Ultra-narrow bandwidth 4-kHz ArF excimer laser for 193-nm lithography

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ABSTRACT

We have developed a 4-kHz ArF excimer laser with ultra-narrow bandwidth, which is applicable to high-NA scanners for sub-0.13-µm microlithography. In this paper, we describe a 4-kHz ArF excimer laser for mass production: the model G40A, which has an output power of 20 W and energy dose stability of less than ±0.3% (20-ms window) at 4 kHz. This dose stability is comparable to the performance of an existing 2-kHz ArF excimer laser, the model G20A. The new laser also has the following specifications: a long pulse duration of over 40 ns, spectral bandwidth of less than 0.35 pm (FWHM), and spectral purity of less than 1.0 pm (95%). These characteristics are better than those of the G20A. A lifetime test of over 7 billion pulses has been conducted at 4-kHz operation. The new laser has maintained an energy dose stability of less than ±0.3% (20-ms windows) and demonstrated performance suitable for mass production even after over 7 billion pulses.

Keywords: excimer laser, ArF, 193-nm, microlithography, line-narrowing, high repetition rate, long duration pulse

1. INTRODUCTION

KrF excimer lasers are already widely used as mass-production tools for lithography. Their performance and reliability have improved drastically. On the other hand, remarkable progress also has been made in developing ArF excimer lasers, which are the next generation light source for sub-0.13-µm microlithography. ArF excimer lasers are now changing to mass-production tools. Such ArF excimer lasers for mass production must have the following characteristics.

(1) High repetition rate and high energy stability.
High repetition rate and high energy stability are required to achieve high throughput and good CD control. ArF excimer lasers for mass production must operate at a high repetition rate of 4 kHz. This repetition rate is 2 times larger than that of KrF excimer lasers, which are already widely used for mass-production lines.

(2) Narrow bandwidth and high wavelength stability
Narrow bandwidth and high wavelength stability are most important for high NA scanners, in order to achieve high resolution and good CD control. The required spectral bandwidth is less than 0.5 pm.

(3) Low CoO (cost of operation)
Low CoO is the most important requirement for semiconductor manufacturers. Laser operating costs directly affect the cost of their products. Two of the main factors determining CoO are module lifetime and reliability. A lifetime of at least 5 billion pulses is required for mass production.

We have already reported the development of a highly durable, 2-kHz ArF excimer laser: the model G20A, which has an output power of 10 W, a spectral bandwidth less than 0.5 pm (FWHM), and a chamber lifetime of 5 billion pulses [1]. Moreover, we have already presented initial data for a 4-kHz ArF excimer laser [1, 2]. Based on these results, we have developed a mass-production type, 4-kHz ArF excimer laser: the model G40A.

In this paper, we describe the performance of this laser, which has the following specifications: a repetition rate of 4 kHz, output power of 20 W, pulse duration of 40 ns, FWHM spectral bandwidth below 0.35 pm, and spectral purity below 1.0

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pm . We also discuss a lifetime test conducted for over 7 billion pulses.

2. FEATURES AND SPECIFICATINS

Table 1 lists the main performance characteristics of the G20A and G40A. The main differences between them are spectral bandwidth and operational repetition rate. We have applied the following technologies in the G40A to achieve the narrower spectral bandwidth and higher repetition rate.

(1) A high dispersion LNM (line-narrowing module)
To achieve a narrower spectrum, we developed a high-dispersion LNM . This module consists of a high–dispersion, high-efficiency grating and high-transmittance prisms. The LNM also uses the most suitable design for an ArF excimer laser. Moreover, the spectral profile depends on the laser pulse duration. A long pulse duration of over 40 ns provides a narrower spectral bandwidth and greater purity.

(2) A laser chamber with a fast, uniform gas flow system and a high-efficiency discharge circuit.
During high-repetition operation, fluctuating gas density causes gas to accumulate in the discharge area. This leads to unstable discharge and unstable laser pulse energy. Generally, a 4-kHz laser needs two times the gas velocity of a 2-kHz laser. We achieve stable 4-kHz operation at only 1.5 times the gas flow velocity of the G20A by reducing the gas flow fluctuation. Moreover, a newly developed laser chamber includes a low floating inductance discharge circuit with a low-input homogeneous pre-ionizer. This circuit improves the laser efficiency and reduces the required input energy.

(3) A high efficiency PPM (pulse power module) with a fast voltage rise time.
Applying a fast-rise-time voltage to the electrodes improves the laser performance [3]. To achieve a fast voltage rise time we improved the MPC (magnetic pulse compression) circuit.We thus improved the efficiency by adopting the new circuit and selecting a low-loss MPC material. As a result, we achieved a 15% improvement in PPM efficiency compared to the G20A.

Table 1 Performance of ArF excimer laser

Items	G20A	G40A
Repetition rate	2000 Hz	4000 Hz
Output power	10 W	20 W
Pulse energy	5 mJ	5 mJ
Energy dose stability	<±0.3%	<±0.3%
Spectral bandwidth (FWHM)	<0.5 pm	<0.35 pm
Spectral purity	<1.3 pm	<1.0 pm
Wavelength stability	<±0.05 pm	<±0.05 pm
Pulse duration (Tis)	30 ns	40 ns

3. PERFORMANCE

3.1. Spectral characteristics

The spectral profile and wavelength stability are the most important specifications for achieving the highest resolution and lowest CD variation for a high-NA scanner. Figure 1 shows the spectral bandwidth and E95% for the G40A, as measured by the HEXA (holographic and echelle grating expander arrangement) spectrometer developed by Gigaphoton. The slit function was 0.1 pm, and this was measured by using a 193-nm coherent light source [3]. This process provides a very precise estimation of the true laser spectrum. The spectral bandwidth (FWHM) was measured as 0.22 pm with convolution and 0.18 pm with deconvolution. The spectral purity for 95% energy was measured as 1.11 pm with convolution and 0.43 pm with deconvolution. These values are better than those of the G20A. The newly developed high-dispersion LNM and the long-duration pulse contribute to this improved performance.

Figure 2 shows maximum and minimum values of the averaged wavelength error (50-pulse window) for 1000 continuous bursts. The laser was operated in burst mode (0.1 sec on, 0.1 sec off) at 4-kHz. The stability was less than ±0.04pm, which is low enough for application to real exposure tools

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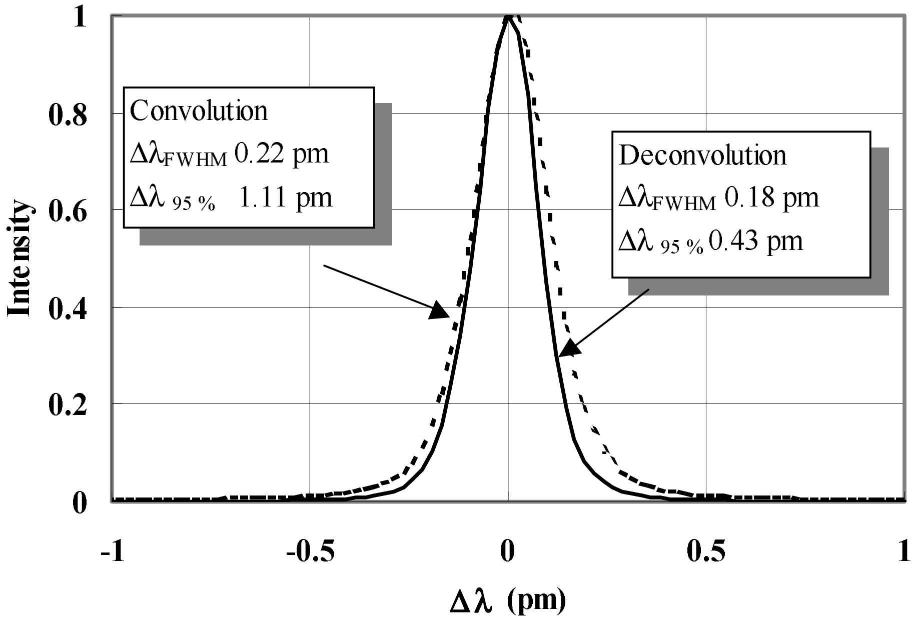

Fig. 1 Spectra for the whole laser beams measured by a HEXA spectrometer

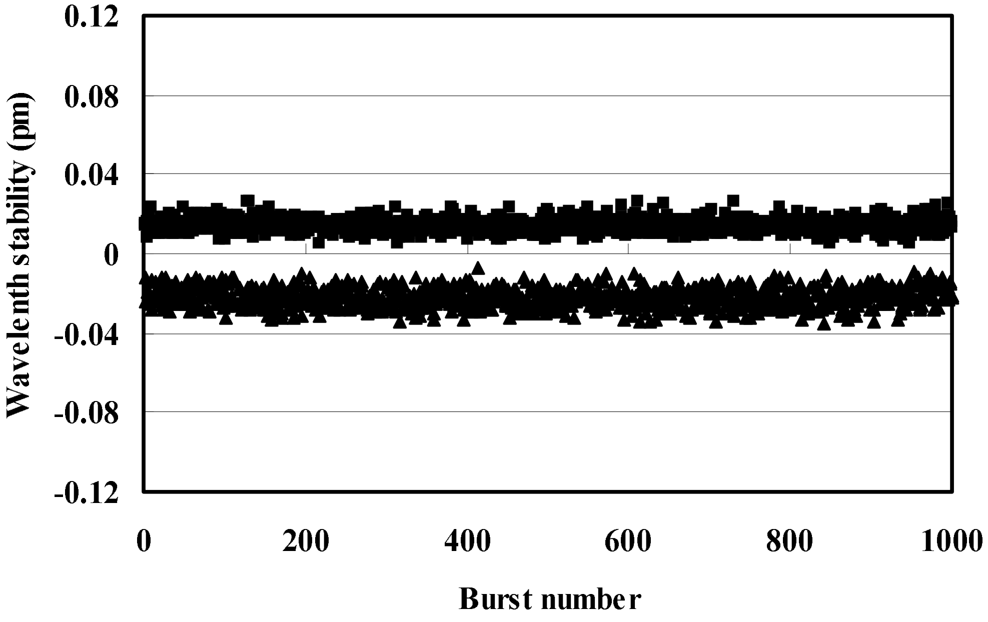

Fig. 2 Average wavelength stability (50-pulse window)

3.2 Energy characteristics

Figure 3 shows average power and energy stability (sigma) as a function of repetition rate at constant voltage. The average power increased linearly up to 4 kHz, and the energy stability at 4 kHz was 2.5% (sigma). The variation in laser pulse energy was small from 1 to 4 kHz. This performance is very important because 4-kHz ArF excimer lasers will be used over a wide range of repetition rates.

Energy dose stability is also important for scanning-type exposure tools. Figure 4 shows the dose stability over a series of 20000 bursts (23-ms window). The laser was operated in burst mode (0.1 sec on, 0.1 sec off) at 4 kHz. The stability was less than ±0.3%.

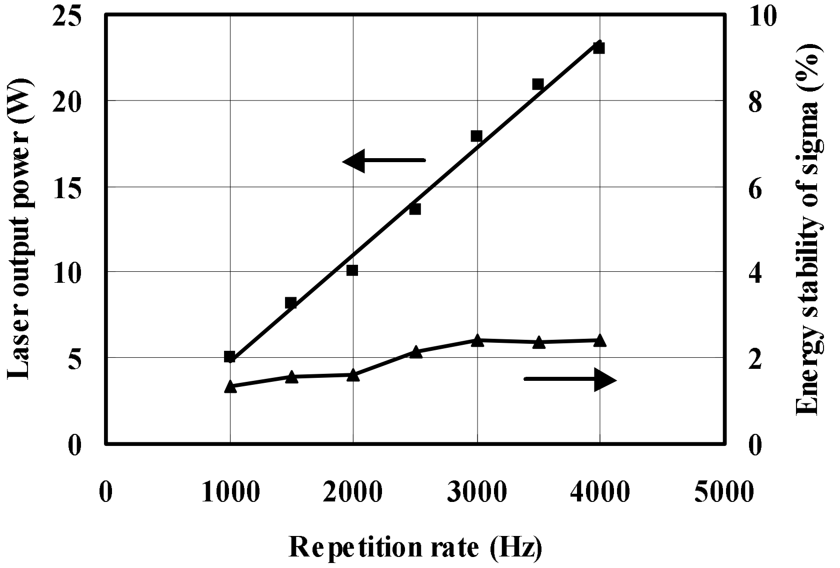

Fig. 3 Average power and energy stability (sigma) as a function of repetition rate

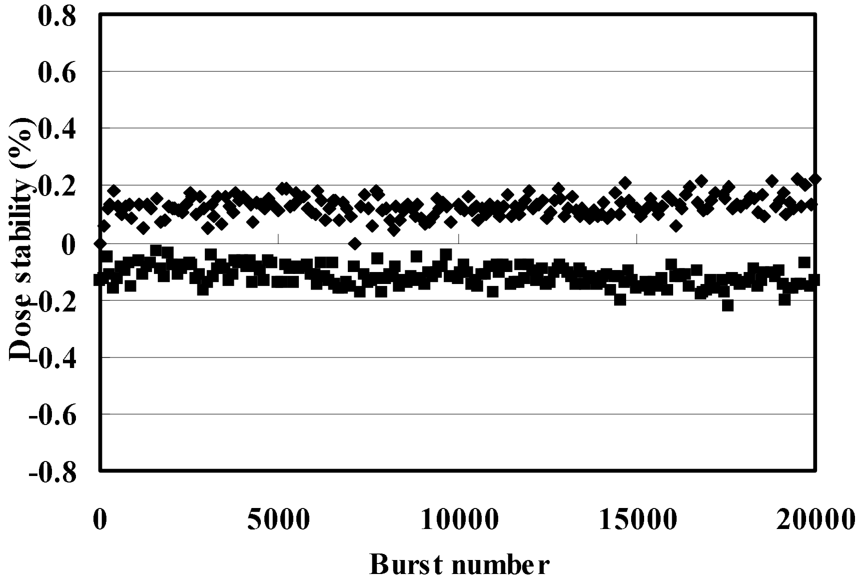

Fig. 4 Energy dose stability (23-ms window)

3.3 Pulse duration

A longer pulse duration is considered to minimize laser-induced optics damage in expoursure tools. Moreover, it helps narrow the spectral profile by increasing the number of round trips of the laser cavity. Figure 5 shows a typical temporal laser pulse waveform for 4-kHz operation. The time integral-squared pulse width (Tis) was 46 ns [4]. This long pulse can be achieved by using the pulse-stretching technique, which is based on using the fast PPM and the high-efficiency laser chamber.

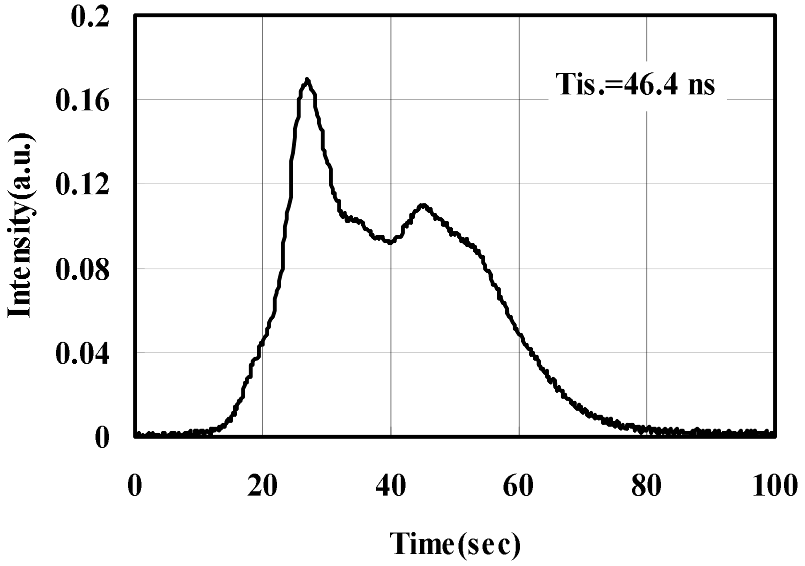

Fig. 5 Temporal laser pulse waveform

4. LIFETIME TEST RESULTS

The operating cost of excimer lasers is of major concern for chip manufacturers because it directly affects the cost of their products. We are intensively working to reduce operating costs by improving the lifetimes of core modules such as the laser chamber and the optics modules. We have applied the following technologies to improve the module lifetimes.

(1) Laser chamber

One of the main factors limiting chamber lifetime is electrode ablation by the discharge [6]. Electrode ablation degrades laser performance characteristics such as laser efficiency and energy stability. Constriction discharge directly affects the lifetime of electrodes. We achieved homogeneous discharge by using uniform pre-ionization. Moreover, electrode ablation depends on the input energy. In the G40A, lower input operation is achieved by using the high-efficiency discharge circuit.

(2) Optics module

Damage to the optics coating and material determines the optics lifetime. All the optics, including the LNM and mirror, consist of CaF_2. We selected high-purity CaF_2, as determined by using fluorescence spectrum analysis and measuring degradation during ArF laser irradiation tests. We also used a coating resistant to ArF laser light.

Gigaphoton is currently conducting an extended lifetime test of the G40A core technology described above. The total operation number is over 7 billion pulses since the test started in the fall of 2000. To date, no significant failures have occurred during this test.

We previously reported that our energy compensation method during the chamber lifetime was to increase the gas pressure [5]. This is because the laser pulse energy increases with increasing gas pressure. In addition, the gas-pressure operating range is wider than the high-voltage operating range. Therefore, we used gas pressure increase as the energy compensation method for the G40A as well. Of course, for pulse-to-pulse energy control, high voltage adjustment was used.

Figure 6 shows the operating voltage and gas pressure during the lifetime test. The operating conditions of the test are as follows:

Pulse energy: 5 mJ
Repetition rate: 4000 Hz
Operation mode: burst mode (0.125 sec on, 0.125 sec off)

The initial gas pressure was 2600 hPa, and the gas pressure after 7 billion pulses was 3100 hPa. A simple extrapolation of the data gives a projected chamber lifetime of nearly 10 billion pulses. This value is almost the same as that for a 2-kHz KrF excimer laser.

Figure 7 shows the trend of the energy dose stability data (20-ms windows) during the lifetime test. Figure 8 shows histograms of the minimum and maximum deviations from the target energy dose for 100000 bursts after 3 and 7 billion pulses. Both figures show that the dose stability was almost always below ±0.3% during the test. Even over 7 billion pulses, the dose stability maintains the ±0.2%-level, and the change in dose stability during the test is negligible. These data show that the laser stability has not changed during this test.

Figure 9 shows temporal laser pulse waveforms initially and after 7 billion pulses. Even after 7 billion pulses the laser pulse duration (Tis) was still 40 ns. This characteristic is considered to be helpful in reducing optical damage.

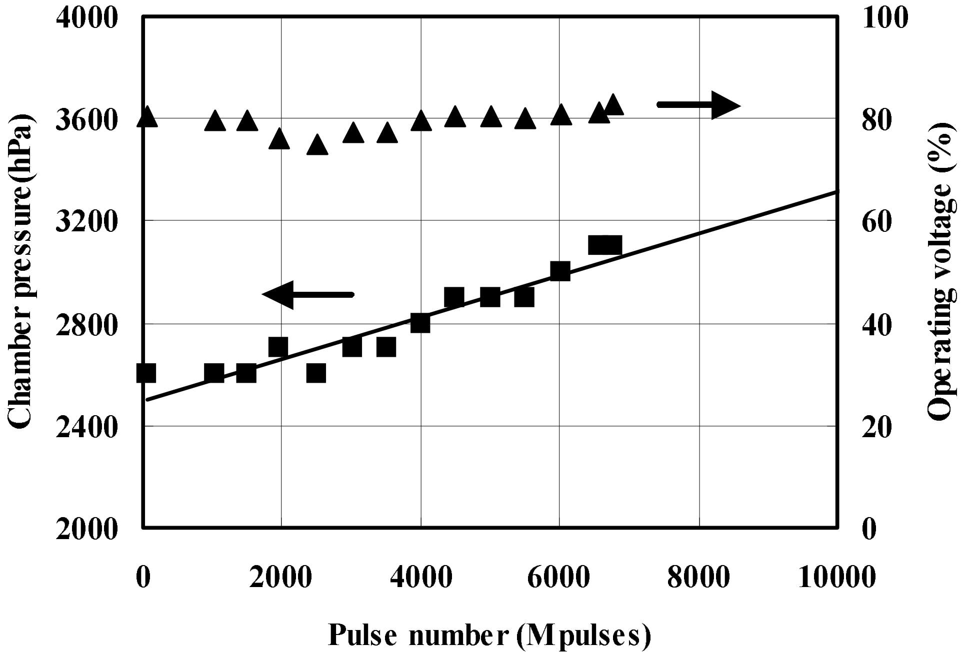

Fig. 6 Gas pressure and operating voltage during the lifetime test

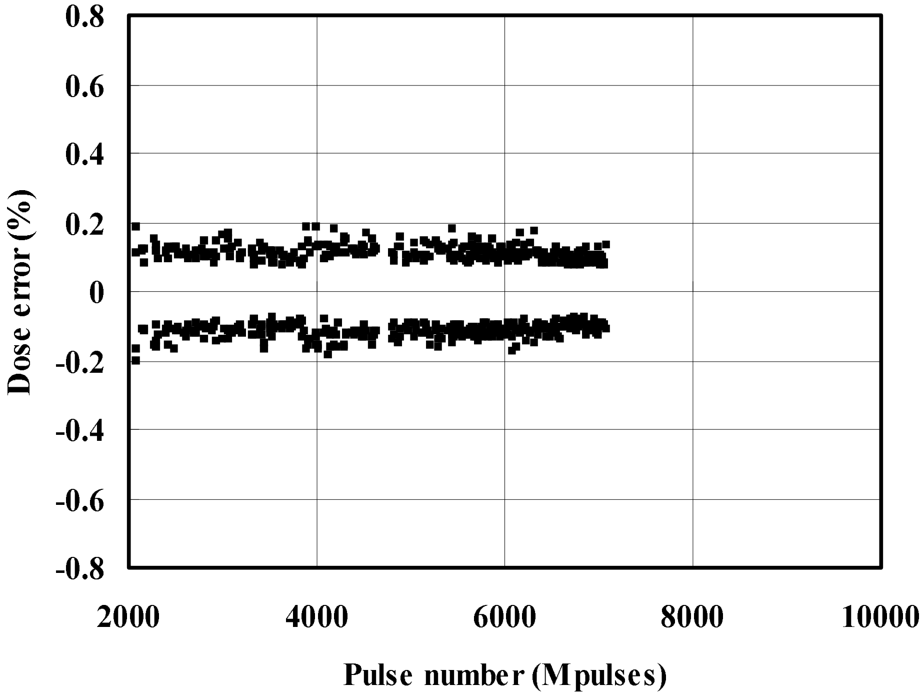

Fig. 7 Dose stability during the lifetime test

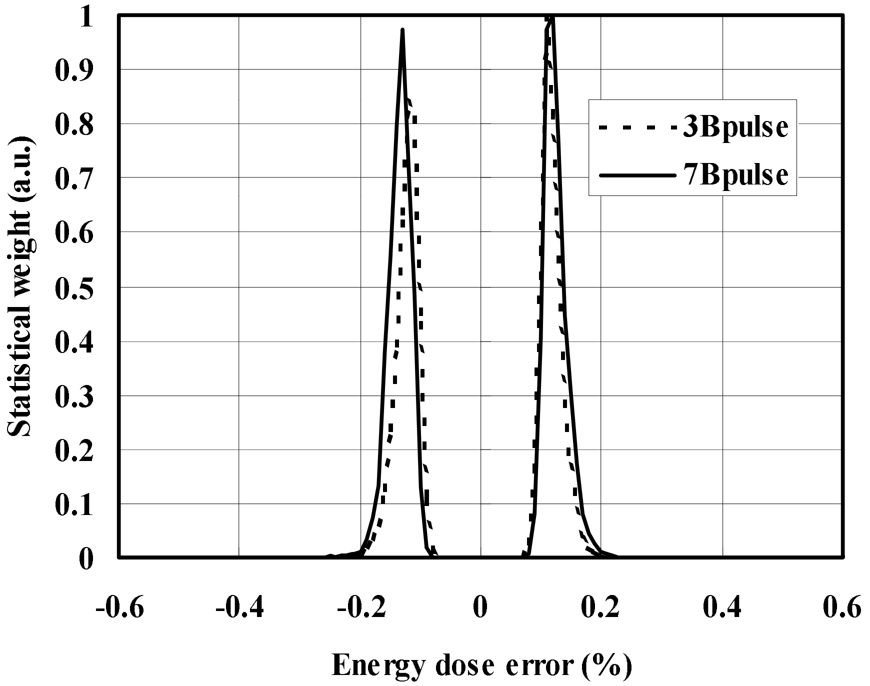

Fig. 8 Histograms of the minimum and maximum deviation from the target dose for 100000 bursts after 3 and 7 billion pulse.

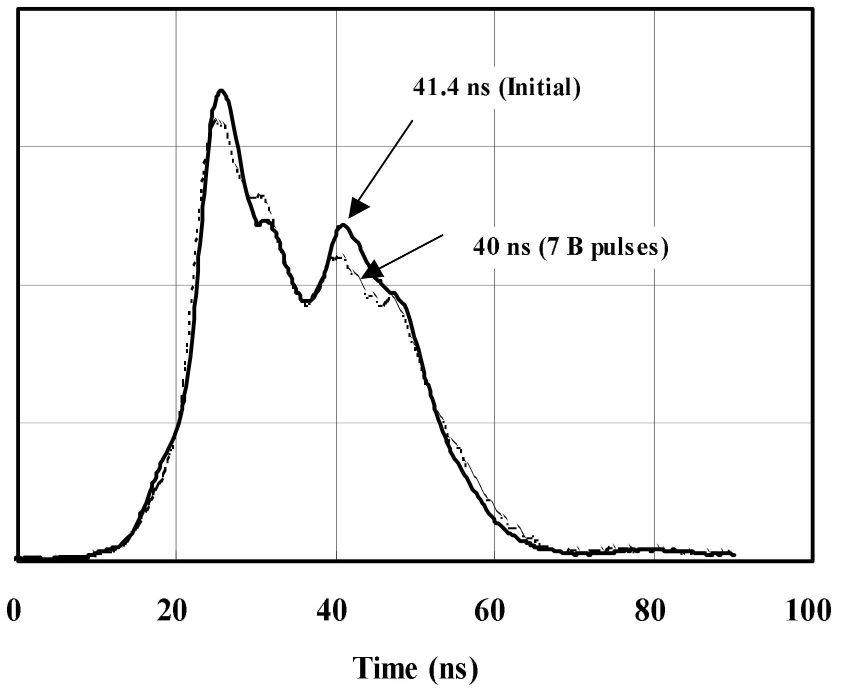

Figure 9 the temporal laser pulse waveforms at 3 and 7 billion pulse

5. COST OF OPERATION

As noted previously, ArF excimer lasers for mass production are required to operate under high–performance conditions, such as high repetition rate and narrow spectral bandwidth, and with reduced CoO. In KrF excimer laser technology, a 30% reduction in operation cost has been achieved every year. Our lifetime test results for the G40A core technology show the possibility of a drastic reduction in ArF excimer laser operation cost. Target maintenance intervals for the G40A are listed in Table 2.

Table 2 Target maintenance intervals for core modules of the ArF laser

Items	**Target maintenance interval**	
	2001/1Q	2002/1Q
Gas lifetime	>100 million	>100 million
Laser chamber module	>5 billion	>6 billion
Line narrowing module	>6 billion	>8 billion
Monitor module	>7 billion	>10 billion
Front mirror	>7 billion	>10 billion

4. SUMMARY

We have introduced the G40A, a mass-production type, 4-kHz ArF excimer laser with ultra-narrow bandwidth applicable to high-NA scanners. This laser produces an output power of 20 W at 4 kHz, with a dose stability of less than ±0.3 % (20-ms window). This dose stability is comparable to the performance at 2 kHz. The laser also has the following specifications: a long pulse duration of over 40 ns, spectral bandwidth of less than 0.35 pm (FWHM), and spectral purity of less than 1.0 pm (95%). We have also generated lifetime and reliability test data for over 7 billion pulses. These results show that this 4-kHz ArF excimer laser can be used in the semiconductor industry.

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