Aalto University

MIKES

Predictable Quantum Efficient Detector (PQED)*

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Outline

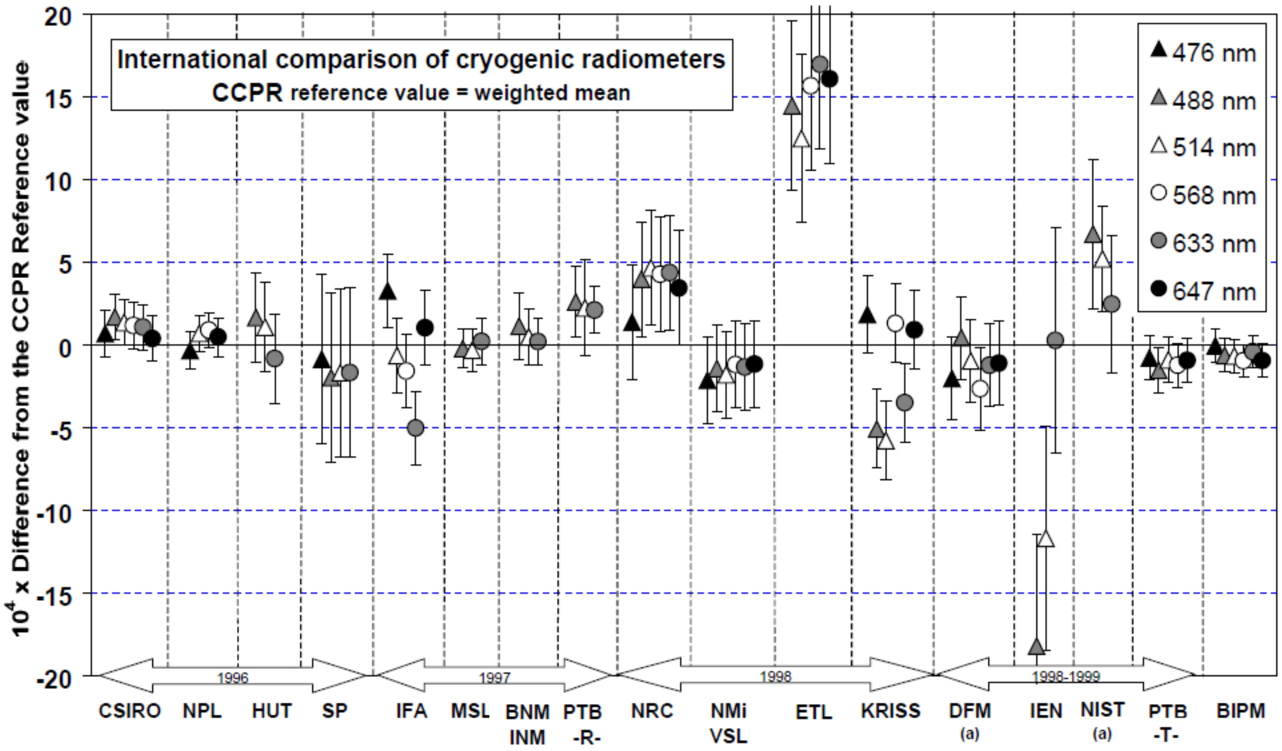
- ✓Motivation for developing PQED
- ✓What is PQED?
- ✓How is PQED different from other silicon detectors?
- ✓Tools and techniques for predicting the quantum efficiency
- ✓Characterization of PQED
- ✓Conclusions

Motivation

Achieve lower uncertainty in absolute optical power measurements

- ☐ Silicon photodiode self-calibration technique : Geist et al 1980
- ☐ Room temperature silicon trap detectors : Zalewski et al 1983
  Typical uncertainty : 2000 ppm
- ☐ Development of Cryogenic radiometers : Martin et al 1985, Varpula et al 1988, ...
  Typical uncertainty : 100 ppm

Performance Validation of Cryogenic Radiometers (CCPR-S3 comparison)



Measurement with Crygenic Radiometers requires expertise, it is time consuming and expensive ➔ **something better**?

How to reach 1 ppm uncertainty in optical power?

A visionary approach proposed by Geist et al* in 2003

Envisaged uncertainty : 1 ppm

Identify and control phenomena that limit near-100% quantum efficiency

- ❖ Custom-made self-induced photodiodes from p-type high-purity wafer
- ❖ Clean room operation
- ❖ Trap detector structure
- ❖ LN temperature
- ❖ High reverse bias voltage

* J. Geist, G. Brida and M. L. Rastello, Prospects for improving the accuracy of silicon photodiode self-calibration with custom cryogenic photodiodes, Metrologia **40**, 132-135, 2003.

What is PQED?

Predictable Quantum Efficient Detector (PQED) is

- ☐ a silicon detector

What is PQED?

Predictable Quantum Efficient Detector (PQED) is

☐ a silicon detector

☐ using large custom-made self-induced photodiodes
☐ in a trap configuration to control reflectance losses
☐ behind a Brewster window

What is PQED?

Predictable Quantum Efficient Detector (PQED) is

- ☐ a silicon detector

- ☐ using large custom-made self-induced photodiodes
- ☐ in a trap configuration to control reflectance losses
- ☐ behind a Brewster window

- ☐ with spectral responsivity predictable within 1 to 100 ppm

Spectral Responsivity of a Quantum Detector

$$R(\lambda) = \frac{e\lambda}{hc}\left(1-\rho(\lambda)\right)\left(1-\delta(\lambda)\right)$$

$e\lambda/hc$: responsivity of an **ideal quantum detector** expressed by fundamental constants

λ : vacuum wavelength

Non-ideal factors

$\rho(\lambda)$: reflectance

$\delta(\lambda)$: internal quantum deficiency (IQD)

Ideal silicon crystal without impurities and lattice defects

→ no recombination losses of holes and electrons!

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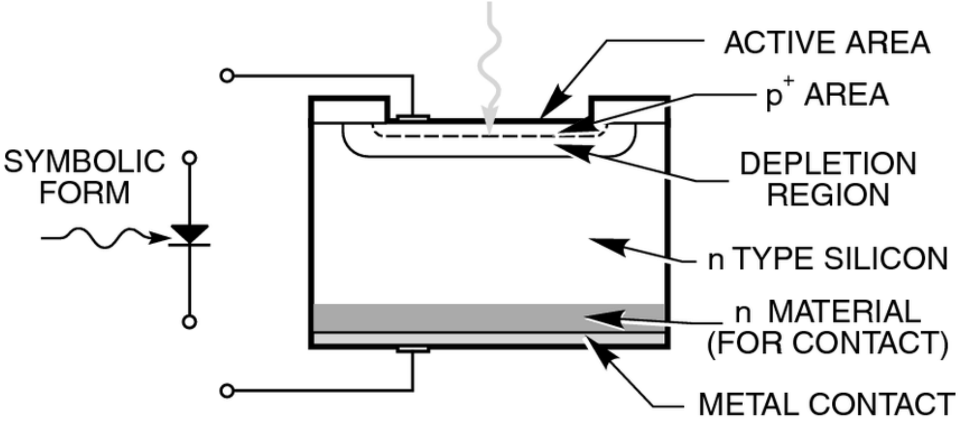
Features of conventional silicon photodiodes

Disadvantages:

☐ pn junction is made with impurity doping ➔ recombination losses due to impurities

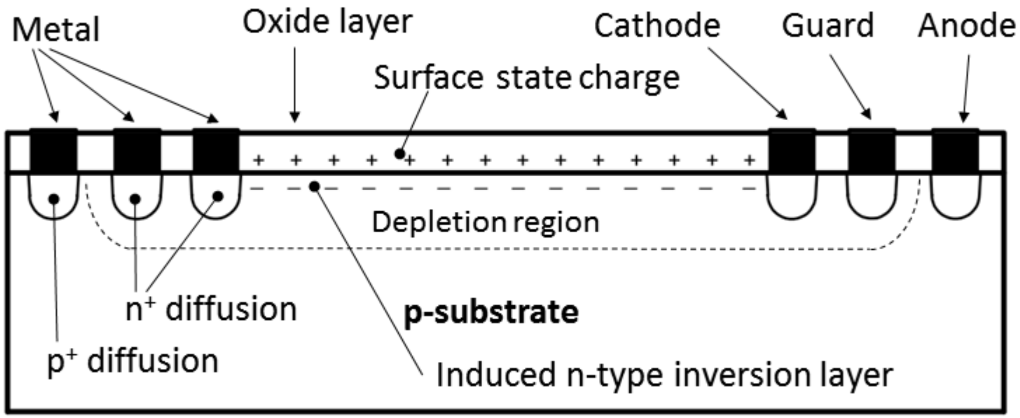
☐ doping level of $>10^{14}$ cm^{-3} ➔ narrow depletion region reduces charge-carrier collection efficiency

Structure of an ordinary photodiode made of n-type silicon



☐ Advantage: Minimal oxide thickness on top of the silicon substrate

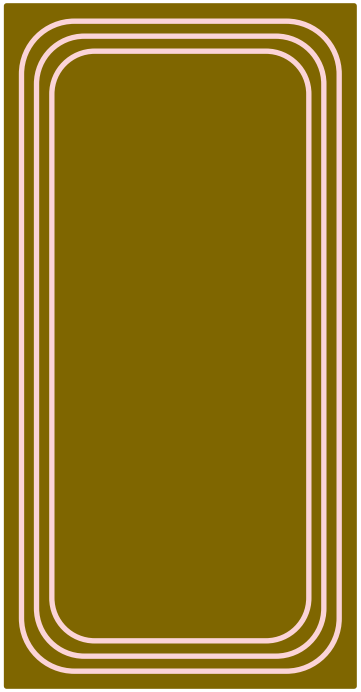
Design of the PQED photodiodes



cross section of the PQED photodiodes

- Low doping level of $2 \cdot 10^{12}$ cm^{-3} in p-type silicon
- Self-induced np junction (no additional doping)
- Thermally grown **thick** oxide layer >200 nm

Please visit poster presentation by *M. Sildoja et al*, PQED I: Photodiodes and design, DBR_OR_047.



Top view of a photodiode chip, 11 mm x 22 mm

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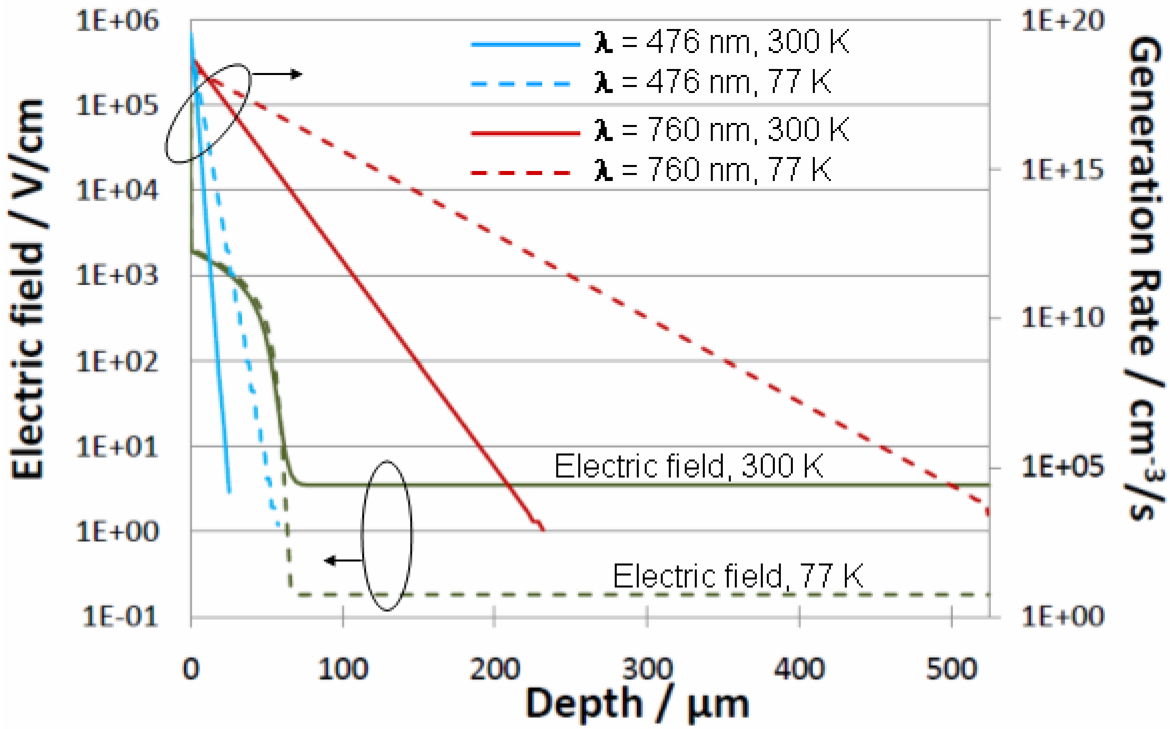
Charge-carrier generation in PQED photodiodes



Penetration depth inceases at 77K

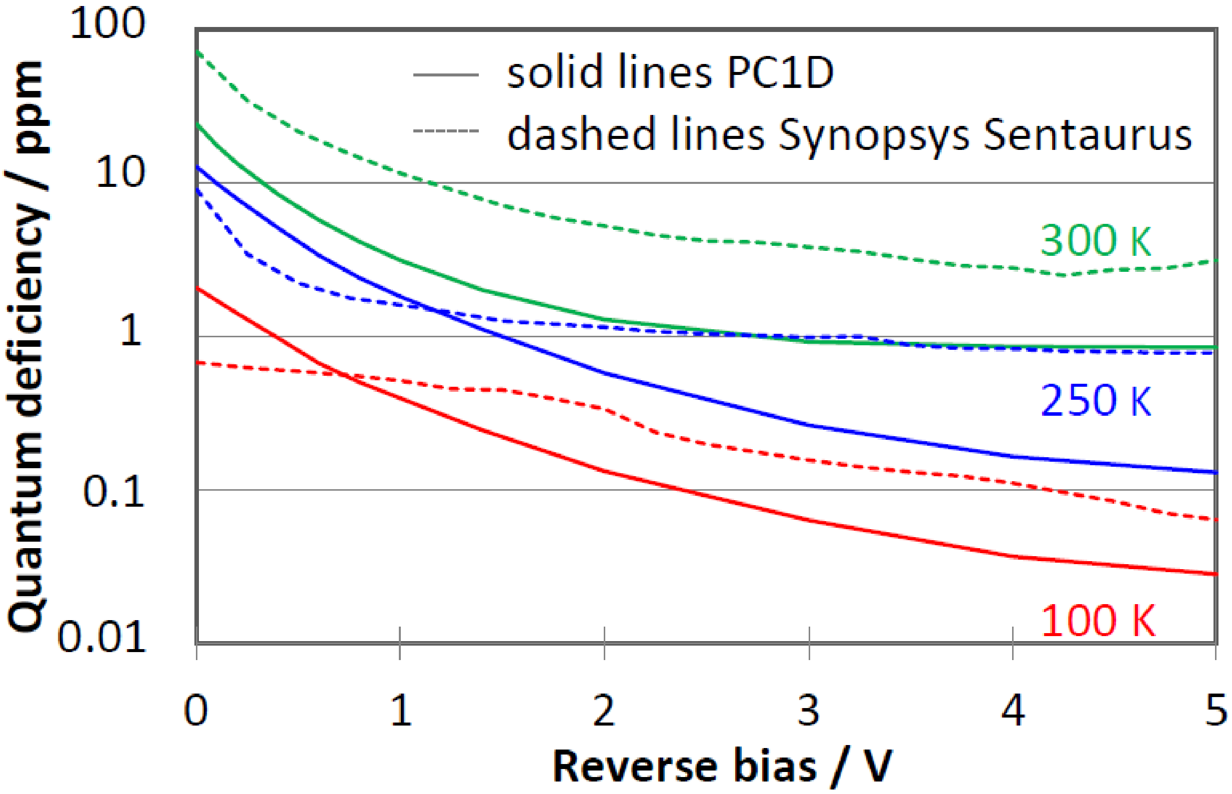
At small depth in silicon: almost all charge carriers are generated at short wavelengths and with large E field ➔ low IQD

For long wavelengths: part of charge carriers move by slow diffusion
➔ recombination losses

Improved mobility of charge carriers at 77K

IQD = internal quantum deficiency

Reliability of IQD Predictions



Comparison of IQD predictions of two software packages

- Easy to use one-dimensional PC1D

- Advanced three-dimensional Sentaurus

Conclusion: PC1D results are reliable within a factor of ten

Please visit poster presentation by J. Gran et al, Simulations of PQED with PC1D, DBR_PO_044

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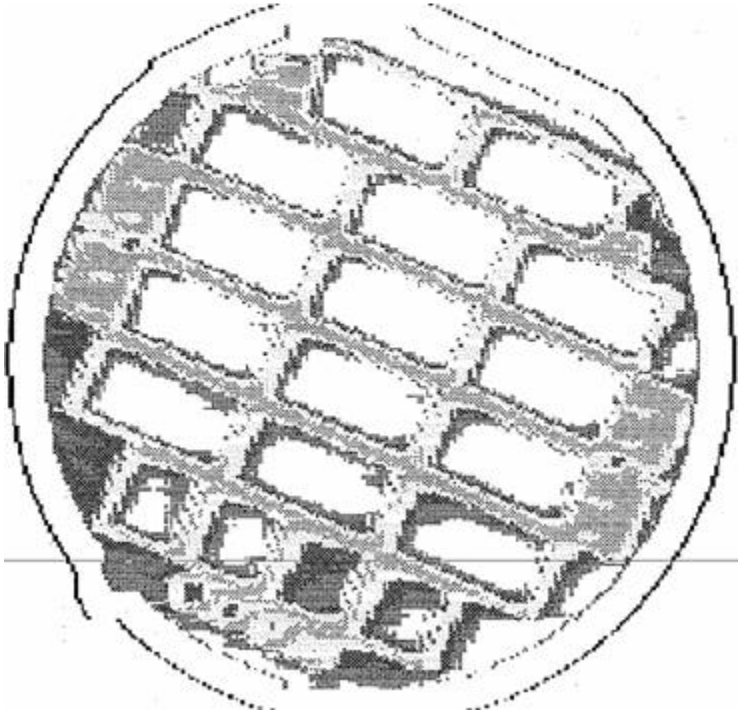
Diffuse reflectance of photodiodes

- Measurements of the final processed wafer
- The white areas (photodiodes) correspond to diffuse reflectance **less than 0.05 ppm**
- The grey areas indicate high diffuse reflectance (about 0.5 ppm) from the implanted electrodes
- No change in the diffuse reflectance after cutting and washing the photodiodes

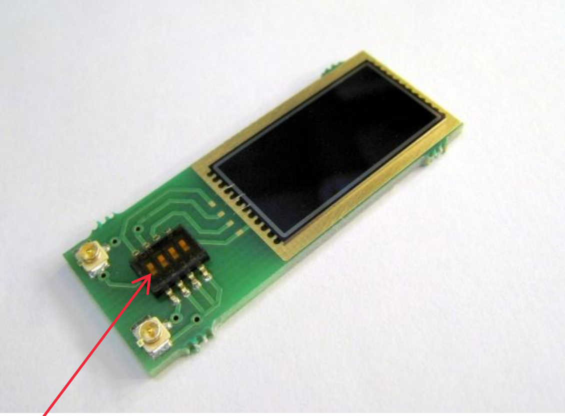


Wafer processing made by VTT
Diffuse reflectance measurements by Okmetic

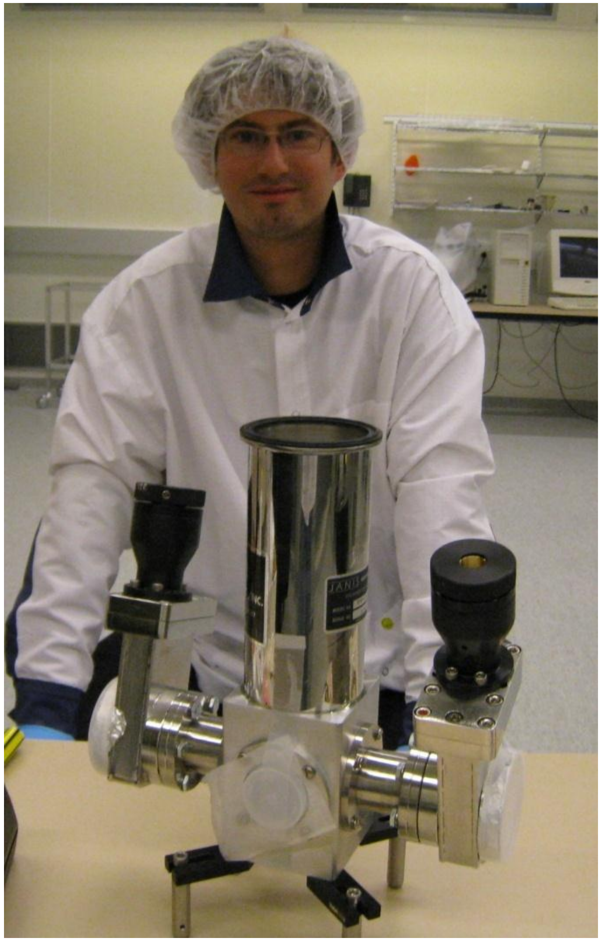
Photodiode sizes: 11 mm x 22 mm and 11 mm x 11 mm

Preparations for test measurements

After the wafer tests, we put the PQED photodiodes in clean environment in a liquid nitrogen cryostat

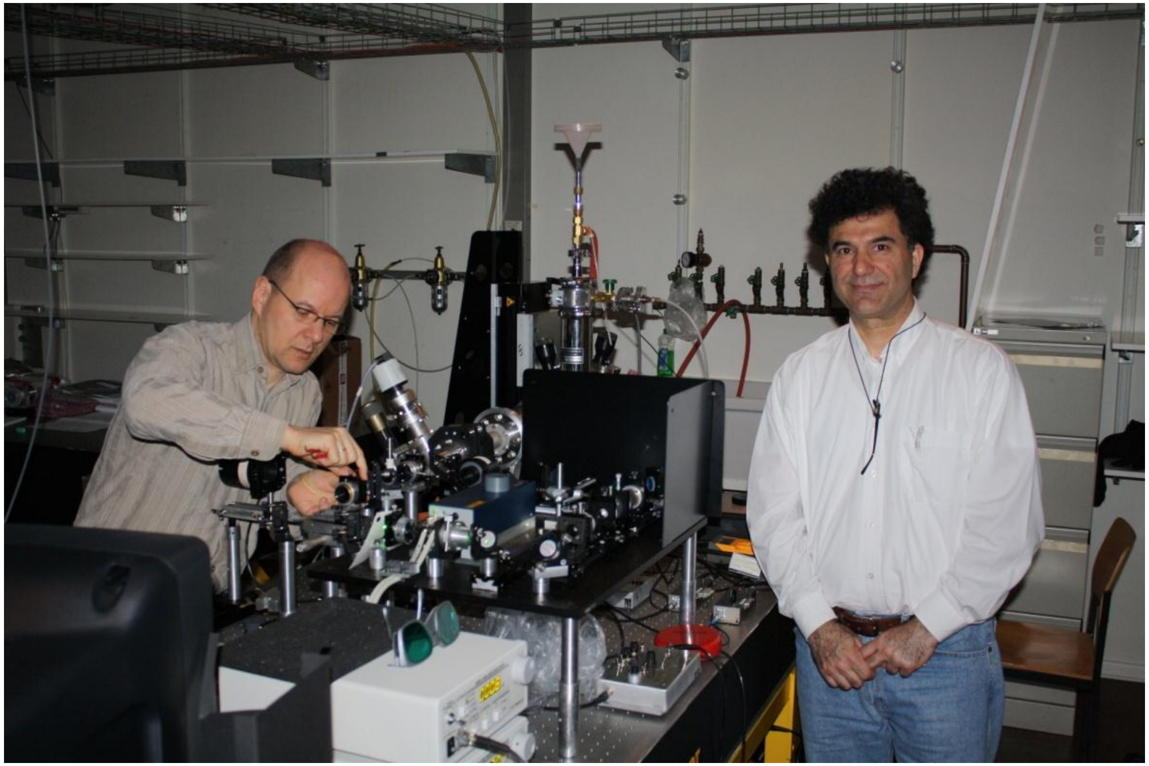


DIP switch to test different operational modes

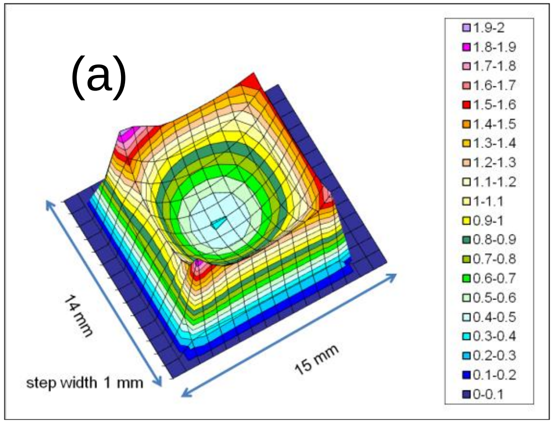


Optical setup for uniformity measurements

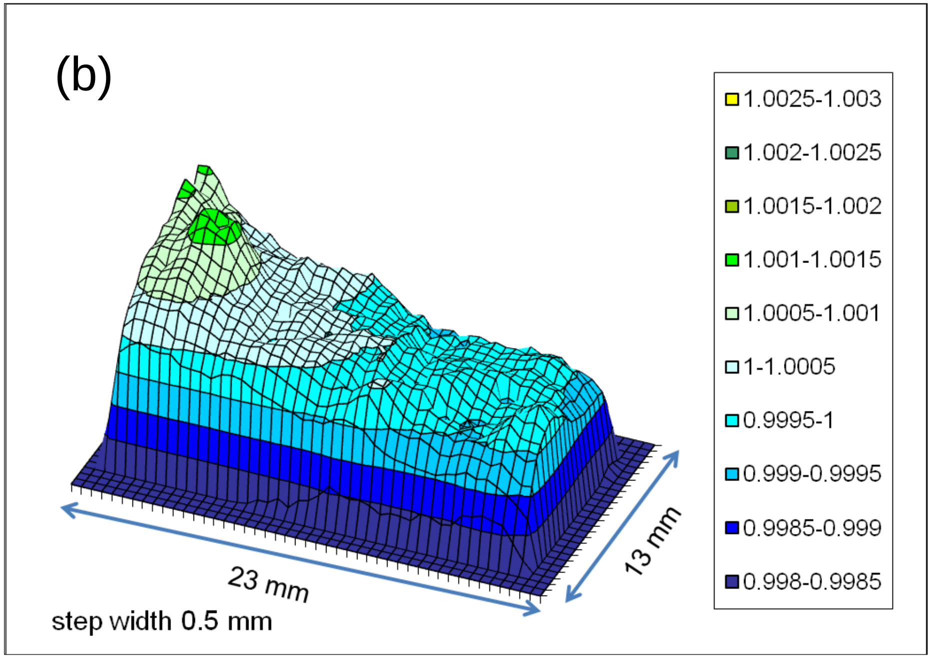
- ✓ Stationary Brewster window
- ✓Motorised translation stages
- ✓Stabilised DFB laser at 760nm



Uniformity of photodiodes



Relative uniformity of 100 nm oxide layer photodiode of the first batch.

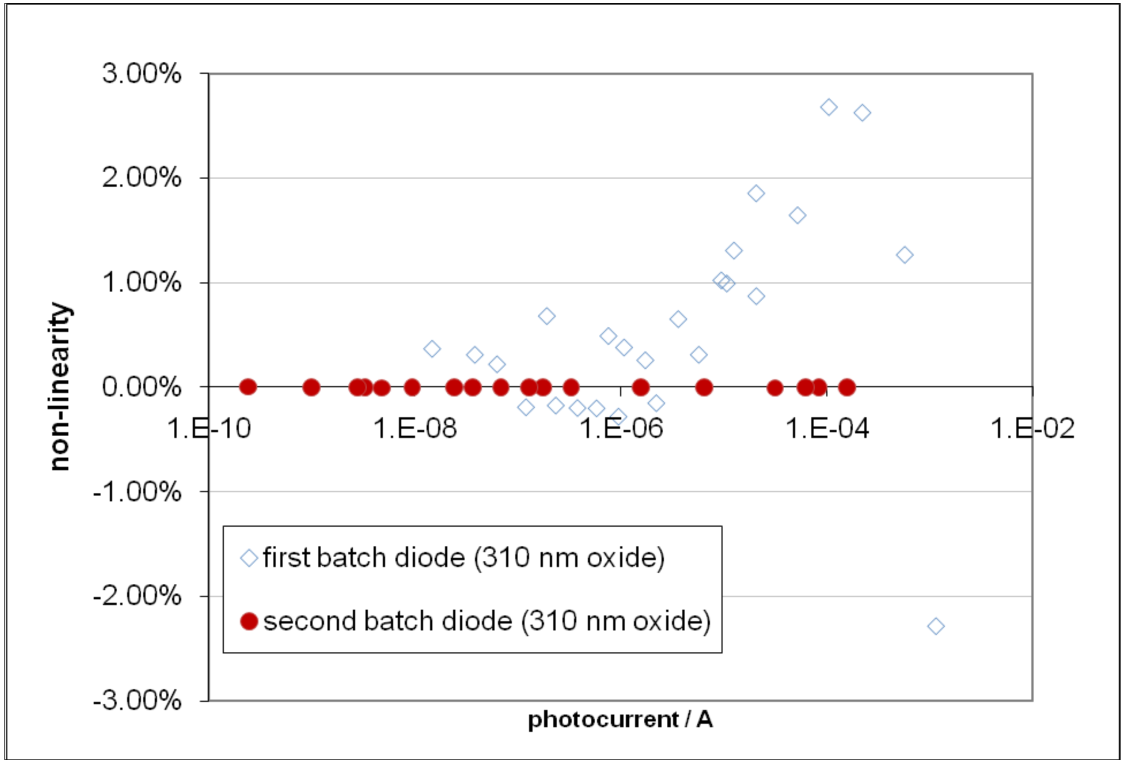


Relative uniformity of 210 nm oxide layer photodiode of the second batch at 760 nm
Uncertainty= 43 ppm
Note that the scales of (a) and (b) differ by a factor of 400

Please visit poster presentations by
I. Müller et al, PQED II: Characterization results, DBR_OR_029
S. Hoem et al, Physics of self-induced photodiodes, DBR_PO_042

Linearity of PQED photodiodes

Comparison of the linearity of two photodiodes from the first and second batch at of 760 nm.



Second batch: No significant nonlinearity within the standard uncertainty of 25 ppm

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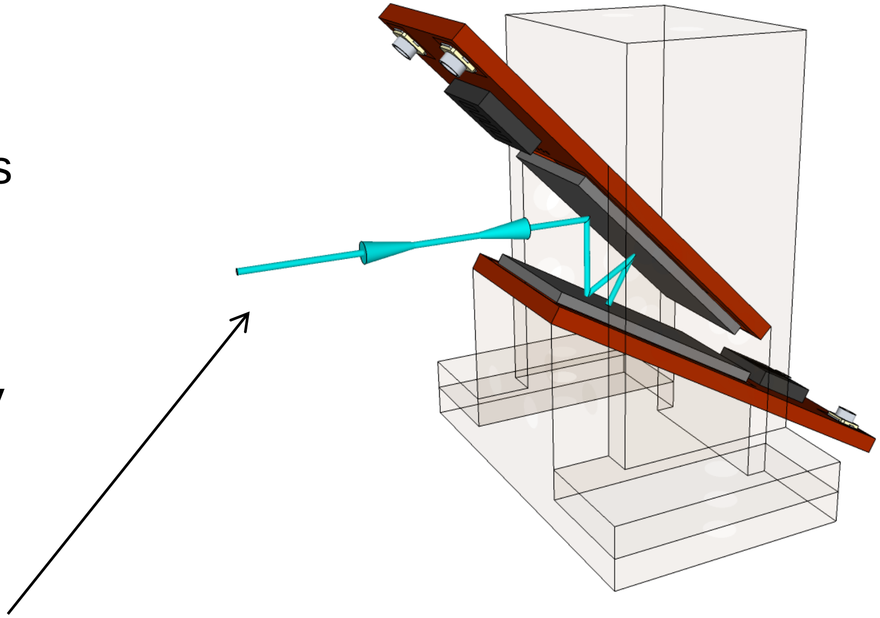
Preparation of PQED for responsivity measurements

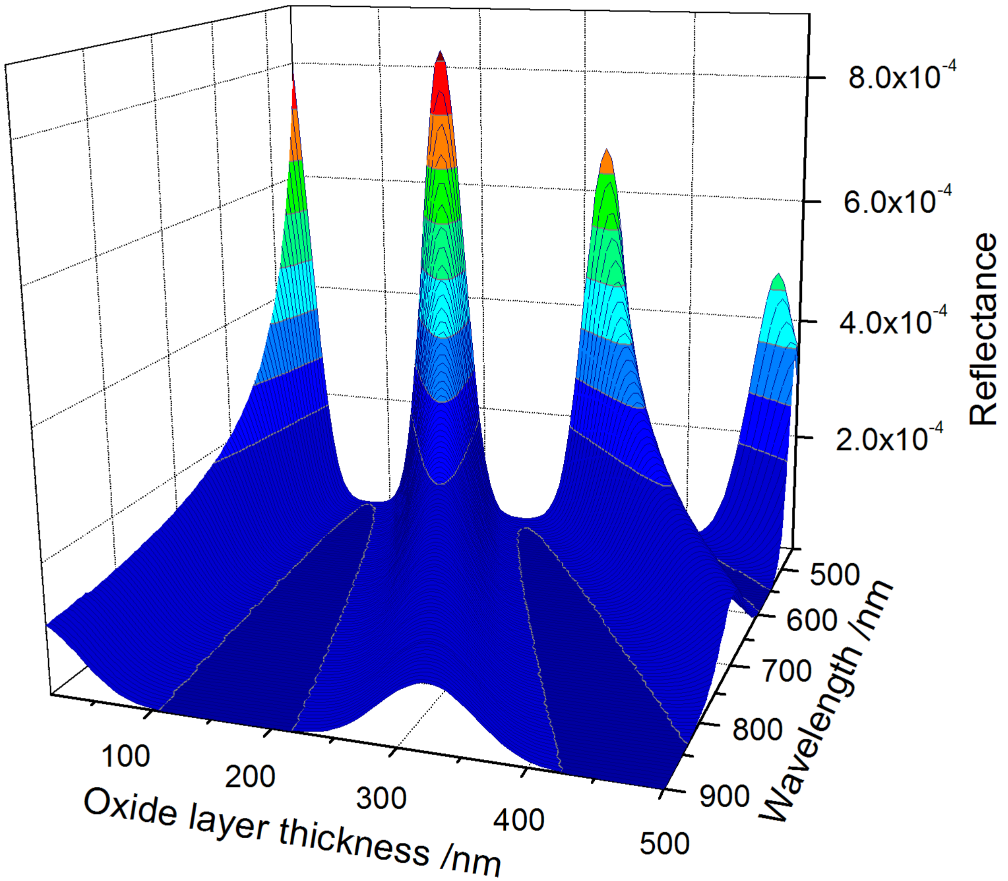
- ☐ PQED trap detector constructed of two photodiodes

- ☐ The structure allows minimum loss of optical power due to reflection and possibility for alignment



Entering laser beam returns from the trap structure after 7 reflections

Specular reflectance of PQED

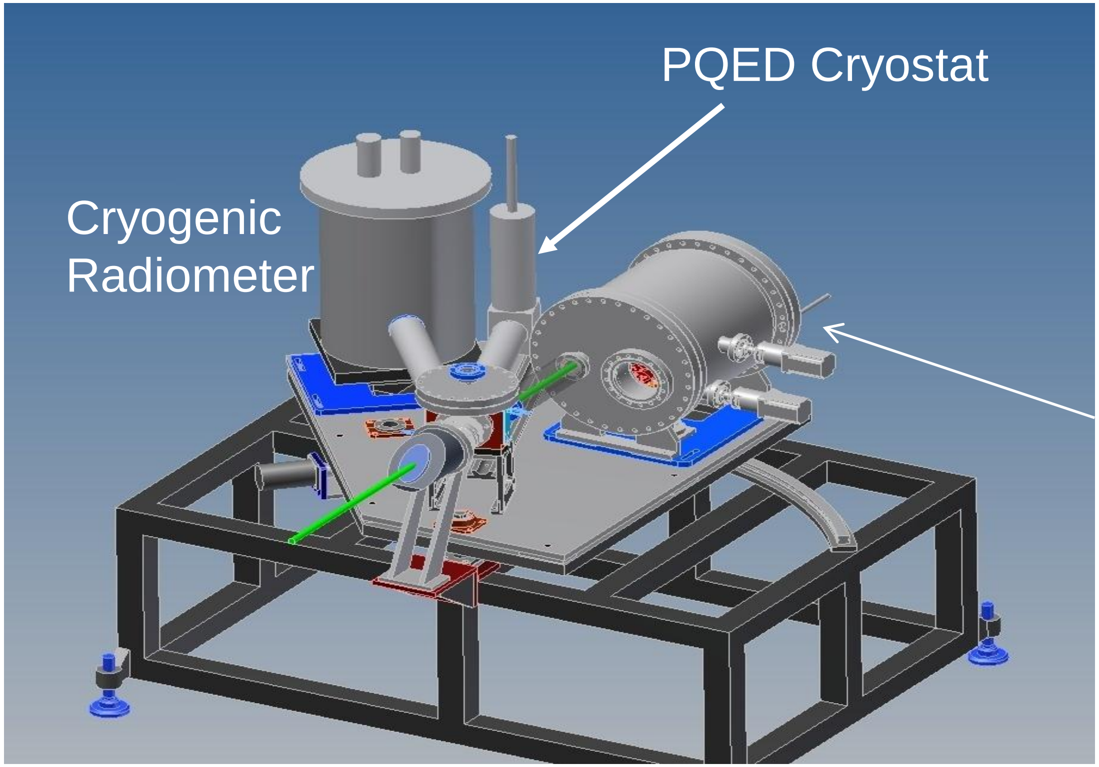


Reflectance from the PQED with 7 reflections and two similar photodiodes

The PQED reflectance is
30 ppm measured at 476 nm

M. Sildoja et al, Reflectance calculations for a predictable quantum efficient detector, Metrologia 46, S151-S154, 2009.

Setup for PQED-Cryogenic radiometer comparison

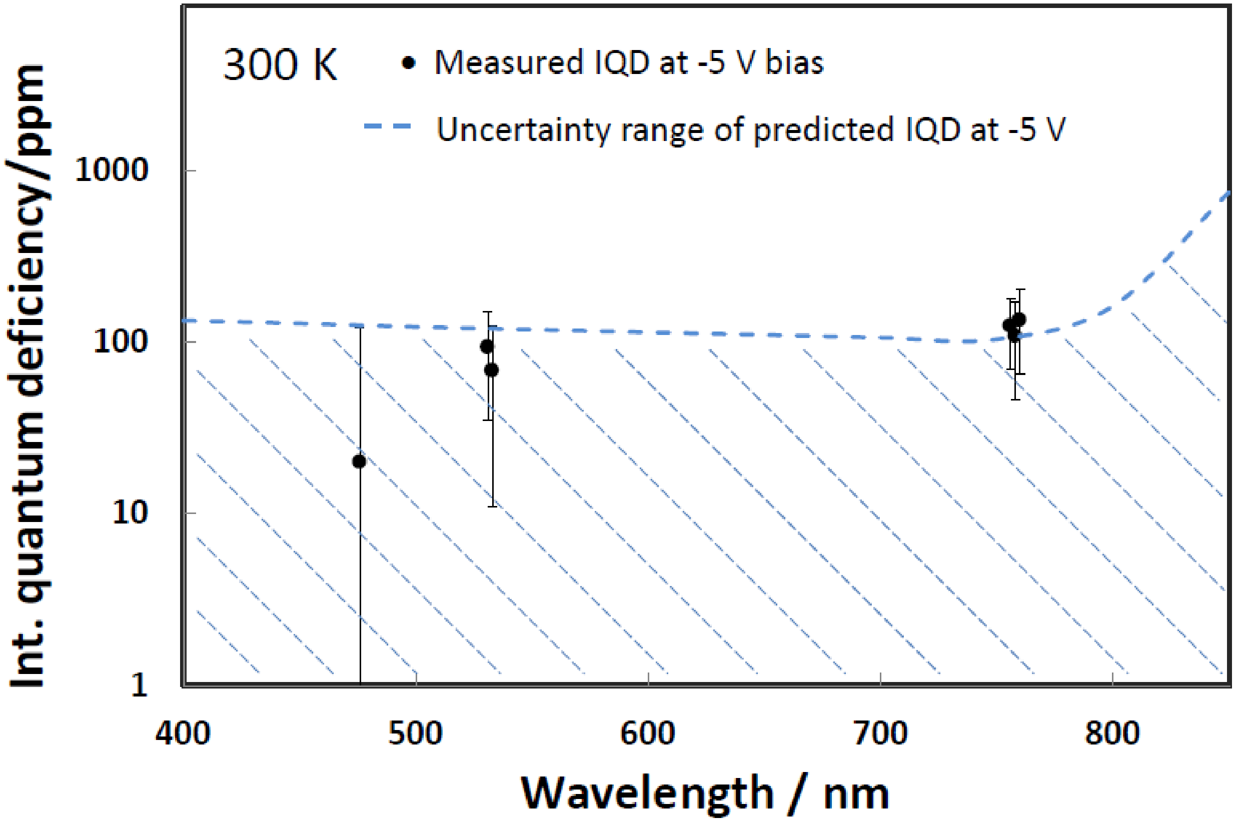


The devices are behind a common Brewster window

Test detector chamber (not used with PQED)

Please visit poster presentation by *I. Müller et al*, PQED II: Characterization results, DBR_OR_029

PQED quantum deficiency at room temperature as measured with Cryogenic Radiometry (CR)



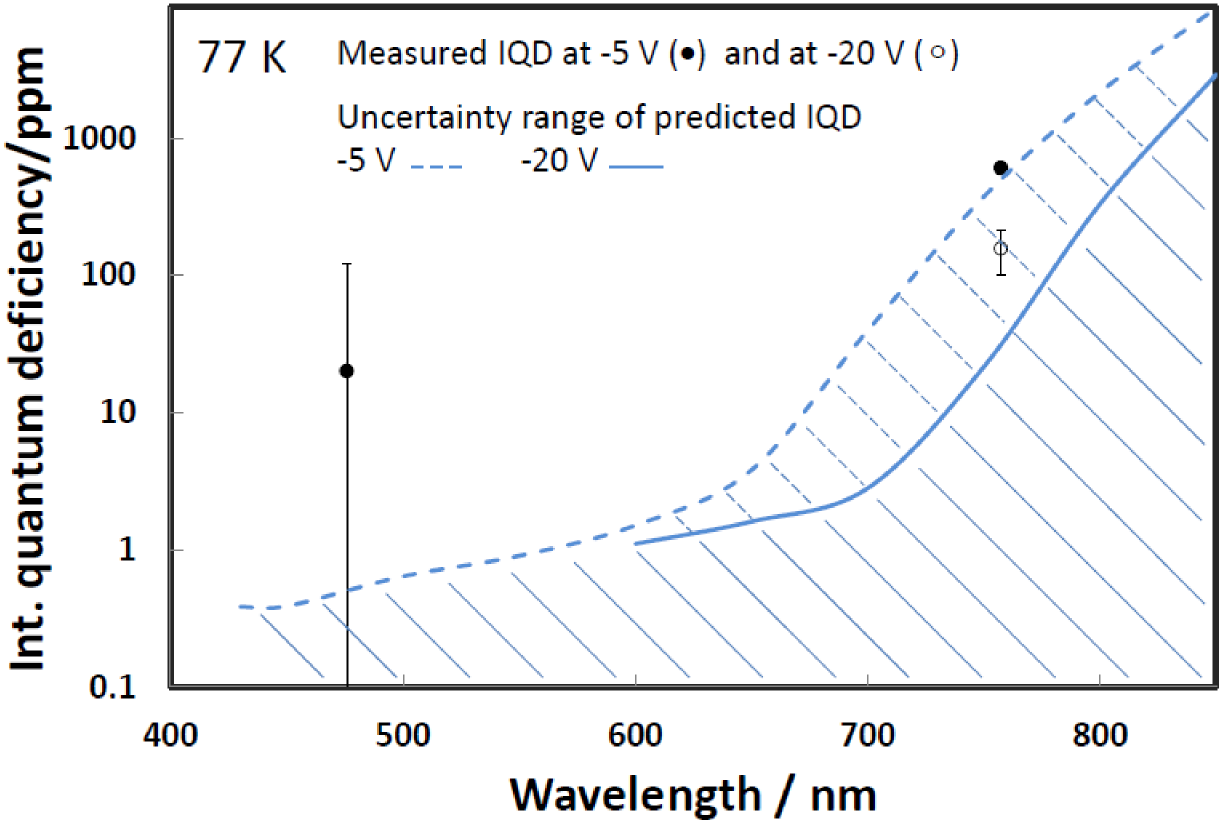
PTB improved CR to 30 ppm uncertainty (behind the same window)

PQED uncertainty increases at NIR because of longer penetration depth

PQED agrees with CR

PQED is potentially as accurate as conventional CR

PQED quantum deficiency at liquid nitrogen temperature as measured with CR



PQED uncertainty increases at NIR because of longer penetration depth

PQED agrees with CR

PQED is potentially two orders of magnitude more accurate than conventional CR

Conclusions

- PQED works at room temperature within 100 ppm uncertainty

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- Cryogenic radiometry (CR) improved to previously unachievable uncertainty level of 30 ppm to test the PQED

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- Room temperature PQED can be purchased from the Finnish company Fitecom (www.fitecom.com)

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- Experimental results are compatible with PQED uncertainty of 1 ppm at 77 K

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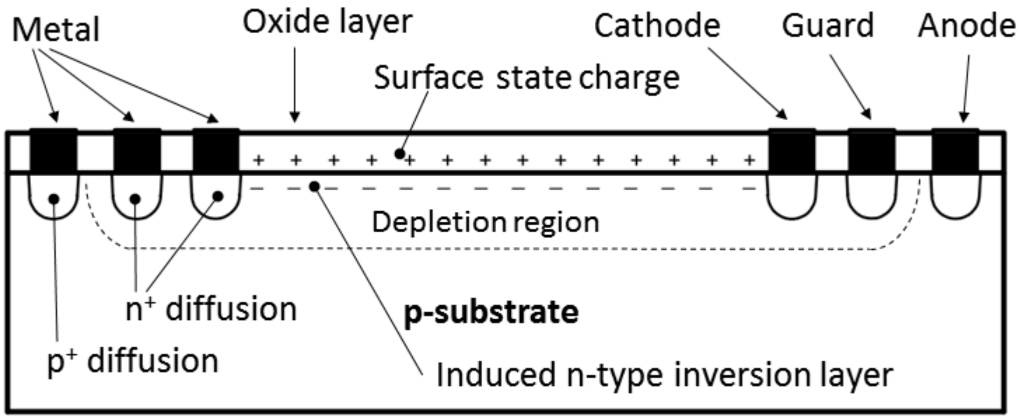
- Experimental results are compatible with PQED uncertainty of 1 ppm at 77 K

➔ potentially new primary standard of optical power

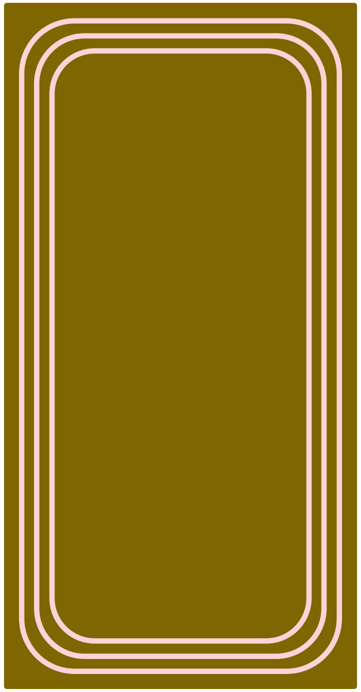
Design of the PQED photodiodes



cross section of the PQED photodiodes

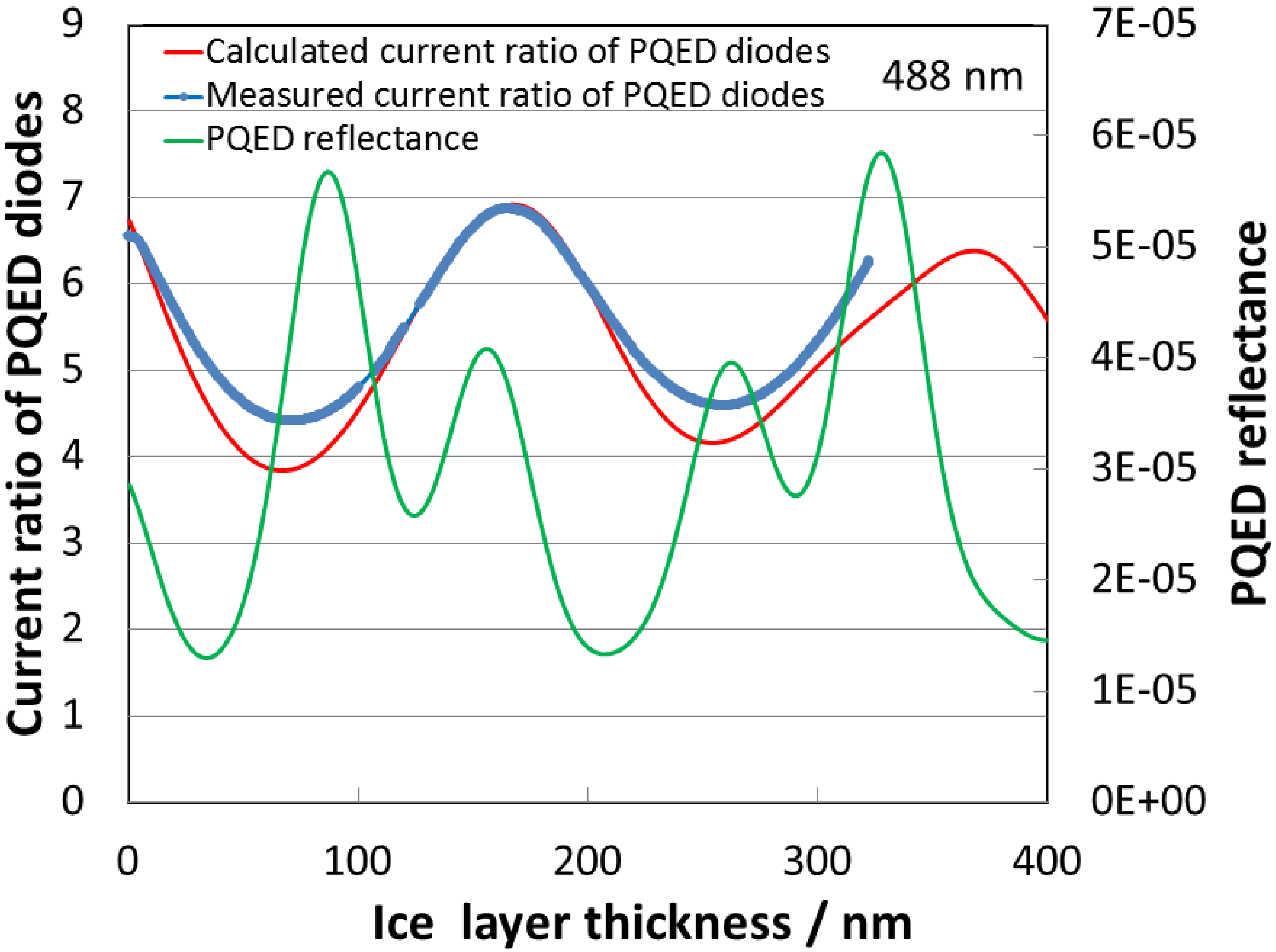
- Inherent positive surface charge in thermally oxidized silicon, **thickness layer** >200 nm
- Self-induced np junction (no additional doping)
- Low doping level of $2{\cdot}10^{12}$ cm^{-3} in p-type silicon

Please visit poster presentation by *M. Sildoja et al*, PQED I: Photodiodes and design, DBR_OR_047.



Top view of a photodiode chip, 11 mm x 22 mm

Preparations


Calculated current ratio of PQED diodes
Measured current ratio of PQED diodes
PQED reflectance
488 nm
Current ratio of PQED diodes
0
1
2
3
4
5
6
7
8
9
PQED reflectance
0E+00
1E-05
2E-05
3E-05
4E-05
5E-05
6E-05
7E-05
0
100
200
300
400
Ice layer thickness / nm