Quantum yield of Predictable Quantum Efficient Detector at ultraviolet and short visible wavelengths

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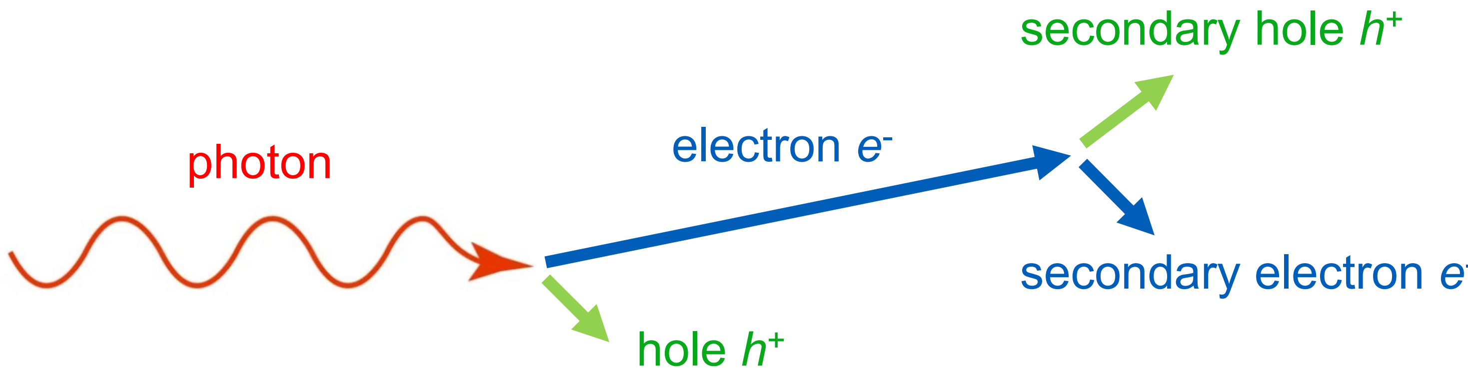
Motivation and Outline



Absorbed photons in Si produce e^- - h^+ pairs and secondary charge carriers via impact ionization

=> Increase of responsivity of Si photodiodes, but quantification not easy because of losses due to reflectance and e^- - h^+ recombination

=> Here first experimental results on impact ionization at UV and VIS, and quantitative comparison with a theoretical model

PQED = Predictable Quantum Efficient Detector

PQED detector

Silicon detector responsivity

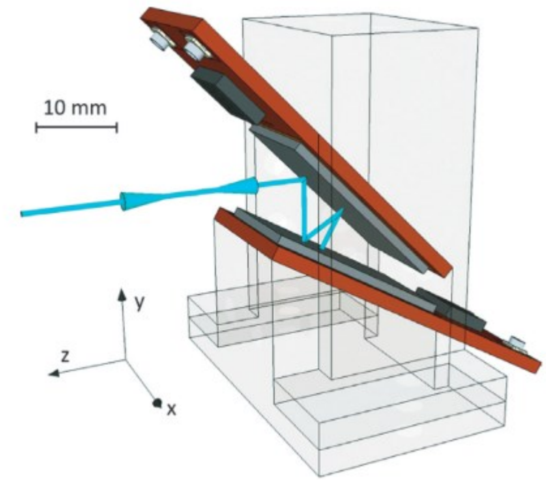
$$R(\lambda) = \frac{e\lambda}{hc}\left(1-\rho(\lambda)\right)\left(1-\delta(\lambda)\right)\left(1+g(\lambda)\right)$$

ideal responsivity

reflectance losses
(tens of ppm in visible range)

recombination losses
(up to 0.28% in UV)

effect of impact ionization
(the topic of this talk)



Schematic diagram of the PQED photodiodes' assembly. The blue arrows depict the incident beam.

Meelis Sildoja *et al,* 2013, *Metrologia* **50** 385

Key device to assess quantum yield, the factor $1 + g(\lambda)$, in silicon photodiodes

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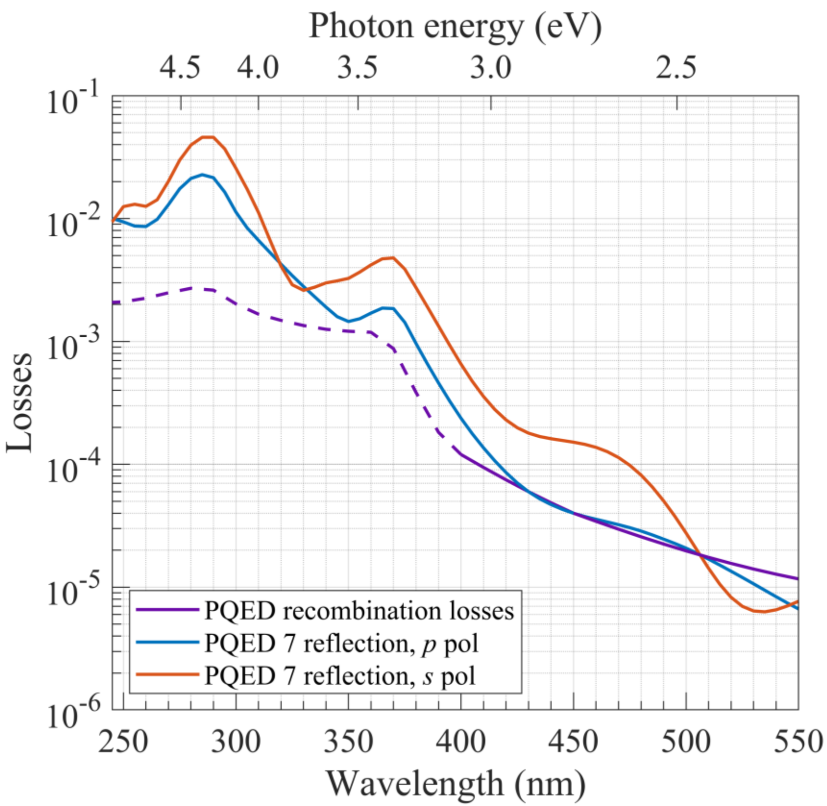
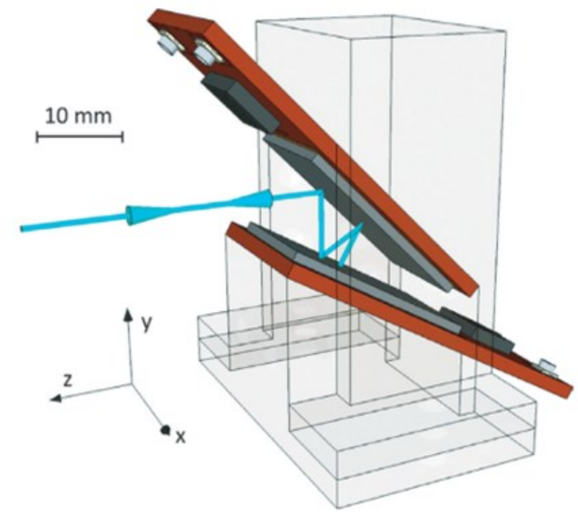
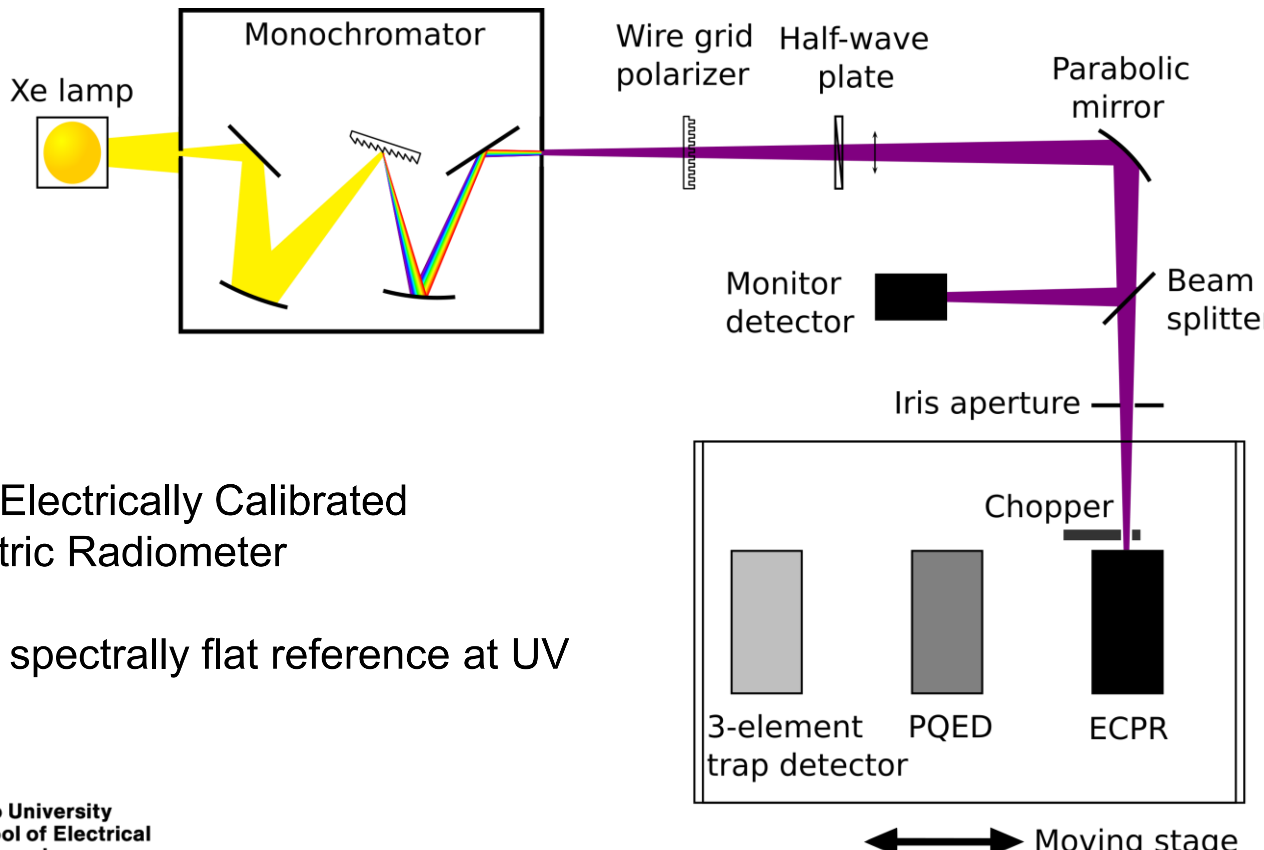
Calculated losses of PQED





- Recombination losses calculated by 3D model in VIS (Tran et al, *Metrologia* **59**, 045012, 2022)
- Recombination losses extrapolated by absorption coefficient at UV (Korpusenko et al, *AIP Advances* **13**, 085119, 2023)

Measurement setup



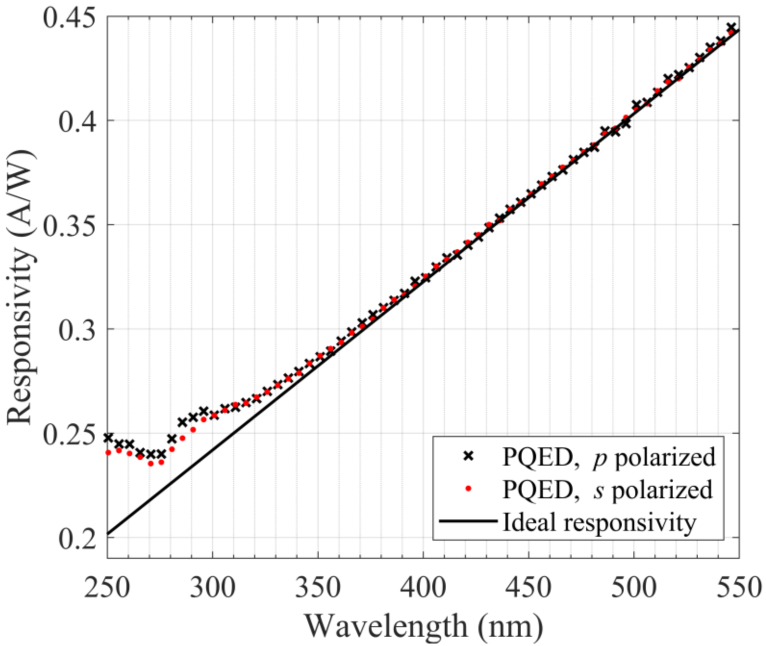
ECPR = Electrically Calibrated Pyroelectric Radiometer

Provides spectrally flat reference at UV

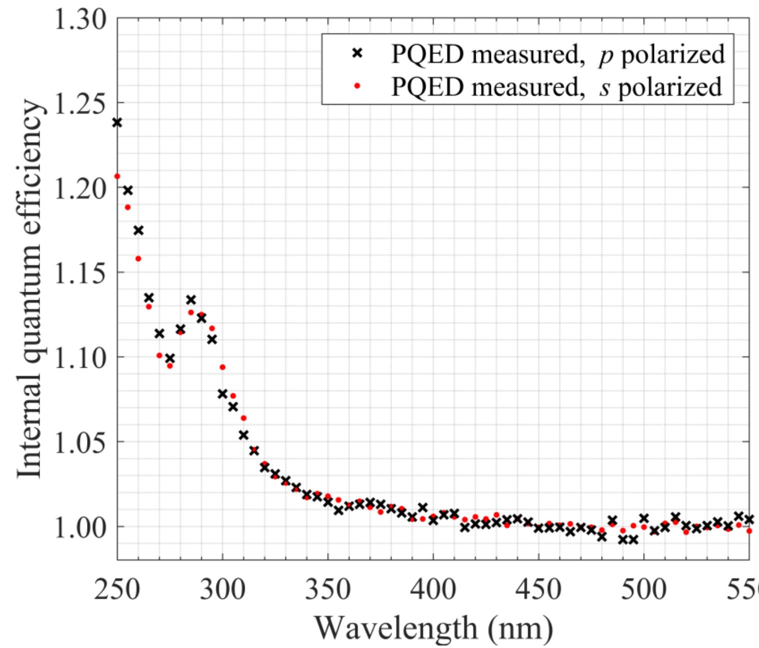
Experimental results on PQED responsivity

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

$$\eta_i(\lambda) = (1-\delta(\lambda))(1+g(\lambda))$$



Measured responsivity of PQED

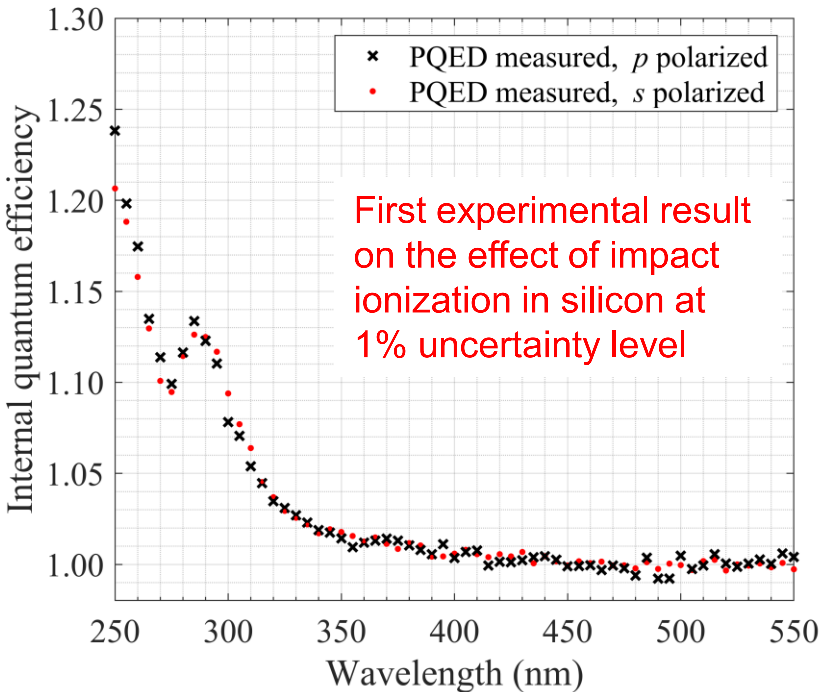


Measured internal quantum efficiency of PQED

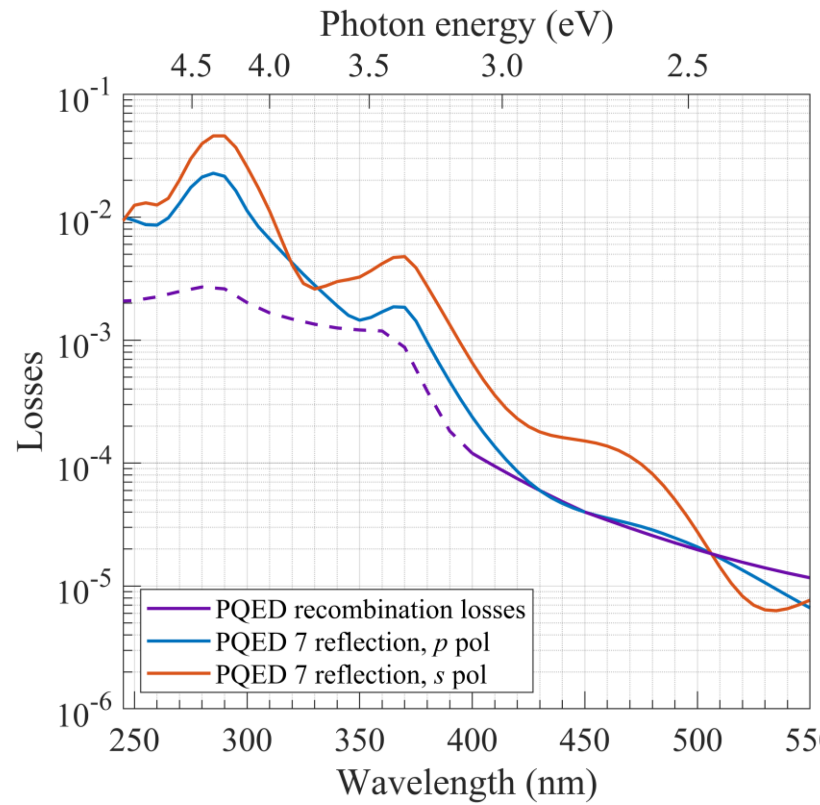
Korpusenko et al, *AIP Advances* **13**, 085119, 2023

Experimental results on impact ionization

$$\eta_i(\lambda) = (1 - \delta(\lambda))(1 + g(\lambda))$$



First experimental result on the effect of impact ionization in silicon at 1% uncertainty level



Korpusenko et al, *AIP Advances* **13**, 085119, 2023

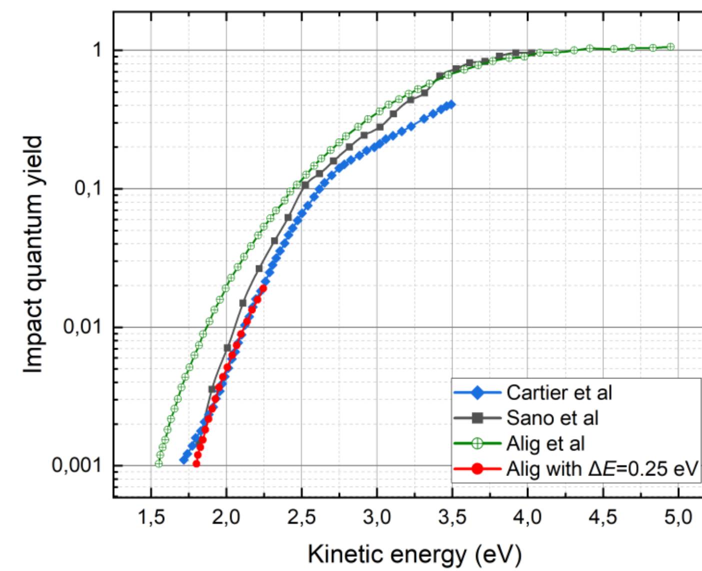
Theoretical results

Simplifying assumptions (Alig et al, Phys. Rev. B **22**, 5565, 1980; Ramanathan et al, Phys. Rev. D **102**, 063026, 2020)

- Electrons and holes taking part in impact ionization are described by the density of states of free particles
- Electrons and holes are assumed to contribute equally
- Available energy is assumed to be taken either by the electron or the hole
- Considered energy dissipation processes are electron-hole pair creation and emission of optical phonons (energy E_{ph})

$$g(\lambda) = \left[1 + A_1 \left(\frac{hc}{\lambda} - E_g - E_{ph} - \Delta E\right)^{1/2} / \left(\frac{hc}{\lambda} - 2E_g - \Delta E\right)^{7/2}\right]^{-1}$$

E_g = 1.12 eV is Si indirect energy gap and A_1 = 86.9 eV^3



Wolf et al, J. Appl. Phys. 83, 4213, 1998

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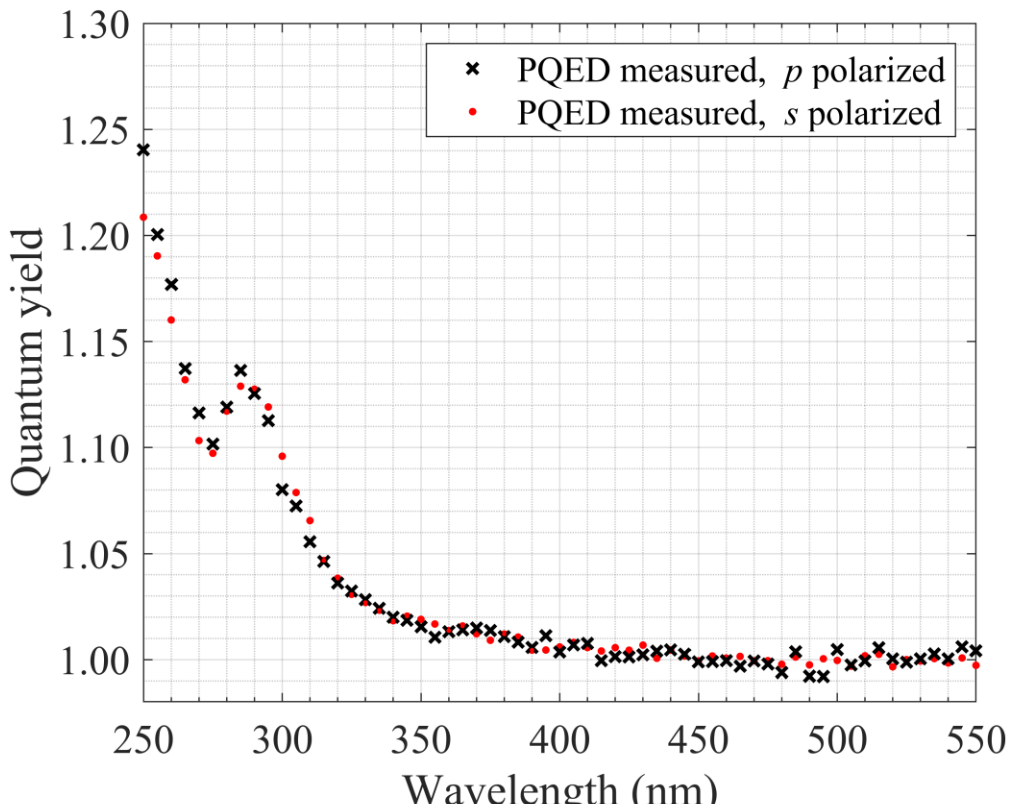
At kinetic energies below 2.2 eV, the impact ionization processes appear to have reduced efficiency which can be described by the energy shift of ΔE = 0.25 eV

Compare measurement and theory

$$g(\lambda) = \left[1 + A_1\left(\frac{hc}{\lambda} - E_g - E_{ph} - \Delta E\right)^{1/2} \Big/ \left(\frac{hc}{\lambda} - 2E_g - \Delta E\right)^{7/2}\right]^{-1}$$



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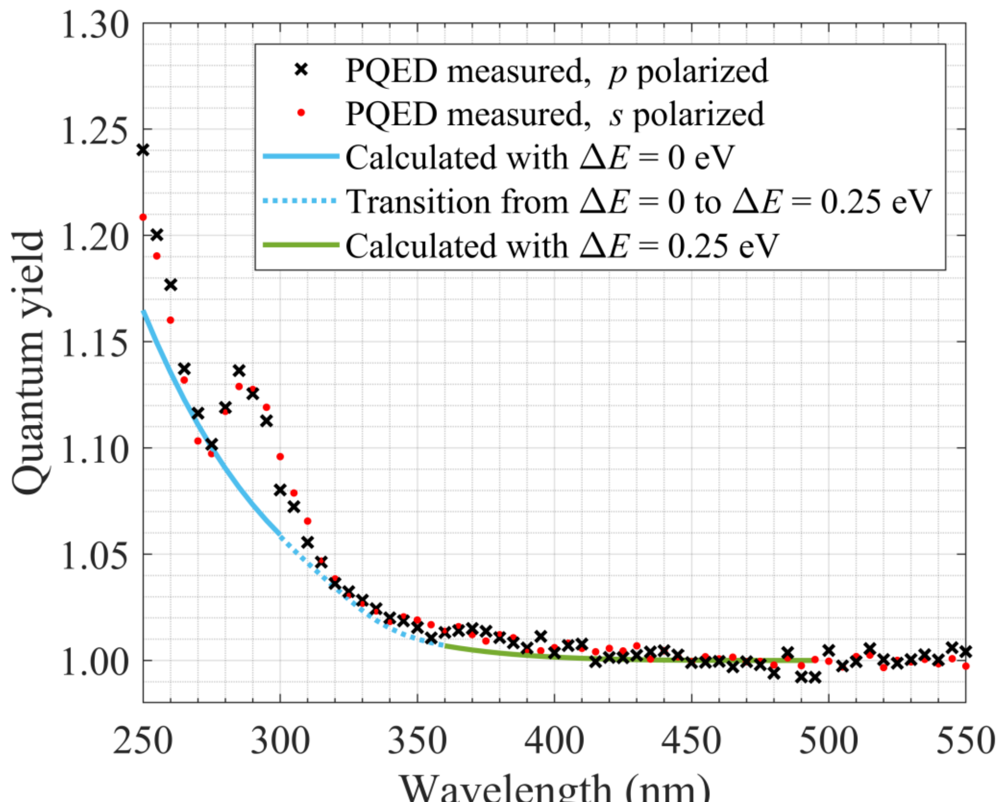
Compare measurement and theory

$$g(\lambda) = \left[1 + A_1\left(\frac{hc}{\lambda} - E_g - E_{ph} - \Delta E\right)^{1/2} / \left(\frac{hc}{\lambda} - 2E_g - \Delta E\right)^{7/2}\right]^{-1}$$



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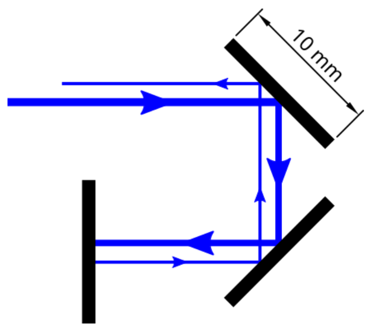
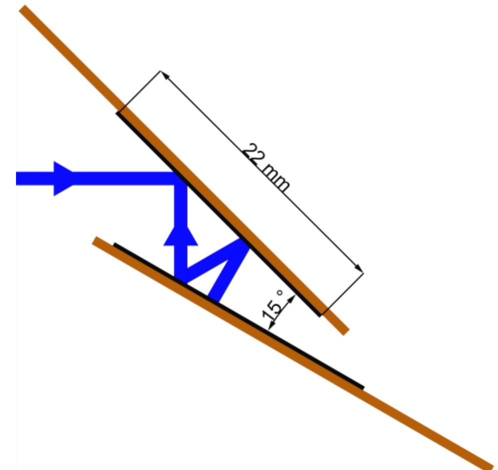
Applications to other Si detectors



3-element trap detector equipped
with Hamamatsu S1337 photodiodes

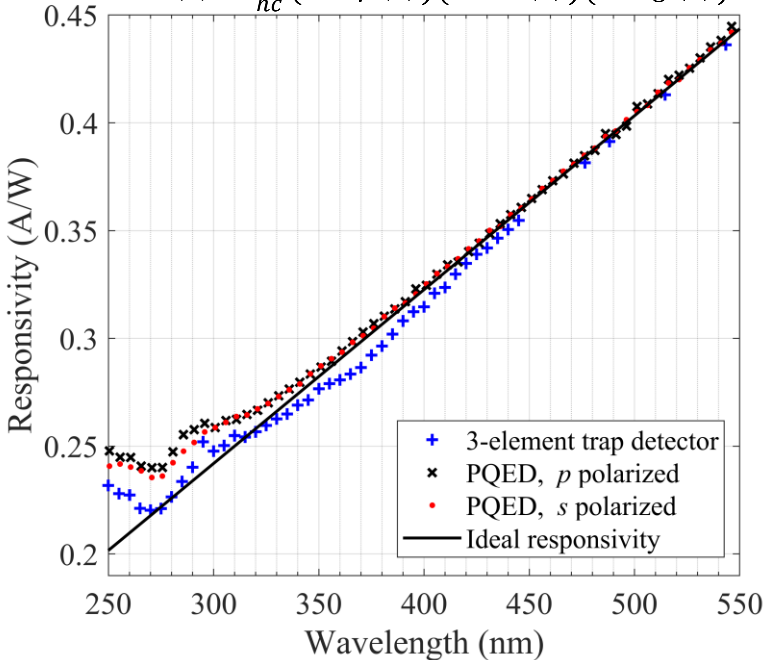


PQED

Schematic structure of 3-element trap detector (left) and 2-element PQED with seven reflections (right). The five reflections of 3-element trap detector are usually arranged in three dimensions so that the responsivity becomes independent on the polarization state of incident light, whereas the responsivity of PQED is sensitive to polarization

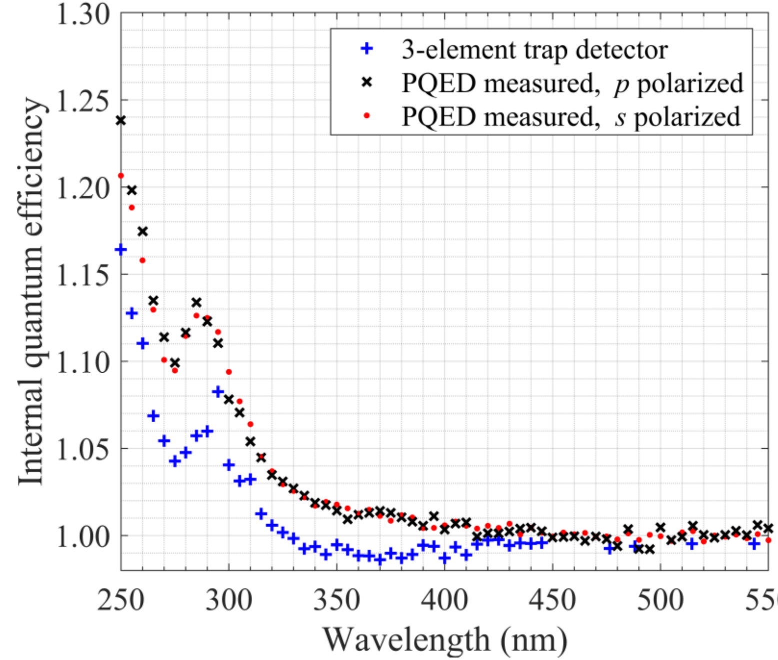
PQED responsivity and comparison to Hamamatsu trap detector

$$R(\lambda) = \frac{e\lambda}{hc}\big(1-\rho(\lambda)\big)\big(1-\delta(\lambda)\big)\big(1+g(\lambda)\big)$$



Measured responsivity of 3-element trap detector and of PQED

$$\eta_i(\lambda) = \big(1-\delta(\lambda)\big)\big(1+g(\lambda)\big)$$



Measured internal quantum efficiency of 3-element trap detector and of PQED

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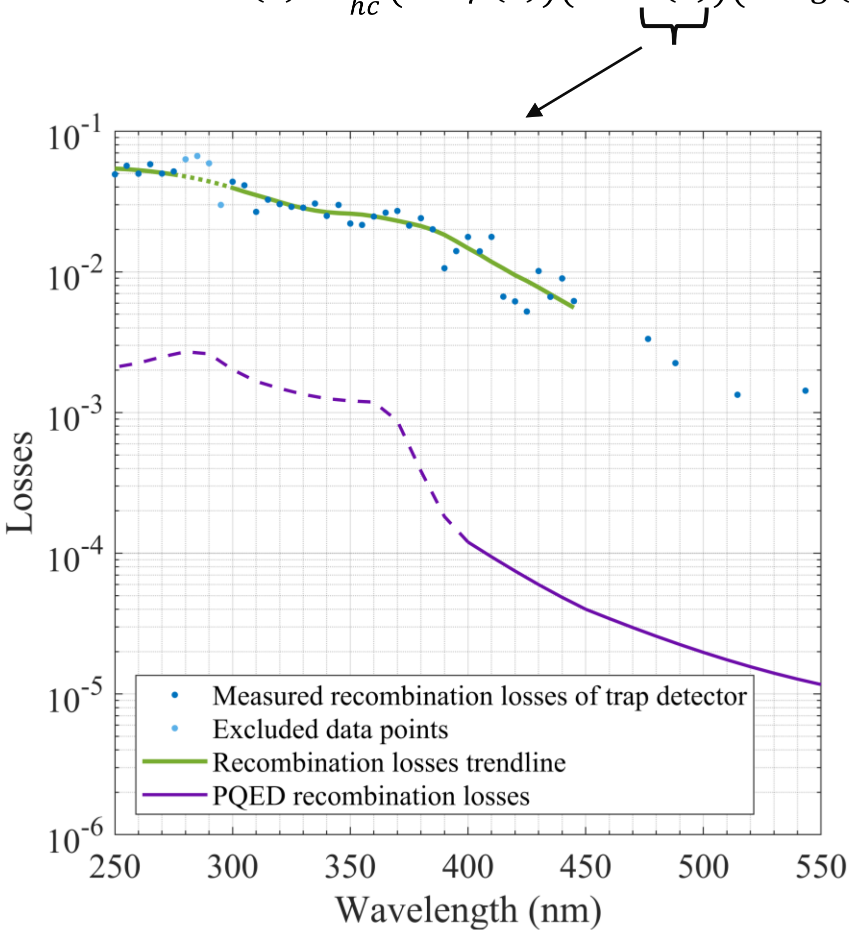
Korpusenko et al, *Metrologia*, accepted, September 2023

Recombination losses of S1337

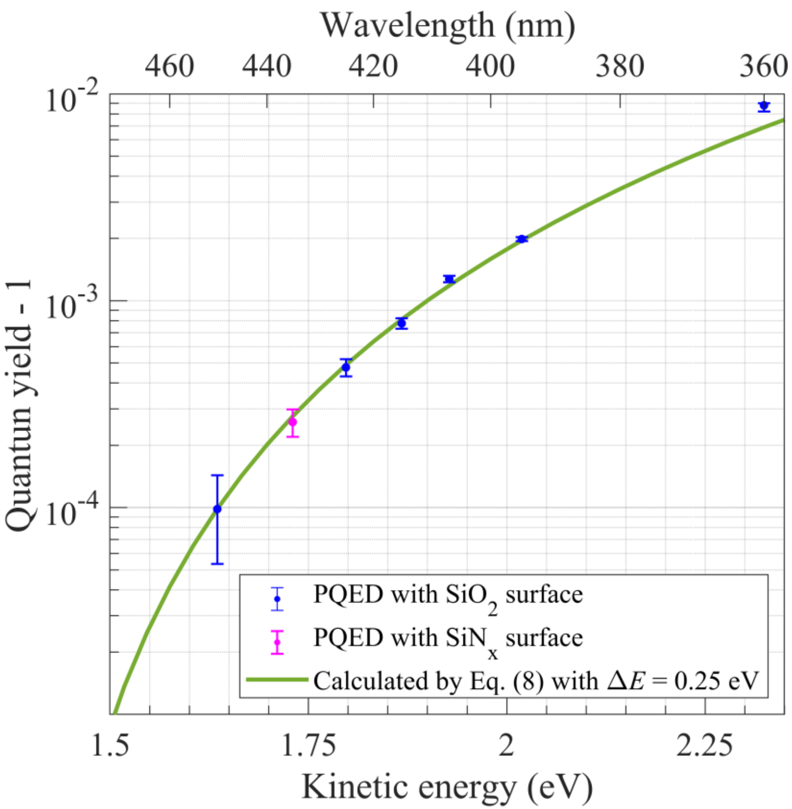
$$R(\lambda) = \frac{e\lambda}{hc}(1-\rho(\lambda))(1-\delta(\lambda))(1+g(\lambda))$$



- Solid line – simulation by Tran et al*
- Dashed line – extrapolation of the solid line
- Blue points – trap losses measured against PQED
- Green line – measured points trendline

*Tran T et al, 2022 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

Measured quantum yield and theoretical results at short VIS



Blue dots – L. Werner et al, Quantum Yield in Induced Junction Silicon Photodiodes at Wavelengths around 400 nm, NEWRAD 2021 proceedings, https://doi.org/10.5281/zenodo.4882793

Pink dot – SiNx photodiodes

Results

- PQED's quantum yield is above unity at short VIS range
- Theoretical model predicts quantum yield of PQED in short visible range with uncertainty at 0.01% level
- The model can be used to predict quantum yield of PQED at short visible wavelengths for both oxide and nitride coated photodiodes

$$g(\lambda) = \left[1 + A_1\left(\frac{hc}{\lambda} - E_g - E_{ph} - \Delta E\right)^{1/2} / \left(\frac{hc}{\lambda} - 2E_g - \Delta E\right)^{7/2}\right]^{-1}$$

Conclusions

- Impact ionization is a **useful process** which increases the silicon detector responsivity at UV
- For a large part of the spectral range from 250 nm to 450 nm, an **accurate theoretical model** of quantum yield exists
- PQED responsivity can be predicted at short visible wavelengths for two **different types of induced junction photodiodes**
- The results can be used to **extract recombination losses** in doped junction photodiodes, such as Hamamatsu S1337

Acknowledgements

chipS·CALe — Self-calibrating photodiodes for the radiometric linkage to fundamental constants (18SIB10)

S-CALE-UP — Self-calibrating photodiodes for UV and exploitation of induced junction technology (22IEM06)

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Thank you for listening

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