Absolutely calibrated EUV spectra of Xe laser plasma radiation for lithography needs

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Abstract. Spectra of Xe laser plasma radiation were measured using Si/Mo and Mo/Be interference mirrors. The intensity within the 11.0-11.8 nm wavelength band has been shown to be 6-7 times as high than that in the 12.5-14 nm range. The spectra obtained by means of the mirrors are compared with those measured earlier using a spectrometer.

1. Introduction

At present, the EUV (Extreme UltraViolet) lithography with working wavelength of $\lambda = 13.5$ nm encounters a difficulty at entering the large-scale production due to insufficient intensity of working radiation and an intensive flux of debris from its laser-plasma source with a target of solid tin [1]. In search of a way out of this situation, the Institute for Physics of Microstructures of the Russian Academy of Sciences (IPhM) has put forward an idea to change the wavelength to $\lambda = 11.2$ nm with simultaneous replacement of the radiation source with that where a Xe gas-jet target was used [2]. This type of source was first proposed for the $\lambda = 13.5$ nm EUV lithography as early as in the 90s [3-4] but had been abandoned due to its low radiation power. However, in the 11-nm range, the Xe laser-plasma source is expected to be 4-5 times brighter than that at $\lambda = 13.5$ nm [5-6] and with that, according to estimates in [2], it should appear to be substantially more effective than the $\lambda = 13.5$ nm source with the tin target. Until recently, a lithography at $\lambda = 11.2$ nm was considered to be impossible because of the lack of effective interference mirrors for this wavelength. But by now, the IPhM has created the world's first Be-containing mirror samples suitable for the 11-nm range [7-8].

In [5-6], the Xe plasma spectrum have been shown to look like a wide continuous peak in the range of $\lambda = 9.5\text{–}14$ nm with its maximum near $\lambda = 11$ nm rather than an ensemble of discrete spectral lines. Numerous spectra obtained in [9] under different experimental conditions demonstrate a noticeable variability. This work is aimed at quantitative measuring intensity of the Xe laser plasma radiation in energy units over the 11 to 14 nm wavelength band and so at obtaining reliable data on the intensity ratio at two wavelengths, $I_{11.2}/I_{13.5}$. The Bragg diffraction on turnable Mo/Be and Si/Mo interference mirrors is used to realize the measurements.

The main data bulk of the study can be found in [10], and the present article is a brief account adapted for the conference format.
2. Description of the experiment

A scheme of the experiment is shown in Fig. 1. A general description of the experimental setup can be found in previously published papers (e. g., [11]). The laser spark was excited in a supersonic Xe gas jet with a focused Nd:YAG laser beam with $\lambda = 1.064$ μm wavelength and pulse duration of $\tau \approx 15$ ns. Delivered to the plasma pulse energy was $E_{\text{las}} = 1$-1.2 J. The beam focus was targeted onto the jet axis at a distance of $\Delta X = 1$ mm from the nozzle outlet. Parameters of the gas in the jet were provided by a fluid dynamics numeric simulation described in [11, 12]. All the experiments in the present work were performed at the Xe pressure before the nozzle $P_0 = 13$ atm. At this pressure the atomic/ionic density in the focus point was $n \approx 7 \times 10^{18}$ cm$^{-3}$.

The EUV radiation propagates from the plasma to the interference mirror, after the reflection passes through a Si/Mo multilayer spectral filter, which suppresses a long-wave part of the plasma emission, and then comes to the photodiode window. After a preamplifier mounted on one circuit board with the photodiode, the signal of the EUV emission is registered by an oscilloscope. A specially designed mechanism supporting both the mirror and the photosensor enables separate incidence/reflection angles control that facilitates establishing one of them equal to another.

The multilayer interference mirror reflects a radiation only within a narrow band, with its central wavelength depending on the angle of incidence/reflection, $\alpha$, in accordance with the Bragg law,
\[ \lambda = 2d \sin \alpha, \] where \( d \) is the mirror period (the total thickness of a pair of adjacent layers). Thus, varying the angle results in scanning over a wavelength range.

Two manufactured in the IPhM mirrors have reflectivity about 63-67% each. Allowable angles are restricted within a span of \( \alpha = 70^\circ-84^\circ \) for the Mo/Be mirror (\( \lambda = 11.1-11.7 \) nm, respectively) and \( \alpha = 65^\circ-84^\circ \) for the Si/Mo mirror (\( \lambda = 12.6-13.9 \) nm). Lower limits are specified by absorption edges of mirror materials and the upper ones are defined with the photosensor external dimensions.

3. Results obtained

Values of the EUV signal were averaged over 15-30 pulses (due to the high reproducibility the term "EUV signal", hereinafter, relates to the amplitude value). Relative rms interpulse scattering of the signals did not exceed 3.5-4%. The primary result, that is, values of the EUV signals as a function of the angles is shown in Fig. 2a.

The measured signal (in volts) is:

\[
U(\alpha) = A \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} I_\lambda(\lambda)R(\lambda, \alpha)T(\lambda)S(\lambda) d\lambda, \tag{1}
\]

where \( A = 3000 \) V/A is the preamplifier gain, \( I_\lambda(\lambda) \) W/nm is the power spectral density of the radiation entering the photodiode window, \( R(\lambda, \alpha) \) is the mirror reflection spectral characteristic for different angles, \( T(\lambda) \) is transmission of the Si/Mo spectral filter, \( S(\lambda) \approx 0.225-0.255 \) A/W is the photodiode sensitivity. For our experiment conditions, limits of integration in (1) were assumed to be \( \lambda_{\text{min}} \geq 5 \) nm and \( \lambda_{\text{max}} \leq 20 \) nm. The first of them was defined with plasma parameters and the second one was due to the absorption of the spectral filter. The expression (1) is the Fredholm integral equation of the first kind for the unknown \( I_\lambda(\lambda) \) with \( R(\lambda, \alpha) \) as the kernel.

To find out an approximate solution of the equation (1), some assumptions have been made. For each separate value of the angle \( \alpha \), the reflectivity function, \( R(\lambda) \), was considered to be limited by a narrow wavelength band, \( \Delta \lambda \), around the point of the maximum reflection, so that the reflection was \( R = 0 \) outside \( \Delta \lambda \). The width of \( \Delta \lambda \) was chosen to contain inside some 0.75-0.8 of the total value of the integral \( \int R(\lambda) d\lambda \) over the infinite wavelength interval. At such a definition, the \( \Delta \lambda \) width (i. e., spectral resolution) turns out to be \( \Delta \lambda_{\text{Mo/Be}} = 3-3.5 \) Å for the Mo/Be mirror, and \( \Delta \lambda_{\text{Si/Mo}} = 5.5-6 \) Å for the Si/Mo one. Within

![Figure 2](image.png)

Figure 2. Spectral measurements of the EUV plasma radiation using the interference mirrors. a – primary data from the photosensor as a function of the incidence/reflection angle: 1 – with the Si/Mo mirror, 2 – with the Mo/Be mirror. b – a composite spectrum derived from the measured signals, with horizontal fields at the points describing spectral resolution of the measurements (\( \Delta \lambda \)).
these narrow bands, the value of $I_λ$ can be taken to be constant and equal to its average: $I_λ(λ) = \text{const} = <I_λ>_λ$, with no appreciable damage to accuracy. Then the integral equation (1) is reduced to a simple algebraic one:

$$U(α) = A <I_λ>_λ \Deltaλ \int R(λ, α)T(λ)S(λ)dλ = A <I_λ>_λ \Deltaλ \text{Instr}(α),$$

where $\text{Instr}(α) = \int R(λ, α)T(λ)S(λ)dλ$ is a spectral characteristic of sensitivity of the registration system as a whole. Values of $I_λ(λ)$ calculated with the help of (2) for the two wavelength ranges are shown in Fig. 2b. To avoid an overlapping of the $Δλ$ bands, only three values of $I_λ$ were selected in each of the ranges for composing the graph.

### 4. Discussion and conclusion

In one of our previous works quoted above [9], a series of Xe laser plasma spectra was obtained using an EUV spectrometer for different parameters of the gas target and laser pulse energies. All of them had high and indefinite pedestals of a scattered light that did not allow any quantitative conclusions. In Fig. 3, the spectrum obtained in the present study and shown in Fig. 2b is compared with a spectrum from [9] taken under the same experimental conditions. One can see that, first, height of the spectrometric pedestal is easily deduced from the comparison for the range of $λ = 11-14$ nm for which the present measurements were carried out. Second, the agreement between two spectra measured by means of quite different methods appears to be quite satisfactory.

![Figure 3. Superimposition of spectra obtained with two different ways and finding a scattered light pedestal.](image)

And finally, average radiation intensity of the dense Xe laser plasma within the $λ = 11-11.8$ nm range exceeds that in the $λ = 12.5-14$ nm wavelength band by a factor of 6 or 7. Moreover, important for the lithography ratio of narrow-band intensities, $I_{11.2}/I_{13.5}$, turns out to be even higher – it amounts up to 10 - 11 that promises favorable prospects for the transition of the EUV lithography from $λ = 13.5$ nm to $λ = 11.2$ nm with the Xe laser plasma source.

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