

High-accuracy detector calibration for EUV metrology at PTB

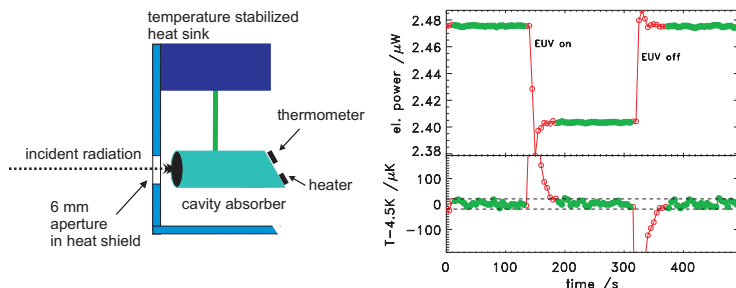


Frank Scholze, Johannes Tümmler, and Gerhard Ulm

Introduction

The Physikalisch-Technische Bundesanstalt (PTB) has been operating a laboratory for high-accuracy radiometry in the UV, VUV, and soft X-ray spectral region since 1982^{1,2}. At PTB, radiometry for EUV sources is based on detectors. Photodiodes are calibrated as transfer detector standards³ with a relative uncertainty of $u=0.26\%$ by comparison to a cryogenic electrical substitution radiometer⁴. With these high-accuracy calibrations⁵, PTB serves the EUVL source program within in the European MEDEA+ framework⁶ and international benchmarking efforts like the "flying circus"⁷.

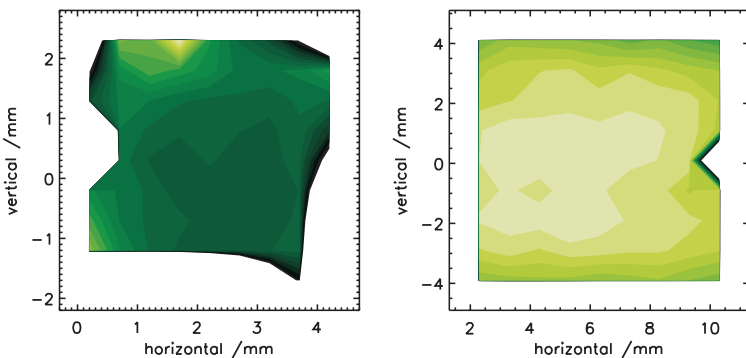
Electrical Substitution Radiometer



Left: Schematic drawing of the cryogenic electrical substitution radiometer (ESR) used as primary detector standard.

Right: Operation scheme, the absorber temperature is obtained either by heating due to the incident radiant power or, without incident radiation, by electrical heating.

| Quantity | Relative standard measurement uncert. /10 ⁻³ |
|--|---|
| heating power difference | 1.0 |
| radiant energy conversion efficiency | 0.3 |
| thermal non-equivalence between radiant and electrical heating | 0.12 |
| electrical heating power measurement | 0.025 |
| normalized radiant power | 1.1 |



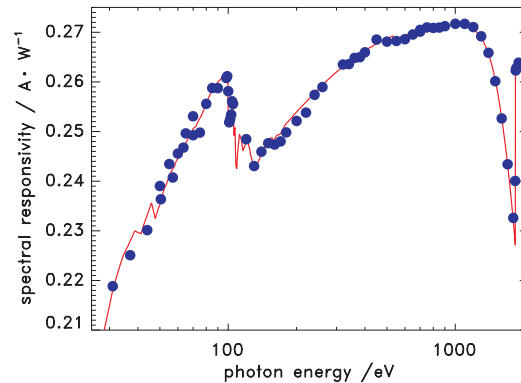
Homogeneity of photodiode responsivity

Left: GaAsP/Au Schottky diode G1127 (4.6mm by 4.6mm active area).

Right: SXUV100 diode with TiSiN top.

The shading is in steps of 0.1% from 98% (dark) to 100% (bright).

Photodiode responsivity

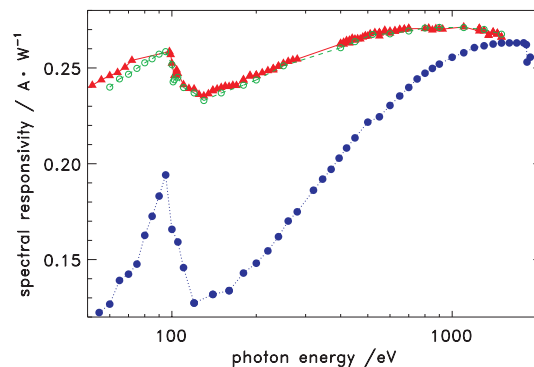


Spectral responsivity of an AXUV100G photodiode, measured by comparison to the ESR. Solid line: fit using a physical model.³

Compilation of Uncertainty

| Quantity | Relative standard measurement uncertainty /10 ⁻³ |
|---|---|
| radiant power | 1.1 |
| measured diode photocurrent | 1.0 |
| higher diffraction orders | 0.6 |
| diffuse scattered light | 2.0 |
| angle of incidence at diode (normal +/- 5°) | 0.05 |
| diode homogeneity | 1.0 |
| spectral responsivity | 2.8 |

Stability of photodiodes



Spectral responsivity of an AXUV100G photodiode. Shown are measurements of 1995 (red), 1997 (green), and 2001 (blue).

Between 1995 and 1997, the diode was stored in dry air and used only occasionally in ultra high vacuum at moderate irradiance levels below $1 \mu\text{W}/\text{cm}^2$. Between 1997 and 2001, the diode was frequently used at irradiance levels of several $\mu\text{W}/\text{cm}^2$. The last measurement shows an increase of the silicon oxide layer by 20 nm and a decrease of the collection efficiency by 30%.⁸

1 G. Ulm, and B. Wende, "Radiometry laboratory of Physikalisch-Technische Bundesanstalt at BESSY," Rev. Sci. Instrum. 66, 2244-2247 (1995)

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3 F. Scholze, H. Rabus, and G. Ulm, "Mean energy required to produce an electron-hole pair in silicon for photons of energies between 50 and 1500 eV," J. Appl. Phys. 84, 2926-2939 (1998)

4 H. Rabus, V. Persch, and G. Ulm, "Synchrotron-Radiation Operated Cryogenic Electrical-Substitution Radiometer as High-Accuracy Primary Detector Standard in the Ultraviolet, Vacuum Ultraviolet and Soft X-Ray Spectral Ranges," Appl. Optics 36, 5421-5440 (1997)

5 F. Scholze, J. Tümmler, G. Ulm "High-accuracy radiometry in the EUV range at the PTB soft X-ray radiometry beamline," Metrologia 40 (2002), S224-S228

6 G. Schriever, M. Rahe, U. Rebhan, D. Basting, W.J. Walecki, H. Layuth, R. Lebert, K. Bergmann, D. Hoffmann, O. Rosier, W. Neff, R. Poprawe, R. Sauerbrey, H. Schwoerer, S. Düsterer, C. Ziener, P. Nickles, H. Stiehl, I. Will, W. Sandner, G. Schmah, D. Rudolf, Proc. SPIE, 4146, 113-120 (2000)

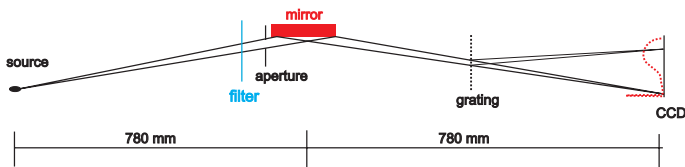
7 R. Stulk, F. Scholze, J. Tümmler, F. Bijkerk, Nucl. Instrum. Meth. A492, 305-316 (2002)

8 F. Scholze, G. Brandt, P. Müller, B. Meyer, F. Scholz, J. Tümmler, K. Vogel, and G. Ulm, "High-accuracy detector calibration for EUV metrology at PTB", SPIE 4688, 680-689 (2002)

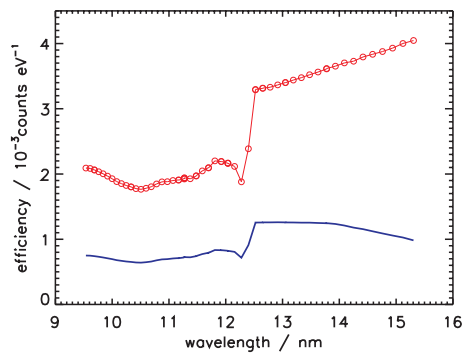
The key issues of metrology for EUV sources are: determination of absolute in-band power, spectral distribution in the EUV and the other spectral regions, spatial distribution of emitting volume, and angular distribution of the emission.

For customer source characterization, an imaging spectrometer and a multilayer in-band power meter were set up and calibrated at PTB. The results shown are obtained at an Au LPP-source⁹ for an EUV reflectometer¹⁰.

Imaging spectrometer



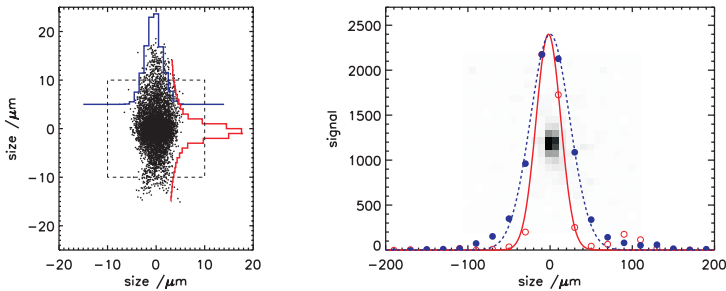
Scheme of an imaging spectrometer used to characterize the spectral distribution of EUV radiation and the spatial distribution of emitting volume.



Uncertainty budget

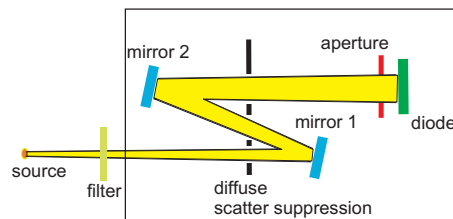
| Quantity | Relative uncertainty contribution u/% |
|--------------------------------|---------------------------------------|
| radiant power | 0.5 |
| higher diffraction orders | 0.03 |
| diffuse scattered light | 0.2 |
| CCD Integration time | 5 |
| aperture area | 0.5 |
| distance to source | 2.6 |
| Spectrometer efficiency | 5.7 |

Efficiency of grating plus CCD, measured by comparison to a photodiode using monochromatized radiation. Measured points are shown as open circles, the line is only to guide the eye. The lower line shows the efficiency including a 300 nm freestanding Zr-filter.

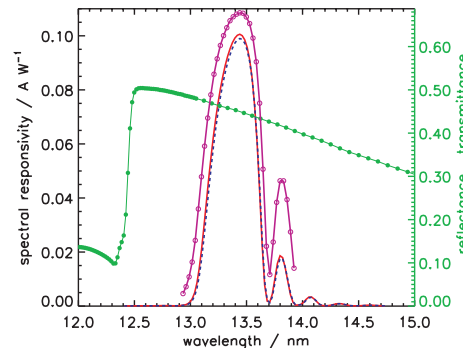


Left: Ray trace simulation of the focal spot. The size of one pixel of the CCD is indicated by the square. Right: Image of an Au LPP-source. CCD-image in the background, horizontal cross section ($\sigma=15 \mu\text{m}$, red), vertical cross section ($\sigma=25 \mu\text{m}$, blue).

In-band powermeter



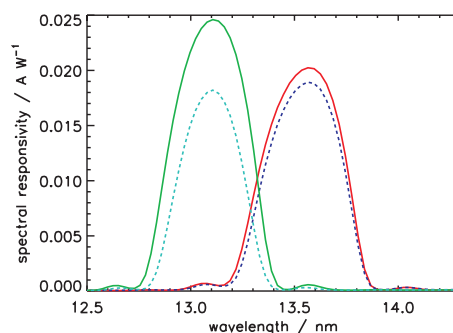
Scheme of the in-band power meter. The tool consists of two flat multilayer mirrors serving as the band pass filter. The solid angle of detection is defined by the aperture in front of the diode. Filters can be additionally used to suppress out-of-band radiation.



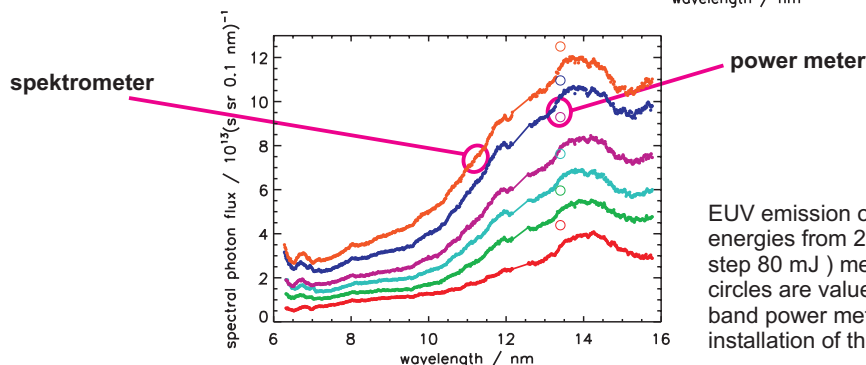
Uncertainty budget

| Quantity | Relative uncertainty contribution u/% |
|---------------------------------|---------------------------------------|
| radiant power | 0.5 |
| higher diffraction orders | 0.03 |
| diffuse scattered light | 0.2 |
| aperture diameter | 0.7 |
| distance to source | 1.4 |
| Power meter responsivity | 1.7 |

Spectral responsivity of an in-band power meter for s-(red line) and p-polarized (blue dashes) radiation with 5° to normal incidence angle at the mirrors. Due to the double reflection, only 6% of the wavelength integrated responsivity belong to radiation in side maxima. Also shown is the transmittance of a Si/Zr filter (green) and the reflectance of a single mirror (pink), right scale.



Responsivity of double multilayer in-band power meters with different incidence angles at the mirrors: 18° (green, light blue) and 10° to normal (red, dark blue) for s- (solid line) and p-polarization (dashes). The relative bandwidth is 3.2% and 3.1% at 10° , for s- and p-polarization, respectively, and 3.2% and 2.7% at 18° .



EUV emission of a Au LPP-source at laser pulse energies from 200 mJ to 640 mJ (bottom to top, step 80 mJ) measured with the spectrometer. The circles are values obtained at 13.4 nm with the in-band power meter about a month later after re-installation of the source at an other location.

⁹ "Characterization of a laser produced plasma source for a laboratory EUV reflectometer"

Frank Scholze, Frank Scholz, Johannes Tümmeler, Gerhard Ulm, Herbert Legall, Peter-Viktor Nickles, Wolfgang Sandner, Holger Stiel, Ludwig vanLoyen, SPIE 5037-84 (2003)

¹⁰ "A New Laboratory EUV Reflectometer for Large Optics using a Laser Plasma Source"

Ludwig van Loyen, Thomas Böttge, Stefan Braun, Hermann Mai, Andreas Leson, Frank Scholze, Johannes Tümmeler, Gerhard Ulm, Herbert Legall, Peter V. Nickles, Wolfgang Sandner, Holger Stiel, Christian Rempel, Mirko Schulze, Jörg Brutscher, Fritz Maccio, Stephan Müllender, SPIE 5038-3 (2003)