Irradiation Studies on the TAPD-SiPM

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22.02.2022

Outline

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Novel TAPD-SiPM

- New SiPM design optimized for red sensitivity (application in LiDaR)
- Shows great performance in PDE, timing resolution and dynamic range

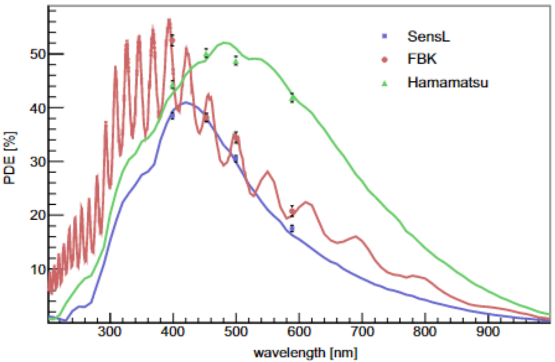
TAPD-SiPM in High-D

- Key requirement for high energy experiments: radiation hardness
- Is the radiation hardness competitive to planar devices?

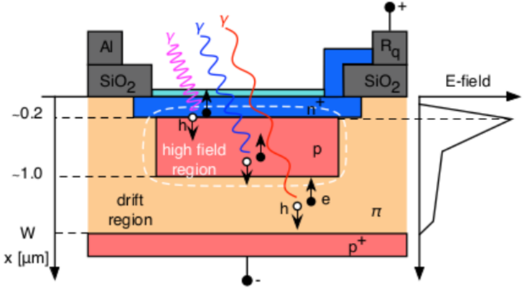
Analysis

- Irradiation with neutrons
- Analysis of current-voltage characteristics

Planar Blue-Sensitive SiPM



PDE of blue-sensitive SiPMs [1].



Exemplary cross section of SiPM pixel [5].

Spectal Response of Silicon

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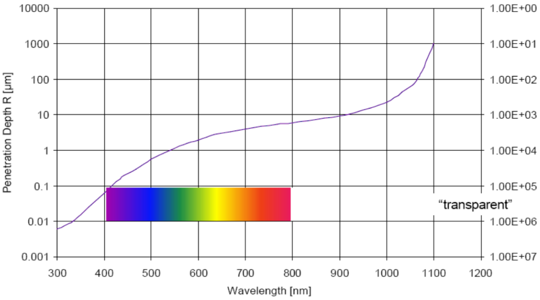
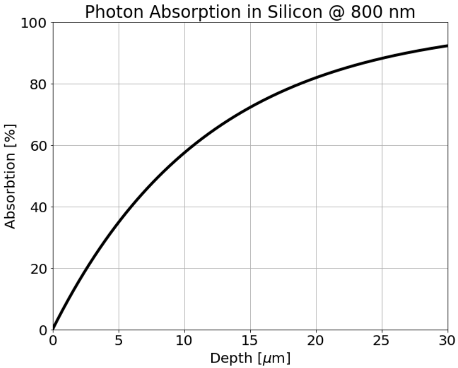


Absorption length in silicon



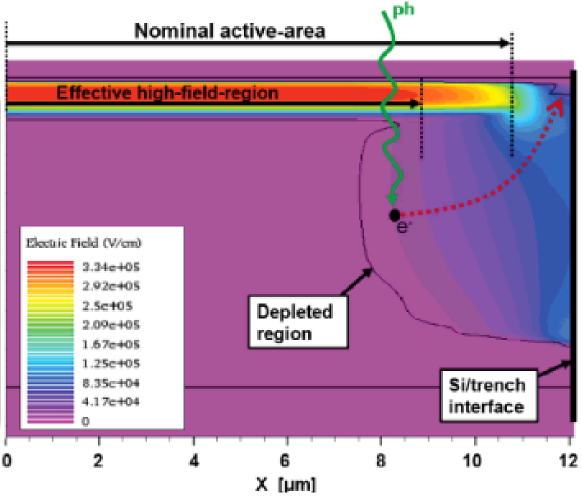
Absorption of red light in silicon

$\Rightarrow$ Deeper collection depth needed!

Planar Red-Sensitive SiPM

Limitations with planar devices:

- Higher Operating Voltage required
- PDE loss due to Border Effect:
  - Electric field stretches from pixel border into center
  - Charge carrier drifts away from multiplication zone
  - ⇒ Active Area decreases with layer thickness



Simulation of border effect [4].

Tip Avalanche PhotoDiode (TAPD) Design

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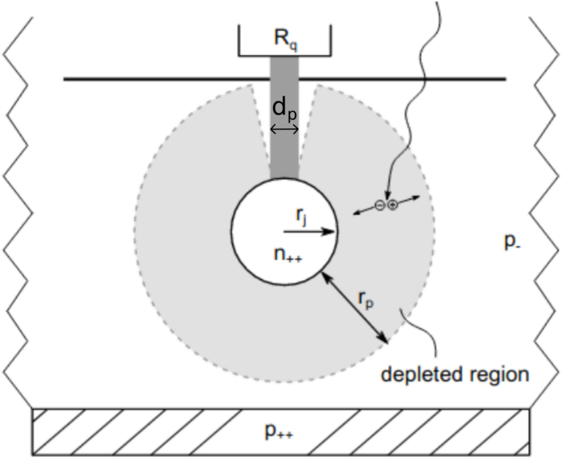
Design developed by KETEK + MEPhI
$\rightarrow$ now broadcom

- Quasi-spherical pn-junction allows depletion of thick layer at low voltage
- No border $\Rightarrow$ no border effects

Electrical Field

- Focused at the tip
- Large drift area ($r \approx 7\,\mu$m)
- Multiplication near tip ($r \approx 2\,\mu$m)

Structure is characterized by pillar diameter d_p.



Cross-section of TAPD-SPAD [2]

TAPD-SiPM Performance

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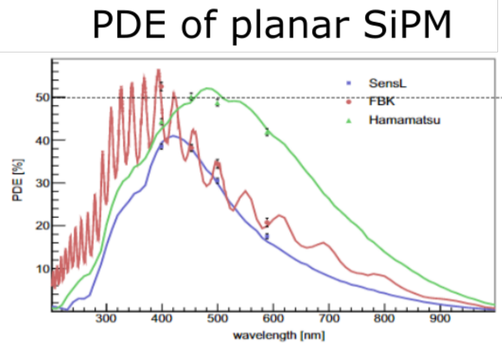
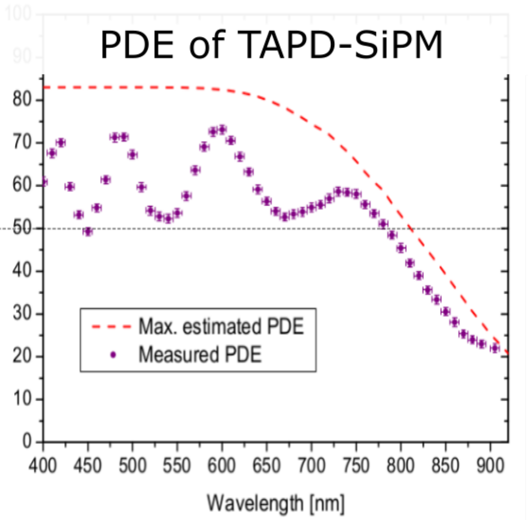
TAPD reaches record values for pixel pitch of 15 µm:
- 73% @ 600 nm
- 22% @ 900 nm

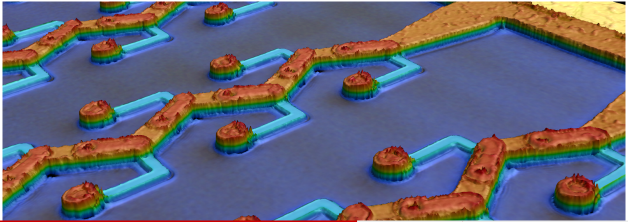


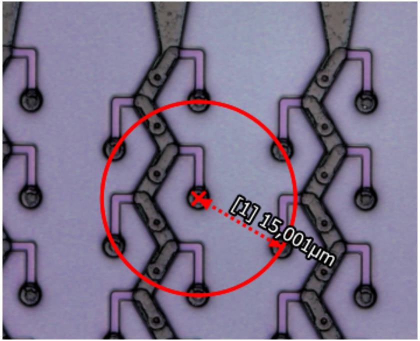


SiPM Prototype Design

Layout

- $1 \times 1\,\mathrm{mm}^2$ array of 5016 pixel
- Bias supply and quenching resistor on top
- Pixel pitch 15 μm
- d_p: 0.6, 0.8 or 1.0 μm
- Hexagonal Lattice: $\sim$ 83% geometrical efficiency





The Prototype under the Laser Microscope

Reverse Bias

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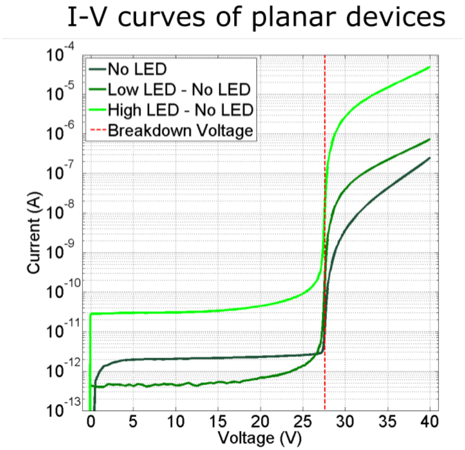
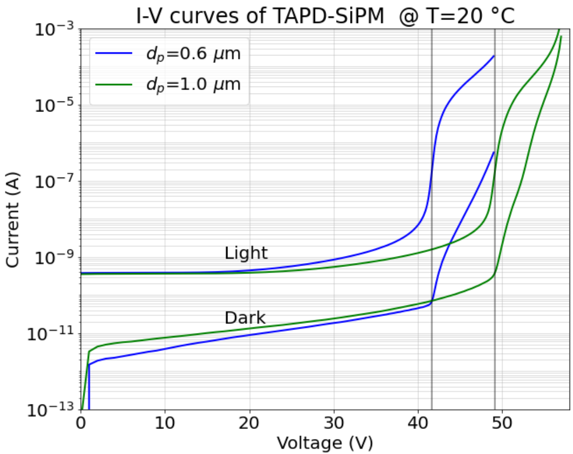
Planar device: 4832 pixel á $15 \cdot 15\,\mu$m from [6]



Slope in dark current below breakdown



Reverse Bias

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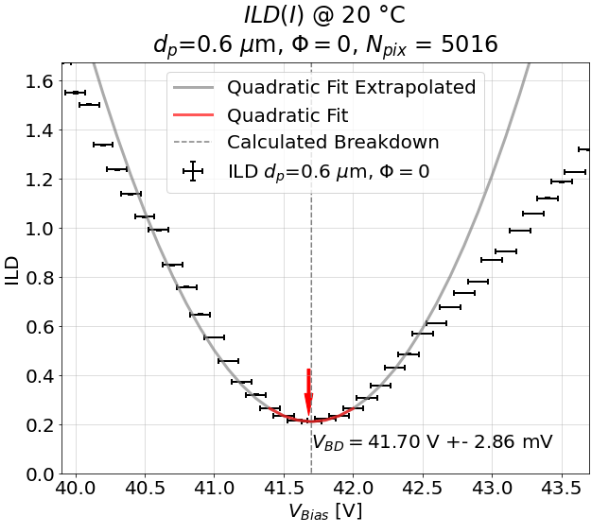
Determination of Breakdown Voltage

- Breakdown determined by current ⇒ V_{BD}^{IV}:
- Find minimum of *I*nverse *L*ogarithmic *D*erivative $ILD = \frac{I}{I'}$ using Quadratic fit
- Precision of dark current measurement not sufficient: ⇒ determine Breakdown with I_{light}



Current Measurement

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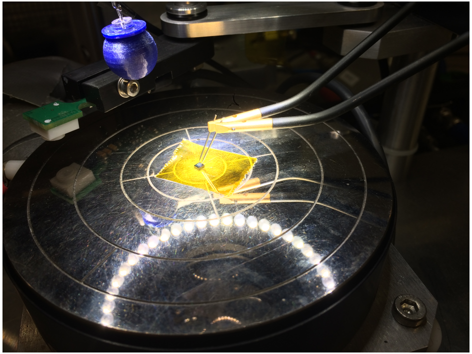
Keithley parameters

- Voltage source & ammeter: Keithley 6517B
- Sample on cold chuck for temperature control
- Air pump for fixation of sample
- Contact with needles
- Cold chuck in light tight box
- Dry air flux for humidity control
- Diffused LED light
- All cables & box shielded with ground potential

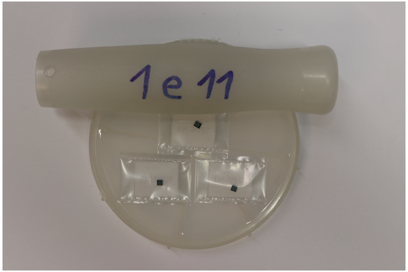


The SiPM on the Cold Chuck

Effects of hadronic irradiation

Effects on the SiPM

- Change in N_{eff}: Possibly shift of V_{BD}
- Change of quenching resistance
- Increase in DCR
- Possibly change in PDE

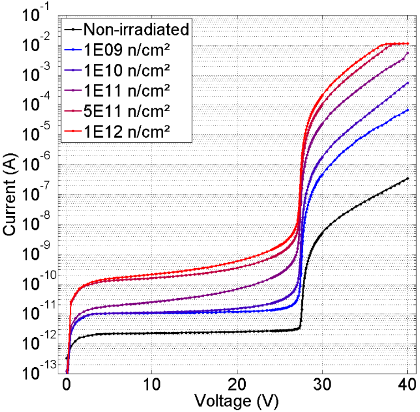


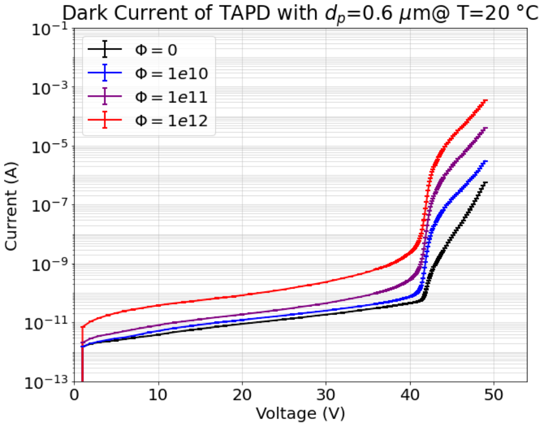
Irradiation

- For each pillar size ($d_p = 0.6, 0.8, 1.0\ \mu$m) irradiation with neutrons
- Fluences: $\Phi = 10^{10}, 10^{11}, 10^{12}\ \frac{\text{neq}}{\text{cm}^2}$
- Irradiation in nuclear reactor at Jozef Stefan Institute Ljubljana

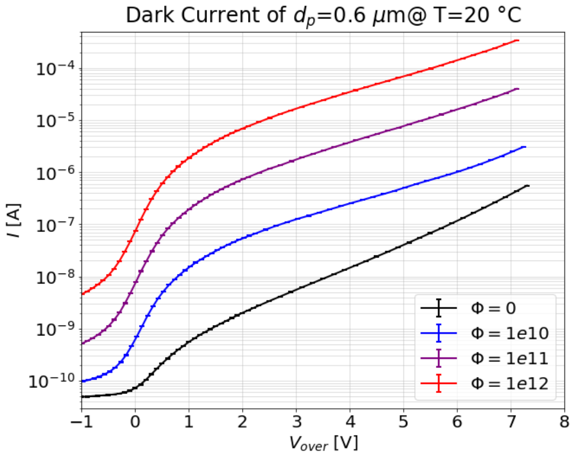
Dark Current after Irradiation

Dark current of irradiated planar SiPMs





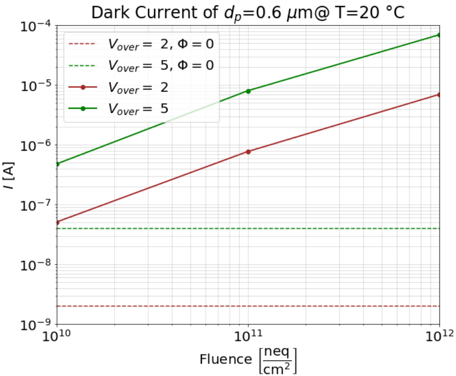
Dark Current above Breakdown



$$V_{over} = V_{Bias} - V_{BD}^{IV}$$

Increase of dark current $\frac{I(\Phi=10^{12})}{I(\Phi=0)}$:

- For TAPD: roughly $I_{dark}(\Phi) \propto \Phi$
- For planar: 2 magnitudes for $\Phi = 10^9$
  5 magnitudes for $\Phi = 10^{12}$



Approximation of DCR and Pixel Occupancy

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Extract noise rate and pixel occupancy using (IV) measured values and knowledge on Δt:
Use current model for $V > V_{BD}$:

$$I_{dark} = G \cdot q_0 \cdot DCR(1 + CN) = G \cdot q_0 \cdot \frac{N_{pix} \cdot \eta_{DC}}{\Delta t}$$

- DCR: **D**ark **C**ount **R**ate, CN: **C**orrelated **N**oise (afterpulse & crosstalk), $G \cdot q_0 = (V_{Bias} - V_{BD}) \cdot (C_{pix} + C_q)$, and C_{pix}, C_q: pixel and quenching capacitance
- η_{DC}: pixel occupancy due to dark counts, N_{pix}: # of pixels, Δt: pixel recovery time

Approximation of DCR and Pixel Occupancy

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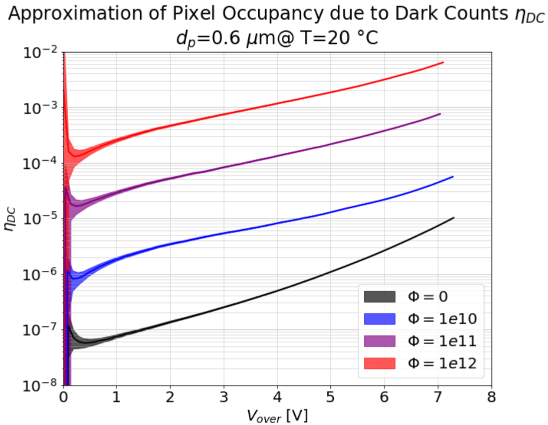
$$\eta_{DC} = \frac{I_{dark} \cdot \Delta t}{G \cdot q_0 \cdot N_{pix}} = \frac{I_{dark} \cdot R_q}{(V_{Bias} - V_{BD}) \cdot N_{pix}}$$

- With $\Delta t \approx \tau = (V_{Bias} - V_{BD}) \cdot R_q$
- Take $R_q = 671 \pm 2\,\mathrm{k\Omega}$ from forward $I - V$ of single pixel
- Take $V_{BD} = V_{BD}^{IV}$

$\Rightarrow$ Pixel occupancy @ 5 V for $\Phi = 10^{12}$: 0.2%



Approximation of DCR and Pixel Occupancy

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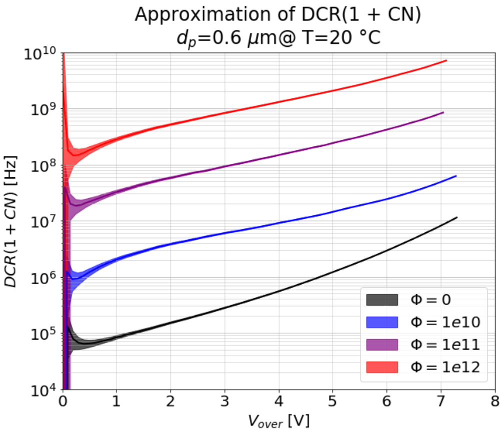
$$DCR(1+CN) = \frac{N_{pix} \cdot \eta_{DC}}{\Delta t}$$

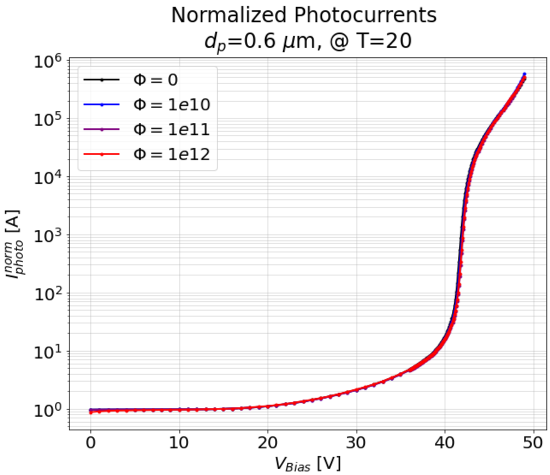
Take $\Delta t = \tau = 4.5\,\text{ns}$ from [2]

$\frac{DCR}{\text{mm}^2}$ @ $V_{over} = 4.5$	$\Phi = 0$	$\Phi = 10^{12}$
Planar	480 kHz	29.5 GHz
TAPD	800 kHz	1.8 GHz



Normalised Photocurrent

- $I_{photo} = I_{light} - I_{dark}$
- $I^{norm}_{photo} = \frac{I_{photo}}{I_{photo}(V=10)}$
- Enables comparison of response to light
- $I^{norm}_{photo} = q_0 \cdot G \cdot PDE \cdot (1 + CN)$
- If $\frac{I^{norm}_{photo}(\Phi)}{I^{norm}_{photo}(\Phi=0)} \neq 1$
  $\Rightarrow$ Change due to irradiation



Normalised Photocurrent

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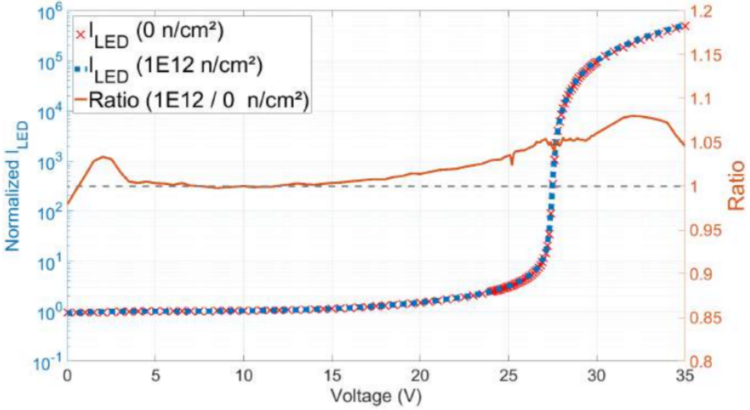
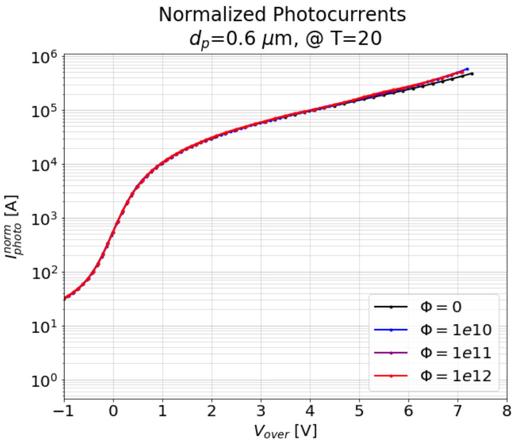
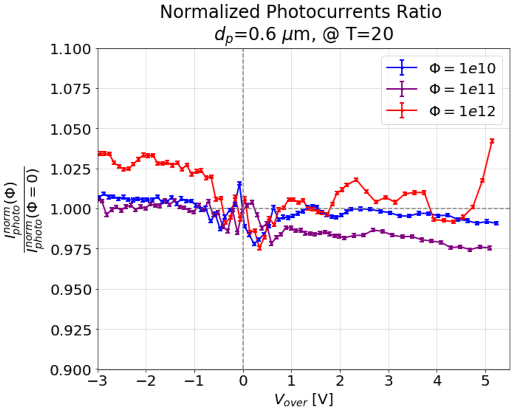
Normalized Photocurrent of planar device:
Variation within 10 %



Normalised Photocurrent





⇒ Deviation less than 5 %. No trend visible.
Further knowledge on G and CN desired.

Conclusion

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- Characterisation of promising SiPM ongoing
- Increase of DCR with irradiation smaller for TAPD than for planar device
- Response to light requires further examination
  $\rightarrow$ charge measurements (DCR, V_{BD}^{G}, G, CN, etc.)

More on TAPD @ DPG Frühjahrstagung by Wolfgang Schmailzl (broadcom) and me

References I

[1] A. N. Otte et Al. “Characterization of three high efficiency and blue sensitive silicon photomultipliers”. In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectromete 846 (2017), pp. 106–125.

[2] E. Engelmann et Al. “Tip Avalanche Photodiode - A new generation Silicon Photomultiplier based on non-planar technology”. In: Nucl. Instrum. Methods Phys. Res. A 737 737 (2014).

[3] E. Garutti et Al. “Characterisation of highly radiation-damaged SiPMs using current measurements”. In: (2017).

References II

[4] F. Acerbi et Al. "Silicon photomultipliers and single-photon avalanche diodes with enhanced nir detection efficiency at fbk". In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectromete IEEE. 2018.

[5] L. E. Büttgen. "Investigation of neutron-induced radiation damage on SiPMs". University of Hamburg, 2020.

[6] M. S. Nitschke. "Characterization of Silicon Photomultipliers Before and After Neutron Irradiation". MA thesis. University of Hamburg, 2016.

SiPM Prototype Design

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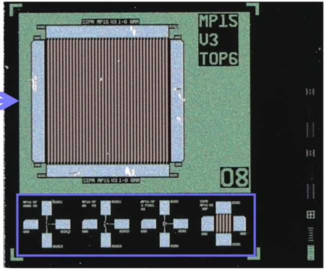
5016 pixels (1mm²)

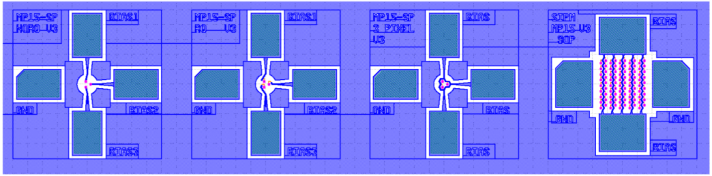


3x single pixel without quenching resistor

3x single pixel

3 pixels

90 pixels



Determination of quenching resistance

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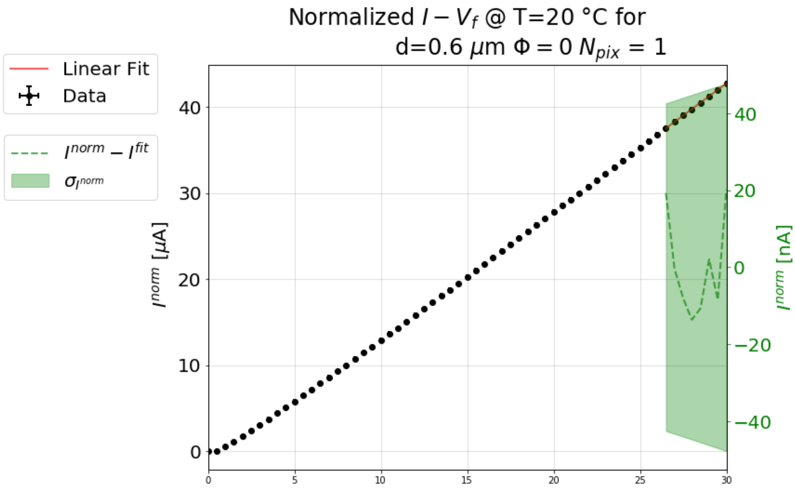


Normalized $:= I/N_{pix}$

Tip Avalanche PhotoDiode (TAPD) Design

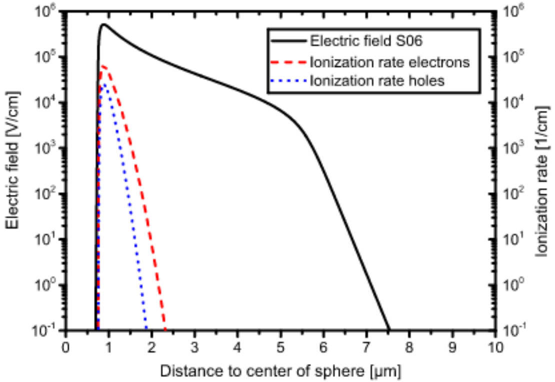
Design by KETEK + MEPhI

- Quasi-spherical pn-junction allows depletion of thick layer at low voltage
- No border ⇒ no border effects

Electrical Field

- Focused at the tip
- Large drift area ($r \approx 7\mu$m)
- Multiplication near tip ($r \approx 2\mu$m)

Structure is characterized by pillar diameter d_p.



Electric Field Simulation [2]

Normalised Photocurrent

Comparison with highly irradiated SiPMs [3]: