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Energy meter system for gas-puff laser plasma

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The authors demonstrate a detection system of EUV radiation pulses. The system provides energy measurements with uncertainty of 7.3% in the range of wavelengths 13.5 ± 0.5 nm (FWHM = 7.3%). The calibration of the system was taken using the E-Mon commercial meter and a laser-plasma source. The procedures made it possible to determine a calibration factor for the laser-plasma source with helium-xenon gas puff target. The factor is exploited for the purpose of standardizing measurements of EUV radiation with FWHM = 2%. A substantial improvement in the system responsivity is demonstrated.

Keywords: EUV radiation, EUV energy meter, nanolithography.

1. Introduction

The absolute measurement of radiation energy is one of the last research methods employd in EUV nanolithography. These procedures are very important for diagnostics of EUV radiation sources and other elements used in nanotechnology. The most important parameters of energy meters are the measurement accuracy (ΔE) and the wavelength ranges of operation.

Recent progress in the construction of meters is the result of the development of semiconductor detectors and multilayer optics. Current commercial meters measure energy with uncertainty less than 5% in the range of wavelengths 13.5 ± 0.13 nm [1–3]. This wavelength range has been considered as a metrology standard (FWHM = 2%) during characterization of EUV source features. The measurement parameter of the energy meter considering the radiation spectrum is described by its responsivity. This parameter is formed by spectral characteristics of the detector and optical filters used. Nowadays, maximization of the system responsivity in the narrowest wavelength band (nearby $\lambda = 13.5$ nm) is the main difficulty faced by the meter constructors.

An analysis of multilayer mirror construction showed that its reflectivity decreases with an improvement in its selectivity [4]. This situation also causes a decrease in the meter responsivity. A special calibration factor ensures minimization of this effect and mirrors with worse selectivity can be used. This factor gives opportunity to determine radiation energy in the narrower spectral band based on wider ones. The factor value depends on parameters of the energy meter and the spectrum of measurement radiation which is strictly connected with the type of radiation source.

The paper presents experimental investigation of the detection system prepared for control of the laser-plasma source with Xe/He double gas puff target [5]. The system was constructed at the Institute of Optoelectronics, MUT (Warsaw, Poland). The features of the system elements were analyzed and measured. The influence of the condition of plasma generation in the source on the value of the calibration factor was described. The experimental results were also used to estimate energy value in the wavelength range of 13.5 ± 0.13 nm. The calibrated responsivity was expressed by a product of the measured responsivity of the system and calibration factor. The calibrated responsivity was determined for optimal energy efficiency of the laser-plasma source with xenon gas target. The results were compared with the data measured by spectrometer (reflective grating 1200 l/mm).

2. Detection system

The detection system consists of a multilayer mirror, a detection head (detector and charge-sensitive preamplifier) and a signal processing unit.

The mirror was constructed at Fraunhofer Institute (Jena, Germany). The reflectivity of the mirror was optimized for the incidence angle of 45° and a wavelength of 13.5 nm [6]. In the detection head, a calibrated silicon photodiode (series AXUV 100 Zr/Si) produced by IRD Inc was used [7]. The responsivity of the detector was fitted into EUV spectrum using absorption filters placed on its active surface. The spectrum characteristics of the photodiode responsivity and mirror reflectivity are shown in Fig. 1.

The output signal from the detector was applied to the charge-sensitive preamplifier input. The voltage amplitude from the preamp is proportional to the charge created in the detector. The energy value of radiation pulses is determined

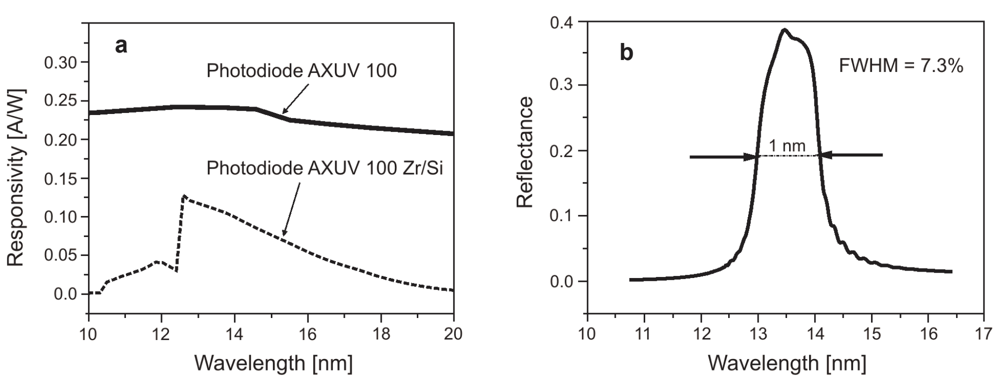

Fig. 1. Spectrum characteristic of photodiode responsivity (**a**) and multilayer reflectivity (**b**).

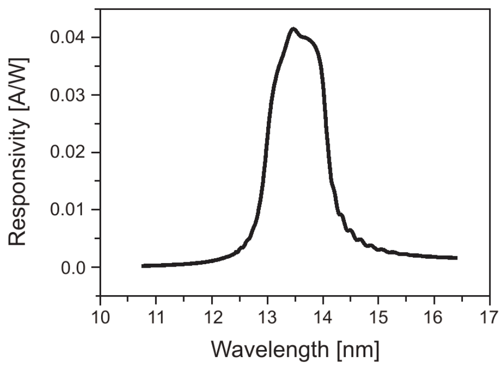

Fig. 2. Theoretical characteristic of the system responsivity determined by catalogue parameters of its elements.

by the measured voltage amplitude and so-called conversion factor. The value of the processing factor takes into consideration the measurement conditions, for example, the responsivity of the system, a distance between the source and the detector, active surface of the detector, charge sensitivity of the preamplifier.

3. System responsivity $R_{\text{M-EUV}}$

A value of the system responsivity depends on the detector and mirror parameters. The shape of the spectrum characteristic of the responsivity is mainly determined by the mirror reflectivity $R(\lambda)$. The theoretical characteristic of the system responsivity is shown in Fig. 2. The calculation was performed based on catalogue parameters of the system elements. The maximum value of the responsivity is 0.043 A/W. The range of measured wavelengths is 13.5 ± 0.5 nm (FWHM = 7.3%).

4. Calibrated responsivity of the system $R_{S_{\text{M-EUV}}}$

The calibrated responsivity gives opportunity to determine radiation energy in the range of wavelengths 13.5 ± 0.13 nm based on a measurement in the spectrum range 13.5 ± 0.5 nm. The energy value is described by

$$R_{S_{\text{M-EUV}}} = \int_0^\infty I(\lambda) R_{\text{M-EUV}}(\lambda)\,\mathrm{d}\lambda \tag{1}$$

where $I(\lambda)$ is the normalized function describing spectrum distribution of source radiation. The function is defined by

$$\int_{(13.5 \pm 0.13)\,\mathrm{nm}} I(\lambda)\,\mathrm{d}\lambda = 1 \tag{2}$$

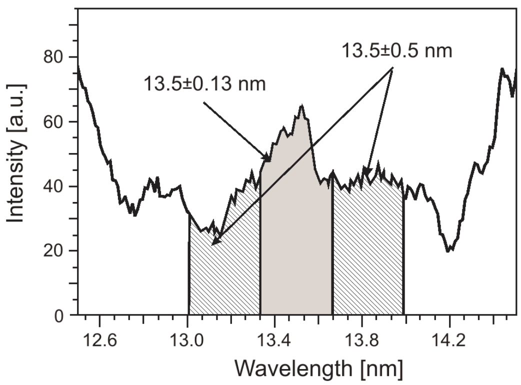

Fig. 3. Spectrum of radiation emitted by laser-plasma source with Xe/He gas puff target in two analyzed ranges of wavelengths.

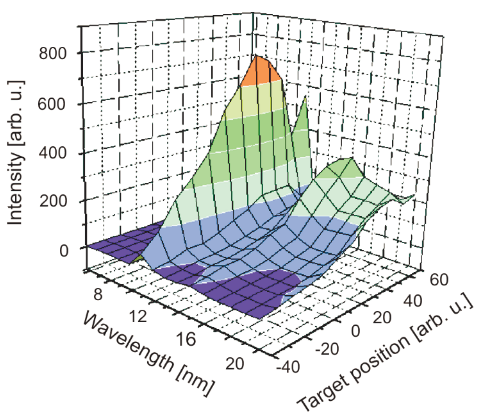

Fig. 4. Spectrum of radiation emitted by laser-plasma source for different positions of laser beam on target surface.

The spectrum of measured radiation from the laser-plasma source with Xe/He gas puff target is shown in Fig. 3. The spectrum can be shifted by changes of conditions of plasma generation. These conditions also influence the normalized function $I(\lambda)$ and can change the value of the calibrated responsivity of the system. For example, the shift of spectrum distribution caused by position changes of a laser beam on the target surface is shown in Fig. 4.

5. Experimental research of detection system

5.1. Measurement of system responsivity

The main aim of the research was to determine some features of the system elements. The parameters directly specify the system responsivity. The elements under

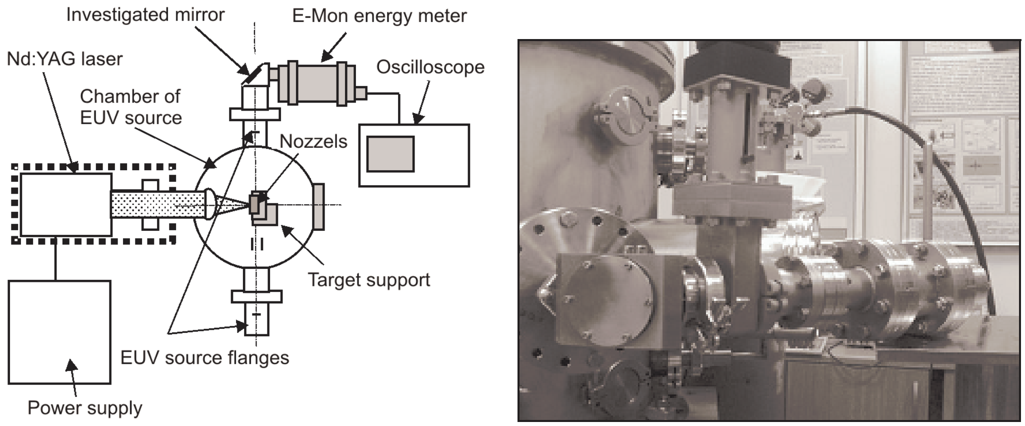

Fig. 5. Scheme and view of laboratory setup for measurements of the features of the system elements.

investigation were multilayer mirror and photodiode. The measurements were taken at the laboratory setup shown in Fig. 5. The radiation was generated by a laser-plasma source with a solid target. The target consisted of powered tin and lithium fluoride. The main advantage of this source over the gas puff target one is the higher intensity and better stability of emitted radiation. The radiation energy was measured by E-Mon energy meter.

The measured value of the mirror reflectivity was 33.8 ± 0.7%. A special construction of the measuring head was prepared for investigation of the photodiode. The head enabled us to mount the detector as close to the radiation source as possible and apply its output signal to the oscilloscope input. The measuring procedure of the photodiode consisted of two parts. First, the value of the radiation energy was determined using E-Mon energy meter. In the second part, the head with the detector being tested was exchanged for E-Mon energy meter. The charge created in the detector was calculated based on the signal registered by the oscilloscope. The measured value of the photodiode responsivity was $R_{det} = 0.122 \pm 0.008$ A/W. This value is compared with catalogue data given by the detector producer.

Verification of the results was performed by comparison of the measured energy of radiation received from the system with the measured one using the calibrated E-Mon meter. The experimental determined responsivity of the system was 43.3 ± 3.1 mA/W.

5.2. Measurement of calibrated responsivity – measuring procedure

Investigation of the calibrated responsivity was carried out using laboratory setup equipped with the laser-plasma source with Xe/He gas puff target and E-Mon energy meter. During the experiments, the ratio of the energies in two spectrum ranges was determined. These ranges were 13.5 ± 0.5 nm (FWHM = 7.3%) and 13.5 ± 0.27 nm (FWHM = 3.3%). The wavelengths were described by spectral characteristics of optical elements used in the detection system and E-Mon energy meter. The characteristics of the mirror reflectivities are presented in Fig. 6.

The calibrated factor ($W_{\text{M-EUV}}$) was determined based on energy measurements taken by the detection system and E-Mon meter. The value of the factor is given by

$$W_{\text{M-EUV}} = \frac{E_{7\%(\text{M-EUV})}}{E_{3\%(\text{E-Mon})}} \tag{3}$$

where $E_{7\%}$ and $E_{3\%}$ are the energy values measured in the wavelength bands of 13.5 ± 0.5 nm and 13.5 ± 0.27 nm, respectively.

The factor makes it possible to calculate the calibrated responsivity of the detection system in the range of wavelengths 13.5 ± 0.13 nm (FWHM = 2%) and is expressed by

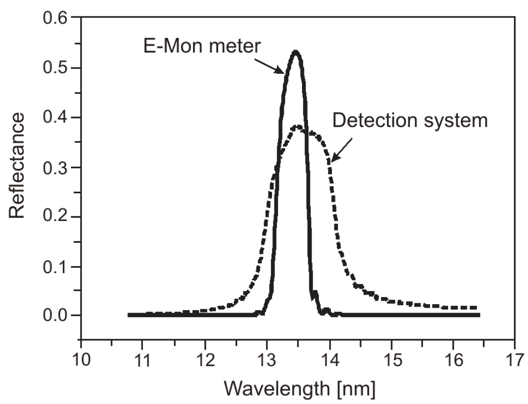

Fig. 6. Spectrum characteristics of mirrors reflectivity used in the detection system and E-Mon energy meter.

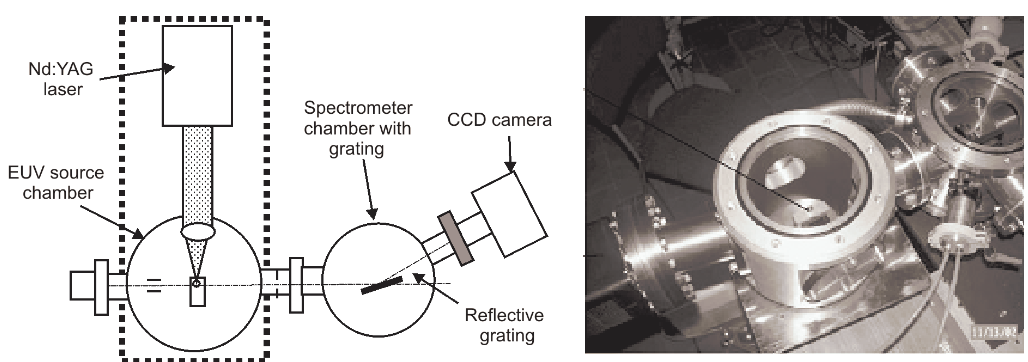

Fig. 7. Scheme and view of the spectrometer.

$$R_{S_{\text{M-EUV}}} = R_{S_{\text{E-Mon}}} W_{\text{M-EUV}} \tag{4}$$

where $R_{S_{\text{E-Mon}}}$ is the calibrated responsivity of E-Mon energy meter given in its calibration certificate.

The value of the calibration factor $W_{\text{M-EUV}}$ can be changed by shifting condition of plasma generation in the source. The changes concerned such parameters as:

– delay time of the nozzles valve opening with respect to a laser pulse ($W_{t_{\text{Xe}}}$, $W_{t_{\text{He}}}$),
– power density of Nd:YAG laser radiation on the target surface (W_E),
– position of a laser beam focus with respect to the gas target axis (W_Y),
– pressure of the remaining gases in the source chamber ($W_{P_{\text{He}}}$, $W_{P_{\text{Xe}}}$),
– pressures of gases in the valve nozzles ($W_{p_{\text{Xe}}}$, $W_{p_{\text{He}}}$).

The results were verified by spectrum measurements of the source radiation and characteristics shown in Fig. 6. The spectrum measurements were taken by a reflective grating fabricated by Hitachi and CCD camera produced by Roper Scientific. The scheme and view of the spectrometer are shown in Fig. 7.

6. Results

The spectral distribution of the source radiation and the values of the calibration factor were determined during the experimental investigation. The calculations were carried out based on a series of 30 measurements. Changes of the values of the calibration factor measured by the detection system and E-Mon energy meter for different conditions of plasma generation are shown in Figs. 8–12. In the figures, the results are compared with the ones obtained from spectral measurements.

The measured values of the calibration factor have been collected and presented in Fig. 13. The mean value of the factor measured by the detection system and E-Mon energy meter was 1.82 ± 0.06.

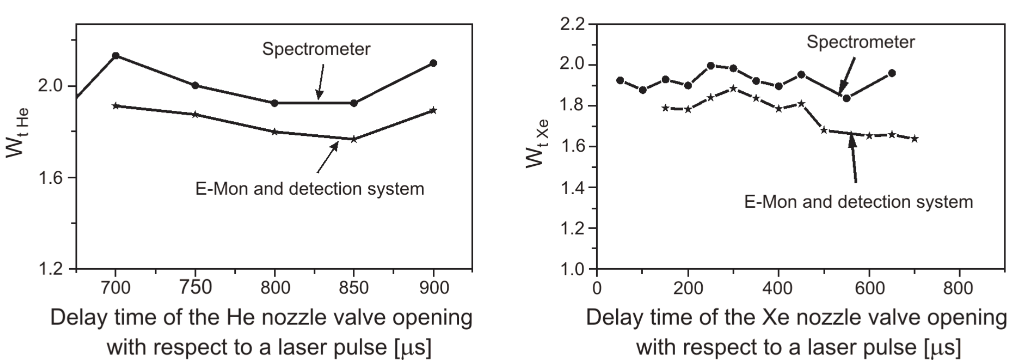

Fig. 8. Influence of delayed time of nozzle opening relative to Nd:YAG laser pulse on the calibration factor.

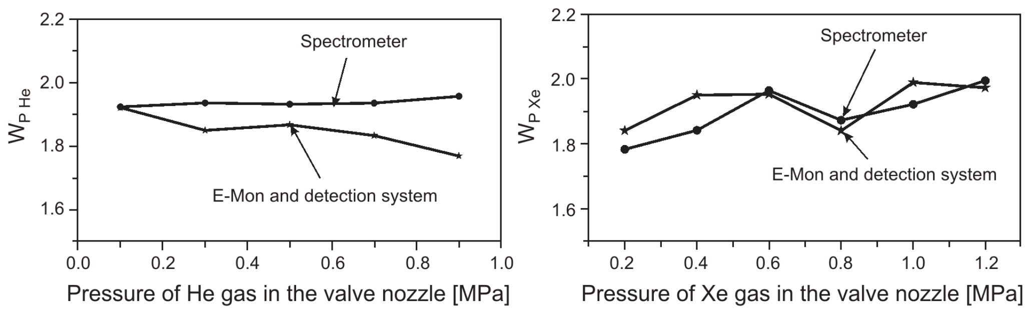

Fig. 9. Influence of the pressures of gases in the target nozzle on the calibration factor.

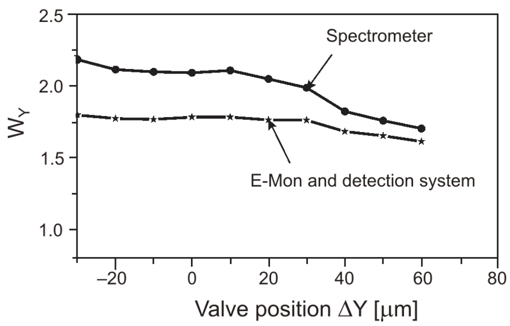

Fig. 10. Influence of the valve position relative to Nd:YAG laser beam on the calibration factor.

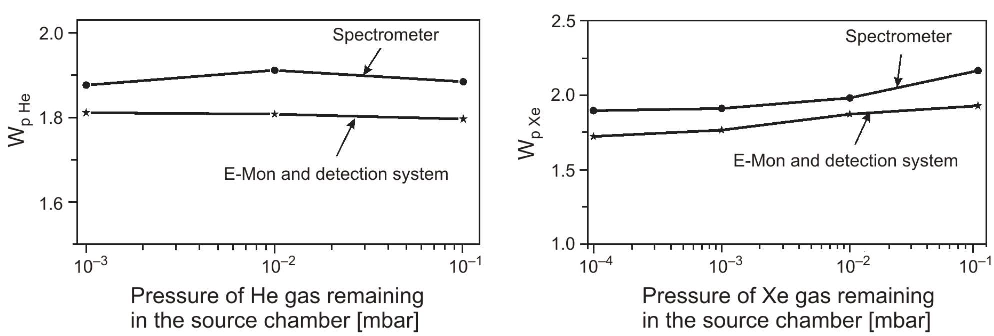

Fig. 11. Influence of pressure of the remaining gases in the source chamber on the calibration factor.

The calibration factor for the optimal conditions of plasma generation in the source was $W_{\text{M-EUV(opt)}} = 1.79 \pm 0.03$. The calibration responsivity of the system calculated from Eq. (4) is 0.291 ± 0.027 A/W. Accepting a constant value of the calibration factor, regardless of the conditions of plasma generation, could cause a significant measuring error. The maximum value of the error equals even 14%.

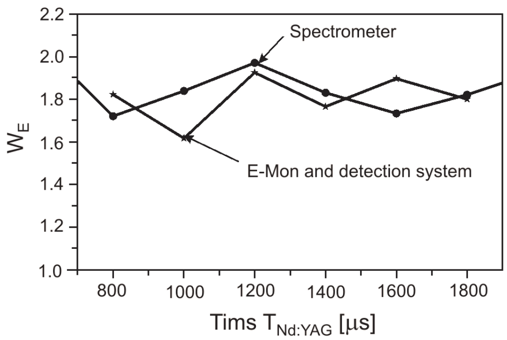

Fig. 12. Influence of the energy of Nd:YAG laser on the calibration factor. The maximum value of the laser energy is 500 mJ and it corresponds to the time value $T_{\mathrm{Nd:YAG}}$ = 1200 µs in the figure; the data are taken from the documentation provided by the laser producer.

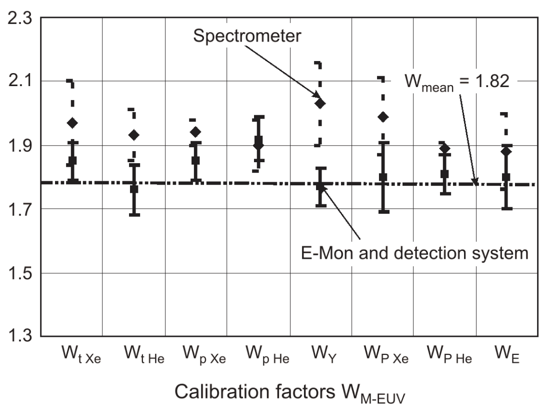

Fig. 13. Measured values of the calibration factor.

For the laser-plasma source under invastigation, the most significant differences between the results obtained from measurement systems and spectrometer are observed in the case of the position changes of the Nd:YAG laser beam focus on the target surface (12%), pressure changes of the remaining gases in the source chamber (9.5%) and the different values of the delayed time of opening target nozzles (8.8%).

7. Summary

In this paper, we have presented a detection technique developed in order to provide energy measurements with responsivity of 43 mA/W for the range of wavelengths of 13.5 ± 0.5 nm and uncertainty of 7.3%. The accuracy of measurement is independent of the radiation spectrum in this wavelength range. As a result, the system can correctly cooperate with any kind of EUV radiation source. The main advantage of the system compared with commercial ones is its low price and costs of exploitation, good measuring parameters, integrated construction, small dimensions, and automated measuring procedures.

The ability of extension of the system features was demonstrated. Determination of the calibrated responsivity makes it possible to measure energy in the selected range of wavelengths. The value of this parameter describes a characteristic of the source and that is why some extra measurements of the radiation spectrum are necessary. By exploiting the calibration factor for the laser-plasma source with Xe-He gas puff target, we were able to achieve the calibrated responsivity of 0.291 ± 0.027 A/W at the wavelength range 13.5 ± 0.13 nm. In conclusion, we have demonstrated that our detection technique with the calibrated factor increases a relative value of the system responsivity. Further work concerning determination of the calibration factor for other gas targets is currently under way.

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References

[1] MISSALLA T., SCHÜRMANN M.C., LEBERT R., WIES C., JUSCHKIN L., KLEIN R., SCHOLZE F., ULM G., EGBERT A., TKACHENKO B., CHICHKOV B., *Metrology tools for EUV-source characterization and optimization*, Proceedings of SPIE **5374**, 2004, pp. 979–90.

[2] BIJKERK F., STUIK R., BRUINEMAN C., *EUVL Source Workshop*, ISMT, Santa Clara 2002.

[3] *Cross-Calibration of Extreme Ultraviolet (EUV) Energy Sensors*, International SEMATECH Technology Transfer #04024498A-TR, http://www.sematech.org/docubase/document/4498atr.pdf.

[4] http://www.iof.fhg.de/departments/optical-coatings/vuv-euv-xray/projects/euv_schmalband_e.html.

[5] FIEDOROWICZ H., BARTNIK A., SZCZUREK M., DAIDO H., SAKAYA N., KMETIK V., KATO Y., SUZUKI M., MATSUMURA M., TAJIMA J., NAKAYAMA T., WILHEIN T., *Investigation of soft X-ray emission from a gas puff target irradiated with a Nd:YAG laser*, Optics Communications **163**(1–3), 1999, pp. 103–14.

[6] FEIGL T., YULIN S., BENOIT N., KAISER N., *EUV multilayer optics*, Microelectronic Engineering **83**(4–9), 2006, pp. 703–6.

[7] http://www.ird-inc.com.

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