Uncertainties in traceable radiometric calibration of EUV instruments using synchrotron radiation

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Frank Scholze (EUV detector-based radiometry)
Roman Klein (Source-based calibrations)
Traceability

... or: what metrology institutes are good for.

**common radiometric SI units:**

- radiant flux (power) \( \Phi_e \) \( \text{W} \)
- spectral power \( \Phi_{e,\lambda} \) \( \text{W} \cdot \text{m}^{-1} \)
- radiant intensity \( I_e \) \( \text{W} \cdot \text{sr}^{-1} \)
- spectral radiance \( L_{e,\lambda} \) \( \text{W} \cdot \text{m}^{-1} \cdot \text{sr}^{-1} \cdot \text{m}^{-2} \)
- spectral irradiance \( E_{e,\lambda} \) \( \text{W} \cdot \text{m}^{-1} \cdot \text{m}^{-2} \)

⇒ power \( \otimes \) spectrum \( \otimes \) geometry
Traceability

source based radiometry

traceability to:

primary source standard

emission calculable based on basic physical principles

in UV, VIS, IR: black body radiator

Planck’s law, $\Phi_{e,\lambda} \sim T^4$

$T < 3800$ K $\Rightarrow \lambda > 200$ nm

in VUV/EUV: electron storage ring

Schwinger equation

detector based radiometry

traceability to:

primary detector standard

(cryogenic) electrical substitution radiometer (ESR)

based on equivalence between electrical and radiative heating

radiometric measurement is traceable to measurement of electrical quantities
Characterisation of space-based instruments in the VUV / EUV spectral range by PTB:

- reference source calibration
- detector calibration
- filter transmission
- mirror reflectivity
- grating efficiency
- spectrometer characterisation

Examples: EUV instrument calibrations
PTB facilities for synchrotron radiation

1982 – 1999: BESSY I
located in (West-)Berlin, Wilmersdorf

since 1999: BESSY II
BESSY II: multi-user facility, circumference 250 m, electron energy 1.7 GeV
located in Berlin-Adlershof

since 2008: MLS
Metrology Light Source MLS: PTB-owned facility, circumference 48 m, electron energy 100 - 630 MeV
located in Berlin-Adlershof
PTB facilities for synchrotron radiation

- since 1999: BESSY II
- since 2008: MLS

![Graph showing radiant power vs. photon energy and wavelength]

Bandwidth \( \Delta E/E = 10^3 \)

- PTB special 900 MeV
- 600 MeV
- 470 MeV
- 200 MeV

Wavebands:
- far IR and IR
- VIS
- UV
- VUV / soft X-rays
- X-rays
Source-based radiometry

use of electron storage ring as primary source standard (calculable radiation)

direct calibration

(a) calibration of energy-dispersive detectors & spectrometers

storage ring

energy-dispersive detector or spectrometer

primary source standard

(b) calibration of radiation sources

storage ring

monochromator

detector

secondary source standard

primary source standard
Calculable Synchrotron Radiation

- electron beam and storage ring parameters
  - $W$: electron beam energy
  - $I$: electron current
  - $\sum_y$: vertical extension and divergence of the beam
  - $B$: magnetic induction

- geometrical quantities
  - $d$: distance
  - $r$: radius of aperture
  - $\psi$: emission angle

Schwinger equation:

radiant flux $\Phi = \Phi (W, I, B, \sum_y, \psi, d, r)$
Uncertainty Budget

Example: MLS

\( W \)  electron energy
\( I \)  electron current
\( B \)  magnetic induction
\( d \)  distance
\( \Sigma_y \)  vert. beam size
\( \psi \)  emission angle

The spectral radiant power is available with rel. uncertainties well below 0.1 %

Direct calibration

direct calibration:

- spectrometer must fit at the beamline (!)
- spectrometer must not vignette incident beam
- divergent beam, source is not $\infty$
- white beam: higher orders with grating spectrometer
- SR is (strongly) linear polarised

*will add uncertainties "+ X %"
*depending on the individual instrument

*so far not done at PTB for external partners

new instrumentation @ PTB
"space tank": max. 1,50 m length, 100 kg weight
Transfer source calibration

Calibration of transfer standards

D₂ lamp ($\lambda > 120$ nm) cont. spectrum
HC ($\lambda < 100$ nm) discrete spectrum

- "One step more"
- transfer standard itself adds (high) uncertainty
- t.s. has only limited spectral width
- t.s. has only limited "lifetime" (aging)

Advantages:
- transfer standard available at your lab
- re-calibration campaigns possible

Hollandt et al., Metrologia 30 (1993) 381-388

well-known examples: SUMER-, CDS source.

typical uncertainties (HC), $k=2$:

12 - 16 % radiometric calibration incl. 10 % reproducibility (40 h operation)
Validation

Bilateral PTB – NIST comparison

spectral radiant intensity of deuterium lamps 200 nm – 350 nm

(NIST: spectral irradiance)

combined uncertainty $U (k=2): 5.4 \%$

Agreement of calibrations (= scales of spectral radiant intensity) within combined uncertainty $\approx 5 \%$

Arp et al., Metrologia 48 (2011) 261-267
Detector-based radiometry

- primary detector standard:
  (cryogenic) electrical substitution radiometer
  - Optimized for VUV radiation (40 nm to 400 nm)
  - 100 mK/µW sensitivity
  - 120 s time constant
Uncertainty in power determination

main contributions from ESR (@ 200 nW)

- non-equivalence correction: 0.17 %
- temperature deviations: 0.05 %
- electrical calibration: 0.03 %

... total: 0.19 %

main contributions from SR radiation (@ 60 nm)

- false light (higher orders): 0.15 %
- wavelength & bandpass: 0.02 %
- stability: 0.18 %

... total: 0.24 %

PTB's VUV beamline 40 nm – 400 nm

Scale of spectral responsivity

... as realised at PTB from UV to X-ray using synchrotron radiation
... using "well-behaving" (?) semiconductor photodiodes as secondary standards

why \( u > 0.5 \% \) for \( \lambda < 120 \) nm?
The weak point

main contributions from "good" secondary detector ( @ 60 nm)

- photocurrent measurement: 0.30 %
- dark current variability: <0.01 %
- thermal stability: <0.01 %
- spatial uniformity: 0.20 %
- polarisation dependence: 0.05 %

... total: 0.37 %

largest contribution to total uncertainty

for wavelengths 25 nm < \( \lambda \) < 140 nm:
- available radiant power low (< 300 nW)
- detector responsivity low
- strong detector non-uniformities

detector aging still not covered (!) in calibration uncertainty budget

... as it will occur in use of the detector after the calibration.
Physical reasons

Si absorption length

- absorption of radiation within top layer < 10 nm
- photon energy sufficient to create photoelectrons

SiO₂ absorption

In particular for 70 nm < \( \lambda \) < 200 nm:

- absorption of radiation within top layer < 10 nm
- photon energy sufficient to create photoelectrons

L. Shi et al., (data from Palik, Henke)

VUV absorption of synthetic quartz glasses
Si absorption length

In particular for $70 \text{ nm} < \lambda < 200 \text{ nm}$:

- high surface sensitivity
- high degradation potential

not only for detectors, but for any optical component (filter, mirror, grating)
Photon-detector interaction

- absorption within the first few nm
- condensates, adsorbates, carbon growth
- photoemission → secondary effects, chemistry
- surface charging (oxide)
- radiation damage (chemical bond-breaking)
- recombination losses → loss in responsivity
### The ideal detector?

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Pros</th>
<th>Cons</th>
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</table>
| Si n – p with thin (6 nm) nitrided oxide layer | + highest responsivity  
+ high uniformity  
+ "100% internal QE" | - STRONG degradation                                                |
| Si n – p with metal/nitride filter | + high stability                                                    | - low responsivity                                                   |
| PtSi-nSi Schottky                  | + high irradiation stability  
+ contamination removal    | - low responsivity  
- low uniformity  
- high dark current  
- electrically instable |
| Boron technology p – n, "PureB-diode" <10 nm dead layer | + high stability  
+ high responsivity | - low uniformity  
- availability (?)       |

- **So far, all available detectors for this spectral region have drawbacks**
- **The PureB technology has the potential to overcome this**
Detector stability

... under VUV irradiation

@ synchrotron

with 157 nm F$_2$-Laser


PtSi-nSi

Schottky

Si n–p

(AXUV)
Detector stability

... when stored (1-year recalibration cycle)

Relative stability of different secondary standards over a one-year recalibration cycle

- no common behaviour: wavelength/type/individual dependant
- calibration can not be better than drift of secondary standard
Validation by comparisons

- PTB internal comparison source vs. detector standard  
  Klein et al., Metrologia 48 (2011) 219
- CCPR comparison PTB-NIST  135 nm – 250 nm  
  Gottwald et al., Metrologia 48 (2011) 02001
- CCPR comparison PTB-NIST-NMIJ 10 nm – 20 nm  
  Scholze et al., Metrologia 47 (2010) 02001

Agreement within combined uncertainties < 2%
Best calibration strategy?

- Realization of the radiometric scale(s) by NMIs is available with low uncertainties

** HOWEVER **

- Dissemination of the scale by secondary (transfer) standard adds (large) uncertainties
- Direct calibration of instruments adds (large) uncertainties due to "non-equivalence" between calibration and measurement (beam) conditions
- Secondary standards as well as the instruments itself are affected by ageing (degradation) issues

- Instruments should be designed in a way that they are suitable for direct calibration with synchrotron radiation
- For the VUV range, development/improvement/commercialisation of stable transfer standards is urgently needed
- Ageing (& contamination) must be handled (witnessed. avoided. removed.)
Thank you for your attention.

View of the MLS experimental hall