Spectral Metrologies for Ultra-Line-Narrowed F_2 laser

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1. ABSTRACT

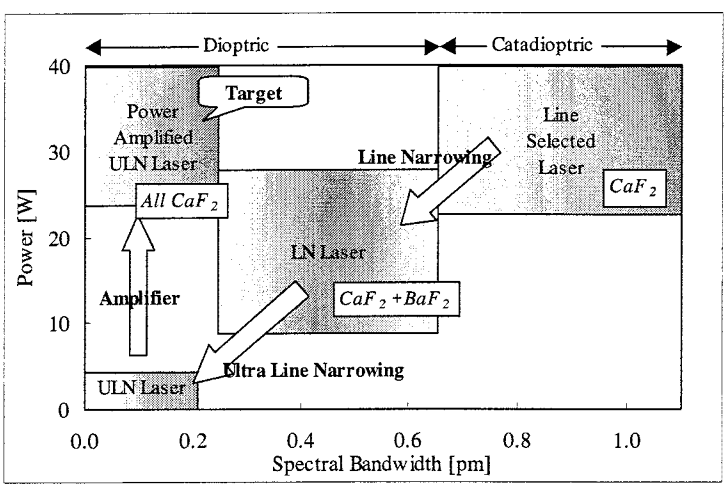
The roadmap of semiconductor fabrication predicts that the semiconductor market will demand 65nm node devices from 2004/2005. Therefore, an Ultra-Line-Narrowed F_2 laser for dioptric projection systems is being developed under the ASET project "The F_2 Laser Lithography Development Project". The target of this project is to achieve a F_2 laser spectral bandwidth below 0.2pm (FWHM) and an average power of 25W at a repetition rate of 5 kHz. Accurate measurements of the laser spectrum and of the laser wavelength stability are therefore very important.

We therefore developed a VUV wavemeter with a Br-lamp to measure the absolute F_2 laser wavelength. We obtained 157.631nm for the main F_2 laser transition using the Br-lamp reference lines at 157.4840nm and 157.6385nm,

We have also developed a VUV high-resolution spectrometer to measure spectral profiles, which was calibrated by 157nm coherent light source (157CLS). The 157CLS is a very narrow line-width, which can be approximated by delta function. The 157CLS had a line-width of 0.008pm(Full-Width-At-Half-Maximum, FWHM) and a power of 0.1mW. The instrument function of the high-resolution spectrometer measured by the 157CLS was 0.10pm(FWHM). As a result, the deconvolved FWHM of the ultra-line-narrowed F_2 laser is 0.12pm, the deconvolved spectral purity containing 95% of the total energy (E95) was less than 0.45pm.

Keywords: F_2 Laser, wavelength, linewidth, spectrometer, 157nm microlithography, line-narrowing, injection locking,

2. INTRODUCTION



[Fig.1] Laser Type, Spectral Bandwidth and Lens Design

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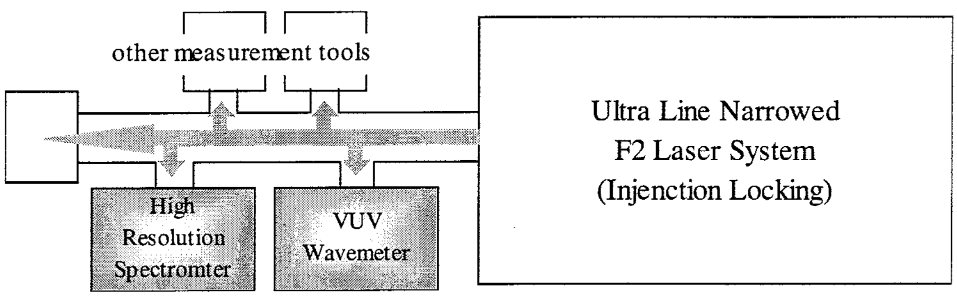
Basically two optical designs exist for 157nm exposure tools that will be used for 65nm devices: Dioptric and Catadioptric. Contrary to the Catadioptric design the dioptric design is a very common design for microlithography systems. Dioptric is therefore the "state of the art" design of current exposure tools and this is certainly a "driving force" for stepper suppliers to prepare Dioptric F_2 laser microlithography systems for the market within the given time frame.

[Fig.1] shows the relation between the laser spectral bandwidth and the laser output power necessary for the two lens designs. For the Dioptric design the chromatic aberration has to be corrected by applying at least two different lens materials: for example CaF2 and BaF2. Or, alternatively, a very narrow spectral light source at 157nm has to be used. The Catadioptric design uses mirrors, which avoids wavelength dispersion. Therefore, the Catadioptric design has a much larger margin for the spectral bandwidth of the light source. The Catadioptric design requires a bandwidth (FWHM) of 0.8 ~ 1.2 pm at 157 nm, whereas the Dioptric design requires a FWHM below 0.2 pm. Dioptric design. But standard metrology tools for spectral evaluation do presently not exist. Hence, the metrology development for the ultra-line-narrowed F_2 laser, especially for spectral bandwidth and absolute wavelength, is an important issue.

An absolute wavelength measurement of a F_2 laser using a Pt-Ne hollow cathode lamp as a wavelength standard was reported by Claig et al. [1] However, the Pt-Ne hollow cathode lamp emission is too weak to measure the absolute wavelength of an ultra-line-narrowed F_2 laser. Therefore, we developed a new VUV wavemeter that uses a Br-lamp as a wavelength reference. [2]

Earlier, we evaluated the spectral profile of the ultra-line-narrowed F_2 laser with a VUV grating spectrometer calibrated by a 153nm coherent light source (153CLS). [3] In the meantime we developed a VUV high-resolution spectrometer and a 157CLS in cooperation with The University of Tokyo, Japan, which was used to recalibrate the spectrometers. By using the newly developed VUV high-resolution spectrometer, we have succeeded in measuring the spectral profile of the ultra-line-narrowed F_2 laser more accurately. [4,5,6]



[Fig.2] 5kHz Ultra-Line-Narrowed F2 Laser System with Spectral Metrology Tools

A diagram of the Ultra-Line-Narrowed F_2 Laser System including the VUV wavemeter and the VUV high-resolution spectrometer is shown in [Fig.2].

3. REQUIREMENT OF SPECTRAL METROLOGIES FOR ULTRA-LINE-NAROWED F_2 LASER

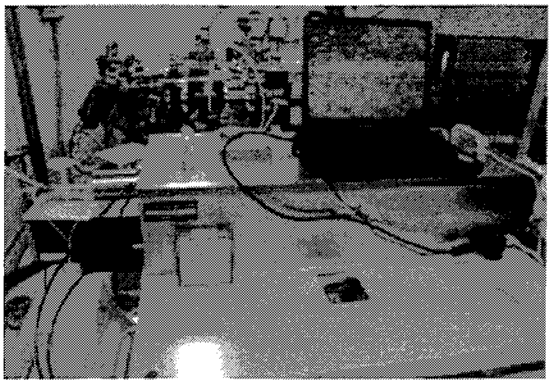
Requirements of the F_2 laser linewidth evidently depend on the specific design of the microlithography projection system. A dioptric design requires, for example, an ultra-line-narrowed F_2 laser that has a FWHM-bandwidth of 0.2pm and a wavelength stability of less than +-0.05pm.

For microlithography projection systems, it is necessary to measure the wavelength in a moment. And the wavelength as well as the spectral profile have to be kept constant for various F_2 laser operation conditions. However, instruments to measure the absolute wavelength and the spectral profile of ultra-line-narrowed F_2 lasers are commercially not available. Hence, a VUV wavemeter to measure the absolute wavelength and a high-resolution spectrometer to measure the spectral profiles have to be developed by us.

Since the FWHM of the ultra-line-narrowed F_2 laser is below 0.2pm, it is important to reduce the error of the spectrometer. There are two important categories to calibrate a spectrometer. One is the dispersion that decides the unit of wavelength axis and the other is the instrument function that describes the resolution of the spectrometer. The knowledge of the instrument function is necessary for the precise evaluation of the spectral profile by deconvolution. A 157CLS is therefore need in order to measure the instrument function of this high-resolution spectrometer.

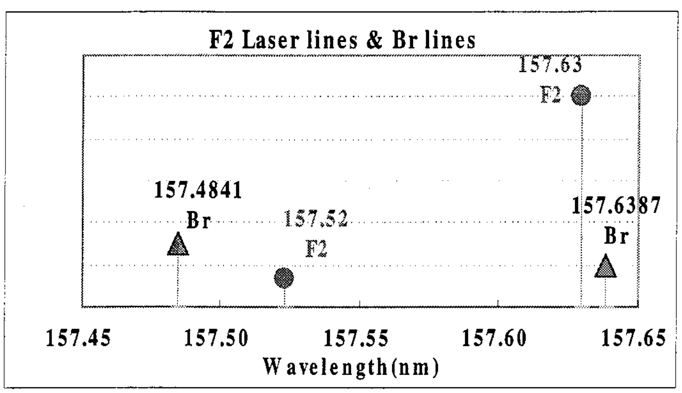
4. ABSOLUTE WAVELENGTH MEASUREMENT

4.1 Wavemeter with Br-lamp

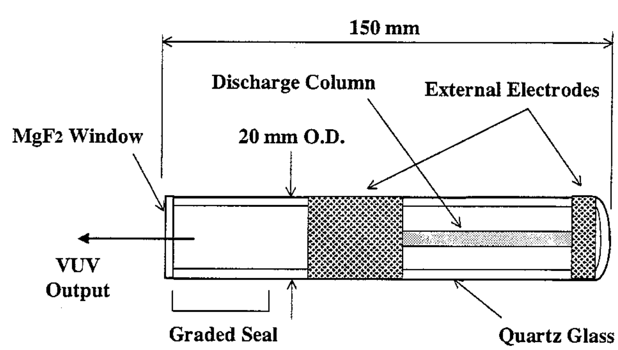


[Fig.3] VUV wave-meter with Br- lamp

In the 157nm region, Pt-Ne hollow cathode lamps are very weak and have many emission lines. They are therefore not suitable for absolute wavelength measurements. Therefore, we have developed a new Br-lamp that emits several high-intensity lines around 157nm. We selected two lines, 157.4841nm and 157.6387nm, as reference lines. The VUV-wavemeter is a modified-Czerny-Turner spectrometer in combination with a magnifying concave-convex mirror configuration. [7] The new VUV-wavemeter with the Br-lamp is shown in [Fig.3]. The wavemeter size is 780W*320D*200H (mm), the output focal length is 1890mm and the dispersion is 0.215pm/ch. It is purged with N2 gas. The Br-lamp emission and the F_2 laser beam homogenized by a diffuser plate are measured simultaneously. We can also immediately monitor ASE components of the F_2 laser emission. A spectral map of measured F_2 laser and Br-lamp lines is shown in [Fig.4]



[Fig.4] Relationship between F2 laser lines and Br-lamp lines



[Fig.5] Schematic View of the new Br-lamp

4.2 Br-lamp

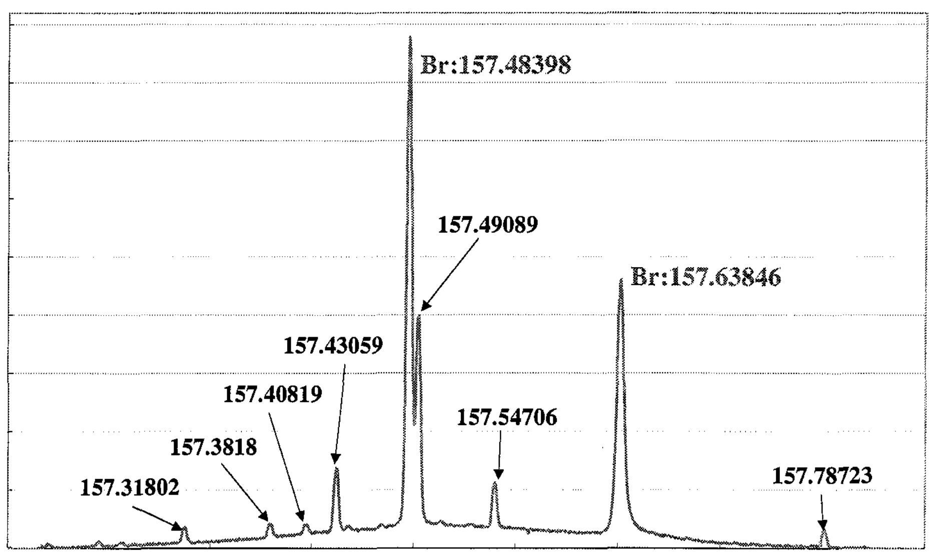
Several atomic or molecular emission lines, for example, Br, Pt, Fe, D_2 are considered as candidates for a F_2 laser wavelength calibration. Emission lines have to have a high wavelength stability of +-0.01pm and a high intensity in order to be used for calibration. In addition, for an accurate calibration, emission lines should be, firstly, as close as possible to the F_2 laser wavelength and, secondly, spectral profiles of the emission lines should be as stable as possible. We selected Bromine and developed a new Br-lamp. A schematic view of our new Br-lamp is shown in [Fig.5]. The cylindrical discharge tube is made by quartz glass and its typical diameter and length were 20mm and 150mm, respectively. The end of the tube was graded seal to adjust for the thermal expansion of the MgF_2 crystal window. The window was hermetically sealed to the tube with solder glass. A pair of electrodes was externally placed at both ends of the discharge tube. The shape, the area and the location of each electrode was designed from the consumed electric power of the lamp, the electric constant of quartz glass, the conditions of applied voltage and so forth. A square-wave high-voltage pulse was applied to the electrodes to start and generate a discharge inside the tube. Typical applied voltages and frequencies were 1000 – 2000V and 20 –70 kHz, respectively.

4.3 Br-lamp calibration

The analysis of the spectrum of atomic Br(I) by Tech [8] is a very significant study. In this paper, it was reported that the Br emission was close to the F_2 laser wavelength. At first we modified the VUV wavemeter in order to monitor both emission lines: of the Br-lamp and of the Pt-Ne hollow cathode lamp. Both spectra were measured simultaneously and are shown in [Fig.6]. We determined the wavelength of the Br-lamp by using the wavelength of the Pt-Ne hollow cathode lamp given in the NIST database. As a result, we confirmed that the calibrated wavelength was almost the same as given by Tech [Table.1].

Tech		This work
Observed Wavelength [nm]	Calculated Wavelength [nm]	Calibrated Wavelength [nm]
157.4841	157.4844	157.4840
157.6387	157.6381	157.6385

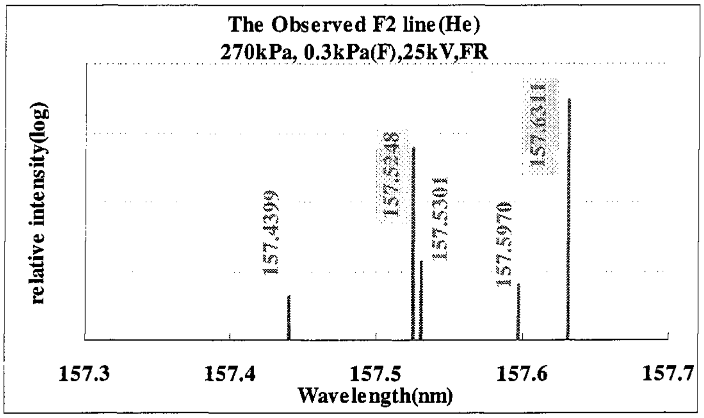
[Table.1] Standard Br lines Tech & Calibrated wavelength



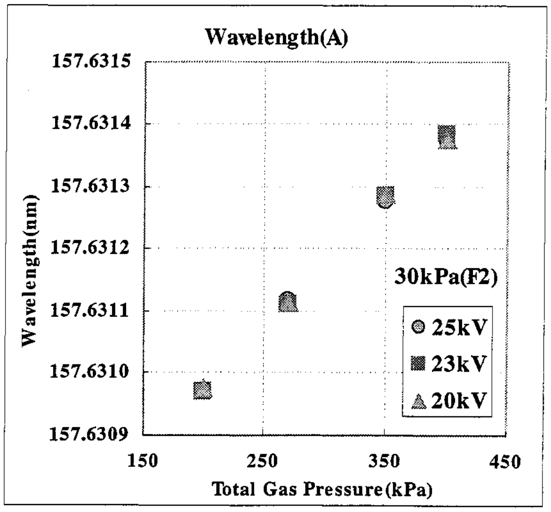
[Fig.6] Pt & Br-lamp emission lines in the region of 157nm

4.4 Absolute Wavelength of Free-Running F_2 laser

Observed emission lines of a Free-Running F_2 laser with a He buffer are shown in [Fig.7]. The main wavelength (A) was 157.6311nm and the sub-wavelength (B) 157.5248nm. In addition, a 156.73nm line was observed. The absolute wavelength shift of the main line with total gas pressure is shown in [Fig.8]. It was confirmed that the absolute wavelength of the F_2 laser clearly depends on the total gas pressure but only little on the input energy.

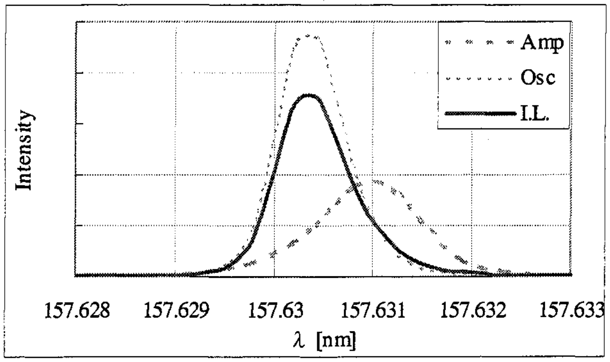


[Fig.7] Observed F_2 lines

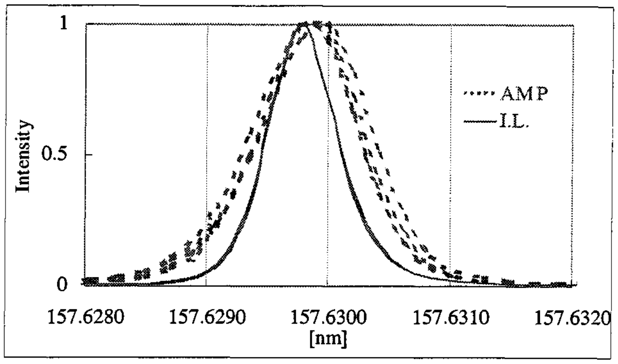


[Fig.8] Absolute wavelength shift

4.5 Relationship between Oscillator and I.L. system absolute wavelength



[Fig.9] Wavelength for each laser



[Fig.10] Changes of the absolute wavelength

The Ultra-Line-Narrowed F_2 laser system that has developed at ASET consists of two lasers: an "Oscillator laser" and an "Amplifier laser". Emitted wavelengths are shown in [Fig.9]. The thin dotted line shows the wavelengths of the oscillator, the thick dotted line shows the wavelength of the amplifier laser, and the solid line shows the wavelength of the Injection Locked system. It is evident that the wavelength of the injection locked system is related to the oscillator laser wavelength, irrespective of the amplifier laser wavelength. [Fig.10] shows the wavelength of the amplifier laser and the Injection locked system. In this case we changed the total gas pressure of the amplifier laser chamber in order to change the wavelength, but the wavelength of the Injection locked system remained constant. This shows that the wavelength stability of the Injection Locked system depends on the oscillator laser wavelength stability.

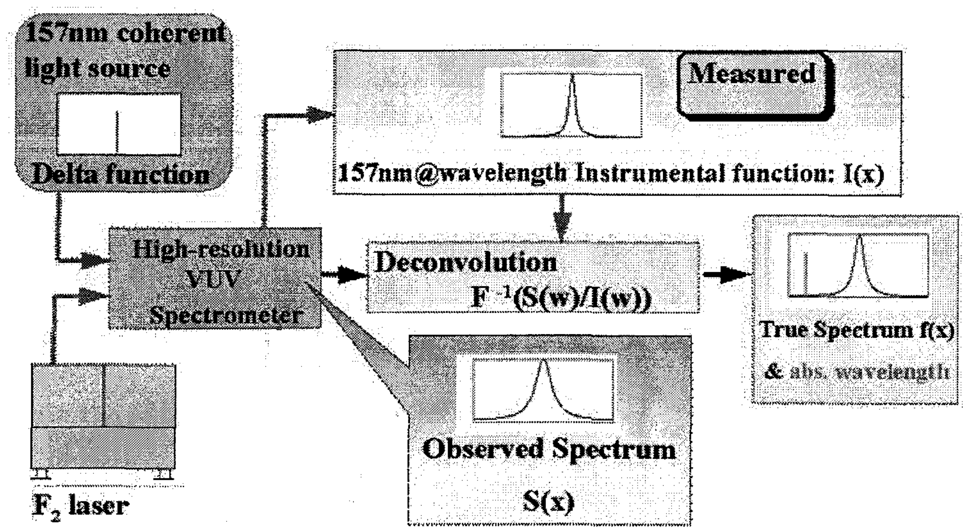
5. SPECTRAL PROFILE MEASUREMENT

5.1 Spectral profile measurement with coherent light source and spectrometer

The resolution of a spectrometer is limited by its instrument function. Hence, to measure spectra more precisely, the measurement of the instrument function and the deconvolution of the spectra are necessary.

[Fig.11] shows a schematic diagram of a very accurate method to evaluate a laser spectrum. When the spectrum of the 157CLS can be approximated by a delta function, the instrument function of the spectrometer can be directly measured using the 157CLS. The F_2 laser spectral profile is convolved with the instrument function. The true laser spectrum can then be calculated by deconvolution using the measured instrument function of the spectrometer.

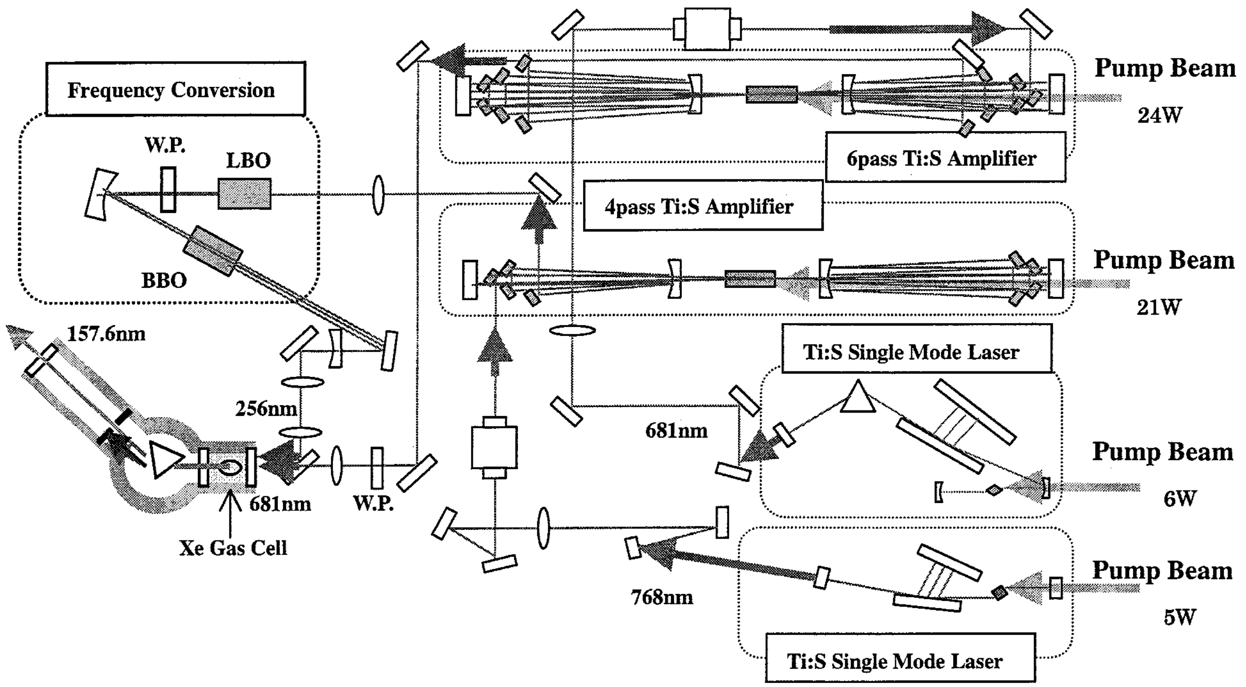
Last year we reported a VUV grating spectrometer calibrated with a 153CLS which is less complex than the 157CLS. For the precise measurement of the instrument function, however, we need the 157CLS, which has the same wavelength as the F2 laser. With the newly designed 57CLS we evaluated the high-resolution spectrometer.



[Fig.11] Schematic diagram of an accurate measurement method of laser spectra

5.2 157nm Coherent Light Source

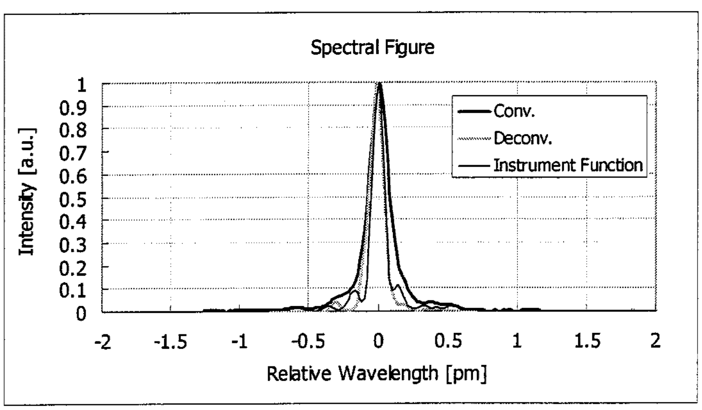
The optical arrangement of the 157CLS is shown in [Fig.12]. The 157CLS system consists of two single-mode Ti-Sappire oscillator-amplifier stages at 768nm and 681nm, pumped at 1kHz with the second harmonic of a Nd-YLF laser, a nonlinear crystal frequency conversion unit and a Xe gas cell. A Littman-type, single-mode oscillator produces an output power of 0.5W at 768nm with 28-MHz bandwidth and 18ns pulse length. The output power is amplified to 6W by a 4-pass confocal amplifier. The amplified beam is frequency-tripled with LBO and BBO to 256nm. The 256nm-output power is 1.1W. The significant difficulty of the system is that the gain factor at 681nm is a factor 5 lower than at 768nm for the same pump fluence. We therefore adopted a three-mirror confocal cavity for the 681nm oscillator to reduce the beam size in the Ti-Sapphire crystal. A SF6 Brewster prism was inserted to suppress the self-oscillation at the longer wavelength and to obtain single-mode oscillation. The oscillator produces an output power of 25mW at 681nm with 64-MHz bandwidth and 55-ns pulse length. The output was amplified to 1.4W by a 6-pass confocal amplifier also containing a SF6 Brewster prism to suppress the self-oscillation at the longer wavelength. For generating a wavelength of 157.6nm, we used two-photon resonant four-wave mixing in Xe, where the excitation wavelength of the two-photon transition 5p1S0 $\rightarrow$ 6p[5/2,2] is 256.015nm (ω1). The 157.6nm (ωVUV) wavelength is generated by mixing ω1 with 681nm (ω2) ($\omega_{VUV} = 2\times\omega_1 - \omega_2$). The spectral linewidth of the157CLS is estimated from the bandwidths at 768nm and 681nm, assuming a Gaussian spectral profile, to be less than 0.008pm (FWHM). The absolute wavelength at 157nm can be determined with 0.2-pm accuracy from the wavemeter used at 681nm because 256nm is exactly locked to Xe 6p[5/2,2]. An output power of 60 μW was measured with a power meter after a CaF_2 lens and a CaF_2 prism. The output power generated after the Xe cell is therefore estimated to be 0.1mW considering the losses of the lens and the prism. The pulse duration was 8.6-ns (FWHM).



[Fig.12] Optical Arrangement of 157.6nm Coherent Light Source System

5.3 Spectral profile of Ultra-line-narrowed F_2 laser systems

The spectral shape of the Injection Locked ultra-line-narrowed F_2 laser system is shown in [Fig.13]. Convolved and deconvolved spectra are shown together with the Instrument Function of the spectrometer. Convolved and deconvolved spectral bandwidths are, respectively; 0.16pm and 0.12pm. The deconvolved spectral purity (E95%) is 0.45pm.



[Fig.13] Convolved and Deconvolved Spectra with Spectrometer Instrument Function

6. SUMMARY

We have designed and evaluated a VUV wavemeter using a Br-lamp as a wavelength standard and a VUV high-resolution spectrometer calibrated with a 157CLS. Using these instruments, we evaluated an ultra-line-narrowed F_2 laser system. The ultra-line-narrowed F_2 laser system has sufficient performance to be used as a microlithography light source in near future.

We conclude that the developed metrology will accelerate the development of ultra-line-narrowed F_2 laser.

ACKOWLEDGMENT

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REFERENCES

1. Claig J. Sansonetti and Joseph Reader, "3rd International UV Laser symposium", Lambda Physik
2. M. Yoshioka, T. Kitagawa, T. Arimoto, H. Matsuno, T. Hiramoto, T. Suzuki and K. Hotta, "Br Lamp for F2 Laser Wavelength Calibration [ML4346-129]", *Optical Microlithography XIV*, pp. 1238-1243. 2001
3. O. Wakabayashi, J. Sakuma, T. Suzuki, H. Kubo, N. Kitatotchi, T. Suganuma, T. Nakaike, T. Kumazaki, Kazuaki Hotta, H. Mizoguchi and K Nakao," Spectral Measurement of Ultra Line-Narrowed F2 Laser [[ML 4346-108]", *Lithography Optical Microlithography XIV*, pp. 1066-1073. 2001
4. T. Suganuma, H. Kubo, O. Wakabayashi, H. Mizoguchi, K. Nakao, Y. Nabekawa, T. Togashi and S. Watanabe, "157-nm Coherent Light Source for F2 Laser Lithography [CPD7-1]", *CLEO 2001Postdeadline Papers*, 2001
5. Naoki Kitatochi, T. Kumazaki, H. Watanabe, Yoshifumi Ueno, Kotaro Sasano, Tatsuya Ariga, Osamu Wakabayashi, Ryoichi Nohdomi, Kazuaki Hotta, H. Mizoguchi, K. Nakao, "Spectral Properties of Ultra Line Narrowed F_2 Oscillator Laser", SEMATEC 2nd international Symposium on 157nm Lithography Digest Abstracts, 2001
6. T. Ariga, H. Watanabe, T. Kumazaki, N. Kitatochi, K. Sasano, Y. Ueno, M. Konishi, T. Suganuma, M. Nakano, T. Yamashita, T. Nishisaka, R. Nohdomi, K. Hotta, H. Mizoguchi, K. Nakano, "Development of 5KHz Ultra Line Narrowed F2 Laser for Dioptric Projection System[ML4691-65]",Lithography Optical Microlithography XV, 2002
7. J. Fujimoto, T. Nakaike, T. Suzuki, S, Nagai, T. Yabu, G. Soumagne, T. Chiba, O. Wakabayashi and H. Mizoguchi, "Spectral characteristics of the molecular fluorine laser", *SEMATEC 2nd international Symposium on 157nm Lithography Digest Abstracts*, 2001
8. Jack L. Tech, J. Res. NBS., 67A, 505-554 (1963)