Optical Studies of High Performance Predictable Quantum Efficient Detector Based on Induced-Junction Photodiodes Passivated with SiO²/SiNˣ

Mikhail Korpusenko[1], Ozhan Koybasi[2], Farshid Manoocheri[1], Jarle Gran[3], and Erkki Ikonen[1,4]

1. Metrology Research Institute, Aalto University, Espoo, Finland
2. Department of Microsystems and Nanotechnology (MiNaLab), SINTEF Digital, Oslo, Norway
3. Justervesenet, 2027 Kjeller, Norway
4. VTT MIKES, VTT Technical Research Centre of Finland Ltd., 02150 Espoo, Finland

Corresponding e-mail address: mikhail.korpusenko@aalto.fi

Predictable Quantum Efficient Detector known as PQED is a seven-reflection wedge trap based on two induced junction Si photodiodes (Figure 2). *Mise en pratique* for the definition of candela allows to use PQED as a primary optical standard for measuring of absolute optical power in visible range. PQEDs which are used by national metrological institutes are traceable to absolute cryogenic radiometers with internal losses (IQD) of 0.01%. To achieve smaller internal losses, we executed optical studies of PQEDs based on induced-junction photodiodes passivated with SiO_2/SiN_x with optimized surface passivation[1].

Ideal responsivity

$$R_0(\lambda) = \frac{e\lambda}{hc}$$

λ – vacuum wavelength
e – electron charge
c – speed of light in vacuum
h – Planck's constant

Responsivity of photodetector

$$R(\lambda) = R_0(\lambda)(1-\rho(\lambda))(1-\delta(\lambda))(1+g(\lambda))$$

$\rho(\lambda)$ – reflectance losses
$\delta(\lambda)$ – internal quantum deficiency
$g(\lambda)$ – quantum yield

Predictable quantum efficient detector (PQED)

The light sensing element of PQED is inversion-layer silicon photodiodes:

- A p-n junction is naturally formed by the inversion of silicon surface by the fixed charge (Q_f) in the passivation dielectric (Figure 1).
- The recombination-generation centers at the silicon-dielectric interface are the main limiting factor for quantum efficiency besides the reflection and absorption losses in the dielectric:

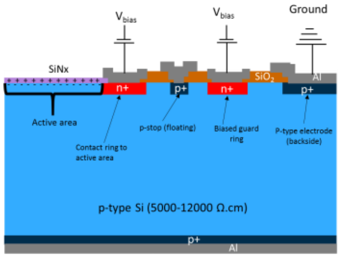


Figure 1. Inversion layer photodiode structure and biasing scheme

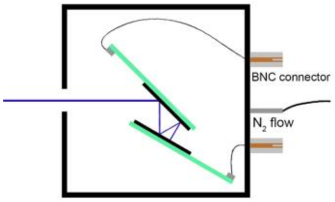


Figure 2. Photodiodes assembly and light path in a PQED

The recombination losses at the interface of silicon and passivation layer can be minimized by optimizing the passivation dielectric for low surface recombination velocity (SRV) by

- minimizing interface trap density (D_{it})
- maximizing fixed charge density (Q_f)

The optical losses can be minimized by

- optimization the passivation dielectric for low absorbance and reflectance
- assembly of photodiodes in light-trap configuration (Figure 2)

All losses are very small and can be quantified with auxiliary measurements

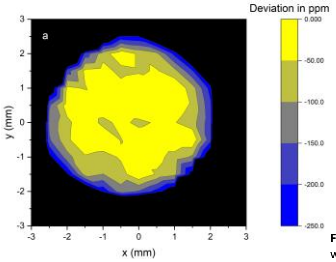


Figure 3. Spatial uniformity of PQED

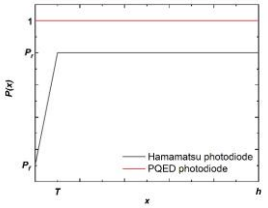


Figure 4. Models for variation of the collection probability $P(x)$ with distance into a photodiode of thickness h where Pf ≈ 0.98 and Pr ≈ 0.999 at T ≈ 0.3 µm. Collection probability of Hahamatsu trap detector is taken from T. Gentile et al., Internal quantum efficiency modelling of silicon photodiodes. **Applied Optics, 49, 1859-1864, 2010**

- Average uniformity is 40-50 ppm (Figure 3)
- PQEDs collection probability is around **0.99995** (1 - δ(λ)) (Figure 4)
- Reflectance losses ρ(λ) are **below 1 part per million (ppm)** in visible range
- I-V measurement gives a saturation point of the PQED (Figure 5)

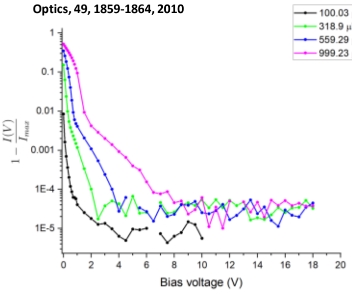


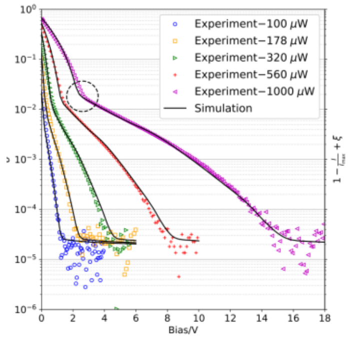
Figure 5. Bias voltage dependent measurement of PQED

Comparison measurements against old SiO_2 p-type PQED

SiN_x p-type PQED vs SiO_2 p-type PQED **P18-55-45** - identification number of the photodetector	Photocurrent ratio	Reflectance losses of old SiO_2 PQED (ppm)	IQD(SiN_x PQED) - IQD(SiO_2 PQED)
SiN_x + SiO_2 (P18-55-45) 488 nm	1.000036	28	- 8 ppm
SiN_x + SiO_2 (P18-54-44) 488 nm	1.000016	28	12 ppm
SiN_x + SiO_2 (P14-xx-xx) 488 nm	1.000059	28	- 31 ppm
SiN_x (P24-xx-xx) 488 nm	1.000009	28	19 ppm
SiN_x + SiO_2 (P18-55-45) 785 nm	1.000120	45	**-75 ppm**

Responsivity of new SiN_x PQEDs is the same at 488 nm as of old p-type PQEDs with SiO_2 as a passivation layer. In near-infrared region responsivity of SiN_x PQEDs does not change while SiO_2 PQEDs have a decreased responsivity.

Fitted simulated Internal Quantum deficiency of n-type PQED, δ



Measured data with noise level below 100 ppm as from Figure 5 can be used in 3D simulation model of charge carrier recombination losses to retrieve fundamental constants of PQED[2].

Experimental and fitted parameters of studied n-type PQED

Parameters	PQED 2
Wavelength λ – *measured*	488 nm
Substrate doping p – *fitted*	1.95×10^{12} cm^{-3}
Fixed charged density Q_f – *fitted*	3.0×10^{11} e cm^{-2}
Bulk lifetime τ_{bulk} – *fitted*	2.5 ms
Surface recombination velocity S_0 – *fitted*	3000 cm/s
Offset $\xi(\lambda)$ – *fitted*	0 ppm

References

1. Ozhan Koybasi, **Sensors 21 7807, 2021.**
2. Trinh Tran et al, **Metrologia 59 045012, 2022**.

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