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5 AUTHORS, INCLUDING:

Jürgen Hartmann
Fachhochschule Würzburg-Schweinfurt

Peter Meindl
Physikalisch-Technische Bundesanstalt

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ORIGINAL ARTICLE

Traceable Radiometric Calibration of Semiconductor Detectors and their Application for Thermodynamic Temperature Measurement

J. HARTMANN*, J. HOLLANDT, P. MEINDL, D. TAUBERT and L. WERNER
Physikalisch-Technische Bundesanstalt, Abbestraße 2-12, D-10587 Berlin, Germany
**e-mail: juergen.hartmann@ptb.de*

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Abstract

The non-contact measurement of temperature by using the emitted thermal radiation has been an innovative field of measurement science and fundamental physics for more than a hundred years. It saw the first highlight in Gustav Kirchhoff's principle of a blackbody with ideal emission characteristics and culminated in Max Planck's formulation of the law of thermal radiation, the so-called Planck's law, forming the foundation of quantum physics. A boost in accuracy was the development of semiconductor detectors and the cryogenic electrical substitution radiometer in the late 1970s. Semiconductor detectors, namely photodiodes, deliver an electrical current proportional to the absorbed optical radiation. Due to the measurements of thermal radiation over a wide range of temperature and wavelength, thermodynamic temperature measurements with radiometric methods have set benchmarks to all, the electrical, dimensional and optical metrology. The paper describes the measurement of the spectral responsivity of semiconductor detectors traceable to the SI units and their application for thermodynamic temperature measurement by the absolute measurement of thermal radiation using filter radiometers with calibrated spectral irradiance responsivity.

1. Introduction

At the end of the 19th century electrification started to revolutionize lighting in Germany. However, at the beginning people had to be convinced that electrical lighting is more efficient than the traditional gas lighting. This needed absolute radiometric and photometric measurements. Werner von Siemens, a German industrialist in those days, strongly supported the idea that the German empire should establish a measurement authority which independently develops standards for all physical measurements, including radiometric ones. In 1887 the Physikalisch-Technische Reichsanstalt PTR (re-named in Physikalisch-Technische Bundesanstalt PTB in 1950) was founded with its first president, Herman von Helmholtz. One of its first tasks was devoted to radiometry and photometry and blackbody radiators were developed and investigated as absolute standards of radiation. The PTR measurements supported Max Planck to find his famous law on thermal radiation in 1900, based on the revolutionary assumption that the energy of light is quantized. Based on his radiation law:

$$L_{b,\lambda} = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1} \tag{1}$$

blackbody cavity radiators have served since these days as calculable sources of thermal radiation at PTB [1, 2].

The first radiation detectors in the late 19th century were thermal detectors [3]. They were fabricated with micro machined processes and consisted of thin platinum layers covered by a black paint. The change in resistance with respect to the temperature was measured by using a Wheatstone bridge [3]. While the main principles for the generation of calculable thermal radiation via blackbody radiators remained the same, seminal progress has been made on the detector side by the discovery and utilisation of semiconducting materials and the cryogenic electrical substitution radiometer allowing a direct and highly accurate traceability of the spectral responsivity of detectors to the SI units Ampere and Volt [4 , 5]. Using modern blackbody cavity radiators and semiconducting photodiodes together with an accurately defined geometry thermal radiation can be measured with very low uncertainty. By using Eq. (1) the measured detector signal can be used to determine the thermodynamic temperature of the blackbody by primary methods, without any connection to the International Temperature Scale [6]. This allows an independent realisation of thermodynamic temperatures. In Section 2 of the paper the primary detector standard, the cryogenic radiometer, is presented and the traceable calibration of photodiodes with respect to the cryogenic radiometer is described. Section 3 gives a short overview over modern state of the art blackbody cavity radiators, while Section 4 summarizes the measurements and the availability of the necessary optical apertures for defining the geometry of the measurement. In Section 5 the details of the thermodynamic temperature measurements are presented. A conclusion and an out-look given in Section 6 complete the paper.

2. Detector Standard for the Spectral Responsivity

The measurement of thermodynamic temperatures of blackbody radiators is the application of spectral responsivity calibrations with

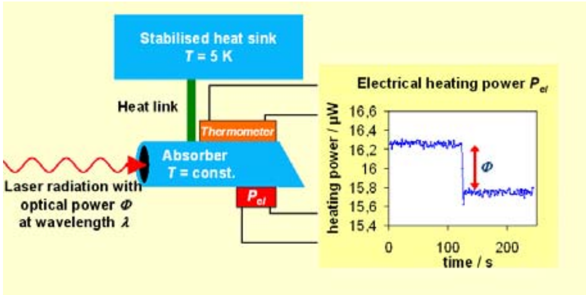


Fig. 1. Functional principle of a cryogenic substitution radiometer. The absorber cavity is held on a fixed temperature by a regulated electrical heating. If any optical radiant power additionally heats the cavity, the electrical heating power must be reduced to hold the cavity on a constant temperature. Considering the absorptance of the cavity, the difference in the electrical heating power equals the amount of optical power

the highest requirements regarding uncertainty [1]. For this application relative uncertainties in the order of 10^{-4} are required. To obtain such very low uncertainties sophisticated experimental facilities together with elaborated calibration and fitting procedures have been developed at the PTB.

Calibration of the spectral responsivity requires precise absolute detector standards. In the late 1970s the cryogenic electrical substitution radiometer (Fig. 1) has been invented which allows the measurement of optical radiant power with lowest possible uncertainties [5]. Relative uncertainties in measuring optical power with the cryogenic radiometer have reached the 10^{-5} level, and hence responsivity calibrations with respect to the cryogenic radiometer have reached a very high accuracy level [7]. The development of smaller and faster cryogenic radiometers allows the absolute measurement of low-power radiation, e.g. available at a monochromator-based set-up [8]. On the other hand, laser-based cryogenic radiometers enable the measurement of spectral radiant power with the lowest possible uncertainties. Continuously tuneable cw laser radiation is not easily available for all wavelength ranges, and calibration with lowest uncertainties are still time consuming and cumbersome. Therefore, PTB performs the calibration of spectral responsivity of silicon detectors with a laser-based cryogenic radiometer only at distinct wavelengths where

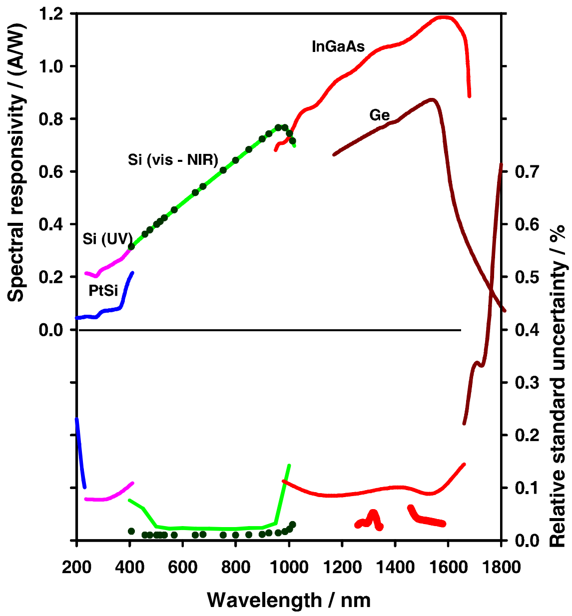


Fig. 2. Spectral responsivity of selected semiconductor detectors used at PTB. The lower part of the diagram shows the standard uncertainties of the spectral responsivities. The solid line in the visible range indicates the uncertainty of the interpolated values between the laser wavelengths at which the responsivity has been measured (dots) [7, 10]. The uncertainties in the UV and NIR have been obtained by using a monochromator-based cryogenic radiometer set-up [8]. Around 1.3 µm and 1.55 µm a tuneable diode laser has additionally been used to reduce the uncertainty (thick lines)

intense and highly stable laser radiation is available. To achieve a continuous spectral responsivity scale for all required wavelengths an interpolation of the measured spectral responsivity values is required. The modality of the interpolation depends on the type of detector used and, therefore, on the wavelength range in which these detectors are applied.

PTB employs different types of semiconductor detectors in different spectral ranges (Fig. 2). In the ultraviolet range from 200 nm to 400 nm single silicon photodiodes (Hamamatsu types S1337 and S5227) and PtSi detectors (Schottky-barrier silicon photodiodes with a PtSi front contact) and trap detectors made up of these photodiodes are used. In the range from 400 nm to 1000 nm trap detectors based on silicon photodiodes (Hamamatsu types S3411 and S6337) have proved to be the best detectors for optical power, as they provide a high detectivity and a very high quality [1]. Finally, in the range from 1 µm to 2 µm InGaAs- and germanium photodiodes are utilized.

In the visible and adjacent spectral range, the interpolation of the spectral responsivity of silicon photodiode based trap detectors is performed with a physical model, justifying the spectral responsivity in-between the calibrated wavelengths by physical reasons [1]. The interpolation on the basis of a physical model can be performed with relative uncertainties down to 0.02 % in certain wavelength ranges [1, 9, 10]. On the other hand, in the ultraviolet (200 nm to 400 nm) and near infrared range (above 1 µm) such an interpolation is not applicable to reach the lowest possible uncertainties. Therefore, a calibration at a few selected laser wavelengths is not sufficient in these wavelength ranges. Consequently, tuneable radiation has to be applied. Hence, the PTB uses a monochromator-based set-up in these wavelength ranges. However, the uncertainty of a detector calibration in these wavelength ranges is about 0.1 % due to the lower optical radiant power at a monochromator-based set-up and the poorer quality of the photodiodes when used in the UV. The calibration facility is furthermore equipped with tuneable laser systems for selected wavelength ranges around 1.3 µm and 1.55 µm allowing for an uncertainty of about 0.03 % in these spectral ranges.

3. Filter Radiometers for Thermodynamic Temperature Determination

Taking advantage from the high accuracy of the spectral responsivity disseminated by means of trap detectors and single photodiodes as transfer detectors (TD), beginning with 1995, PTB uses absolutely calibrated and highly stable [11] filter radiometers (FRs) in irradiance mode (see section "Thermodynamic temperature measurements") for the measurement of the thermodynamic temperature of blackbodies with low uncertainties in the temperature range from 400 °C to 3000 °C [12-17]. A schematic view of the filter radiometers applied is shown in Fig. 3. These FRs consist in principle of a precision aperture, a wavelength selecting element (typically an interference filter) and a photodiode as the optical radiation detector.

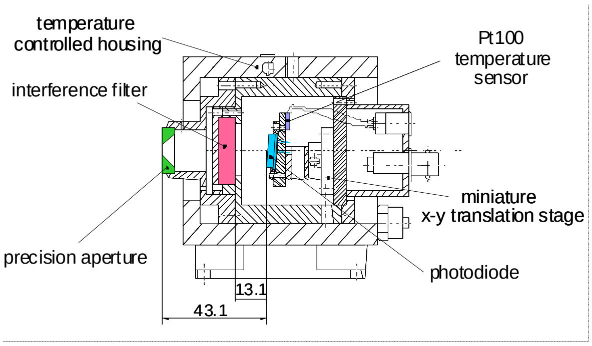


Fig. 3. Schematic view of an interference filter based radiometer used at PTB for thermodynamic temperature determinations

The properties of the precision apertures and their area measurement are discussed in the section "Precision apertures". The interference filters are custom made with centre wavelengths ranging from 476 nm up to 1595 nm and an out-of-band blocking better than five orders of magnitude with respect to the maximum transmittance. The spectral bandwidth (FWHM) varies from about 20 nm for the FRs with Si photodiodes to 50 nm respective 100 nm for the FRs with InGaAs photodiodes. Depending on the centre wavelength of the interference filter either 10 mm × 10 mm windowless silicon photodiodes (Hamamatsu S1337) or 5 mm diameter windowless InGaAs-photodiodes (Fermionics / GPD) are employed, carefully selected with respect to their shunt resistance and the homogeneity of the spectral responsivity [16].

The FRs are calibrated in terms of their spectral irradiance responsivity by direct comparison with a TD at the monochromator-based spectral comparator facility of PTB. Figure 4 shows a schematic view of the setup and the optical path of the facility.

From the measured ratio $Q_{\mathrm{FR,TD}}(\lambda)$ of the photocurrents of the FR and the TD, the spectral irradiance responsivity of the FR $s_{\mathrm{E,FR}}(\lambda)$ can be calculated according to

$$s_{\mathrm{E,FR}}(\lambda) = Q_{\mathrm{FR,TD}}(\lambda).\, s_{\mathrm{TD}}(\lambda).A_{\mathrm{TD}} \qquad (2)$$

where $s_{\mathrm{TD}}(\lambda)$ and A_{TD} denote the spectral responsivity and the aperture area of the TD, respectively. A comprehensive description of the experimental setup and the calibration procedure is given in [18, 19]. The

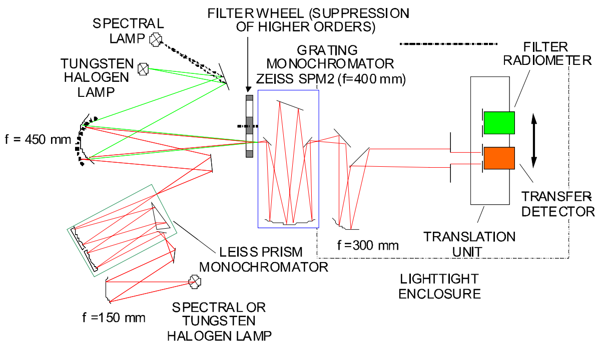


Fig.4. The monochromator based spectral comparator facility of PTB for the calibration of filter radiometers against broadband transfer detectors. A tungsten halogen lamp as a continuum source is imaged via a prism monochromator as a predisperser onto the entrance slit of a monochromator. After monochromatization, the beam is collimated with a mirror optics and overfills the apertures of the transfer detector respective of the filter radiometer.

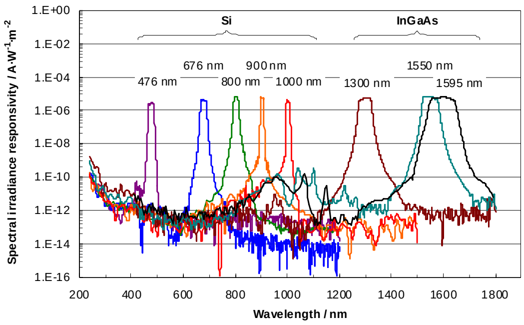


Fig. 5. The calibrated spectral irradiance responsivity of the PTB narrow band, interference filter based filter radiometers with Si- resp. InGaAs-photodiodes as photon detectors.

spectral irradiance responsivities of all interference filter based FRs currently applied at PTB for the thermodynamic temperature determination are presented in Fig. 5.

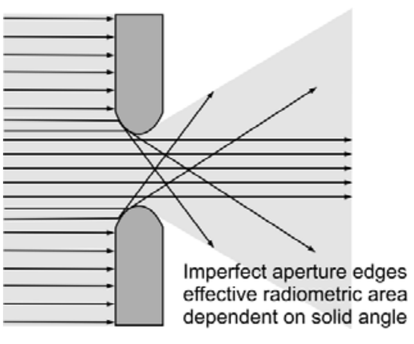
Depending on the centre wavelength, the typical contributions of the filter radiometer calibration to the relative standard uncertainty (k=1) for the measurement of the spectral irradiance in front of a blackbody to determine its thermodynamic temperature are ranging from 0.03 % to 0.06 % for the Si photodiode based FRs [19] and from 0.06 % to 0.14 % for the InGaAs photodiode based filter radiometers [16].

4. Blackbody Radiation Sources

For the calculable generation of thermal radiation high quality blackbody radiators are necessary. Already the theoretical considerations of Gustav Kirchhoff in 1864 led him to the result that the radiation inside a closed cavity should be independent of shape and material of the cavity. However, it took nearly half a century until Max Planck found the accurate description of the thermal radiation of a blackbody radiator with his so-called Planck's law of thermal radiation given in Eq. (1). This law of thermal radiation relates the spectral radiance, i.e. the energy per radiating area and wavelength interval in a given solid angle solely to the temperature of the blackbody. Consequently, the knowledge of the temperature is sufficient to calculate its emitted spectral radiance. However, it is important that the radiating area is as close as possible resembling a blackbody, having an emissivity as close as possible to unity. Already W. Wien and O. Lummer in the late 19th century realised that a cavity radiator, i.e. a long tube closed at one side and uniformly heated, is a very good approximation of a blackbody [20]. Important for the quality of the blackbody is the ratio of the opening area to the inner surface area - this should be as small as possible - and the temperature distribution along the cavity walls - this should be as homogeneous as possible. If these requirements are fulfilled emissivities close to unity can be obtained [1, 2]. Depending on the temperature range required different designs of blackbody radiators are applied. In the range from -60 °C up to about 1000 °C so-called heat-pipe blackbodies are best suited. Here the cavity of the blackbody is formed of a doubled walled tube filled with a small amount of a substance, which is around the boiling point for the desired temperature, resulting in an equilibrium between the liquid and the gaseous phase of the substance. This unique equilibrium gives the possibility that at the hot locations of the cavity walls more liquid is evaporated, lowering the respective temperature, while at the colder locations the gaseous phase is condensing, increasing the temperature due to the released heat of condensation. For the temperatures above 1000 °C electrically heated blackbodies with cavities made from graphite, CC reinforced graphit and pyrolytic graphite are used, details of which can be found in Ref. [1].

5. Precision Apertures

For thermodynamic temperature measurement using Eq. (1) the solid angle of the measurement geometry must by known with high accuracy. For this the areas of the apertures defining this solid angle must be measured with sufficent low uncertainty. As the edges of such high-precision apertures must be very thin to prevent inter-reflection, non-contact measurement methods are necessary. A variety of methods has been proposed [1, 21, 22] to measure the absolute area of such apertures, and also various methods for relatively measure these areas with respect to a reference area have been published [1, 23, 24]. To definitely define the solid angle the edges must be thin and of a proper structure, as shown schematically in Fig. 6.



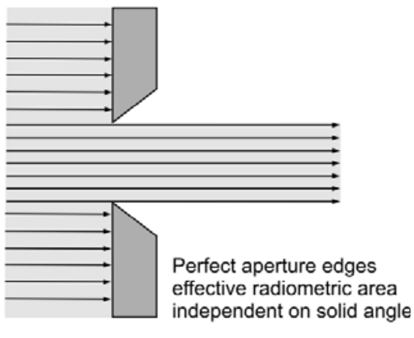


Fig. 6. Schematic representation of a bad (left) and good (right) edge structure. In case of a good edge the area defined by the aperture is not depending on the solid angle covered by the detector [1]

The quality of the edges has also been identified within an international comparison of methods to measure the aperture area to critically affect the uncertainties of the used area measurement [25]. Beside the measurement of such apertures their fabrication is just as well a delicate problem [1].

6. Thermodynamic Temperature Measurements

The basic experimental setup for the measurement of the thermodynamic temperature of a blackbody with absolutely calibrated filter radiometers in irradiance mode is depicted in Fig. 7.

The photocurrent I_{photo} of the applied filter radiometer, calibrated in terms of its spectral irradiance responsivity $s_{\mathrm{E,FR}}(\lambda)$ is equal to:

$$I_{\mathrm{photo}} = \varepsilon . G . \int s_{\mathrm{E,FR}}(\lambda) .\ L_{\lambda,\mathrm{BB}}(\lambda, T)\, d\lambda \qquad (3)$$

with $L_{\lambda,\mathrm{BB}}(\lambda,T)$ as the spectral radiance according to Planck's law for an ideal blackbody at the temperature T and ε the emissivity of the blackbody. The factor G in Eq. (3) describes the geometrical extent and is defined by the radii r_1 and r_2 of the precision apertures and the distance d between these apertures.

$$G = \frac{2\pi r_1^2}{r_1^2 + r_2^2 + d^2 + \sqrt{\left(r_1^2 + r_2^2 + d^2\right)^2 - 4 r_1^2 r_1^2}} \qquad (4)$$

Depending on the required uncertainty, the distance d is determined either by an interferometer method or with a precision micrometer gauge. The iterative calculation of the thermodynamic T is carried out by numerical integration of Eq. (3).

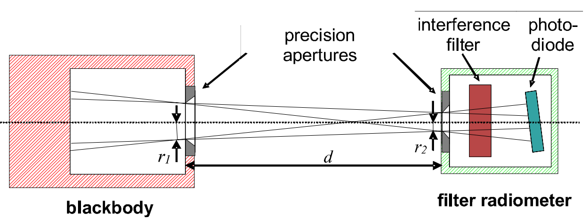


Fig. 7. Experimental setup for the thermodynamic temperature determination of blackbodies applying absolutely calibrated filter radiometers

One of the main motivations for the measurement of thermodynamic temperatures of blackbodies at PTB with absolute radiometry is the investigation of the thermodynamic accuracy of the International Temperature Scale of 1990 (ITS-90) in the temperature range from the tin fixed point (Sn-FP) at 231.928 °C up to the silver FP at 961.78 °C. Employing a sodium double heatpipe blackbody as high accuracy source for thermodynamic temperature measurements and Si photodiode FRs with centre wavelengths at 676 nm and 800 nm, first results were obtained for the difference between the thermodynamic temperature T and the ITS 90 temperature T_{90} (T-T_{90}) in the temperature range from the Al-FP to the Ag-FP. [13, 18, 26]. The significant improvement of the accuracy of the spectral responsivity disseminated on trap detectors up to a wavelength of 1020 nm [9], lead to the construction of Si photodiode FR with centre wavelength of 900 nm and 1000 nm, which could be calibrated with uncertainties comparable to the already existing FRs. These FRs where then successfully applied for the determination of T-T_{90} in the temperature range from 419 °C (Zn-FP) to 660 °C (Al-FP) [14, 15]. Due to the extension of the high accuracy spectral responsivity in the NIR up to wavelengths of about 1.7 µm, disseminated on single InGaAs photodiodes, completely new type, InGaAs photodiode based FRs were designed and constructed with centre wavelength at 1300 nm, 1550 nm and 1595 nm, suitable for thermodynamic temperature measurements down to the Sn-FP. Up to now these FR have been used for the measurement of T-T_{90} in the range from the Zn-FP to the Al-FP. The obtained results show an excellent agreement with the results for T-T_{90} determined with the Si-FRs [16, 17].

7. Conclusion and Out-Look

Due to the development and improvement of the cryogenic radiometer as the primary detector standard the calibration of the spectral responsivity of semiconductor based optical detectors has reached a very high level of accuracy, especially from the near UV to the near IR spectral range. In this wavelength range relative uncertainties in the 10^{-4} range can be obtained. Using such detectors, together with high quality blackbody radiators and an elaborated technique for measuring the radiometric apertures thermodynamic temperatures can be measured at

PTB with uncertainties in the 100 mK range up to temperatures of 3000 °C [1, 27]. As such measurements require an outstanding expertise and experimental facilities, only very few national metrology institutes are able to cope with these requirements. To allow other institutes and industry to make use of such low uncertainties in radiometric temperature measurement, high-temperature metal carbon eutectic fixed-points are presently investigated as transfer standards of thermodynamic temperatures [28]. Using the above mentioned methods, the thermodynamic temperature of the melting point of the metal carbon eutectic composition is measured and these fixed-points can then be used to provide a source based traceability of optical detectors, not requiring the elaborated traceability chain for the detector based calibration.

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Note: References to commercial products are provided for identification purposes only and constitute neither endorsement nor representation that the item identified is the best available for the stated purpose.

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