The State of the Art of Rare Gas Excimer Lasers and Lamps as a Light Source for Giga-bit Lithography

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Coherent and incoherent light sources using rare gas excimers are reviewed from a point of view of post ArF lithography. Present status of electron beam pumped rare gas excimer lasers are reported. Potentialities of rare gas excimer lasers by discharge pumping are discussed. We have obtained laser gain of $2.2 \times 10^{-3} \text{ cm}^{-1}$ in Kr discharges which was very close to the threshold gain. It is pointed out that gas excimer lasers are suitable for light sources for next generation lithography after ArF lithography in the 21st century, when a compact excitation method is established. A jet discharge excimer lamps are also discussed from a point of view of an incoherent light source for lithography.

Keywords: rare gas excimer, vuv radiation, electron beam excitation, discharge excitation, jet discharge, lithography light source

1. Introduction

It has been long time to introduce excimer lasers in mass production lines of LSI industry. Now KrF excimer lasers of 248 nm wavelength are begun to use for lithography of 64 MDRAM and 250 MHz CPU where 0.3 μm design rules are required. An ArF laser with 193 nm wavelength is a strong candidate for 0.25 μm optical lithography in the next century.

There have been many discussions for exploring the potentialities of advanced optical lithography below 193 nm wavelength. Optical lithography industry will jump to soft x-ray wavelength to obtain even higher spatial resolution. On the other hand, a compact VUV laser could be a strong alternative for post ArF laser lithography.

In this letter the state of the art of VUV lasers is reviewed with a focus on rare gas excimer lasers. Rare gas excimers have long been one of the very few laser media in the VUV spectral region.[1] The emission wavelength of Ar_2^* is 126 nm which is long enough to use transmission optical elements such as MgF_2 and LiF . A Kr_2^* laser has an even longer emission wavelength centered at 146 nm which reduces the conditions for optics and would become a competitor to an F_2 laser at 157 nm. Rare gases are chemically stable which shows a strong contrast to chemically active fluorine in a F_2 laser. In addition to the well known homo-nuclear rare gas excimer continuum, emission from hetero-nuclear rare gas excimers were obtained by mixing a trace of heavier rare gas.

2. Rare gas excimer lasers

2-1. Electron beam pumped rare gas excimer lasers

Rare gas excimer lasers are attractive sources for applications not only in optical lithography but also in various industrial fields such as photochemistry and new types of materials processing. Electron beam pumping, however, is the only excitation method to realize the laser oscillation of rare gas excimers. We have been developing a high peak power Ar_2^* and Kr_2^* lasers using electron beam pumping for fusion plasma diagnosis.[2,3] A part of a typical electron beam machine consisting of a Marx-generator, Blumlein-type pulse-forming circuit and a diode is shown in Fig. 1. The laser gas contained in the tube which was an anode of a coaxial-type diode was pumped by an electron beam with a peak voltage of 700 keV and a pulse duration time of 90 ns in FWHM. The coaxial diode consists of a cathode with 40 cm length and a concentric anode made up of a stainless steel

Fig. 1. Schematic diagram of a coaxial diode and a laser resonator.

tube of 5 mm outer diameter and 80 μm wall thickness (Kobe Steel Co. Ltd.). The ends of anode pipe opened into the high pressure chamber, where the laser mirrors of resonant cavity were placed. The resonant cavity could be composed of an uncoated MgF_2 plate as an output mirror and a Al, SiC or Si plate as a back mirror. Lasing conditions of rare gas excimer lasers are summarized in Table 1. Our efforts have been focused on the Ar and Kr excimer

Table 1 Present status of rare gas excimer lasers

Species	Wavelength[nm]	Peak power[MW]	Band width[nm]	Resonator
Ar	126	16	1	SiC - MgF_2
	124 - 128	> 1	0.3	16 deg. MgF_2 prism
Kr	147	7	1	Si - MgF_2
	145.5 (tuned)	3.5	0.1	32 deg. MgF_2 prism
Xe	172	400	-	-
	170 - 176*	1	0.1	MgF_2 prism

* Ref. [12]

lasers with high peak power which oscillate in the vicinity of 126 nm and 146 nm. The maximum peak output power of the Ar excimer laser was 16 MW with 1 nm spectral width when using a SiC back mirror and MgF₂ output mirror. A Si back mirror and MgF₂ output mirror worked best for the Kr excimer laser, yielding 7 MW in a 1 nm band width. The largest peak power Xe excimer laser, developed by Ault et al. [4], yielded 400 MW, but details of this laser have not been published.

Broad band gain profiles of the rare gas excimer lasers permit laser wavelength tuning by using dispersive optics. A MgF₂ prism with 16 degrees apex angle was inserted in the cavity of the Ar excimer laser to yield a tuning range of 124 nm to 128 nm at a line width of 0.3 nm.[5] A larger apex angle MgF₂ prism with 32 degrees was used in the Kr excimer laser to provide the same dispersion. The tuning range was not fully tested, but a peak power of 3.5 MW in a narrow line width of 0.1 nm was produced.[6]

Despite their high peak power operation in the VUV spectral region, electron beam excitation method may be unsuitable for certain applications such as optical lithography in the next generation, because they require a rather large facility to be operated, resulting in a low repetition rate and low average power of a laser beam. A compact rare gas excimer laser with high repetition operation is in high demand for an optical lithography. Various excitation methods have thus been studied to demonstrate compact rare gas excimer lasers.[7,8,9] We have attempted to obtain a laser oscillation of rare gas excimers by a discharge excitation.

2-2. Discharge pumped rare gas excimer lasers

A discharge pumped rare gas excimer laser is one of the favorable light sources for an optical lithography in the next generation. We have investigated various types of discharge excitations of rare gas excimer lasers.[8,9,10] In order to establish laser oscillation of rare gas excimers by discharge pumping it is considered that stable arc free discharges should be accomplished in a high pressure rare gas.

Fig. 2 shows a schematic diagram of a discharge tube and a laser cavity used in our experiments. Although the discharge tube seems to be the same as those of rare gas halide excimer lasers, some improvements have been done to

Fig. 2. A schematic diagram of a discharge tube and cavity mirrors.

attain an arc free discharge in a high pressure rare gas. In order to obtain strong photo-preionization 102 pairs of pre-discharge pins were set at both sides of main electrodes in the high pressure gas container up to 10 atm.. The inductance of the main discharge circuit was reduced as low as 2.6 nH to obtain first rise time discharges. The electrodes were 108 cm length

with 2 cm width having a Chang-shape structure. The discharge gap was set at 6 mm. A laser cavity was composed of a pair of Al mirrors and set in the pressure chamber at the both ends of the electrodes. One of the Al mirror had a small hole of 1 mm diameter at the center for output coupling. The reflectivity of the Al back mirror was 80 % at 147 nm and the effective reflectivity of the output coupler is estimated about 40 %.

Fig. 3 shows a time-integrated emission spectra from a discharge region observed through the coupling hole. A broad emission centered at 147 nm was identified as an emission from Kr_2^* .

Fig. 3. Time-integrated emission spectra from a krypton discharge.

Several lines in longer wavelength were considered as emissions from Al ions which were sputtered from the pre-discharge pins. Intensities of Kr_2^* emissions at 147 nm were observed through the output coupler with and without the back reflector and represents in Fig. 4 as a function of Kr gas pressure. Although laser oscillation was

Fig. 4. 147 nm Kr emissions intensities.

● : With cavity resonator.

○ : Without cavity resonator.

not observed, it seemed that laser gains increased with increasing the Kr pressure up to 4 atm. When the laser cavity was composed, Kr_2^* intensities rapidly increased with Kr pressure. On the contrary only small change was observed for Kr_2^* intensities without the laser cavity. We estimated laser gains by comparing Kr_2^* intensities with and without laser cavity and found $2.2 \times 10^{-3} \text{ cm}^{-1}$ at 4 atm. of Kr gas pressure which was about one half of threshold gain of $5.7 \times 10^{-3} \text{ cm}^{-1}$ for this laser cavity.

We have obtained laser gain relatively close to the threshold gain, it is, however, difficult to increase the gain in this experimental setup. It was found that plasma impedance became very small value of 0.03Ω , therefore only small amount of charged energy was deposited in the plasma within one cycle of discharge current. According to a computer simulation for electron beam excitation, excitation intensity of about 30 MW/cm^2 should be necessary to lase Kr excimer

lasers. Considering differences between an electron beam excitation and a discharge excitation, excitation intensity of 20 MW/cm³ may be required to deposit in the plasma. In these experiments maximum charged energy into the capacitors correspond to 20MW/cm³ therefore almost all charged energy should be deposited in the discharge plasma to provide laser oscillation.

3. Jet discharge excimer lamps

Rare gas excimer discharge lamps have been developed in quasi-cw jet discharges. Since the detail of the experimental setup has been described in the previous paper [11], only brief description is presented here. A Laval nozzle of 0.4 mm throat diameter was located inside a vacuum chamber and a pair of iron electrodes were placed at 6 mm below the nozzle end and the distance between the electrodes was 5 mm. The electrodes were connected to a 0.53 μ F capacitor, which was charged up to 2 kV. When laboratory-grade rare gas was injected from the nozzle for 5 ms (FWHM) the discharge was initiated.

It was verified experimentally that the rare gas excimers were formed directly from relevant rare gas clusters in expanding jet discharges.[11] As listed in Table 2 sizable outputs with considerably high efficiencies were obtained by approximated point sources which might be favorable as a light source for optical lithography. The outputs of excimer lamps were improved by about 2.5 time by applying a magnetic field parallel to the gas jet discharge current. [9] In addition to the well known homo-nuclear rare gas excimer continuum, emission from hetero-nuclear

Table 2. Outputs and efficiencies of jet excimer lamps.

Species	Wavelength (nm)	Output Power (mW)	Efficiency (%)
Ar ₂ [*]	126	4	0.004
ArKr	134	4	0.004
Kr ₂ [*]	147	130	0.9
Xe ₂ [*]	172	210	1.6

Fig. 5. A hetero-nuclear excimer ArKr^{*} emission spectra from a jet discharge in an argon krypton mixture.

rare gas excimers were obtained by mixing a trace of heavier rare gas. In Fig 5 a clear ArKr^{*} excimer emission centered at 134 nm as well as Ar₂^{*} at 126 nm and Kr₂^{*} at 146 nm are shown, where 12 mmHg of Krypton gas is mixed with 250 mmHg of argon gas. It should be pointed out that the 134 nm source may be desirable for future optical lithography, because it is shortest wavelength where refractive optics will be available.

4. Summary

Coherent and incoherent light sources by using rare gas excimers are reviewed from a point of view of post ArF lithography. Laser medium in rare gas excimer lasers are chemically stable which shows a strong contrast to chemically active fluorine in a F₂ laser, so that rare gas excimer lasers could be a strong candidate for post ArF laser optical lithography. An arc free stable discharge was established in high pressure rare gas up to 10 atm. We have obtained laser gain of $2.2 \times 10^{-3} \text{ cm}^{-1}$ in Kr discharges which was very close to the threshold gain. An establishment of compact and high repetition operation of a rare gas excimer laser will be essential for semiconductor industry in the next century. On the other hand, a jet excimer lamp would become a competitor to a rare gas excimer laser. Jet excimer lamps work well in discharge excitation with considerably high efficiency and high repetition. Improvements of the emission intensities from jet excimer lamps will be desirable.

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