Extreme high NA, High Throughput Scanner Compatible 4 kHz KrF excimer laser for DUV lithography

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ABSTRACT

KrF excimer laser lithography has applications for the less-than-130-nm-design rule by improving the exposure technology, i.e., super-resolution technology. We therefore developed a 4-kHz KrF excimer laser which corresponds to the next generation's high throughput and high number of aperture (NA) scanner requirements, and achieved low cost of operation (CoO) for this light source for mass production uses. We estimated the basic performance requirements of our device, and developed the necessary high repetition rate operation technology that corresponds to a high throughput scanner, and achieved 4-kHz/30-W laser output. We also developed pulse stretching technology for ultra line narrowing, which can accommodate the high NA lens, and achieved more than 30 ns pulse width (Tis). We can thus expect less than 0.45-pm spectral bandwidth (FWHM). Moreover, the relation of the repetition rate operation and main module life was evaluated, and the optimal repetition frequency, which considers CoO, was adopted.

Keywords: lithography, KrF, excimer laser, high throughput, high repetition rate, CoO, pulse stretching

1. INTRODUCTION

The 248-nm wavelength KrF excimer laser scanner is presently the main exposure equipment used in semiconductor lithography to mass produce the latest devices. Recently, the 193-nm wavelength ArF excimer laser scanner has begun to be used because it corresponds to the design rule of less than 130 nm needed for some devices in mass production. [1,2.] But this shorter wavelength poses problems such as the deterioration of the transmission factor or compaction of the optical parts in the laser scanner itself, therefore, the cost of operation (CoO) of the ArF is higher than the KrF excimer laser scanner.

However, it is possible for a KrF excimer laser scanner to conform to the less-than-130-nm design rule. The advancement of super-resolution exposure technologies such as phase-shift or transformed illumination technology has made this feasible, even though the 180-nm design rule was conventionally thought to be the limit.[3] We, the manufacturer of laser equipment, believe that it is necessary to develop and supply this higher performance KrF excimer laser, which will form an integral part of the next generation's high NA and high throughput scanner. In addition, this laser should have an improved CoO to enhance its practicality as a light source in lithography for mass production.

Therefore, a 4-kHz KrF excimer laser, corresponding to high throughput and high NA, was developed at Gigaphoton for 3rd or 4th quarter release in 2001. There were two main technical requirements: the first is 4-kHz high repetition rate operation

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with high stable output energy stability corresponding to the high throughput. The second is the ultra line narrowing technology corresponding to a high NA lens. Here, the fundamental technologies to meet these requirements and the basic performance are described. Moreover, the relationship between the repetition rate and its influence on each module's lifetime are considered, and the repetition rate is optimized accordingly.

2. HIGH REPETITION RATE OPERATION TECHNOLOGY IN EXCIMER LASERS

For high repetition rate operation, the following issues must be solved: 1) The products by electric discharge, such as metric dust and electrified molecules, are difficult to remove from the discharge region by the gas flow because the interval of each discharge is shortened. These molecules and dust destabilize the electric field and discharge unstable, and deteriorate energy stability and laser efficiency. 2) The electrified molecules remaining near the surface of the electrode also deteriorate the energy stability and laser efficiency, and are not easily removed by the gas flow. 3) The increase of the clearance ratio (CR) value caused by the speed-up of the cross flow fan (CFF) motor to achieve faster gas velocity results in an enlarged device that needs increased input electric power.

We addressed the above-mentioned issues as follows. 1) The electric power increase in the CFF motor was suppressed to a minimum by using an efficient gas velocity increment. This improvement resulted from gas velocity distribution analysis between the electrodes. 2) The CR value was decreased by achieving a uniform, arc-free discharge. To generate uniform discharge requires development of the pulse power module (PPM) to generate high-speed, short pulses; which makes the electric field at the beginning of the discharge uniform.

2.1 Improvement of gas velocity between electrodes

In a discharge pumped gas laser, it is necessary to blow off deteriorated gas by discharge with the gas circulation. The electrical discharge causes the depletion of the halogen, the sputtering of the electrode metal, and generates electrified molecules. The necessary gas velocity v_g is given by equation (1). Here, K_c is the clearance ratio (CR) value, w is the width of the discharge and f is the repetition rate.

$$v_g = K_c \times w \times f \qquad (1)$$

Fig. 3 shows the relationship between the gas velocity (the CFF revolutions) and energy stability of sigma, and indicates that the energy stability deteriorates dramatically from specific flow velocity. Usually, a K_c corresponding to a specific gas velocity is called the CR value. However, in an actual laser, a low-energy pulse is observable, though it is a low probability, even if the CR value is greater than necessary. Fig. 1(a) shows the gas velocity distribution between the cathode and anode, which was measured by a model G21K (Mass production type 2-kHz KrF laser). This data indicates that we should pay attention to the gas velocity near the electrode surface if it is likely to be less than 50% of the average velocity. It is thought that the low pulse energy occurs when an irregular gas velocity appears several places at the same time along the discharge region.

An excimer laser for lithography is designed to have a 1.5 times margin over the necessary CR value to avoid the irregular pulses that have negative effects on the dose stability of the exposure system. In other words, laser performance such as energy stability is not decided by the CR value with the average gas velocity, but the CR value with the minimum gas velocity. When we developed our 4-kHz laser, we gave priority to improving the minimum gas velocity, especially near the electrode surface, by redesigning the gas flow path and the structure around the electrodes to keep the increase in electric power to the CFF motor to a minimum. Fig. 1(b) shows the result after redesign, where the minimum gas velocity on the surface of electrodes is improved 1.75 times. This improvement meant an increase in electric power in the CFF motor could be suppressed to 45%.

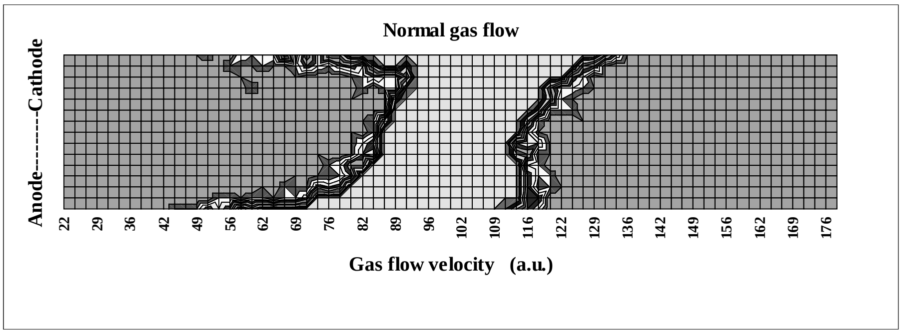

Fig. 1 (a) Gas flow velocity between the cathode and anode – conventional model

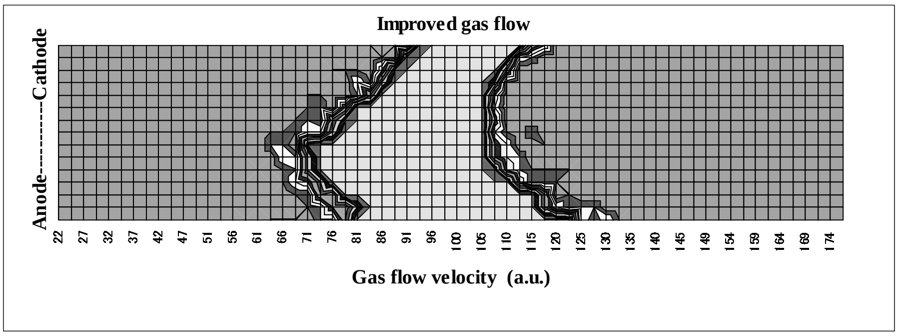

Fig. 1 (b) Gas flow velocity between the cathode and anode – 4kHz KrF

2.2 Improvement of dV/dt

Gas replacement by gas flow cannot be expected at the surface of the electrodes and in the space close to them. Therefore, non-uniform distribution of the residual charge influences the next pulse by causing a nonuniform initial electric field. This influence escalates during high repetition rate operation because the number of charged particles which disappear by recombining decreases. Volume discharge without constriction must continue during the discharge without creating residual, non-uniformly charged particles. Applying a sufficiently high voltage to the electrodes compared to the breakdown voltage can accomplish this.[4] In the development of our 4-kHz high-repetition laser, the volume discharge and its continuity can be achieved by applying the voltage between the peaking capacitor (Cp) with high dV/dt. The charging time of the Cp is shown by equation (2). The shorter the charging time τ, the larger the dV/dt of the charging voltage.

$$\tau = \pi \sqrt{\frac{C_{p-1} C_p \left(L_{sat} + L_c \right)}{C_{p-1} + C_p}} \qquad (2)$$

Here, C_{p-1}, L_{sat}, and L_c are respectively the capacity of the final step capacitor in a magnetic compression circuit, the saturated inductance, and the lead inductance. In order to reduce τ the number of stages of the magnetic compression circuit was increased on the conventional design. However, this modification decreased efficiency, enlarged the device, and increased the cost of the pulse power module. Thus, the balance between performance and cost was optimized with the decrease of L_c by improving the connected structure. Fig. 2 shows the achieved voltage between the electrodes (Vcp). The dV/dt was increased 100%.

Fig. 3 shows how using these high repetition rate operation technologies affects energy stability σ and CFF revolutions. It is understood that the necessary CR value improves 30% from that of the conventional model during 4-kHz operation. The comparison with the frequency characteristics of the conventional model is shown in Fig. 4. The output energy at 4 kHz was improved 10% and σ was decreased to 50%. Fig. 5 shows the comparison of the laser efficiency with that of the conventional model. Clearly, the efficiency was improved more than 50% at the maximum input.

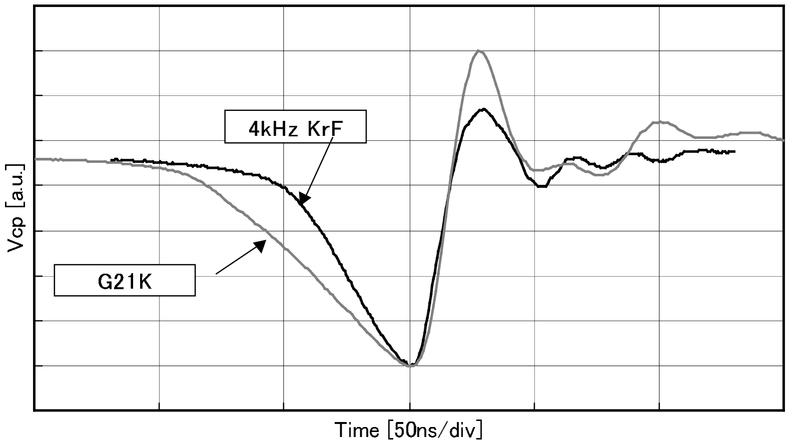

Fig. 2 Vcp shape of waves

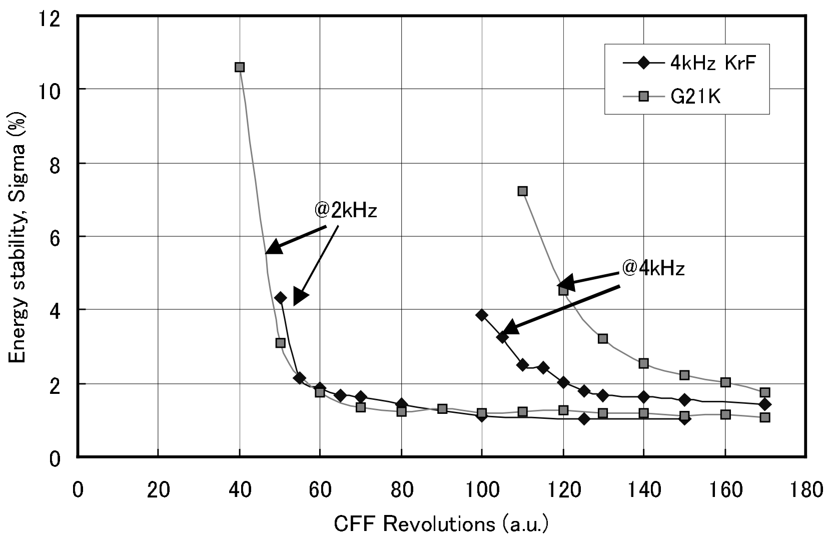

Fig. 3 Energy, σ -frequency characteristic

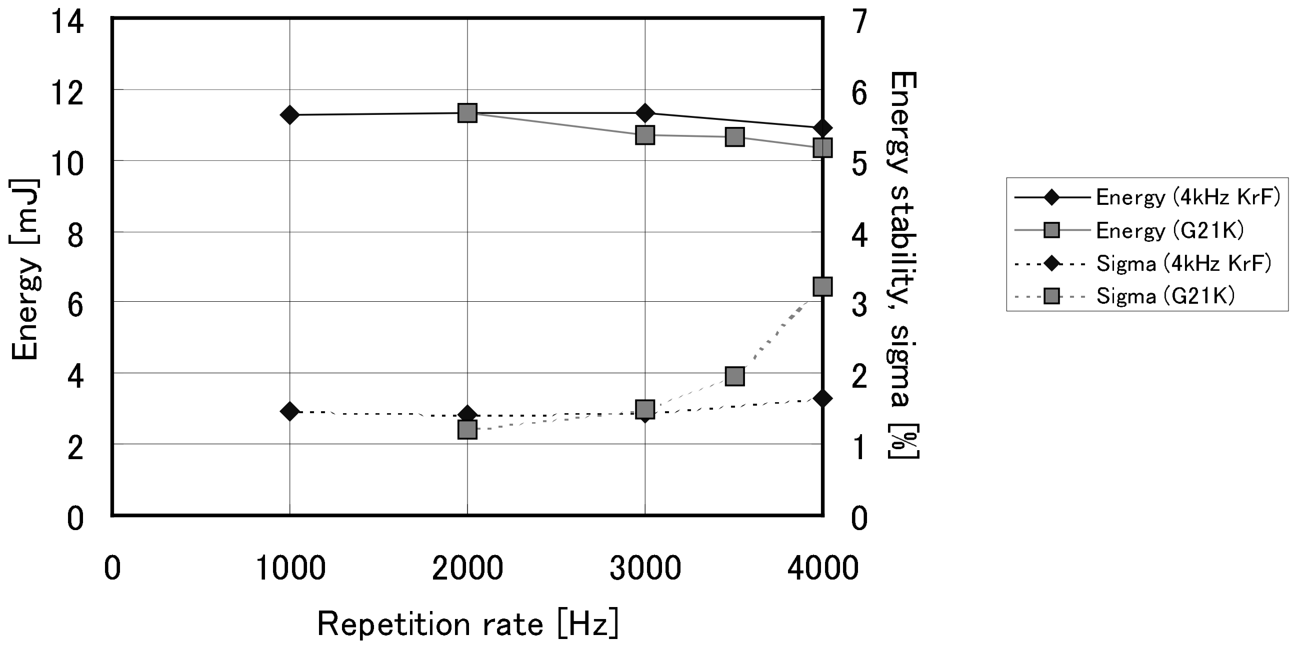

Fig. 4 Frequency characteristics

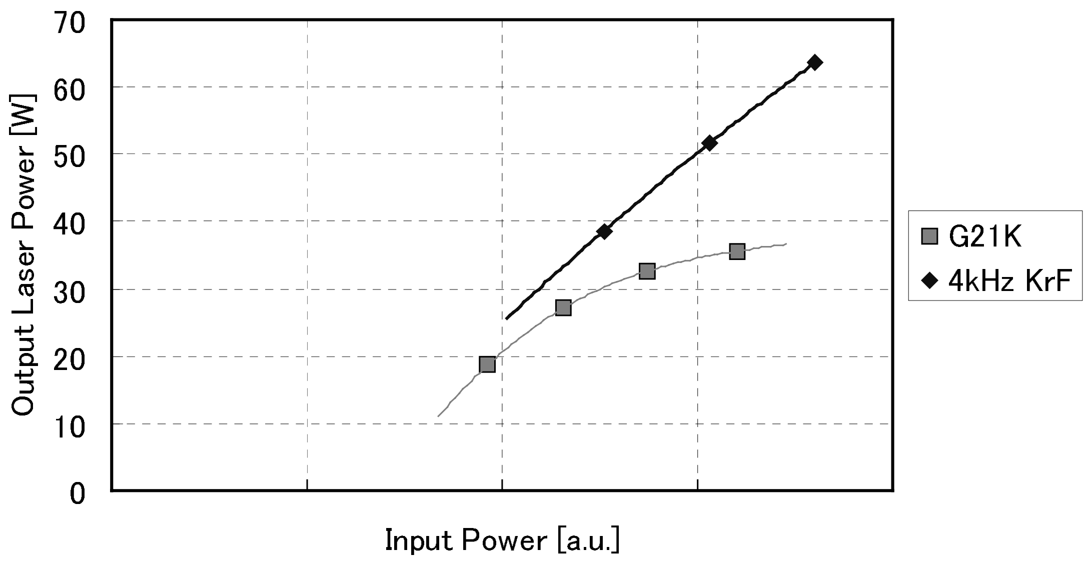

Fig. 5 Input power versus Output power

3. ULTRA LINE NARROWING TECHNOLOGY – PULSE STRETCHING

Pulse stretching techniques and a new line narrowing module are being developed for super line narrowing technology for the 4-kHz KrF excimer laser at Gigaphoton. Here, we discuss the concept of pulse stretching. In general, the pulse stretched laser achieves a narrower spectrum because the number of round trips increases. This is shown in Fig. 6, and conforms to the experiment results of our excimer laser model G10.

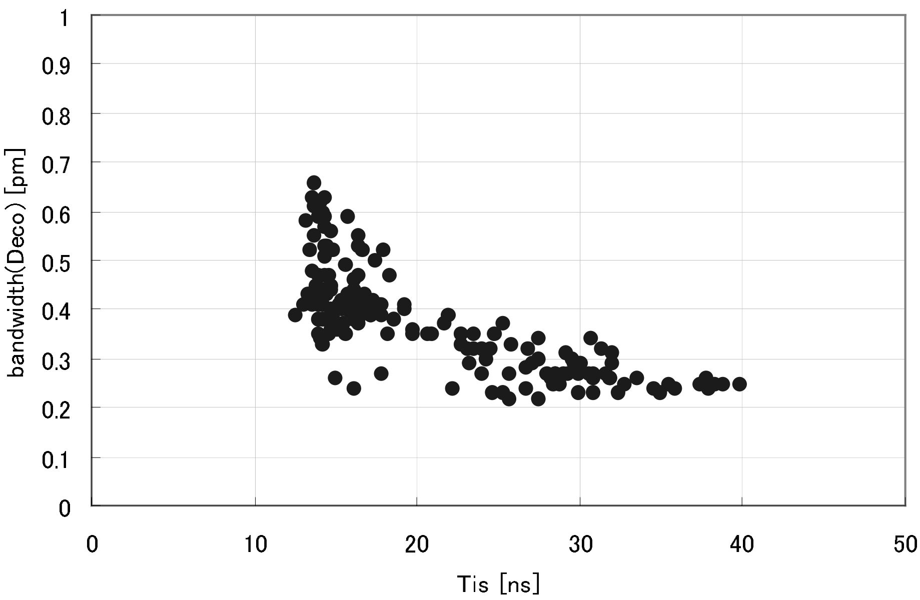

Fig. 6 Spectrum bandwith (Deco) versus pulse duration (Tis)

In order to achieve a spectrum line width of less than 0.4 pm (FWHM), we developed aiming at over 30 ns (Tis) pulse width. It is neccesary for pulse stretching to keep pumping enough energy to maintain the inverted population of the gas molecules and to retain the discharge quality and condition for realizing it. We thus decreased the circuit inductance by redesigning the main circuit structure, and remarkably increased the pre-ionization efficiency by improving the pre-ionizing structure. Decreasing the circuit inductance and using the aforementioned high repetition technology improved the stabilization of the discharge, and highly efficient pre-ionization contributed to increasing continuation of the current by decreasing the load of the main discharge circuit. Fig. 7 shows the pulse profile obtained by these improvements. The pulse profile of Tis>30 ns is obtained under all gas conditions. Tis is defined as follows:

$$T_{IS} = \int [I(t)dt]^2 / \int I(t)^2 dt$$

where I(t) is the time-dependent power of the laser pulse.

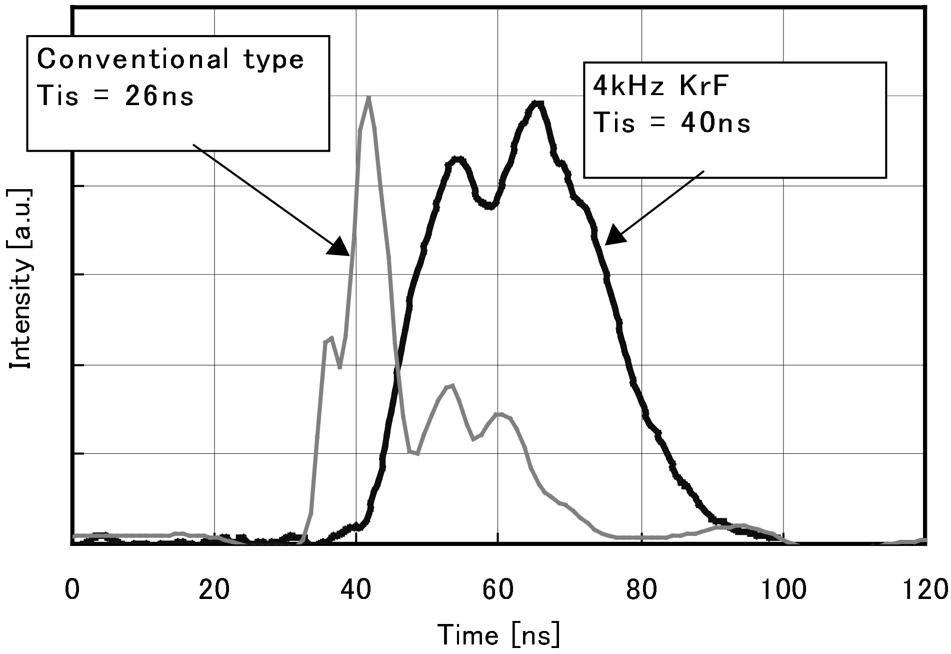

Fig. 7 Output pulse shape

4. PERFORMANCE

The performance obtained from these developments is shown in Table 1. The characteristics which are confirmed to be in a laser system in the near future are denoted as 'targets'.

Table 1 Performance of KrF 4kHz excimer laser

Item	Performance
	4-kHz KrF
Repetition rate	1-4000 Hz
Average power	30 W
Pulse energy	7.5 mJ
Integrated energy stability	<+/-0.35% (target)
Central wavelength	248 nm
Pulse duration	> 30 ns
Spectral bandwidth	< 0.4 pm (FWHM) (target)

5. ESTIMATION OF CoO

We consider the 4-kHz KrF laser to be a more practical light source for scanners for use in mass production, and decided that low CoO should take priority as a development concept. To decrease CoO, it is essential to improve the main modules' lifetime. Therefore, the influences of the repetition rate operation and pulse energy for main modules were considered when output power was increased to30W to improve the throughput. Laser output power *P*, repetition rate *f*, and pulse energy *Ep* are related in equation (3) as:

$$P = f \cdot E_p \qquad (3)$$

From this equation, it is understood that the output power *P* is assigned into repetition rate *f* and pulse energy *Ep* for the laser of the same output of *P*=30 W. There was a limitation for repetition rate *f* coming from an actual exposure system such as the minimum number of light pulses. However, we tried here to evaluate the influence of the repetition rate on the main modules' lifetime in the laser, and calculated the CoO.

5.1 Laser chamber

The laser chamber's lifetime is limited by the electrode's lifetime at present. In comparison to a similar electrode structure, the smaller pulse energy *Ep* is the more advantageous for the electrode's lifetime because the electrode consumption is approximately proportional to the input energy. This smaller *Ep* is expected to result in a longer lifetime because of the compensation for the energy deterioration. On the other hand, when the *Ep* is small, the repetition rate *f* is large, leading to an increase of the number of pulse shots and an increase of the CoO. The relation between repetition rate *f* and chamber CoO is shown in Fig. 8. It is found that the chamber CoO decreases as repetition rate *f* decreases, and that the CoO has a minimum value at *f* = 3000~3500 rps.

5.2 Optical components

Deterioration caused by the compaction of fused silica (SiO2) used in such optical modules as the spectral line narrowing module, monitor module, and front mirror, is shown in equation 4. [5]

$$\delta\rho / \rho \propto \left(NI^2\right)^{0.7} \qquad (4)$$

Here, ρ is the density of the fused silica, *N* is the number of shots, *I* is the laser intensity, and the left side shows the magnitude of the compaction. Comparing the influence of the number of shots with that of the laser intensity, that is, the pulse energy *Ep* upon compaction in the optical components, shows that the former is larger and the CoO decreases as *f* increases, contrary to the results for the chamber. Fig. 9 shows this relation. Incidentally, CaF_2 components in these modules do not deteriorate in such a manner, although we calculated the CoO based on the assumption that the entire module had to be exchanged due to the deterioration of fused silica parts.

The relation between the repetition rate *f* and the CoO of the laser is evaluated in consideration of each aforementioned factor, but the cost weight and other modules such as the flourine trap which are not influenced by them. Fig. 10 shows the result. The CoO of the laser decreases with an increase in *f*, and after a minimum value is taken in the vicinity of *f* = 3500 rps, it begins to increase gradually again. We aimed for *f* = 4000 rps in consideration of this CoO optimum point, dose stability, and the improvement of the stage speed in the future, among other factors.

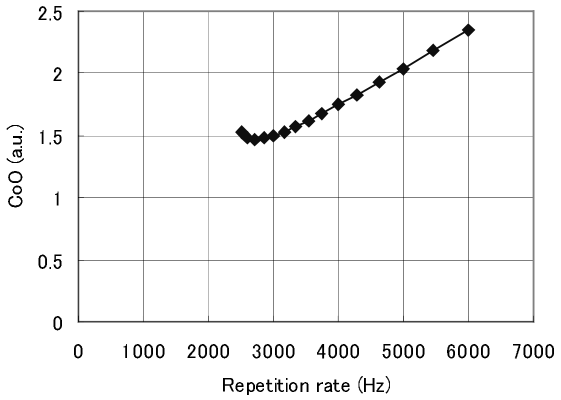

Fig. 8 Chamber CoO estimation

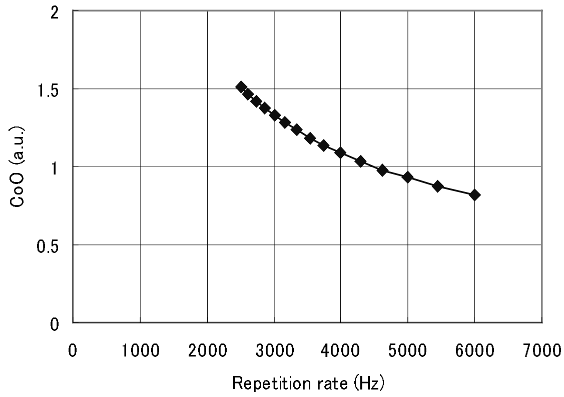

Fig. 9 Optical part CoO estimation

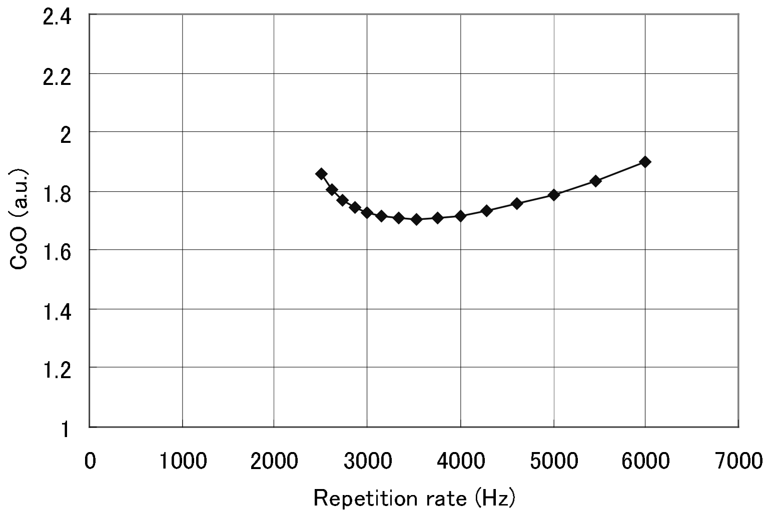

Fig. 10 Device CoO estimation

6. SUMMARY

We refined the KrF excimer laser to meet the needs of advanced lithographic technology. The velocity of the gas flow between the electrodes, and the dV/dt, were improved, and 65-W maximum output was achieved for the high throughput of lithography. At 4-kHz high repetition operation, stability equal to G21K was achieved, and at the same time, remarkable efficiency improvement occurred. Moreover, more than 30-ns pulse durations by using pulse stretching technology was achieved, and less than 0.4-pm spectrum width was applied. The design optimized to a low CoO resulted, and a very practicable characteristic was obtained for an excimer laser light source for mass production applications.

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