Laser Original

ArF Excimer Laser Operated at 10 kHz with Small Electrode Separations

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Argon-fluoride (ArF) excimer laser operations at high repetition rates have been studied with special focus on the distance between electrodes. We find that, for stable laser operations, the maximum repetition rate increases with decreasing electrode separations. This is mainly caused by narrow discharge widths and an electric field intensity distribution that concentrates on the center. For an electrode separation of 8 mm, a homogeneous discharge could be maintained for an ArF excimer laser at a maximum repetition rate of 10 kHz. Results are discussed in detail with special focus on the influence of gas density depletion.

Key Words: ArF excimer laser, High repetition rate, Gas density depletion

1. Introduction

Lithography based on an Argon-fluoride (ArF) excimer laser is increasingly being used for mass production of semiconductor devices. Immersion lithography using an ArF excimer laser is currently applied to extend the technology node of dynamic random access memory to half-pitch 45 nm.1 Furthermore, ArF excimer lasers can be used at the half pitch 32 nm with double patterning.2 This requires an average laser output power of 100 W or higher (currently 60–90 W) with a repetition rate of minimum 6 kHz (currently 6 kHz). An increase in repetition rate would improve the average output power and contribute to the durability of optical elements. Therefore, an increase in the repetition rate to 10 kHz or higher is expected. To achieve 10 kHz operations with a discharge-pumped excimer laser, it is important to identify the conditions for sustaining a homogeneous discharge at 10 kHz. In addition, it is necessary to clearly describe the technical challenges presented by these conditions.

Studies have reported that a homogeneous discharge cannot be maintained at high repetition rates for the following three reasons. (1) Gas density depletion is generated by the momentary heating of gas in the discharge area.3 When gas density depletion remains in or near the discharge area at the next discharge, the discharge will be non-uniform. This non-uniformity occurs in the gas density depletion area, not in the area between electrodes. In addition, discharge products, such as long-lived negative fluorine ions4 and metal evaporated from the electrodes,5 influence discharge uniformity. (2) Hot spots occur on electrode surfaces.6 At hot spots gas density decreases locally, and therefore ionization is enhanced; hence, discharges concentrate at hot spots and become non-uniform. Surface roughness of the electrode may contribute to formation of hot spots.7 (3) Acoustic waves are generated by the momentary heating of gas in the discharge area.8 When acoustic waves still exist in the discharge area at the next discharge, the discharge will be non-uniform. In general, these three problems can be eliminated, and high repetition rates in a discharge pumped excimer laser can be achieved by increasing gas velocity.9

We study the influence of gas density depletion in ArF excimer lasers. In a previous report, results for the discharge width, gas density depletion width, and distance between both areas, at which a homogeneous discharge could be maintained, were presented for gas discharge without fluorine.10 It was suggested that other factors, such as discharge products, were more important than the pressure decrease in the gas density depletion area. In this paper, we examine the influence of decreasing electrode separation on gas density depletion. We have found that decreasing electrode separation has a positive effect on high repetition operations.

2. Experimental Procedure

The laser system used for the experiments was an ArF excimer laser system operating at a repetition rate of 6 kHz. This system consisted of a laser chamber, a pulse power module, a resonator, a monitor module, a gas module, and a controller. The length of the discharge electrodes was 545 mm, and the nominal separation of the electrodes was 16 mm. In this study, the electrode separation was reduced from 16 mm to 13 mm and then to 8 mm. The excitation circuit for the discharge was a capacitor transfer circuit with corona preionization. For the preionization, an internal electrode rod was surrounded by a ceramic tube and an external electrode plate was abutting the surface of the ceramic tube. The corona discharge was produced on the surface of the ceramic tube. The pulse power module supplied pulse energy at 2.1 J to the excitation circuit. Measurements were done at 200 kPa using 3.5% Ar and 96.5% Ne with 10-ppm Xe, or at 220 kPa using 0.1% F2, 3.5% Ar, and 96.4% Ne with 10-ppm Xe. The details of this system were described in a paper by Kakizaki et al.11

The positions and widths of the areas of discharge and gas density depletion were measured using a Mach-Zehnder inter-
ferometer. Figure 1 shows a schematic diagram of the measurement system. The light source was a dye laser with nitrogen laser excitation (LTB, UDL300). The wavelength of the dye laser was 600 nm, the temporal full width at half maximum of the dye laser pulse was 500 ps, and the laser pulse energy was 20 μJ. The interferograms that formed behind the half mirror 2 (see Fig. 1) were acquired with an ICCD camera (PCO, DiCAM PRO). Discharge light was suppressed by a band-pass filter. The delay time between the dye laser pulse and the discharge in the laser chamber was varied using a delay generator (Stanford Research System, DG535). The selected delay time was confirmed by phototubes (Hamamatsu Photonics, R1193U-51) that monitored the dye laser pulse and the discharge light. The time resolution of this Mach-Zehnder interferometer was 500 ps, and the spatial resolution was 0.05 mm.

The discharge width was calculated for the electron density distribution at 30 ns after discharge initiation. Electron density distributions were obtained from the Mach-Zehnder interferograms. The fringes of the Mach-Zender interferometer shift are due to the electron density $n_e$ and gas density change $n_a$. The fringe shift $s$ is given by

$$s = -4.46 \times 10^{-21} n_e L A + \frac{\eta_e L}{\lambda},$$

(1)

where $L$ is the discharge path length (545 mm), $A$ is the wavelength of the dye laser (600 nm), and $\eta$ is a constant that depends on the species of the gas. The time constant of the electron density decrease was approximately 1 μs for gas discharge without halogen. Hence, up to 1 μs after discharge initiation, the fringe shifts were mainly caused by the change in electron density, while after 1 μs the shifts were caused by the change in the gas density. At 30 ns after discharge initiation, the electron density $n_e$ peaked, and the gas density change $n_a$ could be neglected. The electron density $n_e$ was therefore calculated using only the first term on the right hand side of (1). The peak value of the electron density $n_e$ was approximately $1 \times 10^{22} \text{ m}^{-3}$, and the discharge width was defined as the width of the electron density above $1 \times 10^{13} \text{ m}^{-3}$ on the center between electrodes.

The gas density depletion width was calculated for the gas density change distribution in the gas density depletion area that was obtained from the Mach-Zehnder interferograms at 125 μs after discharge initiation. Since the electron density $n_e$ could be neglected at this time, the gas density change $n_a$ was calculated using only the second term on the right hand side of (1). The peak value of the gas density change $n_a$ was about $1 \times 10^{14} \text{ m}^{-3}$, and the gas density depletion width was defined as the width of the gas density change above $1 \times 10^{13} \text{ m}^{-3}$ on the center between electrodes. Since 96.5% of gas in the chamber was Ne, the value used for the constant $\eta$ was that for Ne: $2.46 \times 10^{-30} \text{ m}^3\text{mol}^{-1}\text{atom}^{-1}$.

3. Results

3.1 Discharge width and gas density depletion width

Figure 2 shows the results of the Mach-Zehnder interferometer measurements at 30 ns after discharge initiation. The calculated widths of the discharges are indicated by solid lines. The measurements were done at 200 kPa using 3.5% Ar and 96.5% Ne with 10-ppm Xe. From previous work at an electrode separation of 16 mm, the discharge width was found to be 3.5 mm. Here at an electrode separation of 13 mm, the discharge width was 3.0 mm, and at 8 mm it was 2.3 mm. That is, at an electrode separation of 8 mm, the discharge width decreased by 23% with respect to that at 13 mm, and it decreased by 34% with respect to that at 16 mm. The peak values of electron densities on the centers between electrodes were $6.4 \times 10^{22} \text{ m}^{-3}$ for an electrode separation of 16 mm, $8.6 \times 10^{22} \text{ m}^{-3}$ for 13 mm, and $9.9 \times 10^{22} \text{ m}^{-3}$ for 8 mm.

The results from the Mach-Zehnder interferometer measurements at 125 μs after discharge initiation are shown in Fig. 3. The calculated widths of gas density depletion are indicated by solid lines. Due to gas flow, the gas density depletion area moved to the right and out of the discharge area. With the previous result at an electrode separation of 16 mm, the gas density depletion widths for the three electrode separations were 5.2, 4.4, and 3.7 mm for electrode separations of 16, 13, and 8 mm, respectively. Hence, at an electrode separation of 8 mm, the gas density depletion width decreased by 16% with respect to that at 13 mm and by 29% with respect to that at 16 mm. The peak values of gas density changes on centers between electrodes were $2.8 \times 10^{24} \text{ m}^{-3}$ for an electrode separation of 16 mm, $3.0 \times 10^{24} \text{ m}^{-3}$ for...
13 mm, and $3.3 \times 10^{24} \text{ m}^{-3}$ for 8 mm. On converting to decrease in pressure, the changes in gas density correspond to 13.0 kPa at 16 mm, 13.9 kPa at 13 mm, and 15.5 kPa at 8 mm.

3.2 Discharge voltage drop in the gas density depletion area

To estimate the discharge voltage drop due to the pressure decrease in the gas density depletion area, the discharge voltages were measured at total gas pressures of 200 kPa and 300 kPa. The results are shown in Table 1 at electrode separations of 13 mm and 8 mm. The discharge voltage is almost proportional to the total gas pressure except for the late electron multiplication at low voltage. 10 With the previous result at an electrode separation of 16 mm, the discharge voltage drop due to the pressure decrease is estimated to be 0.30 kV at a 16-mm electrode separation, 0.28 kV at 13 mm, and 0.20 kV at 8 mm. The changes are 1.9% at 16 mm, 2.0% at 13 mm, and 2.0% at 8 mm, or about 2.0% overall.

3.3 Minimum distance between the centers of the areas of discharge and gas density depletion

The minimum distance (MD) between the centers of the areas of discharge and gas density depletion, at which a homogeneous discharge could be maintained, was measured by the following method. Four consecutive discharges were carried out, and a fourth discharge was measured by the Mach-Zehnder interferometer. The repetition rate, i.e., the distance between the centers of the areas of the discharge and the gas density depletion, was varied in the measurement. The gas velocity was lowered to 12–13 m/s. The measurement was done at 200 kPa using 3.5% Ar, 0.1% F$_2$, and 96.5% Ne with 10-ppm Xe. Figure 4 shows typical results at the electrode separation of 8 mm. At a distance of 3.6 mm, the fringe shifts in the gas density depletion area generated by the second and third discharges are symmetric. The fringe shifts between the electrodes due to the fourth discharge are also symmetric. At a distance of 3.4 mm, the fringe shifts in the gas density depletion area generated by the second and third discharges are symmetric, but the fringe shifts between electrodes due to the fourth discharge are asymmetric with an upward slope to the right. The discharge is shifting into the gas density depletion area. Therefore, it can be concluded that the MD is 3.4 mm. Likewise, the MD at an electrode separation of 13 mm is 4.2 mm. In the previous report, the MD was 4.9 mm at an electrode separation of 16 mm. Since the MD decreases as the electrode separation decreases, the repetition rate at which a homogeneous discharge can be maintained increases with decreasing electrode separations at the same gas velocity.

3.4 Maximum repetition rate for gas discharge with fluorine

We observed that the maximum repetition rate, at which a homogeneous discharge could be maintained, increased for gas discharge with fluorine at decreased electrode separations. The fluctuation of laser pulse energy begins to deteriorate at the maximum repetition rate. This deterioration is caused by a non-uniform discharge. Figure 5 shows the measured relation between the repetition rate and the fluctuation ($\sigma$: standard deviation) of the laser pulse energy for the three electrode separations. The fluctuation ($\sigma$) was calculated from the 9,001st to the 10,000th laser pulse from a total of 10,000 continuous laser pulses. The measurement was done at 220 kPa using 3.5% Ar, 0.1% F$_2$, and 96.4% Ne with 10-ppm Xe. The pulse power module was modified to operate at 10 kHz, but due to thermal restrictions, it could only be operated continuously for several seconds. In addition, the measured gas velocities were 53 m/s at a 16-mm electrode separation, 49 m/s at 13 mm, and 46 m/s at 8 mm. The fluctuation of laser pulse energy at an electrode separation of 16 mm rapidly deteriorated after 7 kHz. It can be concluded that the maximum repetition rate is 7 kHz. Likewise, the maximum repetition rate at an electrode separation of 13 mm is 8 kHz. The fluctuation of laser pulse energy at an electrode separation of 8 mm does not deteriorate up to 10 kHz, i.e., a homogeneous discharge could be maintained up to 10 kHz for the ArF excimer laser.

From the maximum repetition rate and the gas velocity, the MDs were estimated to be 7.6 mm at a 16-mm separation, 6.1 mm at 13 mm, and 4.6 mm at 8 mm. The MD for gas dis-
charge with fluorine is longer than the MD for gas discharge without fluorine.

The laser pulse energy is about 7.0 mJ at 6 kHz for a nominal electrode separation of 16 mm. However, the laser pulse energy was 2.2 mJ at 10 kHz for the electrode separation of 8 mm, i.e., the pulse energy was reduced to one-third of that at the nominal electrode separation. The main reason for the energy decrease is the reduced discharge cross section. The discharge cross section at an electrode separation of 8 mm is about one-third of that for the 16-mm electrode separation.

4. Discussion

The influence of gas density depletion was examined by calculating electric field intensity distributions on the centers between electrodes at discharge initiation. Electric field intensity distributions were calculated assuming a vacuum in the laser chamber (Ansoft, Maxwell Ver. 6.5.04). The effects of residual charges and charges produced by the preionization were ignored in this calculation. Figure 6 shows the electric field intensity distributions for the three electrode separations. In addition, following three lines are indicated in Fig. (1) The normalized electric field intensity of 0.98 (2% below its peak value) is indicated by dashed lines. As described above, the discharge voltage drop due to the pressure decrease in the gas density depletion area is estimated to be about 2.0%. Since the discharge voltage drop and the electric field intensity drop are equivalent, the normalized electric field intensity drop due to the pressure decrease is 2.0%. (2) The normalized electric field intensity at the MD position for gas discharge without fluorine is indicated by dashed-dotted lines. (3) The normalized electric field intensity at the MD position for gas discharge with fluorine is indicated by dashed double-dotted lines.

For the normalized electric field intensities of gas discharge with fluorine (dashed double-dotted lines in Fig. 6), the discharge voltages in the gas density depletion area for the three electrode separations are expected to be lower than the discharge voltages in the area between electrodes by 11.6% for 16-mm electrode separations, 12.0% for 13 mm, and 18.1% for 8 mm. The discharge voltage in the gas density depletion area decreases with decreasing electrode separation. However, the maximum repetition rate at which a homogeneous discharge could be maintained increased with decreasing electrode separation. One reason is that, for decreasing electrode separations, the electric field intensity distribution concentrates on the center.

The differences in normalized electric field intensities between the dashed line and dashed dotted line and between the dashed line and dashed double-dotted line are caused by other factors, such as discharge products. For gas discharge without fluorine (dashed-dotted line), the effects of other factors are estimated to be 4.1% at 16 mm, 5.1% at 13 mm, and 10.8% at 8 mm. For gas discharge with fluorine (dashed double-dotted line), the effects of other factors are estimated to be 9.7% at 16 mm, 10.0% at 13 mm, and 16.1% at 8 mm. The influence of other factors is 5.0–8.1 times as great as the influence of pressure decreases. Here, for gas discharge without fluorine, the influence of residual charges in the gas density depletion area is examined. It is not clear how these recombination actions progress. The recombination coefficient used for the dissociative recombination coefficient of Ar at 300 K possesses a large value of approximately $10^{-12} \text{m}^{-3} \text{s}^{-1}$. Further, the maximum charges density value is assumed to be the same as the peak value of electron density on the center between electrodes (i.e., $10^{17} \text{m}^{-3}$). The residual charge density is estimated to be in the order of $10^{15} \text{m}^{-3}$. The residual charge density is almost the same as the electron density due to preionization. The residual charge density is estimated to be $10^{17} \text{m}^{-3}$.
charges seemingly influence the next discharge as the discharge products. For gas discharge with fluoride, the influence of other factors is greater than that for gas discharge without fluoride. One factor for this is the large residual charges density, which is because the discharge interval at the MD position for gas discharge with fluoride is shorter than the discharge interval at the MD position for gas discharge without fluoride.

In this study, a homogeneous discharge could be maintained in the ArF excimer laser for repetition rates of up to 10 kHz using an electrode separation of 8 mm. However, the laser pulse energy was very less at 2.2 mJ. It seems that an increase in the laser pulse energy to a higher value (e.g., 10 mJ). It seems that an increase in the laser pulse energy can be achieved by a twin chamber scheme, which has been adopted in a high power ArF excimer laser for lithography. An injection lock\(^\text{10}\) and a master oscillator power amplifier\(^\text{20}\) are two widely known twin chamber schemes. In both systems an oscillator laser (first chamber) injects a low-energy laser pulse into an amplifier (second chamber) that amplifies the initial laser pulse energy. The amplifier in the injection lock, called a power oscillator, includes an optical resonator, but the amplifier in the master oscillator power amplifier, called a power amplifier, does not include an optical resonator. For high repetition rate operations at small electrode separations, the increase in laser pulse energy is an important technical challenge.

5. Conclusion

The maximum repetition rate at which a homogeneous discharge can be maintained increases with decreasing electrode separation. This is due to a narrower discharge width and an electric field intensity distribution that concentrates on the center. As a result, for the ArF excimer laser, a homogeneous discharge could be maintained for repetition rates of up to 10 kHz at an electrode separation of 8 mm. However, the laser pulse energy was as small as 2.2 mJ due to the reduced discharge cross section. Increasing the laser pulse energy is a major future technical challenge.

In addition, the influence of gas density depletion was examined by calculating the electric field intensity distribution on the center between electrodes at discharge initiation. The influence of gas density depletion could be divided into two factors: (1) pressure decreases, (2) other factors, such as discharge products (residual charges).

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References

1) S. Owa, H. Nagasaka, K. Nakano, and Y. Ohmura: Proc. SPIE 6154 (2006) p.615408-1.
2) V. Wiaux, J. Bekaert, E. Hendrickx, S. Vehaegen, G. Vandenberghe, S. Locorotondo, S. Beckx, J. Finders, and M. Dusa: Digest of Abstract of 3rd International Symposium on Immersion Lithography (2006) 26.
3) G. Imada, W. Masuda, and K. Yatsui: J. IEE Japan 118-A (1998) 1139 (in Japanese).
4) M. R. Osborne and J. M. Green: J. Appl. Phys. 71 (1992) 3127.
5) R. Arutyunyan, V. Borisov, A. Vinokhodov, Y. Kiryukhin, and A. Morozov: Sov. J. Quantum Electron. 16 (1986) 1589.
6) R. Turner: J. Appl. Phys. 52 (1981) 681.
7) R. Dreiskemper and W. Botticher: IEEE Trans. Plasma Sci. 23 (1995) 987.
8) M. L. Sentis, P. Delaporte, B. M. Forestier, and B. L. Fontaine: IEEE J. Quantum Electron. 27 (1991) 2332.
9) S. Takagi, N. Okamoto, K. Kakizaki, S. Sato, and T. Goto: J. Appl. Phys. 68 (1990) 5927.
10) T. Ishihara, T. Hori, K. Kakizaki, and K. Uchino: IEEJ Trans. FM 130 (2010) 1060 (in Japanese).
11) K. Kakizaki, Y. Sasaki, and T. Inoue: Rev. Sci. Instrum. 77 (2006) 035109.
12) A. J. Alock and S. A. Ramsden: Appl. Phys. Lett. 8 (1966) 187.
13) S. Nagai, H. Furuhashi, A. Kono, Y. Uchida, and T. Goto: IEEE J. Quantum Electron. 34 (1998) 942.
14) S. Choroba and W. Botticher: Appl. Phys. B 51 (1990) 379.
15) Y. Saitoh, Y. Sato, and S. Ueguri: T. IEE Japan 115-A (1995) 1180 (in Japanese).
16) T. G. Beuthe and J. S. Chang: Jpn. J. Appl. Phys. 38 (1999) 4576.
17) S. Takagi, S. Sato, and T. Goto: Jpn. J. Appl. Phys. 28 (1989) 2219.
18) K. Fukuda, N. Hayashi, S. Satoh, and C. Yamabe: Rep. Fac. Sci. Eng. Saga Univ. 29 (2000) 35.
19) O. Wakabayashi, T. Ariga, T. Kumazaki, K. Sasano, T. Watanabe, T. Yabu, T. Hori, K. Kakizaki, A. Sumitani, and H. Mioguchi: Proc. SPIE 5377 (2004) p.1772.
20) V. B. Fleurov, D. J. Colon, D. J. W. Brown, P. O’Keeffe, H. Besaucele, A. I. Ershov, F. Trinchouk, T. Ishihara, P. Zambon, R. Rafac, et al.: Proc. SPIE 5040 (2003) p.1694.