Publishable Summary for 18SIB10 chipS·CALe
Self-calibrating photodiodes for the radiometric linkage to fundamental constants

Overview

Optical power measurement is vitally important for spectrally resolved measurements in photonics across industry, environment, health and science. Using today's costly and work intensive methods based on electrical substitution, the optical power uncertainty is limited by the properties and insufficient stability of current silicon transfer standard detectors. chipS·CALe has improved and simplified the traceability chain by taking advantage of the intrinsic quantum properties of PQED silicon photodiodes where their improved response to 99.999 % is determined by the values of fundamental constants. By developing new and improved technology, accompanied by new metrology, chipS·CALe has generated, for the first time, an "NMI-on-a-chip" for optical power. chipS·CALe has also demonstrated that responsivity over a wide spectral range can be predicted based on measurements at one wavelength only.

Need

The European Union had defined Photonics to be one of six Key Enabling Technologies (KET), which is increasingly used in climate monitoring, medical treatment, health and photonic industries, energy saving illumination (LEDs), science, and many more applications. The technological development trend moves in the direction of miniaturisation, more integrated measurement systems and distribution of standalone sensor systems in possibly remote locations. Current metrological systems were not capable of calibrating detectors in integrated systems nor remote locations. Therefore, in both the European technology platform Photonics21's strategic roadmap, "Europe's age of light" from 2021 to 2027 and Quantum Flagship's Strategic Research Agenda March 2020, integration of self-calibrating systems and products were highlighted as one of the technology, research and innovation challenges ahead.

Provided by the best laboratories in the world, the current state-of-the-art spectrally dependent uncertainty of around 0.1 % is limited by the properties and stability of current silicon transfer standard detectors. Previous projects have developed the Predictable Quantum Efficient Detector (PQED), which has proven to have an extremely low external quantum deficiency (EQD) of around 0.01 % and an undetectable drift over 9-10 years. This means that to 99,99 % the responsivity of the PQEDs are determined by the values of fundamental constants. These properties make the PQED a very attractive calibration standard detector and complies well with the low-cost, high-accuracy, transfer standard requested by CIPM's Consultative Committee for Photometry and Radiometry (CCPR). However, the low availability and lack of experimental techniques to independently predict the PQEDs internal quantum deficiency (IQD) has to date prevented it from being exploited as a stand-alone primary standard.

Furthermore, CCPR and EURAMET express the need to measure fundamental constants ratio e/h radiometrically as the ultimate comparison of the two accepted radiometric primary standard detectors, with no preference for either of them, as a contribution to a strengthened and coherent SI system defined by fixed values of fundamental constants.

This project has developed improved PQEDs, a miniaturised primary standard, as an "NMI-on-a-chip" to address these needs. By "NMI-on-a-chip" we mean a technology suitable for miniaturisation capable of being SI-traceable without external calibration. The intrinsic reference given by fundamental constants and new experimental methods to calibrate the individual PQED against its internal reference is developed and makes it a self-calibrating device suitable for integration as requested by Photonics21 and Quantum Flagship. The excellent stability, low loss and low cost meet the international radiometric community needs from CCPR through RMOs and NMIs with improved standard detectors for use also as a transfer standard detector directly linked to fundamental constants defined in the SI system.

Objectives

The overall objective of the project was to develop new experimental techniques for optical power measurements over a wide spectral and dynamic range by the production of an “NMI-on-a-chip” detector developed as a self-calibrating silicon photodiode.

The specific objectives are:

1. To develop improved and validated 3D charge-transfer models to predict the PQED internal quantum deficiency. The target prediction uncertainty is a relative uncertainty of 10 % of the internal quantum deficiency value for high values and an absolute uncertainty of 10 ppm of the internal quantum deficiency for values below 100 ppm.
2. To develop the best possible PQED photodiodes for cryogenic operation by using the improved 3D models and evaluation of passivation layer materials, passivation strategies and charge increasing techniques. To manufacture a batch of optimised PQED photodiodes and to acquire bare-chip photodiodes for room temperature operation.
3. To develop instrumentation and packaging enabling self-calibration of photodiodes. The photodiodes should be operated in both photocurrent and electrical substitution mode with sufficient sensitivity and equivalence between optical and electrical heating over a temperature range from 20 K to 300 K.
4. To provide traceability of the self-calibrating photodiodes to the revised SI by measuring the fundamental constant ratio *e/h* to 1 ppm uncertainty at cryogenic temperatures and to 0.05 % uncertainty at room temperature for wavelengths from 400 nm to 850 nm over a dynamic range from 10 nW to 10 mW.
5. To facilitate the take up of the technology and measurement infrastructure developed by the project by engaging standardisation bodies and international organisations (CCPR, CIE, EURAMET and other RMO TC-PR), the measurement supply chain (accredited laboratories, instrument manufacturers) and end users (photonics industry).

Progress beyond the state of the art

Radiometric measurements of radiant power at discrete laser wavelengths are possible with cryogenic radiometers (CR) with an uncertainty down to 0.005 %. Cryogenic radiometers are accurate for most applications, but are bulky, expensive and require a high skill level to operate. Dissemination outside discrete wavelengths is carried out with silicon trap detectors and interpolation functions. The trap detectors’ properties and insufficient stability is limiting the comparison agreement at the NMI level to a spectrally dependent dispersion around 0.1 %.

Objective 1: To improve the predicted values of PQED response with 3D simulation software.

chipS·CALe has developed a Digital Twin of the PQED photodiode, i.e., an accurate computer model simulating the real device, and used it to:

I. improve the uncertainty in the responsivity to go beyond the IQD losses and
II. independently extract the photodiode model parameters.

In this way, 3D models were used to put intelligence into the measurement system providing improved understanding and enabling new measurement techniques to be developed and applied.

Objective 2: To develop the best possible PQEDs with lower internal losses at cryogenic temperatures.

The PQED’s IQD is limited by the surface recombination velocity (SRV) and fixed oxide charge (Q_f). A search for an optimum detector passivation structure was conducted, by manufacturing a set of wafers / photodiodes with various materials and processes. The fixed charge of the different manufactured devices was found from standard capacitance voltage (C-V) measurements. The passivation material / process giving the best PQED was effectively extracted from minority charge carrier lifetime characterisations combined with improved 2D models, fed into the PQED Digital Twin. This allowed for several development iteration steps without going through a full photodiode manufacturing process.

Objective 3: To develop the required instrumentation and packaging to operate PQED type photodiodes also as a cryogenic electrical substitution radiometer (CESR).

chipS·CALe has developed a self-calibrating dual-mode detector, which can be operated as two independent primary standards with the same absorber. Heat equivalence and signal to noise ratio (SNR) at sufficient accuracy for cryogenic and room temperature operation were studied by the thermal Digital Twin of the dual-mode detector where targets in objective 4 were met.

Objective 4: To demonstrate the metrological applications of the self-calibrating photodiodes at room temperature and cryogenic temperature to unprecedented uncertainties and simplicity.

There are two different routes for self-calibration: i) photocurrent mode with fitted models and ii) dual-mode photodiodes. Exploiting the design of the developed self-calibrating photodiode, the relative measurement, and improved PQED photodiodes and their Digital Twin, allowed radiometric measurement to sub 10 ppm to be developed. The same technology can be used to operate and build self-calibrating photodiodes into applications as an "NMI-on-a-chip" and by that removing the need to move instruments to the lab for calibration. They can calibrate themselves in their own, possibly remote, and unattended location to a lower cost.

Results

Objective 1: To improve the predicted values of PQED response with 3D simulation software

The world's first Digital Twin of the PQED was developed as a 3D charge carrier simulation model. A simplified 3D simulation model was developed and fitted to experimental I-V curves. I-V measurement curves of three different PQED trap detectors (produced in an earlier project) at 476nm, 488 nm and 647 nm was fitted using one unique set of parameters for each PQED. Each I-V set consists of up to five different power levels between 100 µW and 1000 µW and have been produced by two different laboratories. When increasing the bias voltage, the IQD varies several orders of magnitude from tens of percent to tens of ppm depending on optical power, bias voltage and beam size. A simplified model was required as more advanced models have computational limitations that would be too time consuming. Still, a remarkably good fit of the predicted IQD to the IV curves was achieved despite the simplified 3D simulation model used. The excellent fit shows that the Digital Twin model describes very well the performance of the photodiode and demonstrates that a very good understanding of the physics of the device is achieved. Also, it show that measurements at one wavelength only is sufficient to predict the responsivity over a wide spectral range. A paper describing the method is published in Metrologia https://doi.org/10.1088/1681-7575/ac604b [2]. The excellent stability of previous PQEDs over more than a decade has revealed an undetectable drift of this type of detector making it an excellent carrier of a spectral response scale [4].

Extensive characterisations and validations at room and cryogenic temperature have shown that the chipS·CALe PQEDs have better performance than previously developed PQEDs. There is a very good agreement between the modelled properties of the PQED provided by its Digital Twin and actual measurements at various temperatures. These results indicate that the PQED will have better linearity and hence work at higher power levels when cooling the detector to cryogenic temperatures for wavelength up to 760 nm. For longer wavelengths the picture is more complex as the reduced absorption coefficient causes photons to penetrate beyond the depth of the photodiode. At room temperature, the total losses of the PQED, including internal losses, reflectance, potential absorption and scatter, was confirmed to be as low as 10 ppm (with 30 ppm uncertainty), stretching the limits of the cryogenic radiometer. This is two orders of magnitude better than world-wide commonly used transfer standard detectors. However, the improved properties of the new PQED led to a significantly extended computational time. Reducing the computational time is a task for the future.

The work on limitations in PQED prediction uncertainty has revealed that quantum yield (or gain) has to be taken into account for wavelengths below 450 nm for high accuracy applications better than 200 ppm. Measurements on two different PQEDs with different IQD showed the same yield value when correcting for the individual differences in IQD. It was demonstrated that the yield can be modelled with an agreement to measurements of around 100 ppm from 400 nm to 450 nm and hence predictability in the PQEDs response is maintained down to 400 nm by post processing the IQD. The objective was successfully met.

Objective 2: To develop the best possible PQEDs with lower internal losses at cryogenic temperatures

Photodiodes with record low external quantum deficiency were successfully manufactured in chipS·CALe and have thereby reached the most important goal of this project. Different passivation materials (SiO_2, SiN_x and Al_2O_3) were studied. Surface recombination velocity and fixed oxide charge are, based on simulations, highlighted as the key parameters for optimising working PQED photodiodes. The SiN_x passivation process recipe was without any optical absorption in the nitride and a fixed charge 2-5 times higher than well working qu-candela photodiodes was achieved. Measurements of their responsivity show that the photodiodes manufactured in chipS·CALe are the best ever produced for calibration purposes. The increased fixed charge improves the linearity of the photodiodes and enables the dual-mode techniques to be exploited at higher power and thereby with better signal to noise ratio (SNR).

A set-up for charge carrier lifetime measurements from 80 K to 300 K has been successfully developed and used to evaluate different process test samples. To the best of the consortium's knowledge, this is the first time lifetime measurements over such large temperature range has been performed. Simulation models were used to separate bulk lifetime and surface recombination velocity from the lifetime measurement. Unfortunately, the lifetime was reduced on all test samples when reducing the temperature. This means that photodiode parameters are changing with temperature and the expected reduction of losses at low temperature will not be fully achieved. Prediction of the expected photodiode responsivity with various passivation layers, was done based on lifetime measurements. This demonstrates a new independent measurement technique of the photodiode responsivity, based on material characterisations and simulations only.

At room temperature, the IQD of the two produced photodiode types was found from measurements of photocurrent ratios between CESR and chipS·CALe PQEDs. The experimental results were consistent with the predicted IQD of 1-10 ppm and 10-100 ppm for the two types, respectively, and agree with the predictions based on lifetime measurements. There is therefore agreement between the two independent realisations based on the Digital Twin PQED – one from lifetime measurements and one from IV curves, but potential non-accounted error sources may be present.

The IQD performance was found to be insensitive to passivation layer thickness. This enabled us to minimise the reflection losses (for both Al2O3 and SiNx) by optimising the oxide layer thickness based on spectroscopic ellipsometry. This resulted in passivation materials with known refractive indices and photodiodes with optimised EQD. Our examinations indicate that responsivity of these photodiodes mounted in a 7 reflection trap structure deviates in the1 ppm range from an ideal photodiode whose responsivity is given by fundamental constants and the applied wavelength only. Hence, the excellent quality of the manufactured photodiodes reduces the need for accurate prediction of the EQD value. The work towards improved PQED photodiodes is published in Sensors 2021, 21, 7807 https://doi.org/10.3390/s21237807 [1]. The objective was successfully met.

Objective 3: To develop the required instrumentation and packaging to operate PQED type photodiodes also as a cryogenic electrical substitution radiometer (CESR).

The purpose of the objective was to develop the technology enabling electrical substitution of optical power measurements on silicon photodiodes. Packaged devices for both room temperature and cryogenic temperatures have been developed based on thermal models with COMSOL Multiphysics. During electrical substitution of the dual-mode device, the optical heating of the photodiode is made in the centre of the photodiode, whereas electrical heating occurs around the edges. This difference in heating profiles causes a challenge, as the thermal measurement method (electrical substitution) is dependent on equal temperature rise from equal amounts of optical and electrical power. The dual-mode detector design was thus optimised to reduce this thermal non-equivalence to a minimum. With the current design, simulations show that optical and electrical heat equivalence meeting the target uncertainties is achievable.

For room temperature, thermal simulations revealed that the heat equivalence is limited by radiation losses. As a result of the difference in heating profiles, the thermal equivalence changes with around 280 ppm/mm with beam spot position in the vertical direction. The change in the horizontal direction is negligible in comparison. This slope was confirmed experimentally with low noise electrical substitution measurements https://doi.org/10.1088/1681-7575/ac6a94 [3]. The sensitivity with beam position depends on the emissivity of the photodiode, which has been carefully measured. An improved packaging with better heat equivalence at room temperature is designed but not tested.

At cryogenic temperatures, below 1 ppm heat equivalence in the simulated design has been achieved. Different dual-mode modules have been manufactured according to the optimised design for both room and cryogenic temperature and has been tested for experimental set-ups under objective 4.

In addition to the thermal equivalence, dual-mode operation depends on optimised signal to noise ratio in both the thermal and electrical measurements. Evaluation of various temperature sensors for room and cryogenic temperature was conducted to find the best ones for the purpose and were implemented with the chipS·CALe produced photodiodes. In addition, to reduce reflection losses, a new mechanical three-reflection trap detector optimised for dual-mode set-ups, have been designed and manufactured. Dual-mode detectors based on chipS·CALe photodiodes with the best temperature sensors were assembled in the traps and measured. The objective was successfully met.

Objective 4: To demonstrate the metrological applications of the self-calibrating photodiodes at room temperature and cryogenic temperature to unprecedented uncertainties and simplicity

Experimental set-ups for dual-mode photodiode operation are established, one for room and one for cryogenic temperatures. The work has triggered new ideas, and two different types of measurement procedures have been developed and tested, compared to the initially planned one. Furthermore, three different calculation algorithms are tested and agree within their combined uncertainties. Time constants in the dual-mode modules have been measured both during optical and electrical heating and the measured time constants are in fairly good agreement with the modelled time constants across the temperature range from 25 K to 300 K. The high fixed charge of chipS·CALe photodiodes ensures linearity at higher power levels and the room temperature dual-mode experiment can therefore be run with improved SNR. Room temperature dual-mode experiments have improved significantly in terms of signal-to-noise ratio since the start of the project. Work on thermal stabilisation, electrical shielding and improved measurement bridge have resulted in excellent measurement of the IQD of the assembled three-reflection trap dual-mode chipS·CALe photodiode, with a Type A uncertainty of 13 ppm for a power level of 1250 µW in a 6 hour long measurement sequence. The excellent SNR enabled the experimental verification of the modelled change in thermal non-equivalence with beam position, resulting in an apparent IQD changing 280 ppm/mm. The work further revealed that a dust particle on the optical window influenced the IQD measurement with 130 ppm and that design care has to be taken into account when measuring in dual-mode on detectors in a trap structure.

It has been demonstrated that the dual-mode technique is sensitive to wiring conditions and that the two different methods differ at lower power levels but converges at higher power levels around 1 mW for both room temperature and cryogenic temperatures. The IQD measured from dual-mode operation is higher than the expected IQD from the manufacturing of the photodiodes. Optimisation and exploration of achievable uncertainty of the method will be the main focus ahead.

Operating the dual-mode detector at cryogenic temperatures is believed to reduce the uncertainty by several orders of magnitude compared to room temperature. Measurements of dual-mode detectors at cryogenic temperatures have, according to our thermal simulations, improved heat equivalence to better than 1 ppm. In addition, operating the detector at cryogenic temperatures ensures reduced thermal noise, lower heat capacity, increased heat conductivity, lower time constant and better photodiode linearity as compared to room temperature. Improved thermal stabilisation was achieved at the cryogenic measurements and heat cross talk between photodiodes in the trap detector was reduced. The best performance at cryogenic temperatures was achieved at around 110 K in terms of SNR. The room temperature part of the objective was successfully met and guidelines on how to achieve the cryogenic component of the objective have been reported.

Impact

Many consortium members demonstrated project results in the International Conference on New Developments and Applications in Optical Radiometry (NEWRAD 2020, Boulder, CO, US) which was postponed as a digital conference in 2021. The project coordinator was invited by the scientific organising committee to give an oral presentation. In total 7 contributions from the chipS·CALe project were presented at the virtual conference. In total 19 presentations have been given about the project outputs at various conferences.

The project website was developed at the beginning of the project to share our latest publishable results (http://chipscale.aalto.fi/), such as the publishable summary, publications in journals, posters, presentations from conferences, etc., and the project's page on the ZENODO repository (https://zenodo.org/communities/empir_chipscale/?page=1&size=20) allows the publishing of documents with a unique DOI number.

The material research in chipS·CALe has helped SINTEF, as a small-scale detector manufacturer, optimise the manufacturing processes and has resulted in a new SiNx production recipe. Two new and different fabrication processes of PQED type photodiodes are established and SINTEF is now able to offer this technology at full manufacture level. The successful manufacturing of the *mise en pratique* approved primary standard PQEDs closes the availability gap of these devices and opens up for wider exploitation of the PQEDs. The work towards manufacturing improved PQEDs with a production batch predicted responsivity is published in Sensors. Work on making the improved chipS·CALe PQEDs commercially available is progressing. The working principle of the PQED photodiode is explained in an animation video produced in the project [·https://www.youtube.com/watch?v=aNwP1T8e73M].

Impact on industrial and other user communities

The production volume of the European Photonics industry accounted for € 103 billion in 2019. Industry in general requires accurate and cost-efficient calibration methods to maintain traceability to an SI unit of their methods and equipment. Working out an exploitation plan and making the self-calibrating photodiodes commercially available were the most important criteria for uptake of the technology developed in chipS·CALe. Commercialisation of developed products will be targeted after the project ends. The published animation video helps users understand how the devices work and make it appealing to use the devices. The video is also instrumental in the promotion of the project in scientific talks, on the website and in the approach to the wider user community.

Photonics21 is one of the European Technology Platforms, supporting the Key Enabling Technologies (KET) defined by the EU, and has more than 2500 members from the photonic industry, research institutes, academia and public service. The established contact between the consortium and Photonics21 has simplified the transfer of knowledge about project outputs to this important technology platform. In Photonics21 WG5 strategic roadmap "Europe's Age of Light! How photonics will power growth and innovation" for the period 2021-2027 they have already implemented the ideas of chipS·CALe and request "maintenance-free, self-calibrating sensors" as both a technology challenge and a research and innovation challenge for optimised value.

Impact on the metrology and scientific communities

The principles and methods developed in chipS·CALe will support and strengthen the implementation of the new SI system and the radiometric community's position within the SI. The CCPR has requested the possibility of making radiometric measurement of fundamental constants, as has been demonstrated in the project by comparing two independent and inherently different primary standards in one device. The CCPR has also requested better and more stable measurement standards. CCPR Intercomparison in the 300 nm to 1000 nm spectral range is postponed because present photodiodes are not sufficiently stable. Previous PQEDs have shown an undetectable drift over 10 years. With the commercialisation of the chipS·CALe photodiodes the community will have a new chip-scaled device for measuring optical power with unprecedented accuracy in possibly remote operation.

The Researcher Mobility Grant from a researcher from PMOD/WRC is a demonstrator of an early uptake of chipS·CALe technology by the scientific community. PMOD/WRC plays a crucial role in maintaining quality standards in global climate monitoring programmes. The purpose of the RMG was to improve the standard laboratory measurements from the existing 2 % to better than 0.5 %. Promising results was achieved, but more work is required before full implementation can be made.

The validated Digital Twin PQED (3D simulation tool) will be used as a reference to establish a new service for owners of PQEDs based on customer's own relative characterisations. The new service will support laboratories make independent realisations based on PQEDs alone. Presently, computation time limits the usability of the 3D simulations in a computation service, despite the excellent results. Promising results have also been obtained with 1D simulation models, but considerable effort in programming and validation is required before developing a service based on a calibrated 1D model. The self-calibrating device will also help a number of project partners to reduce their CMC uncertainty for in-house customer calibration service. In a perspective beyond chipS·CALe, other European NMIs can develop their capacity based on the self-calibration technology. Prediction of PQED response over a wide spectral range, enabled by its Digital Twin, can be made from characterisations done at one wavelength with an extended characterisation interval due to the excellent stability.

There exist concrete plans in granted projects to exploit PQED photodiodes in conjunction with photonic integrated circuits (PICs) as an absolute embedded standard for extended dynamic range of optical power. This is intended as a first demonstrator and one possible way of exploiting photodiodes in integrated photonics which existing standards are incapable of doing. The embedded reference may be exploited in the future as detectors and their Digital Twin technology become more mature and wide-spread in various applications.

The project coordinator informed the EURAMET TC-PR about the project achievements in workshops in conjunction to the annual TC-PR meetings 2021-2023 including emphasis on the successful manufacturing of improved predictable quantum efficient detectors and ways to exploit them.

Impact on relevant standards

CIE is the international standardisation committee for light and lighting. CIE – Division 2: Physical Measurement of Light and Radiation has requested that the new experimental techniques developed in chipS·CALe are fed into the ongoing revision of TC2-81 Update of CIE065:1985 (Absolute Radiometers). CIE welcomes the idea of an "NMI-on-a-chip" and joined the stakeholder committee to closely follow the progress of chipS·CALe*.* The technical committee leader of TC2-81, a consortium partner in chipS·CALe, presented the project at the CIE 29th Quadrennial Session in Washington June 2019, and has ensured that PQEDs and their use is implemented in the new standard document CIE TC-81 CIE065:1985. It is foreseen that PQEDs could be exploited in future standards and measurement equipment of interest to CIE. Implementation in global standards is expected to further promote and trigger the use of these devices.

Longer-term economic, social and environmental impacts

Photonic sensors are key enablers in a wide range of industrial manufacturing and service sectors including: healthcare, surveillance, and automotives. The resultant leverage makes photonic metrology and sensors a multi-billion euro industry. Improved sensors and simplified traceability will contribute to an improved efficiency in the photonic sensor industry.

The fraction of the population above 65 years age is increasing and this will put more pressure on the health care system. Optical methods are used increasingly both for diagnosis and therapy. Supporting optical methods with improved and simplified calibrations will contribute both on the improved diagnosis and optically based therapy side, as they are known to be faster and less invasive compared to previous surgical methods.

About 2/3 of the Essential Climate Variables (ECV) used to monitor impact of climate change require some sort of optical measurement. SI traceable measurements over decadal timescales require new instrumentation to detect small trends in ECVs from a background of natural variability. A self-calibrating instrument making climate quality measurements in the field, ideally in an autonomous manner, would meet this requirement and is mentioned as an important application of basic science in the environmental roadmap for photometry and radiometry. The self-calibration detector developed in this project is a first step towards such an instrument, and will have a major impact on the quality of Earth Observation data.

List of publications

1. Koybasi O. et al. High Performance Predictable Quantum Efficient Detector Based on Induced-Junction photodiodes Passivated with SiO2/SiNx. *Sensors* **2021**, *21*, 7807. https://doi.org/10.3390/s21237807

2. Tran T. et a..: Determination of the responsivity of a Predictable Quantum Efficient Detector over a wide spectral range based on a 3D model of charge carrier recombination losses. *Metrologia* **59** 045012, https://doi.org/10.1088/1681-7575/ac604b

3. Ulset M. et al.: Dual-mode room temperature self-calibrating photodiodes approaching cryogenic radiometer uncertainty. 2022 *Metrologia* **59** 035008, https://doi.org/10.1088/1681-7575/ac6a94

4. Porrovecchio G. et al.: Long-term spectral responsivity stability of predictable quantum efficient detectors. 2022 Metrologia **59** 065008 https://doi.org/10.1088/1681-7575/ac938c

5. Korpusenko M. et al.: Optical studies of a High-Performance Predictable Quantum Efficient Detector Based on Induced-Junction Photodiodes Passivated with SiO2/SiNx. Engineering proceedings, 2022, 21 (1), 39, https://doi.org/10.3390/engproc2022021039

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

Project start date and duration:	01 June 2019 (36 months + 6 months extension = 42 months)	
Coordinator: Dr Jarle Gran, JV Project website address: http://chipscale.aalto.fi/index.html	Tel: +47 64 84 84 45	E-mail: jag@justervesenet.no
Internal Funded Partners: 1. JV, Norway 2. Aalto, Finland 3. CMI, Czech Republic 4. CNAM, France 5. INRiM, Italy 6. Metrosert, Estonia 7. PTB, Germany 8. TUBITAK, Turkey	External Funded Partners: 9. IFE, Norway 10. SINTEF, Norway 11. USN, Norway	Unfunded Partners:
RMG1: PMOD/WRC, Switzerland (Employing organisation); JV, Norway (Guestworking organisation)		