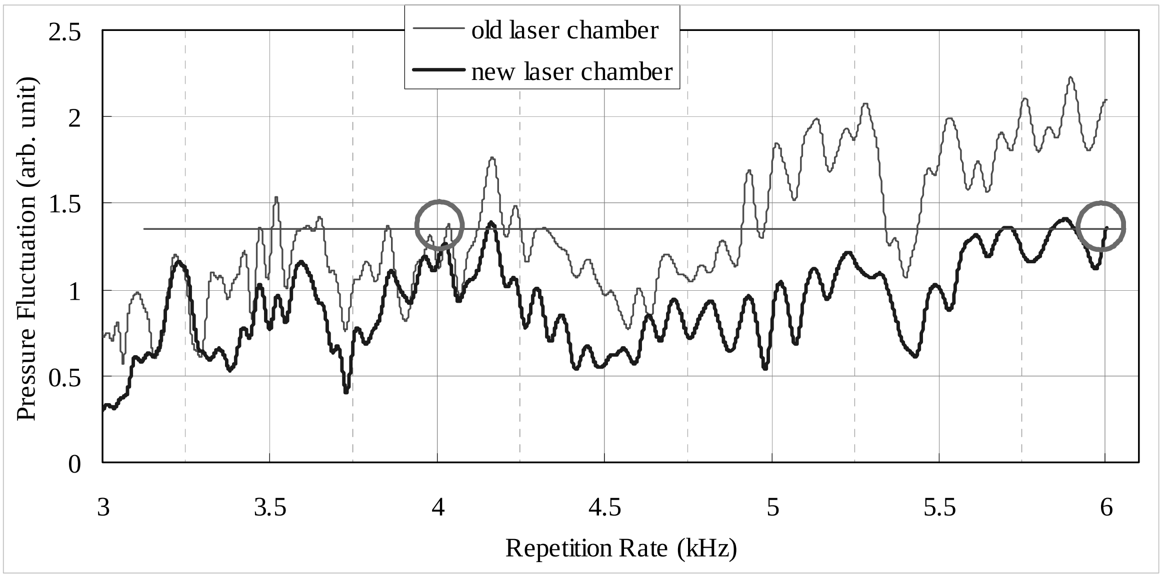


Fig. 7. Calculation results for new laser chamber

operated at a maximum repetition rate of 6 kHz. Figure 8 shows the measured spectral bandwidth between 1 kHz and 6 kHz repetition rate. No critical repetition rate at which the bandwidth increases due to acoustic waves is observed. In addition, the spectral bandwidth remains constant with increasing repetition rate.

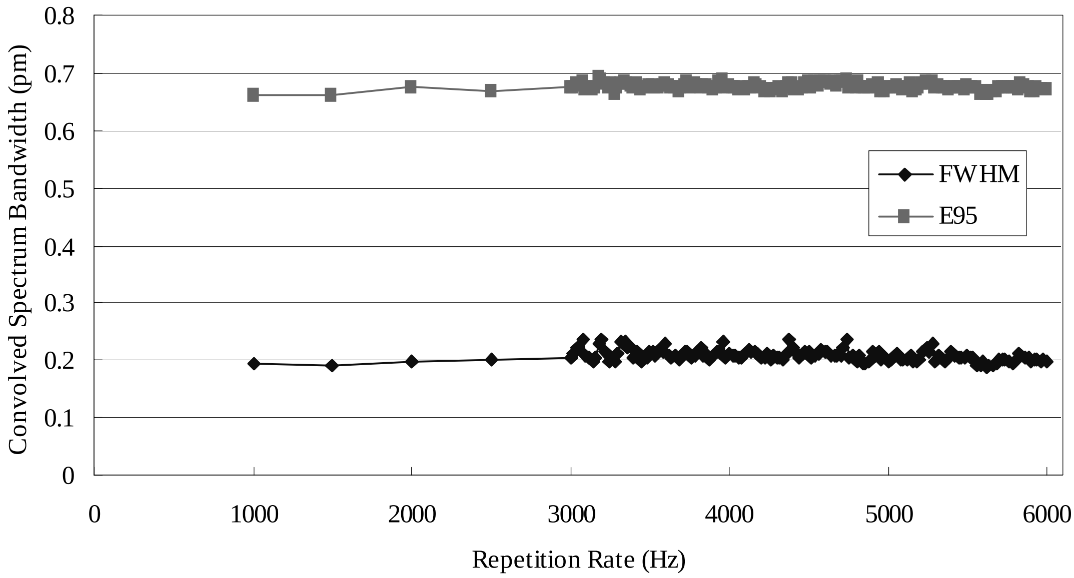


Fig. 8. Spectral bandwidths of improved laser chamber from 1 kHz to 6 kHz operation

4. CONCLUSION

A feasibility study of the next generation 6 kHz ArF laser for lithography has been made. Efficient reduction of acoustic waves, which was a major technical issue, is reported. A computer simulation has been used to effectively design a chamber for 6 kHz repetition rate. Generated acoustic waves inside the laser chamber were visualized in order to optimize calculation results. A quantitative analysis of the calculation predicts the laser spectral bandwidth fluctuation. Improvements of the chamber layout were done based on these calculation results and a laser chamber for 6 kHz operation has been designed. The laser spectral bandwidth was measured and a constant bandwidth was obtained for a repetition rate between 1 kHz and 6 kHz. Therefore, acoustic waves are significantly reduced and the 6 kHz ArF laser improvement has been completed.

Gigaphoton has successfully developed GT40A, an ArF excimer laser for advanced lithography, which is based on Injection Lock technology that has very high oscillation efficiency. The specifications of GT40A are a repetition rate of 4 kHz, 45W average power and 0.2 pm spectral bandwidth (FWHM).

Figure 9 shows the ArF laser roadmap of Gigaphoton. A 60W class ArF laser will be available in 2006 for 45-65 nm HP manufacturing.

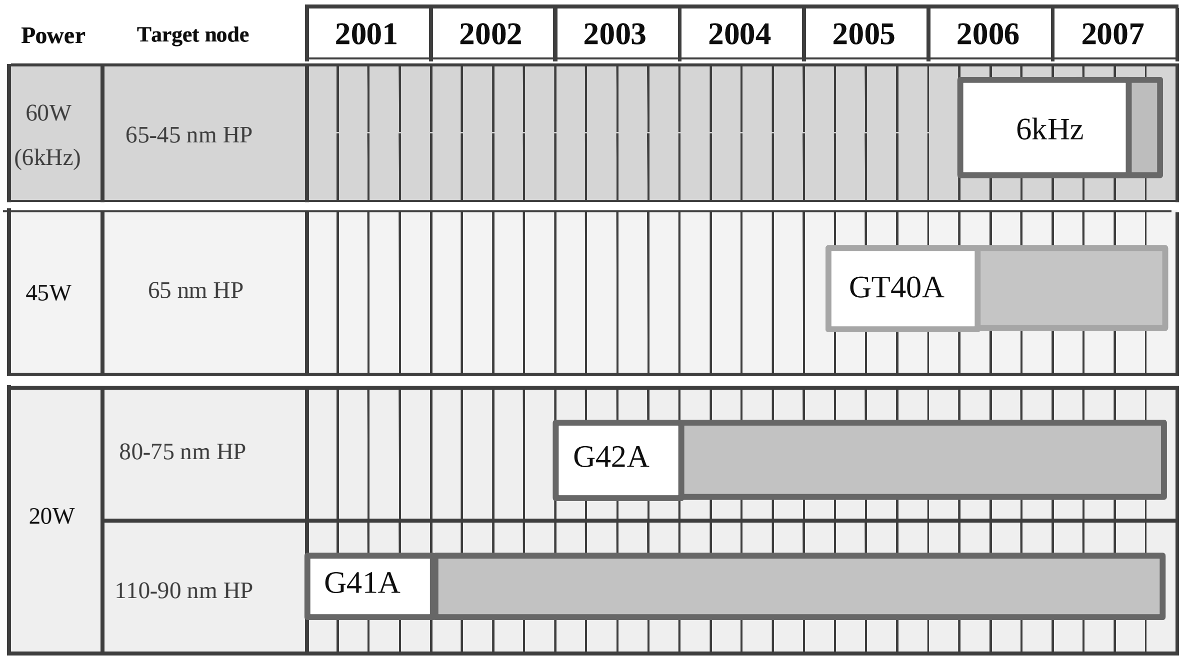


Fig. 9. Gigaphoton roadmap for ArF excimer laser.

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