Publishable Summary for 22IEM06 S-CALe Up
Self-calibrating photodiodes for UV and exploitation of induced junction technology

Overview

Photonics and optics are exciting, rapidly evolving technologies of great value (over 100 billion € in EU) and of importance across industry, environment, health, medicine, energy, lighting and science. The photonic industry and standardisation organisations request miniaturised, cost-effective, integrated and self-calibrating measurement systems that cannot be provided by traditional methods. Recent developments exploiting predictable photodiodes in various ways have demonstrated improved uncertainty of responsivity to 10 ppm and the proof-of-concept of an NMI-on-a-chip suitable for miniaturisation. This project will demonstrate exploitation of the new photodiodes as built-in standards in various applications and develop improved standard detectors for the UV range by exploiting new methods.

Need

There is rapid and exciting technology development within photonics, which is one of six EU defined Key Enabling Technologies (KET) used in climate monitoring, medical treatment, health and photonic industries, energy saving illumination by light-emitting diodes (LEDs), electricity production, science, and many more applications. The technological development trend is towards miniaturisation, more integrated measurement systems and distribution of standalone sensor systems in possibly remote locations. Current metrological systems are not capable of calibrating photodiodes in integrated systems nor in remote locations. Therefore, the European technology platforms Photonics21 and Quantum Flagship highlight the integration of self-calibrating systems and products as one of the technology, research, and innovation challenges ahead. The need is further emphasised in the Photonics21 EPoSS White paper on Integrated Photonics and complies with the envisioned future need outlined by CIPM towards a “CIPM Strategy 2030+”.

Previous iMERA+, EMRP and EMPIR projects have developed the Predictable Quantum Efficient Detector (PQED), which has proven to have an extremely low external quantum deficiency (EQD) of around 10 ppm over a wide spectral and dynamic range, with an undetectable drift over 10 years. These properties make the PQED a very attractive calibration standard detector that complies well with the low-cost and high accuracy transfer standard requested by CIPM’s Consultative Committee for Photometry and Radiometry (CCPR).

Demonstration of the utility and exploitability of the PQED’s properties in various applications is necessary to increase their technological readiness level, bringing them closer to uptake by relevant industry and end-users.

The ultraviolet (UV) range is of great importance to health and earth observations but suffers from detectors with poor stability and lack of predictability. The International Commission on Illumination (CIE), as the world standardisation organisation for light and lighting, has requested research on new low-cost, high accuracy, primary standard detectors of optical radiation allowing better traceability from 200 nm – 2000 nm, which is of importance to industry and will also cover the UV range. Predictable UV detectors with improved stability will be developed in objective 3.

Improved understanding of the measurement system provided by advanced modelling of photodiodes will be explored in objective 1, supported by characterisation measurements from objective 4 will be key in enabling better traceability and will trigger new measurement techniques in remote and integrated measurement systems. In a similar way, dual-mode detectors are needed to enable a pure experimental self-calibrating measurement system in a wider range of applications than those studied in objective 2 for future exploitation also outside the spectral range covered by silicon technology, where photodiodes cannot be accurately modelled.

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European Partnership Co-funded by the European Union

Objectives

The overall objective is to demonstrate the use of improved PQED detectors and associated technology as an NMI-on-a-chip in various photonics applications and to develop models and improved detector manufacturing techniques in order to provide improved traceability into the more challenging UV and NIR spectral range.

The specific objectives of the project are:

1. To develop **3D simulation models** of photodiode charge carrier transportation in Predictable Quantum Efficient Detectors (PQED) for better physical representation, higher calculation speed, wider availability and improved uncertainty approaching 1 ppm between 500 nm and 900 nm, and to extend the quantum yield prediction from 400 nm down to 250 nm with an uncertainty better than 0.1 % and better than 0.2 % from 250 nm to 200 nm.
2. To **use PQEDs** with very low spectral responsivity uncertainty in the 400 nm to 850 nm range as built-in references **in different applications** (e.g. optical power measurement, fibre optics, pulsed laser radiation, photometry without V(λ) filters) taking into account practical aspects, such as current measurements, stray light, geometry, heat and dark current variations.
3. To develop and **fabricate improved photodiodes for the UV range** and validate their stability and suitability as a spectral responsivity standard from 400 nm to 200 nm. Additionally, to develop thermal simulations and packaging technology of dual-mode detectors with heat equivalence better than 0.03 % suitable for implementation at any wavelength over the spectral range from 200 nm to 1000 nm.
4. To **extend the spectral response range** of photodiodes between i) 200 nm and 400 nm, and ii) 850 nm and 1050 nm, with a target uncertainty better than 0.2 %. For this, the improved detectors and packaging developed in objective 3, and improved charge carrier simulation and quantum yield modelling developed in objective 1, will be used.
5. To demonstrate the establishment of **an integrated European metrology infrastructure and to facilitate the take up of the technology** and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrument manufacturers), standards developing organisations (CIE), technical committees (e.g. EURAMET TC-PR, CCPR) and end users (photonics industry).

Progress beyond the state of the art and results

Improved simulation models

The spectral responsivity of PQEDs are to first approximation given by fundamental constants and the radiation wavelength. Deviations from this ideal performance are given by internal quantum deficiency, reflectance and quantum yield models. To have a fully predictable standard detector all quantities have to be independently predicted.

The project builds on the EMPIR 18SIB10 chipS·CALe project, where improved self-induced PQED trap detectors with a record low external quantum deficiency below 10 ppm were developed for the 400 nm to 850 nm spectral range. Simplified 3D simulation models were developed and new experimental techniques where simulation fitted to experimental photocurrent measurement at only one wavelength was proven to be sufficient to predict the responsivity from 400 nm to 850 nm. In previous projects, quantum yield (QY) was found significant at wavelengths as high as 470 nm and to increase with decreasing wavelength. However, the quantum yield was also found calculable to an uncertainty around 200 ppm down to 360 nm. Current 3D simulation capabilities are limited to one NMI, on one type of software, with known limiting simplifications due to calculation speed and the current TRL-level in the 400 nm – 850 nm spectral range is around 3 to 4.

A new software package and two more partners are now involved in charge carrier simulation. Simulations with high performance computer (HPC) systems have been demonstrated. The overall availability and simulation capacity is expected to improve significantly throughout the project, but it requires software that scales well in parallel computing to fully exploit the HPC capabilities.

In S-CALe Up simulation models will be used to

I. improve predictability of the PQED to achieve an uncertainty that goes beyond the IQD losses,

II. independently predict the spectral response of PQEDs from 300 nm to 1000 nm, the spectral range covered by the key comparison CCPR-K2.b.

III. develop improved standard detectors and prediction methods designed for the UV spectral range from 200 nm to 400 nm, the spectral range covered by the key comparison CCPR-K2.c.

Furthermore, reflectance losses and quantum yield will be studied and modelled to enable the development of independently predictable standard detectors for the full spectral ranges covered by CCPR-K2.b (300 nm – 1000 nm) and CCPR-K2.c (200 nm – 400 nm).

Progress have been made on reflectance measurements covering the range of a predictable standard from 300 nm to 1000 nm. Reflectance is below the few ppm range from 400 nm throughout 1050 nm, but increases rapidly into the UV to 10 % down to 300 nm. The measured reflectance will be compared with other techniques as spectroscopic ellipsometry to extract the refractive indices and material thicknesses required to have a fully predictable standard. Initial measurements have been made and analysis of the data are in progress. Especially challenging are the long wavelength range where reflectance from the back surface interfere with the front surface reflection. However, this may be used to improve the predictability, confidence and robustness in the reflectance modelling and will be included in the analysis.

For the quantum yield (QY) progress in the measurement of relative spectral response down to 250 nm is published. The measured spectral response serves as a basis for calculating the QY and existing model describes the general background QY. However, more work is required to establish a model describing all features in the QY spectral dependence.

Applications for photometry, fibre optics and PICs exploiting PQEDs

The PQEDs have proven to be extremely stable with an undetectable drift, independent of wavelength, over ten years with a responsivity directly linked to fundamental constants. This makes the PQED an ideal transfer standard ready to be exploited in applications.

In S-CALe Up, three different applications for providing services to industry with the PQED as a built-in reference will be demonstrated, which will bring the technology closer to uptake by end-users. These demonstrators will simplify realisations, improve traceability and are expected to produce improved calibration and measurement capabilities (CMCs) with reduced uncertainty for the laboratories developing the demonstrators. For the filter-free photometers, partners have acquired PQEDs as a primary standard photometer and work is going on to reduce the uncertainty in the measurement. Spectral measurements of the source with improved calibration of wavelength scale has been conducted and spectral mismatch factor is estimated. Reflectance losses of the detector is also under study. The use of precision aperture and gas lensing effect from purging the PQED have been studied and concluded that purging should be done with synthetic air and not dry nitrogen.

A room temperature fibre optic PQED has been developed and exploited by mounting a fibre holder very close to the first surface of the PQED. Raytracing analysis with simulation software have shown that collecting radiation from two reflections are sufficient to achieve an uncertainty below 0.1 % with chipS·CALe developed PQEDs. It is therefore expected that collecting enough diverging radiation from a fibre tip, to gain high accuracy power measurements, should be easily achievable from standard single mode fibres. Initial measurements from fibre coupled photonic integrated circuits (PICs) have been made. Having a room temperature standard without the influence of back reflectance is expected to improve measurements from fibre coupled PICs further.

A self-calibrating optical power meter based on PQED and low-cost components is under construction and will demonstrate the ability of a self-referenced system derived from first principles measurements to be realised.

Develop and fabricate improved photodiodes for the UV range and technology for improved photodiodes

Silicon transfer standard pn-photodiodes for the UV spectral range from 200 nm to 400 nm are known to deteriorate under UV exposure, but new process advancements have proven to produce more stable photodiodes. Alternative materials and diode types such as PtSi and GaAsP are also used, but they suffer from a large non-uniformity. The self-induced photodiodes in the PQED may be less susceptible to radiation damage, but this has not tested.

In this project, improved photodiodes for the UV range with improved and validated stability will be developed taking advantage of the predictability of the photodiodes. Combining simulation models and fast material characterisations will enable many different processes to be tested to produce optimum and robust passivation.

In order to achieve required radiation hardness and still predictable photodiode, ultra shallow pn junctions is under development. Doping profiles as low as 25 nm with a peak concentration of 1E19 cm^{-3} is already achieved, which is excellent. The expected responsivity of detectors produced with the recipe will be estimated from lifetime measurements and 3D simulation models.

Furthermore, the influence and optimising of the current read-out contacts with carrier selective contacts will be studied. The idea behind the principle is to reduce the probability of recombination at the metal semiconductor interface. Two different processes for deposition and test samples are established. Simulation models in Silvaco ATLAS was adopted to design and optimise the carrier selective passivating contact structures. Based on the results reported in the literature, implementation of carrier selective contacts can potentially enhance the PQED performance. However, we were not able to establish a process of carrier selective passivating contacts with sufficient performance to improve the PQED performance.

In addition to developing new detectors, stability over the full spectral range for the intended use of chipS·CALe photodiodes from 300 nm to 1000 nm are under examination. For chipS·CALe photodiodes we have demonstrated that they will maintain their stability when exposed to radiation down to 300 nm. This is a very promising result that fulfils one of the requirements needed to have a fully predictable standard detector over the full spectral range from 300 nm to 1000 nm.

Extended and validated spectral response scales and packaging technology for dual-mode

In this project, improved photodiodes and modelling will be exploited to establish and validate the fully predictable spectral response scales covering the CCPR-K2.c range from 200 nm to 400 nm and the CCPR-K2.b range from 300 nm to 1000 nm with a target uncertainty below 0.2 %. This will simplify the realisations of spectral response scale as fewer calibration points are needed, and will enable implementation of independent traceability techniques exploiting the state of the art PQEDs. Two different types of PQEDs are under development and in S-CALe Up new packaging enabling use of housing of regular Hamamatsu 1337-1010 is developed. 3-element trap detectors are assembled for testing and use in various measurements in the project. Standard 2-element trap detectors (PQEDs) are used and photocurrent vs voltage experiments have started with the aim of extracting the individual IQD with the use of 3D simulation models.

Improved packaging, for dual-mode experiment, suitable for future industrialisation and implementation with other types of photodiodes than silicon is under development. Alternative calibration methods based on purely experimental self-calibrating techniques referred to as dual-mode detectors (DMD) are demonstrated and is a generic method to provide traceability to a wide spectral range. Current packaging technologies for dual-mode detectors are limited to silicon photodiodes, as they are heated through forward bias, and have a beam position dependent thermal non-equivalence around 280 ppm/mm. Improved experimental capability of dual-mode measurements have been achieved and an IQD of 0.00 +/- 0.03 % is achieved around the central part of the detector with a radiant power of 366 µW at room temperature and thereby meeting the targets of the project already. The uncertainty is limited by systematic effects like background heating and the beam position dependent thermal non-equivalence. New and more robust packaging is designed and assembled. Initial measurements on the new modules show consistent and reproducible results with different wavelengths, stabilising temperature, beam position and background heating. However, some of those experimental sensitivities that are observed cannot be reproduced by simulations. Therefore, the measurements made so far will give valuable input to the improvement of the simulation models. The built-in reference from known ultralow losses of the PQED photodiodes has enabled the development of the dual-mode method in a robust way.

Outcomes and Impact

The project had seven presentations of research outputs from the previous project and the S-CALe Up project at the NEWRAD2023 conference held at NPL September 2023, where PQEDs for the first time had its own session. 22 stakeholders from industry, academia and metrology community receive regular updates about the project progress through the publishable summary. Presentations at the Euramet TC-PR annual meeting and input to TC2-81 “Update of CIE 065:1985 (Absolute Radiometers)” have been made in a dedicated section on PQEDs. This document is a complete draft which is now ready for voting. New detectors, measurement and simulation services will be made available for the user community at the latter half of the project. Information about project progress will be found at the project website https://scaleup.aalto.fi/. The project has conducted two training courses on request by a stakeholder in exploitation, wiring and measurements with

PQEDs and dual-mode modules. A news article about PQED chips was published on Instagram. Several presentations have been made in national conferences in Spain, Italy and Norway. Furthermore, two presentations were held at a space calibration conference in US. Furthermore, a presentation in the Finland - Japan symposium on Optics was given.

Outcomes for industrial and other user communities

Industry in general require improved and simplified measurement standards suitable for miniaturisation. The development trend is moving in the direction of more compact and integrated systems, and this project aims to enable future implementation of traceability to such systems where existing measurement techniques are not capable of providing traceability. By exploiting PQEDs in specific metrological applications, cost efficient realisations of primary photometers and power meters of importance to industry will be demonstrated. The outstanding self-calibrating technology developed in the previous project 18SIB10 chipS·CALe is expected to continue to develop towards more user-friendly solutions so that more applications can profit from it. Implementation of PQEDs in applications will bring the technology closer to the market.

Outcomes for the metrology and scientific communities

Realising primary standard techniques based on silicon photodiodes outline new ways to provide traceability based on the built-in responsivity linked to fundamental constants. With the realisation of the units and their dissemination occurring through the same artefact, the PQED provides the means to shorten the traceability chain and reduce the measurement uncertainty. The microelectronic processing makes the primary standard suitable for miniaturisation and integration into measurement systems where traceability was previously not achievable. Furthermore, the new techniques with predictable spectral response throughout the whole spectral range of interest will ensure better global harmonisation of measurement results and improved access throughout the metrological community to the highest metrological standards.

The structure in the project will enable NMIs to develop and exploit their specific niche of expertise which will be used to meet the project's overall goals, and to develop European robustness in services where more than one NMI can provide the needed services to stakeholders. This collaboration will strengthen the metrological expertise of all contributing NMIs, including small and emerging institutes, support EURAMET's goal for smart specialisation, and assure an internationally leading position.

Outcomes for relevant standards

The International Commission of Illumination (CIE) is the international standardisation organisation on all aspects of light and lighting. Today's conventional techniques for realising absolute standard detectors require expensive equipment, high skill levels to operate, time-consuming methods and interpolation functions to establish a continuous spectral response scale.

The early outcomes of this work will be shared with the following relevant CIE Division 2 Technical Committees:

- TC 2-81 Update of CIE 065:1985 (Absolute radiometers)
- TC 2-90 LED Reference Spectrum for Photometer Calibration
- TC 2-96 Revision of ISO/CIE 19476:2014 Characterization of the Performance of Illuminance Meters and Luminance Meters

The project will contribute to preparing updates to and replacements for CIE 250:2022 Spectroradiometric measurement of optical radiation sources and CIE 127:2007 Measurement of LEDs.

Many European regulations and standards refer directly or indirectly to spectrally resolved absolute measurements of optical radiation power, including European standard EN 14255 "Measurement and assessment of personal exposures to incoherent optical radiation" parts 1 to 4, and EN/IEC 62471:2008/CIE S 009:2002 - Photobiological safety of lamps and lamp systems". These standards require spectrally resolved measurements in the spectral range of about 200 nm to 2000 nm, both in the laboratory and onsite. Improved calibration uncertainty of spectrally resolved equipment will be available as a result of this project. It is also expected that PQEDs will be a suitable reference for various quantum components and sensor system platforms.

Longer-term economic, social and environmental impacts

The European photonics industry has grown from €76 billion in 2015 to €103 billion in 2019 with a growth rate of 7 % per year and a share of 16 % of the global market. Besides components and materials, the major application segments are photonics for consumers' IT, medicine and biology, environment, lighting and energy, and Industry 4.0, indicating its direct involvement in the challenges for the future. The largest segment in Europe, photonics systems for industry – was worth €19.2 billion in 2019 and accounted for a 40 % share in the global markets. Europe is well positioned in the field of photonics systems for production, i.e. industrial laser systems, semiconductor manufacturing and machine vision.

Photonics21 is one of the European Technology Platforms supporting the EU-defined KETs and has more than 3000 members from the photonic industry, research institutes, academia, and public service. Established contacts between the project consortium and Photonics21 will simplify the transfer of knowledge about project outputs to this important technology platform. Successful project outputs will meet Photonics21 WG5 strategic roadmap targets for the period 2021 to 2027 and the new roadmap from 2025-2030, where they request "maintenance-free, self-calibrating sensors, high quantum efficiency" as both a technology challenge and a research and innovation challenge for optimised value; a need outlined also by Quantum Flagship. The microelectronics-based primary standard detector is suitable for miniaturisation and we aim to integrate it with the evolving technology of Photonic Integrated Circuits (PICs) in the future.

The incoming and outgoing radiation measurements are key components of Earth Energy Imbalance (EEI). Using PQEDs as a reference in lab-based calibrations or in future spaceflights could improve future EEI measurements.

Healthcare systems are under increasing pressure due to the aging population. High accuracy radiometric measurements are needed for faster and less invasive techniques in medical diagnostic instruments. This ensures cost efficiency, for example, by enabling analyses of blood samples at the point of care and the fast return of results while the patient is present.

List of publications

[1] M. Korpusenko, A. Vaskuri, F. Manoocheri, and E. Ikonen, "Impact ionization in silicon at low charge-carrier energies,"AIP Advances 13, 085119, 2023, DOI: https://doi.org/10.1063/5.0164405

[2] M. Korpusenko, A. Vaskuri, F. Manoocheri, and E. Ikonen, "Internal quantum efficiency of silicon photodetectors at ultraviolet wavelengths," Metrologia 60, 055010, 2023, DOI: https://doi.org/10.1088/1681-7575/acf5f0

[3] Lutz Werner et al, "Quantum Yield in Induced-Junction Silicon Photodiodes at Wavelengths around 400 nm" was submitted to Metrologia by, DOI: 10.1088/1681-7575/ad310d

[4] Johanne Heitmann Solheim *et al* 2024 *Metrologia* **61** 065007, **DOI** 10.1088/1681-7575/ad7b24

[5]

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 June 2023, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Jarle Gran, JV Tel: +4764 848445; +4790 794154 E-mail: jag@justervesenet.no
Project website address: https://scaleup.aalto.fi/</td></tr>
<tr><td>Internal Beneficiaries:
1. JV, Norway
2. Aalto, Finland
3. CMI, Czechia
4. CSIC, Spain
5. INRIM, Italy
6. Metrosert, Estonia
7. PTB, Germany
8. RISE, Sweden
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<tr><td colspan="3">Associated Partners:
14. SFI Davos, Switzerland</td></tr>
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