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<th>High-repetition-rate (6 kHz) and long-pulse-duration (50 ns) ArF excimer laser for sub-65 nm lithography</th>
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<td>Author(s)</td>
<td>Kakizaki, Koji; Sasaki, Yoichi; Inoue, Toyoharu; Sakai, Yosuke</td>
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I. INTRODUCTION

During the last decade, much progress in ArF excimer lithography has been made as a result of a joint effort of semiconductor manufacturers and their process equipment makers. Device mass production through ArF excimer lithography has started from its target node of 90 nm (half pitch). Recently the long-term stability of over $10 \times 10^8$ pulses in a 4 kHz ArF excimer laser is achieved. In our previous work, we developed a narrow-spectral-bandwidth 4 kHz ArF excimer laser. The main feature of this laser was the oscillation of long laser pulse duration with low-peak power: consequently the narrow-spectral-bandwidth laser light was obtained by increasing the number of round trips of laser light between the cavity mirrors, and the optical damage was reduced.

The laser performances we are seeking in response to demands in the new generation of stepper/scanner technology, e.g., high numerical aperture (NA), high-throughput scanners, etc., are summarized in Table I. To optimize laser for next-generation technologies with sub-65 nm node design rules, we have to develop ArF laser with performances of not only narrower spectral bandwidths but also higher operation rates that exceed 4 kHz. So far, though ArF excimer lasers with over 4 kHz operation have been described, a narrow-bandwidth 6 kHz ArF excimer laser has not been obtained.

In the present article, we report a next-generation ArF excimer laser with a repetition rate of 6 kHz. This laser was reconstructed using a prototype 4 kHz excimer laser designed to analyze the possibilities of achieving higher-repetition-rate operation. We focused to examine on the pulse-to-pulse energy stability and the laser pulse width extension. Their qualities degrade appreciably due to descent of discharge stability at high-repetition-rate operation. Next, we examine laser output characteristics for a repetition rate of 6 kHz.

II. LASER SYSTEM

A. Improvement of 4 kHz ArF laser to 6 kHz operation mode

Figure 1 shows a schematic diagram of a 6 kHz ArF excimer laser system. This system consists of a laser chamber (discharge circuit, main discharge electrodes, preionizer, fan, and laser gas), a pulse power module (switching unit,
magnetic pulse compression circuit, and charger), a spectral
bandwidth narrow module, a monitor module to detect the
optical performance of the laser beam, a gas module to sup-
ply to and exhaust from the chamber, and a controller of each
module. We developed the 6 kHz ArF excimer laser intro-
ducing the following new devices.

1. Laser chamber

A high-efficiency discharge circuit. The floating induc-
tance of the discharge-current circuit was reduced to 5 nH
from 7 nH in order to obtain a short rise-time current pulse,
making the discharge-current road short by improving the
arrangement of the current return plate,6 as shown in the
cross section of the laser chamber in Fig. 2. As a result, the
energy efficiency for laser oscillation was enhanced.

Main discharge electrodes with narrow discharge width.
The discharge width in the gas flow direction was reduced
from 3.5 to 2.5 mm by improving the profile of the main
discharge electrodes (their length: 640 mm) and their sup-
porting system. Figure 3 shows the maximum repetition rate
under arclike discharge free condition in the downstream re-
gion of gas flow (downstream arcing) as a function of an
average gas velocity at the center of the discharge gap (gap
length: 16 mm). In Fig. 3, the solid line shows the case of a
2.5 mm reduced discharge width and the dotted line shows
the case of a 3.5 mm discharge width. The results are shown
in Secs. III B and III C.

A high-speed uniform gas-circulation system. One of the
most important requirements for high-repetition-rate opera-
tion is the optimization of the gas flow condition in the dis-
charge space. We developed a new gas-circulation system to
provide a flow with high-average velocity and high unifor-
mity at any position in the discharge space. We designed
a cross flow fan is 150 mm. The heat exchanger was com-
posed of eight water-cooling pipes. Furthermore, we de-
signed gas flow guides to prevent gas flow on the anode
and the cathode surfaces from decreasing, as shown in Fig. 2.
In this system we did not use acoustic damper. The results are
shown in Sec. III C.

A low-input power and high-intensity surface corona
discharge preionizer. The preionizer electrodes were de-
signed to provide a high-intensity homogeneous surface co-
rona discharge by concentrating the electric field and increas-
ing utilization rates of ultraviolet rays from a ladder
electrode. The preionizer was composed of two cylindrical
corona electrodes with an alumina dielectric tube between
the inner electrode and outer electrode.7 Consequently, the
input power to the preionizer was reduced.

Reduction of impurity effect. Impurities in laser gases
degrade ArF laser performance. We analyzed impurity effects
on the laser performance. It was found that the addition of
Xe gas (10 ppm) into the laser gas enhanced the preioniza-
tion effect.8 The Xe gas, which has low ionization potential,
would mask possible contamination influences9 and stabilize
the laser performance.
2. Pulse power module

A magnetic pulse compression (MPC) circuit with a high compression ratio. The rapidly rising voltage should be applied across the main electrodes so that the gas breakdown takes place by higher over voltage than the dc breakdown voltage. Then, this overvoltage breakdown provides high-density plasma, which may generate the needed excited state density to achieve useful laser gain. This speculation would be supported by that when the rise time is rapid, the breakdown voltage increases, and laser performance is improved. Designing a lower residual inductance for the final stage of the MPC, we improved the SL2 structure and the MPC connection to the laser chamber. Then, the voltage rise time \( T_r \) across the main discharge electrodes was reduced to 50–60 ns from >100 ns.

A high-speed insulated gate bipolar transistor (IGBT) switching unit. We developed a new switching unit (SW) that is composed of several IGBTs for the pulse power module. The switching unit can be operated at repetition rates of up to 8 kHz.

B. Discharge circuit with long duration laser pulse

Figure 4 shows an excitation circuit of the ArF excimer laser. The discharge circuit is comprised of a two-stage magnetic pulse compression circuit using three magnetic switches SL0, SL1, and SL2. SL0 is used for the protection of solid-state switch SW. A two-stage magnetic pulse compression circuit is constructed from the first magnetic switch SL1 and second magnetic switch SL2. First, the voltage of a charger HV is adjusted to a prescribed level and main capacitor \( C_0 \) is charged via SL0 and inductance \( L_0 \). When \( C_0 \) is completely charged, SW turns on. Then the charge in \( C_0 \) transfers to capacitor \( C_1 \). Subsequently, when the charge accumulated in \( C_1 \) reaches the critical value determined by the characteristics of magnetic switch SL1, the magnetic flux in SL1 saturates and the SL1 turns on. Then, the current starts to flow in the loop circuit of \( C_1 \), \( C_2 \), and SL1. The charge accumulated in \( C_1 \) transfers to \( C_2 \). Here, the capacitances of \( C_0 \), \( C_1 \), and \( C_2 \) are almost the same value.

When the charge accumulated in \( C_2 \) reaches the critical value, current starts to flow in the loop circuit of \( C_2 \), peaking capacitor \( C_p \), and SL2. The corona discharge for preionization takes place on the outer peripheral surface of a dielectric tube, when the voltage between the main discharge electrodes \( V_d \) reaches the prescribed voltage. From corona discharge, ultraviolet rays are generated and simultaneously ionized Xe atoms are generated in the main discharge gap.

![FIG. 5. Temporal wave forms of (a) voltage between the main discharge electrodes, (b) discharge current in the main discharge gap, and (c) laser pulse.](image)

![FIG. 6. Laser pulse wave form for (a) \( C_p/C_2: 13.4/15.3 \, \text{nF}, \, T_r>100 \, \text{ns} (T_{\text{is}}=16 \, \text{ns}) \), (b) \( C_p/C_2: 13.4/15.3 \, \text{nF}, \, T_r=50–60 \, \text{ns} (T_{\text{is}}=34 \, \text{ns}) \), and (c) \( C_p/C_2: 9.0/15.3 \, \text{nF}, \, T_r=50–60 \, \text{ns} (T_{\text{is}}=50 \, \text{ns}) \).](image)

![FIG. 7. Spectral bandwidth as a function of time.](image)
As $C_p$ is charged further to the gas breakdown voltage $V_d$, the gap is broken down. The delay time between the main discharge and the corona discharge was about 35 ns. Figure 5 shows temporal wave forms of (a) a voltage between main discharge electrodes, (b) a discharge current in the main discharge gap, and (c) a laser pulse.

As the rise time of the primary current flowing through the main discharge gap is shortened, the peak current value is raised. It the same time, the main discharge continues in a stable manner. Then the charge remaining in $C_2$, which brings the secondly current, is superimposed on the primary current $I_{is}$ see (B) in Fig. 5. By doing so, the laser oscillation is brought by the first half-cycle of the discharge-current wave form and by at least following two half-cycles [see (B) in Fig. 5(c)]. As a result, the present system improved the discharge stability significantly, and accordingly the laser pulse duration stretched beyond 40 ns even when the system was operated at high repetition rates.

The fact shown above indicates that the present devices prevented spatial discharge constriction, which may occur in the latter half of the laser pulse.

III. EXPERIMENTAL RESULTS AND DISCUSSION
A. Laser pulse wave form and spectral bandwidth

Figure 6 shows laser pulse wave forms $P(t)$ in the narrow-bandwidth ArF excimer laser. The laser pulse duration varied according to the discharge circuit constant, $C_p/C_2$ and $T_r$. The pulse wave form (c) shows a full width at half maximum (FWHM) of about 45 ns and a time-integral-squared pulse width $T_{is}$ of 50 ns. $T_{is}$ is defined as follows:

$$T_{is} = \left[ \frac{\int P(t) dt}{\int P(t)^2 dt} \right]^2.$$

The laser energy of all the pulses is 5 mJ.

The pulse with such long duration [see (c) in Fig. 6] can narrow the bandwidth by increasing the number of the round trips in a laser cavity equipped with the spectral bandwidth narrow module. Laser light passes through the spectral bandwidth narrow module every 7 ns because the laser cavity length is about 1 m. We obtained a convolved spectral bandwidth with FWHM of about 0.60, 0.40, and 0.36 pm for $T_{is}$ of 16, 34, and 50 ns, respectively.

Figure 7 shows the time evolution of spectral bandwidth $\Delta \lambda(t)_{\text{FWHM}}$, which is measured through a grating monochromator equipped with a streak camera. The slit function, measured with an ultranarrowed solid-state laser, is 0.19 pm at FWHM. We can see that the $\Delta \lambda(t)_{\text{FWHM}}$ is independent of $T_{is}$. At the beginning of the laser pulse, $\Delta \lambda(t)_{\text{FWHM}}$ is about 1.0 pm. After 30 ns passed, $\Delta \lambda(t)_{\text{FWHM}}$ narrows to 0.35 pm. The dashed line was obtained by the following fitting equation:

$$\Delta \lambda(t)_{\text{FWHM}} = \Delta \lambda_{\text{rms}}(t) \cdot \frac{\int P(t) dt}{\int P(t)^2 dt}.$$

FIG. 8. Spectral bandwidth as a function of $T_{is}$.

FIG. 9. Laser energy as a function of repetition rates for various Ar concentration ratios at a $F_2$ ratio of 0.09% and total pressure of 3 atm.

FIG. 10. Energy stability as a function of repetition rates for various Ar concentration ratios at a $F_2$ ratio of 0.09% and total pressure of 3 atm.

FIG. 11. Pulse width $T_{is}$ as a function of repetition rates for various Ar concentration ratios at a $F_2$ ratio of 0.09% and total pressure of 3 atm.
FWHM = \frac{A}{t^{1/2}} \text{pm}, \quad A = 2.

We can see that \( \Delta\lambda_{\text{FWHM}} \) is inversely proportional to the square root of time. The coefficient \( A \) depends on the resolution of the spectral bandwidth narrow module.

Figure 8 shows the time averaged \( \Delta\lambda_{\text{FWHM}} \) between 30 and 50 ns as a function of \( T_{\text{is}} \). It shows that a longer \( T_{\text{is}} \) results in a narrower spectral bandwidth. We obtain \( \Delta\lambda_{\text{FWHM}} \) of 0.36 pm at \( T_{\text{is}} \) of 50 ns.

**B. Laser characteristics after reducing the discharge width**

The discharge width in the gas flow direction was reduced to 2.5 mm from 3.5 mm by improving the profile of the main discharge electrodes and their supporting system. As a result, the operating repetition rate increased to 5 kHz at 45 m/s, that is, the same gas velocity required for an operating repetition rate of 4 kHz at a 3.5 mm discharge width (see Fig. 2). The clearing ratio (CR) defined by the following equation may explain this result:14

\[
CR = \frac{v}{f_m w},
\]

where \( v \) is the interelectrode gas velocity, \( f_m \) is the maximum repetition rate under downstream arcing free condition, and \( w \) is the discharge width. Low gas velocity or wide discharge width operation causes downstream arcing that degrades energy stability. For the improved ArF excimer laser, \( f_m \) increased because CR is about 3.3.

\[\Delta\lambda(t)_{\text{FWHM}} = A/t^{1/2} \text{pm}, \quad A = 2.\]

\[
\Delta\lambda(t)_{\text{FWHM}} = A/t^{1/2} \text{pm}, \quad A = 2.\]
C. Laser characteristics after improving gas flow velocity and distribution

To improve the pulse-to-pulse energy stability at repetition rates over 5 kHz, we increased an average gas velocity to 50 m/s from 45 m/s at the center of the discharge gap. Furthermore, we designed a gas flow guide to prevent gas flow velocity on the anode and cathode surfaces from decreasing. Figure 13 shows the gas flow velocity distribution between the cathode and anode before and after the new gas flow guide was equipped. The vertical axis represents the gas flow velocity and the horizontal axis represents the distance from the cathode. As we can see, the gas flow on the electrode surfaces increased after the flow guide was equipped.

Figures 14–16 show laser energy, pulse-to-pulse energy stability, and pulse width $T$ as a function of the repetition rate, respectively. The F$_2$ concentration ratios are varied at an Ar ratio of 3.0% in a Ne buffer gas and the total pressure is 3 atm. FWHM was below 0.40 pm in all the F$_2$ concentration ratios. Figure 14 shows that the laser energy reduction against repetition rates as the F$_2$ concentration ratios decrease. Figure 15 shows that the energy stability at 6 kHz improved to 4.5% from 6.0% in Fig. 10 due to improvement of the gas flow velocity and distribution (see Fig. 13). The energy stability at 6 kHz was improved to 3.5% from 4.5% with lowering the F$_2$ concentration ratio of 0.07% and then the laser energy reduction was small as shown in Fig. 14.

Figure 16 shows that the pulse width was hardly reduced in the case of F$_2$ concentration ratio of 0.07% and then $T$ of 44 ns is obtained at 6 kHz.

Figure 17 shows the laser pulse wave form at 6 kHz for the three cases of F$_2$ concentration ratios. The former half intensity of the laser pulse decreased, but the latter half intensity increased with decreasing the F$_2$ ratio.