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SPIE.

Event: SPIE LASE, 2018, San Francisco, California, United States

Improvement of conversion efficiency of DUV light generation at 221-nm using CLBO crystal

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ABSTRACT

We are developing a 100-W level DUV light source using a solid-state seed laser and an ArF amplifier. Seed pulse at 193nm is generated by the sum frequency mixing of the pulse at 221nm and the pulse at 1553nm using CLBO crystals. To realize a compact and robust seed laser, we improved the conversion efficiency of DUV light generation. In case of the 221nm pulse generation, the conversion efficiency was increased from 22% to nearly 50% by optimizing the conversion process which enables the reduction of amplifier unit of fundamental light source to obtain the 1W seed pulse at 193nm.

Keywords: frequency conversion, DUV, CLBO, ArF laser,

1. INTRODUCTION

Deep ultra violet (DUV) lasers are actively used for material micro processing and semiconductor lithography. Argon fluoride excimer laser (ArF excimer laser) is the typical light source which can generate above 100W optical power at the wavelength of below 200nm. Our twin-chamber ArF excimer lasers can generate the high power DUV light with extremely narrow linewidth and uniform flat-top beam profile, which are fundamental to the semiconductor lithography [1]. On the other hand, using all-solid-state DUV light source as a seed laser and amplifying by ArF excimer, both high average power and high beam quality can be realized in the DUV region [2]. The hybrid ArF excimer laser is consisting of two components, the solid-state DUV seed source and the ArF excimer amplifier. The solid state DUV seed source is replaced with the ArF-based master oscillator inside our twin-chamber ArF excimer lasers as shown in Figure 1.

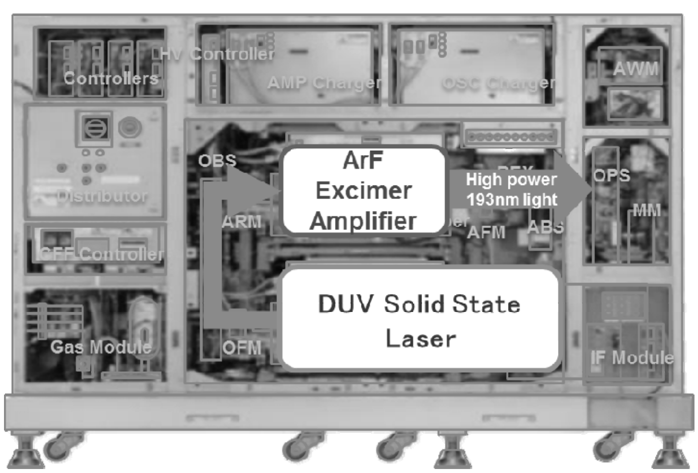

Figure 1 Hybrid ArF laser based on twin chamber excimer laser for semiconductor lithography

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Nonlinear Frequency Generation and Conversion: Materials and Devices XVII, edited by Konstantin L. Vodopyanov, Kenneth L. Schepler, Proc. of SPIE Vol. 10516, 1051602
 · doi: 10.1117/12.2287675

1.1 Progress of solid-state DUV light source

Typical method of DUV generation based on solid-sate laser is frequency conversion using nonlinear crystals. The wavelength of fundamental light generated from solid-state laser is in the region of near infrared (NIR). After the several frequency conversion processes, the NIR light is converted to DUV light. Thus, to obtain a high power DUV light, quite high output power is required to the NIR light. Table 1 shows the resent progress of solid-state based DUV light source development at the wavelength of below 200nm. The output power is still limited up to 1W due to the lack of suitable nonlinear crystals for wavelength conversion. Only few crystals have good transparency and capability of phase matching in this region. Therefore, the hybrid ArF laser is the almost only solution to obtain high power laser light below 200nm.

Table 1 Solid-state DUV lasers below 200nm

Wavelength	Output (W)	NIR Laser	Year	Ref.
193.4 nm	0.14	Er Fiber Laser	2003	[3]
193.5 nm	1.05	Ti:sapphire	2009	[4]
193 nm	0.015	Diode laser	2013	[5]
191.7 nm	0.24	$Nd:YVO_4$	2014	[6]
193.4 nm	0.30	Yb and Er fiber laser	2015	[7]
193.4 nm	1.02	Yb and Er fiber laser	2017	[8]

1.2 Development of DUV seed source and ArF amplification

Figure 2 shows the block diagram of solid-state DUV seed source at 193nm. The seed source contains Yb-doped fiber laser, Yb:YAG amplifier, Er-doped fiber laser and the frequency up-conversion chain using nonlinear crystals. Narrowband nanosecond pulse at the repetition rate of 6kHz is generated from the Yb-doped fiber laser, and amplified by the Yb:YAG amplifier. The second (515nm) and forth (258nm) order harmonics of the amplified pulse is generated by the LBO and CLBO crystals, respectively. The two-stage sum frequency generation using the forth order harmonics pulse and the pulse from Er-doped fiber laser is applied to obtain the seed pulse at the wavelength of 193nm. We have obtained the 193nm light output of 0.3W at the repetition rate of 6kHz.

The generated 193nm pulse was amplified by ArF amplifier. The amplified output was achieved to 120W at the repetition rate of 6kHz [9]. Figure 3 shows the M^2 measurement of hybrid laser. The M^2 values of hybrid laser in horizontal and vertical directions are 1.61 and 1.91, respectively. In contrast, typical M^2 values of the twin-chamber ArF laser in horizontal and vertical directions are approximately 13 and 61, respectively.

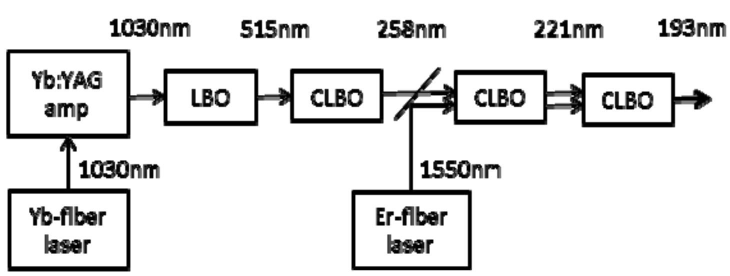

Figure 2 Block diagram of DUV seed source at 193nm for the hybrid ArF laser.

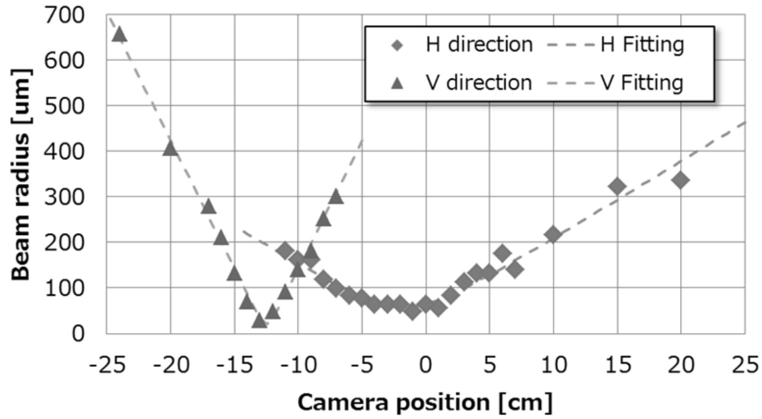

Figure 3 M^2 measurement of the hybrid ArF laser.

1.3 Seed source design for the 200W hybrid ArF laser

We are aiming to obtain the output of higher than 200W from the hybrid laser by increasing the repetition rate from 6kHz to 10kHz, and are developing the DUV seed source working at the repetition rate of 10kHz. To maintain the same pulse energy in both repetition rates, the average power need to be increased to 0.5W at 10kHz. Table 2 shows the required output powers at each wavelength conversion stage to obtain the final output of 0.5W at 10kHz. Assuming that the conversion efficiencies (CEs) at each wavelength conversion stage are same as the 6kHz operation, the output power of fundamental pulse after the Yb rod amplifier is required to higher than 15W. Generally, the higher laser power induces the higher thermal loading; as a result, the beam profile is distorted due to the thermal lensing inside laser gain media and nonlinear crystals. Since the CE of 221nm generation is particularly lower than that of other wavelength conversion process, we focused to improve the CE of 221nm generation. Assuming that the CE of 221nm is increased to 40%, the power of fundamental pulse after the Yb rod amplifier can be reduced to 9.5W which is close to the power in the case of 6kHz operation.

Table 2 Design parameters of DUV seed source for 10kHz operation. CE: conversion efficiency

	6 kHz Power (W)	10 kHz Target Power (W)	CE	Saving 10 kHz Target Power (W)
Er Fiber laser	1	1.67	-	-
Yb Fiber laser	1	1.67	-	-
Yb Rod Amp	9.05	15.1	-	9.5
515 nm	7	11.7	77.3%	7.3
258 nm	3	5.0	42.9%	3.2
221 nm	0.8	1.3	26.7%	1.25
193 nm	0.32	0.5	40.0%	0.5

2. EXPERIMENTAL SETUP

Figure 4 shows the experimental setup of 221nm generation at the repetition rate of 10kHz. An Yb fiber laser generates the 10ns optical pulse at the wavelength of 1030nm. The output power of Yb fiber laser can be adjusted by the combination of half wave plate (HWP) and polarized beam splitter (PSB). The 1030nm pulse is amplified up to 16W by an Yb:YAG rod amplifier with double-pass configuration. The rod amplified is pumped by a fiber coupled CW laser diode at the wavelength of 940nm. The amplified pulse is directed into a LBO crystal to generate second harmonics. After the harmonics generation, the fundamental and the second harmonics pulses are split by first dichroic mirror. Fourth harmonics pulse, of which wavelength is 258nm, is generated using first CLBO crystal with the output power of 5W. The fourth harmonics pulse is combined by second dichroic mirror with an infrared pulse at the wavelength of 1553nm generated from an Er fiber laser. Both 258nm and 1553nm pulses are directed into second CLBO crystal to generate the 221nm pulse via sum frequency generation process. The generated 221nm pulse is separated from other wavelength pulses by using third dichroic mirror.

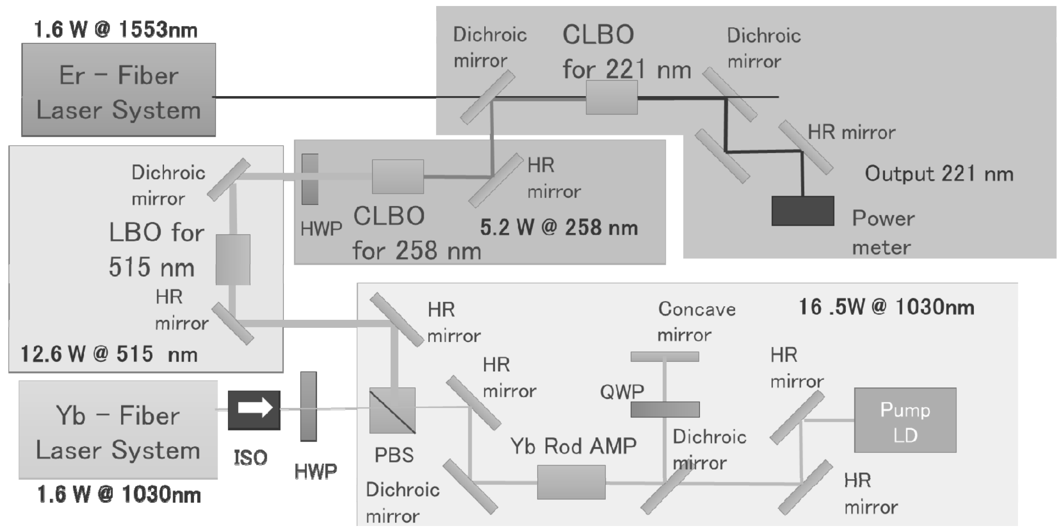

Figure 4 Experimental setup of 221nm generation. ISO: isolator, HWP: half wave plate, QWP: quarter wave plate, PBS: polarized beam splitter, HR: high reflection, LD: laser diode

3. RESULTS OF WAVELENGTH CONVERSION

Figure 5 shows the output characteristics of 221nm generation. We changed the power of 258nm pulse by adjusting the angle of HWP behind the isolator (ISO) of Yb fiber laser. The output of 221nm pulse was achieved to 1.12W with the CE of 22.8% which was slightly lower than that in 6kHz operation. Since the CE tended to saturate at the 285nm power of higher than 4.5W, we slightly increased the input beam sizes. Also we optimized the beam size of both 258nm beam and 1553nm beam so that these two beams covered each other completely inside the second CLBO crystal. After the optimization, the output power was increased to 1.85W with the conversion efficiency of 37%.

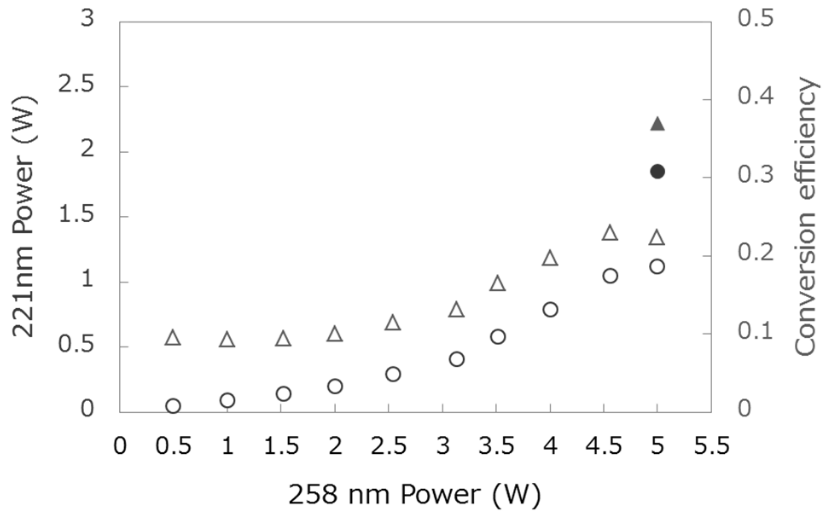

Figure 5 Output characteristics of 221nm generation before/after optimization. Circle: output power, Triangle: conversion efficiency, Filled circle/triangle: after the optimization.

Although the CE of 37% is closed to the expected and aimed value (40%), we further optimized the configuration of 221nm generation and finally obtained the output of 2.38W with the conversion efficiency of 47% as shown in Figure 6. At this moment, we haven't made clear the reason of CE improvement. The CE was greatly improved at the high input (258nm) power whereas no significant improvement at the low input power region. Since we changed the power of 258nm light by using the combination of HWP and PBS, the profile and position of input beam must be maintained. We are trying to make a theoretical model which can explain this phenomenon.

Since the conversion efficiency at the output of 2.38W seems to be saturated, further optimization would be possible to achieve the output of higher than 2.5W.

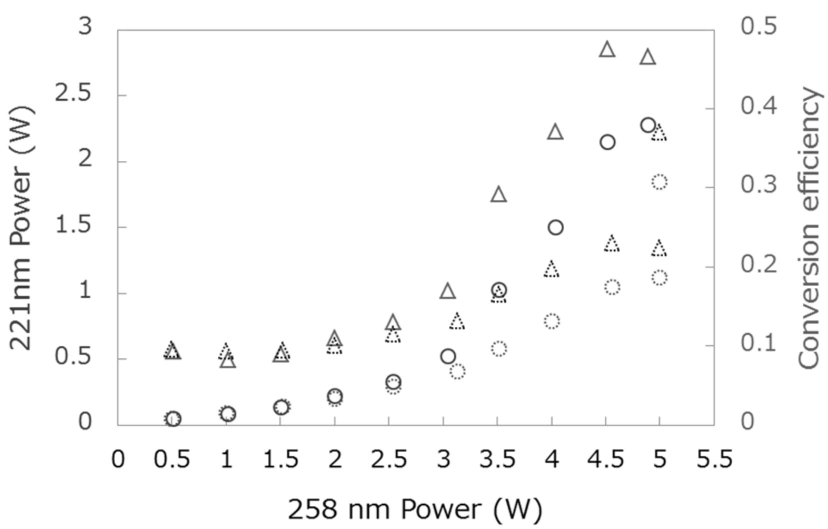

Figure 6 Output characteristics of 221nm generation after the second optimization. Circle: output power, Triangle: conversion efficiency, Dotted circle/triangle: results from Figure 5.

4. SUMMARY

We are developing the DUV solid state-laser as a seed source of hybrid ArF laser. To obtain the output of higher than 200W from the hybrid laser, we are developing the 10kHz DUV seed source and are focusing to the improvement of conversion efficiency of 221nm generation. Figure 7 shows the trend of reported conversion efficiency from NIR light to DUV light. The total conversion efficiency, i.e. the conversion efficiency from NIR to DUV, was improved from 9% to 14%. To the best of our knowledge, this conversion efficiency is high enough in the world record. Based on the obtained 221nm output of 2.38, and assuming that the CE of 193nm generation to 40%, we are expecting to obtain nearly 1W output at 193nm in a compact system.

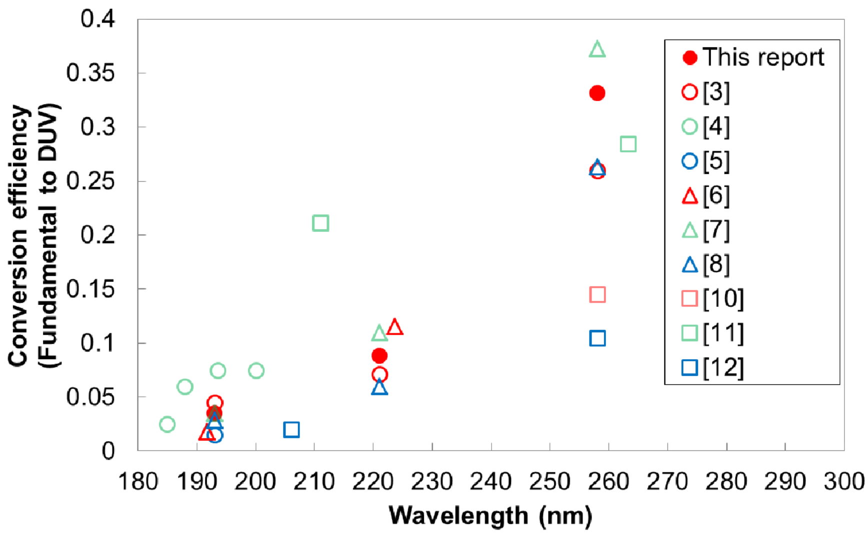

Figure 7 Trend of reported conversion efficiency from fundamental light to DUV light.

5. ACKNOWLEDGEMENT

This work was financially supported by New Energy and Industrial Technology Development Organization (NEDO).

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