A novel Silicon Photomultiplier with bulk integrated quench resistors - utilization in optical detection and tracking applications for particle physics

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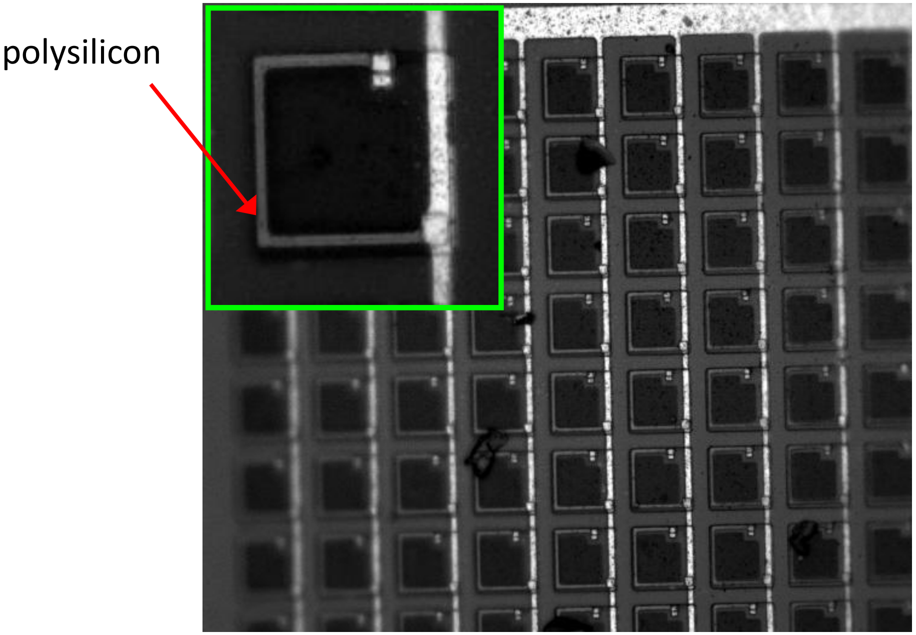
Conventional Silicon Photomultiplier (SiPM)

Conventional Silicon Photomultipliers (SiPMs):

- Array of avalanche photodiodes operated in Geiger-mode
- Read out in parallel → signal is sum of all fired cells
- Passive quenching by integrated polysilicon resistor



<u>Deposition of polysilicon resistor and metal grid on top surface:</u>

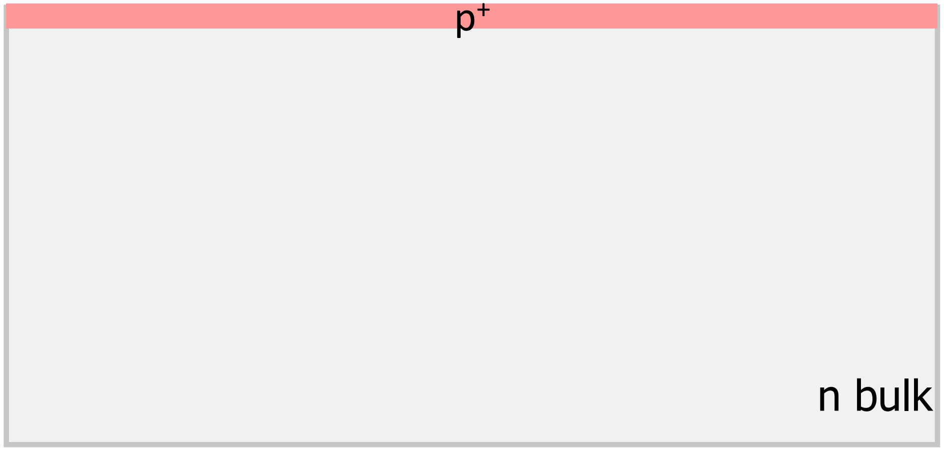
- Several additional process steps
- Increased stray capacitance
- Obstacles for light

→ limitation of the detection efficiency

SiMPl

SiMPl

SiMPl



SiMPl

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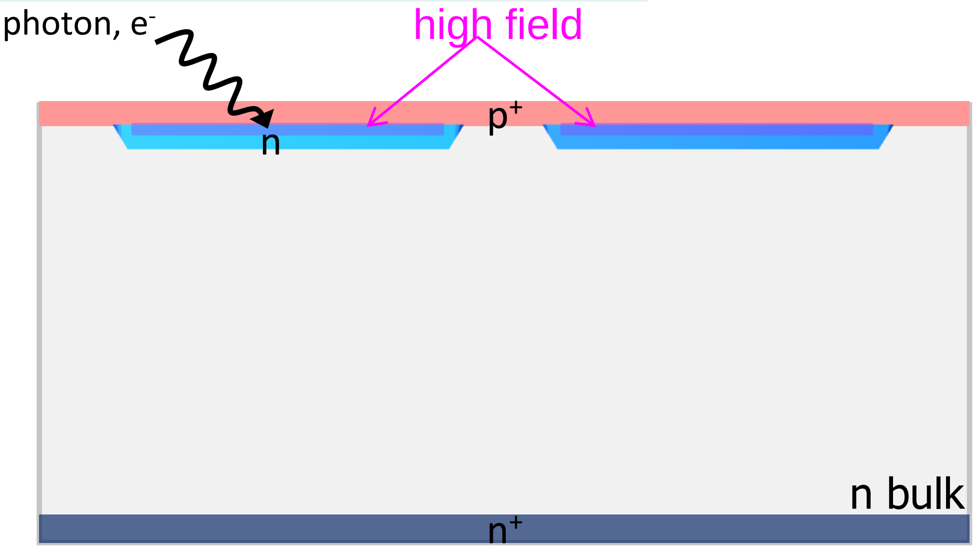

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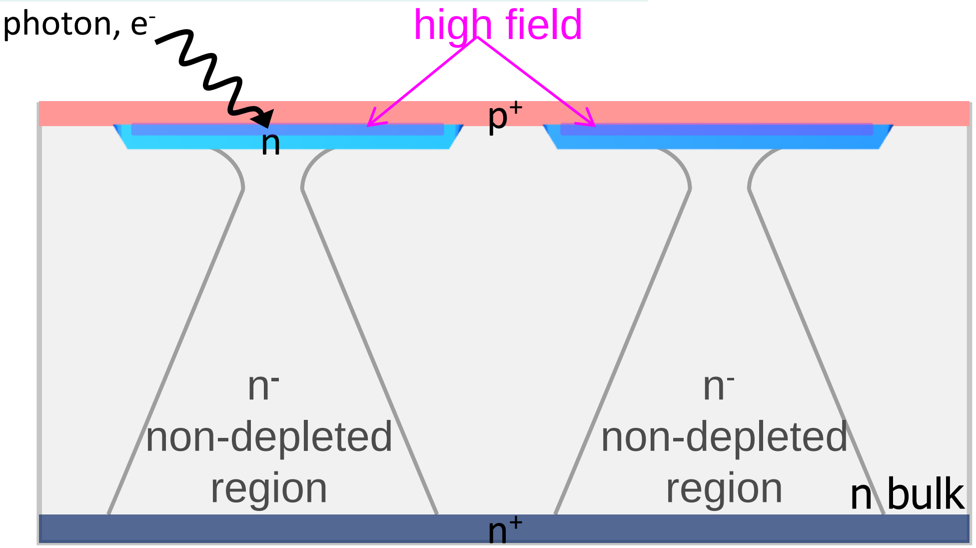
photon, e-
high field
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non-depleted
region
n-
non-depleted
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n bulk
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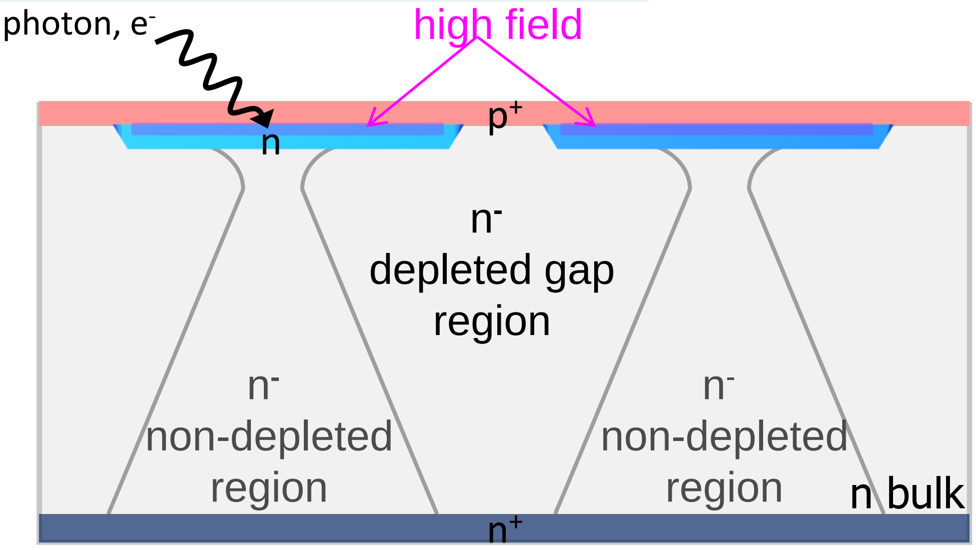
SiMPl


photon, e-
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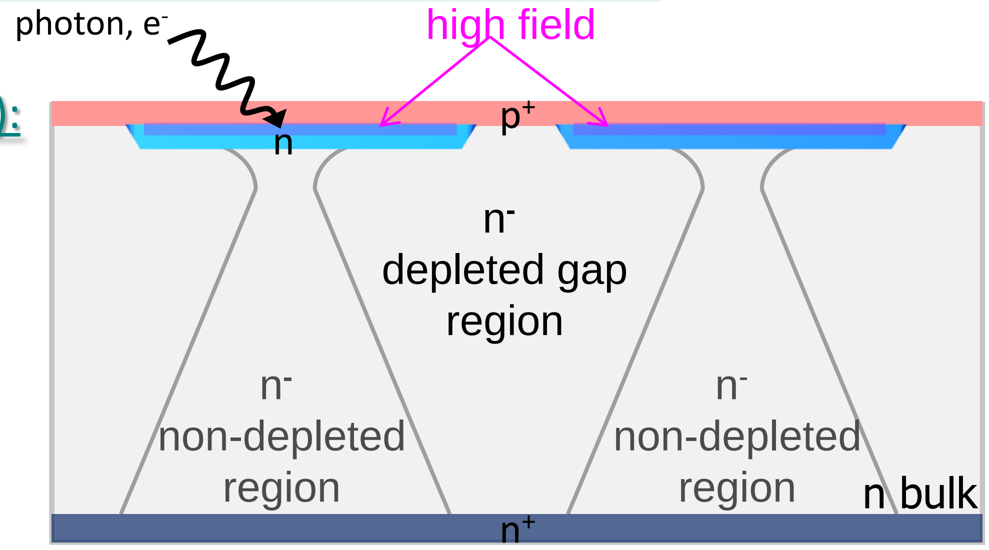
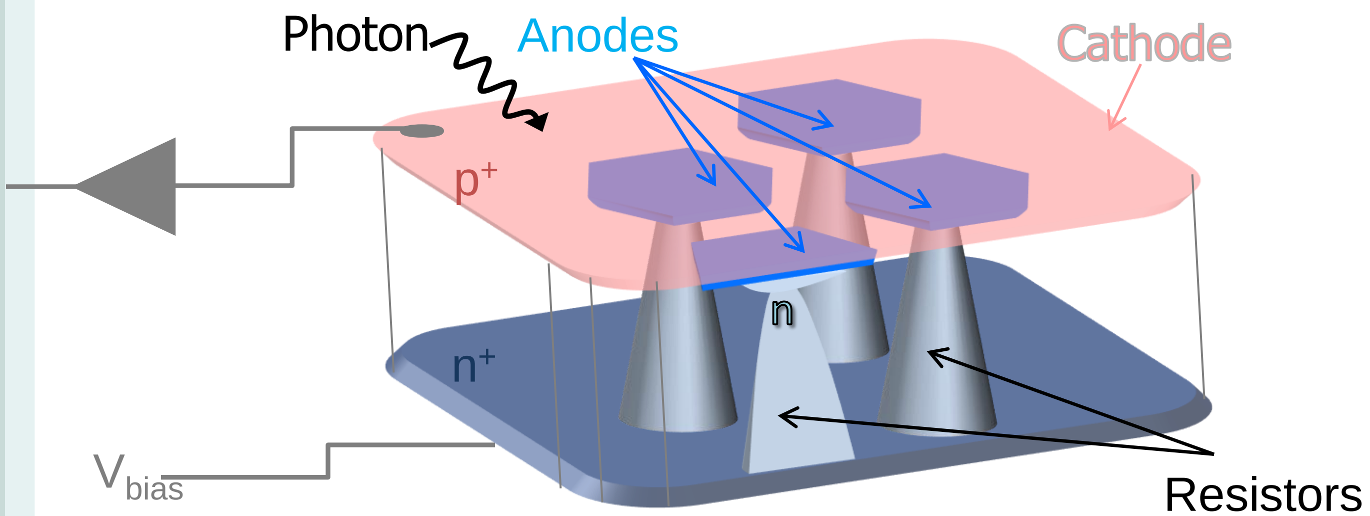
SiMPl

Silicon MultiPixel light detector (SiMPl):

- Bulk integrated quench resistor (formed by non-depleted bulk region)
- Free entrance window for light
- Vertical 'resistor' acts like a JFET





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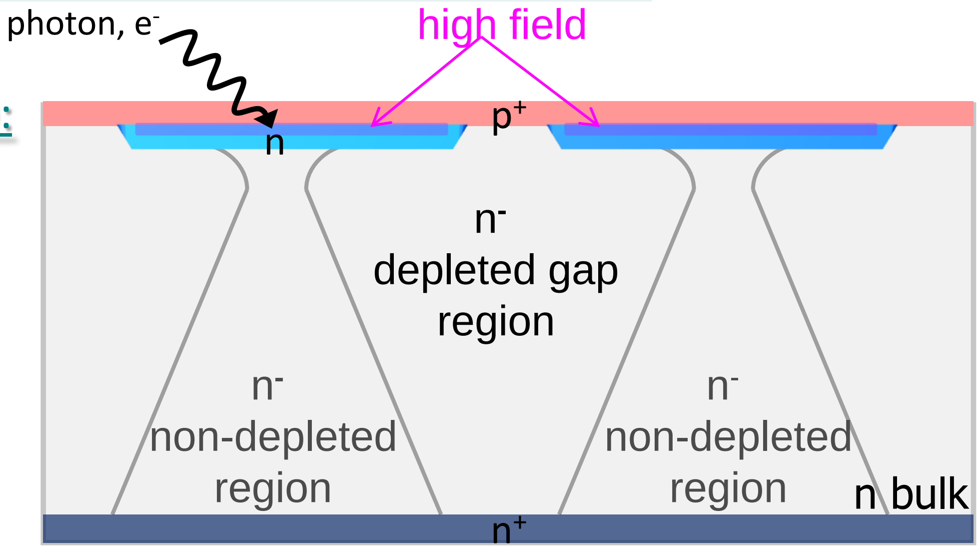

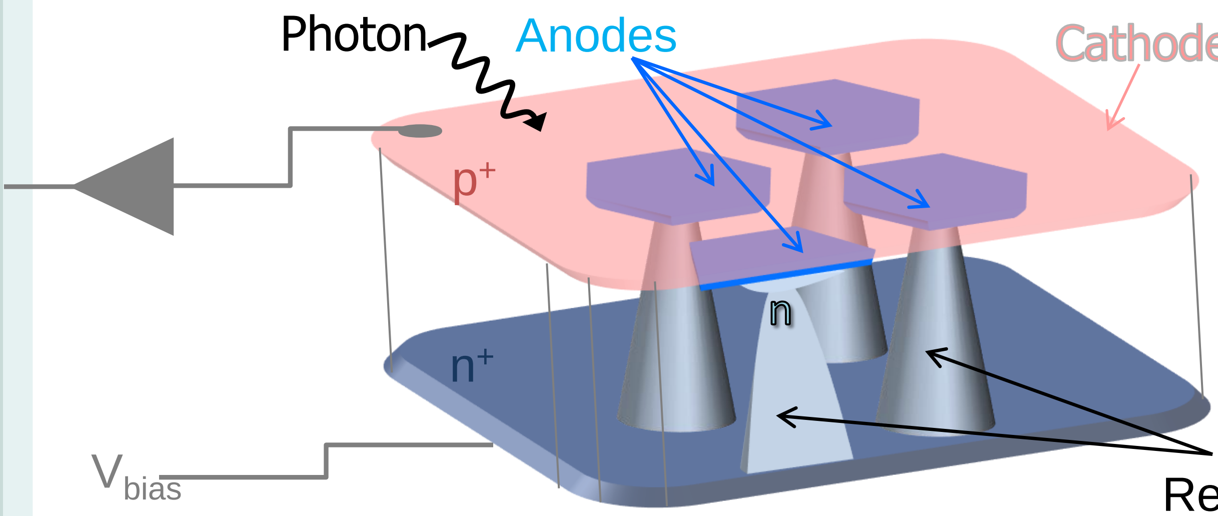

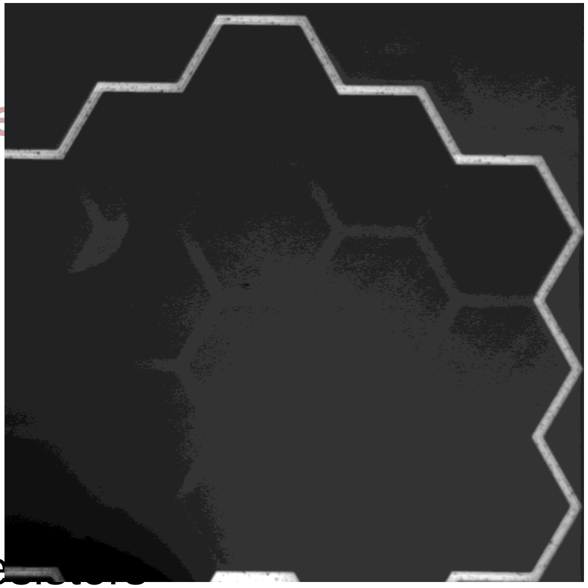

SiMPl – Advantages and Drawbacks

Advantages:

- No need of polysilicon

→ No metal necessary within the array → free entrance window for light → higher fill factor

- Topologically flat surface
- Simple technology → lower costs
- Inherent diffusion barrier against minorities in the bulk → less optical cross talk & less contribution of leakage current

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Drawbacks:

- Required depth for vertical resistors does not match wafer thickness

→ Wafer bonding is necessary for big pixel sizes

→ Significant changes of cell size requires bulk material adaption

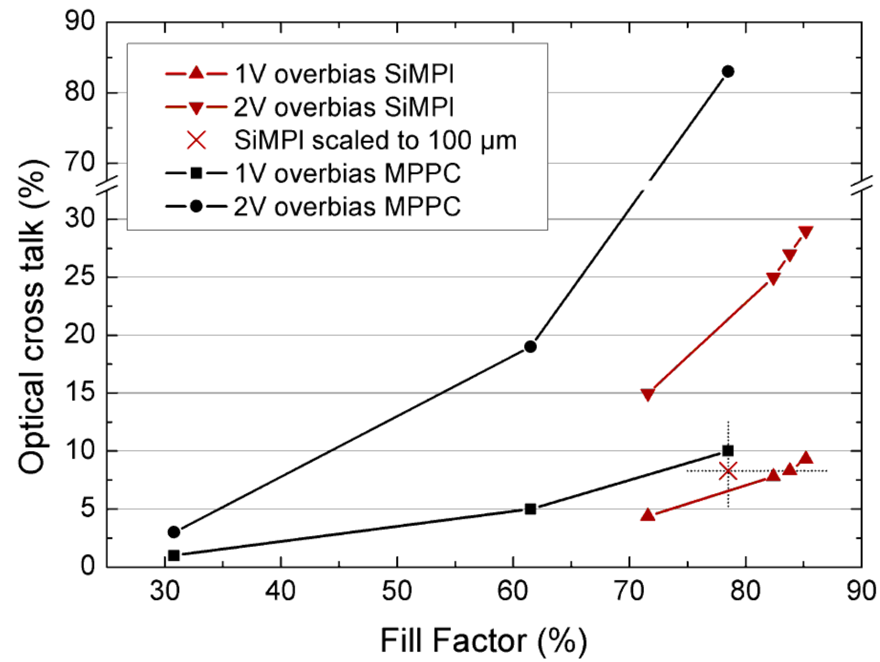
- Vertical ‘resistor‘ is a JFET → non-linear IV → longer recovery times

SiMPl characterisation – Optical cross talk

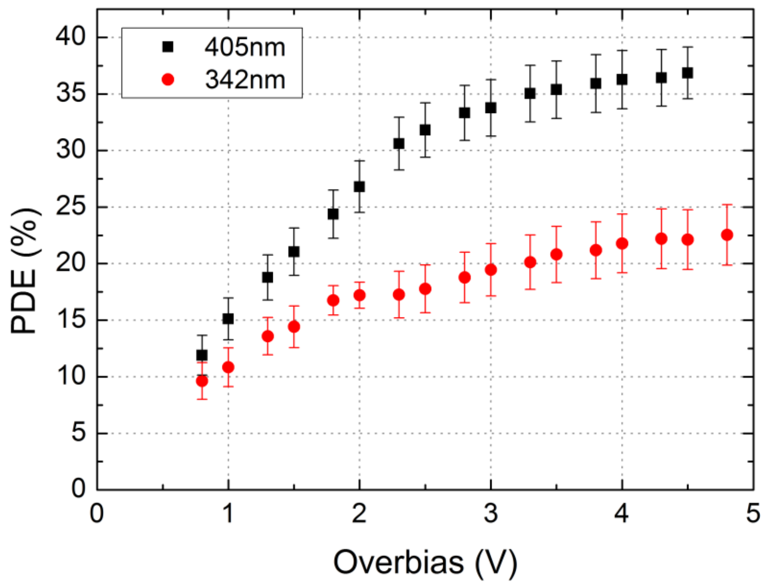
Pitch / Gap	Fill factor	Cross talk (2V V_{ob})
130µm / 10µm	85.2%	29%
130µm / 11µm	83.8%	27%
130µm / 12µm	82.4%	25%
130µm / 20µm	71.6%	15%

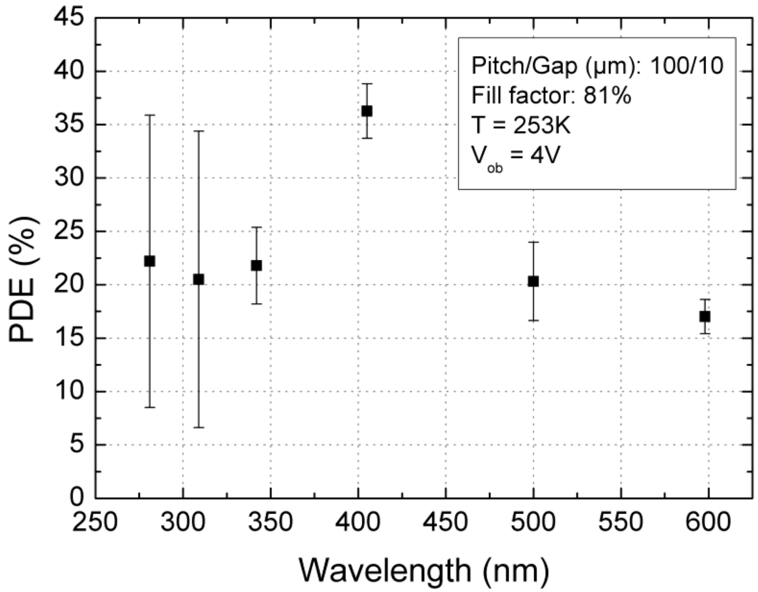
SiMPl:

- No optical trenches
- High fill factor
- Low cross talk in comparison (MPPC w/o optical trenches)



SiMPl – Photon Detection Efficiency





- Temperature: -20°C
- Breakdown voltage: 34.5V
- Fill factor: 0.81
- Laser repetition rate: 300kHz

Pitch/gap	Fill factor	PDE @ 405nm
100/10	81.0%	26.2%
130/10	85.2%	28.2%
130/12	82.4%	27.2%

@ 2V overbias

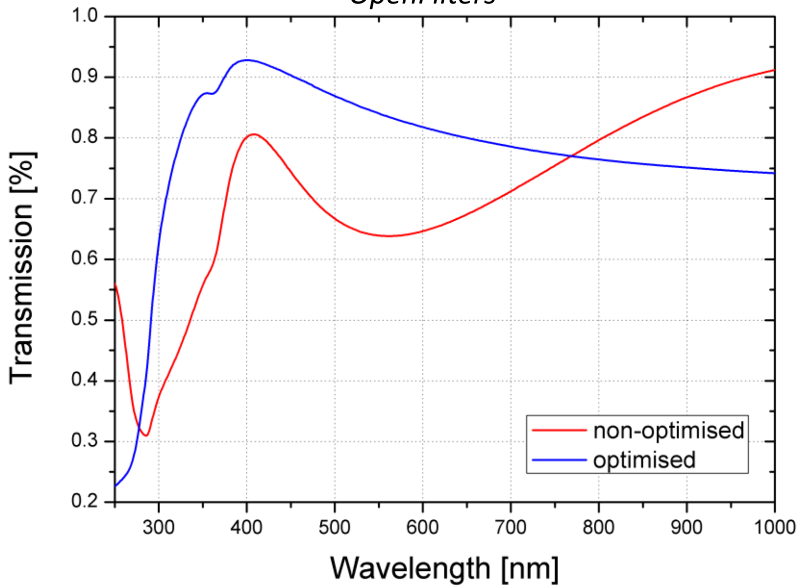
But: no optimised entrance window!

SiMPl characterisation – Entrance window

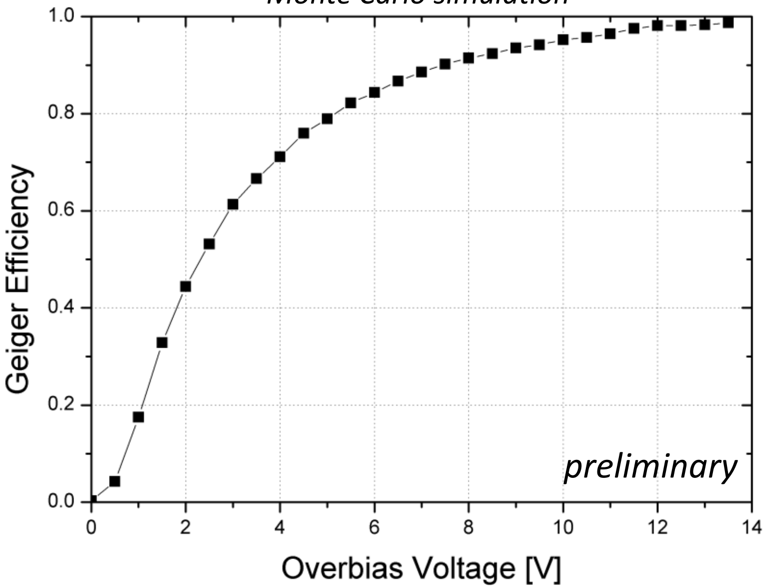
<u>But: Prototype without optimised entrance window!</u>

→ Reduction of light reflections on surface

*OpenFilters**



Monte Carlo simulation



With optimised entrance window (> 90% transmission) and Geiger efficiency ≈ 80%

→ **PDE of 65% achievable**

* *Larouche and Martinu, Appl. Opt., Vol. 47, No. 13, (2008)*

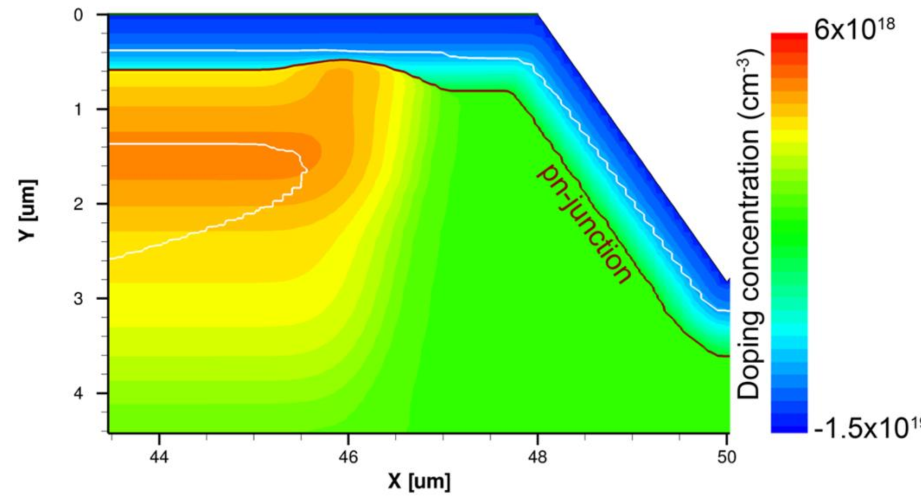
SiMPl photon detection – Future Concepts

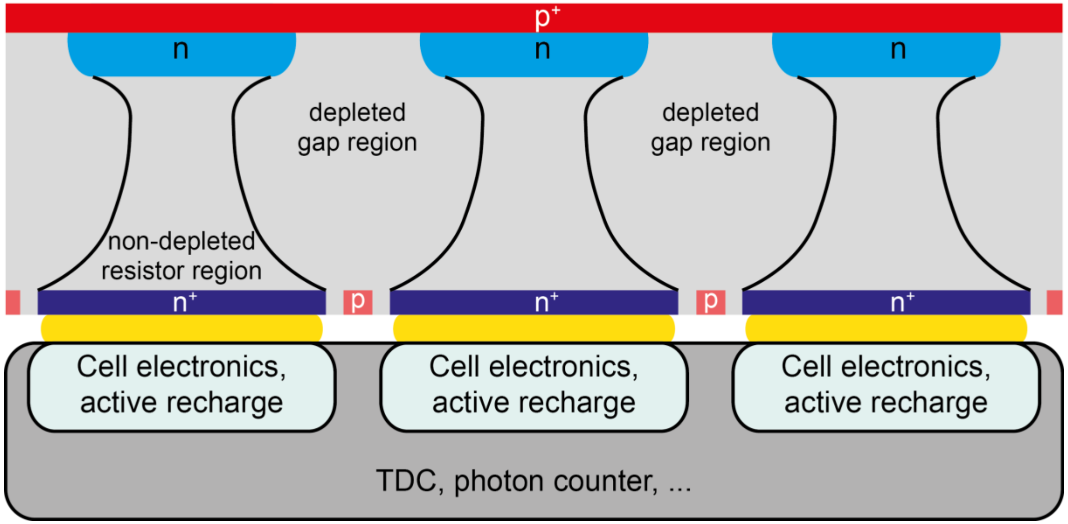
- Optical trenches for improved cross talk suppression

  → Higher fill factor and PDE

- Fabrication of devices with small pixels for high dynamic range

  → Simulations indicate feasibility for 30µm pitch with passive quenching





Imager concept:

- Single cell readout possibility and active quenching by means of structuring the back side
- Connection of electronics to the structured back via bump bonding

Why use avalanche photodiodes for tracking ?

Requirements for a particle tracking detector:

- Fast response
- High signal gain and active area
- Sensitivity to particles
- Insensitivity to magnetic fields
- Simple readout design
- Low mass detectors (< 0.1% X_0 per layer)
- High resolution (pixel size < 50µm)
- Low noise levels

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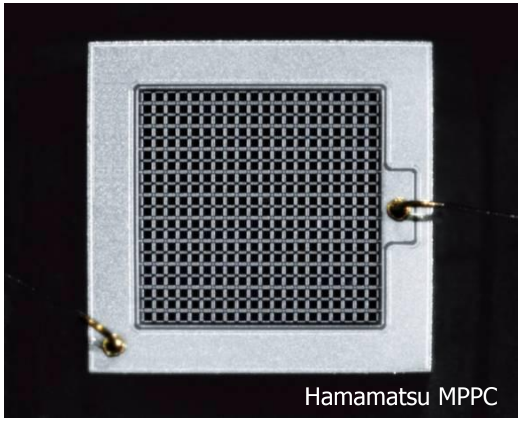
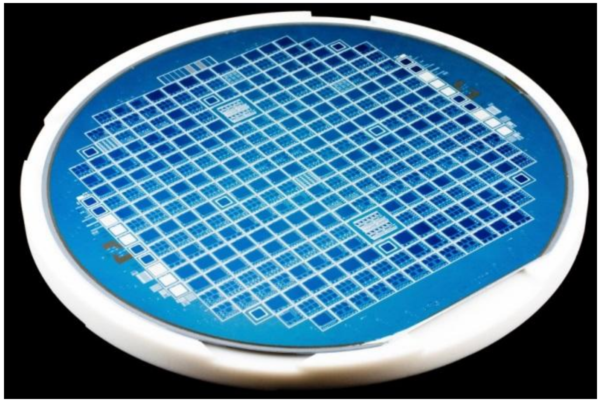
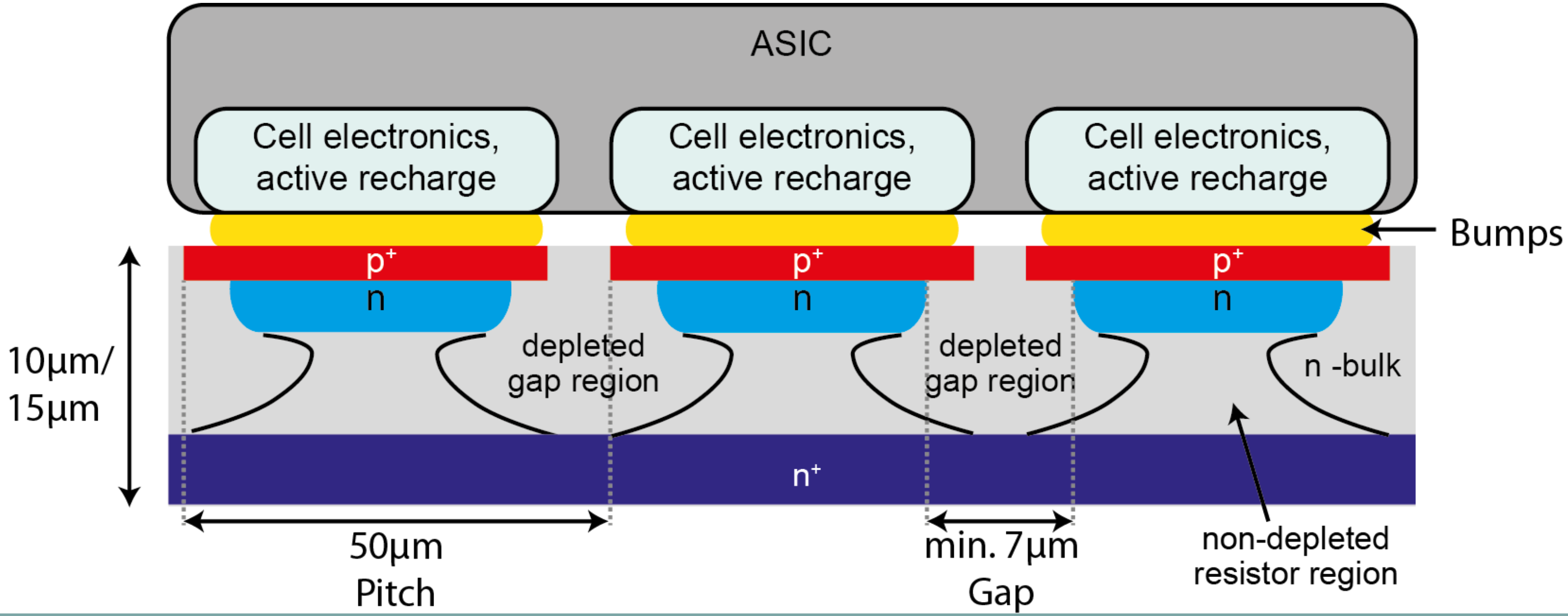


Accomplishable by Silicon Photomultipliers



Particle Tracking with SiMPl

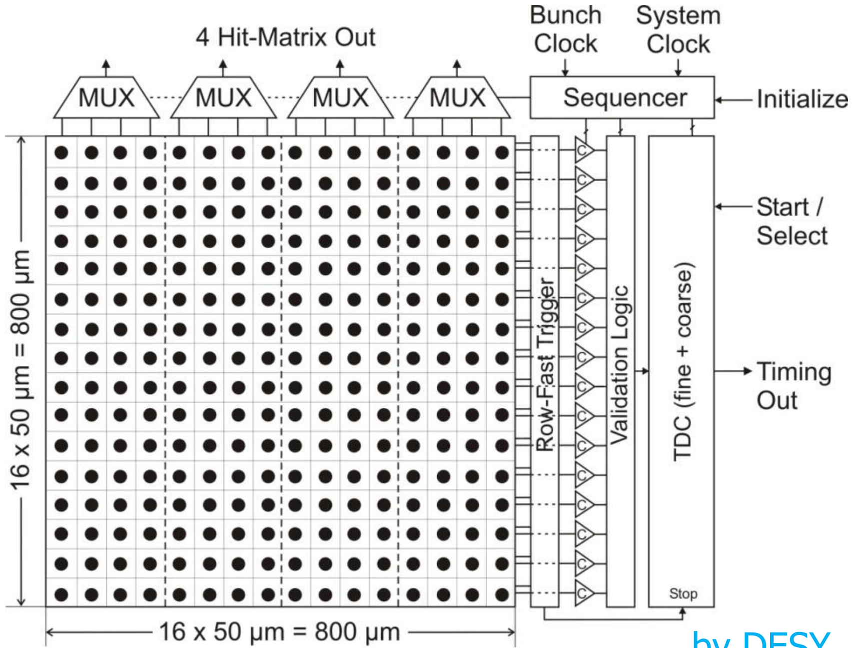
- Excellent time stamping due to fast avalanche (sub-ns)
- MIPs generate roughly 80 e-h-pairs/µm
- Inherently high trigger efficiency
  → Allows operation at low overbias voltage
  → Decrease of dark counts & optical cross talk
- Topologically flat surface → easy coupling to electronics
- High fill factor (pitch limited by bump bonding)
- Requirements for bulk resistor less demanding



Active Quenching Concept

- Overcome longer recovery times by implementing active quenching circuits
- Uses current-mode approach
- Active quenching for single pixels
- Possibility to turn off individual pixels
- Parallel readout and measurement possible
- Event selection with specific trigger conditions (validation logic) → decrease of dark counts & optical cross talk
- Quenching time < 1ns
- Pixel recovery < 20 ns
- 50 µm pitch
- 5 MHz frame rate
- 100 ps timing resolution (TDC)
- Fast trigger < 1 ns

Possible layout

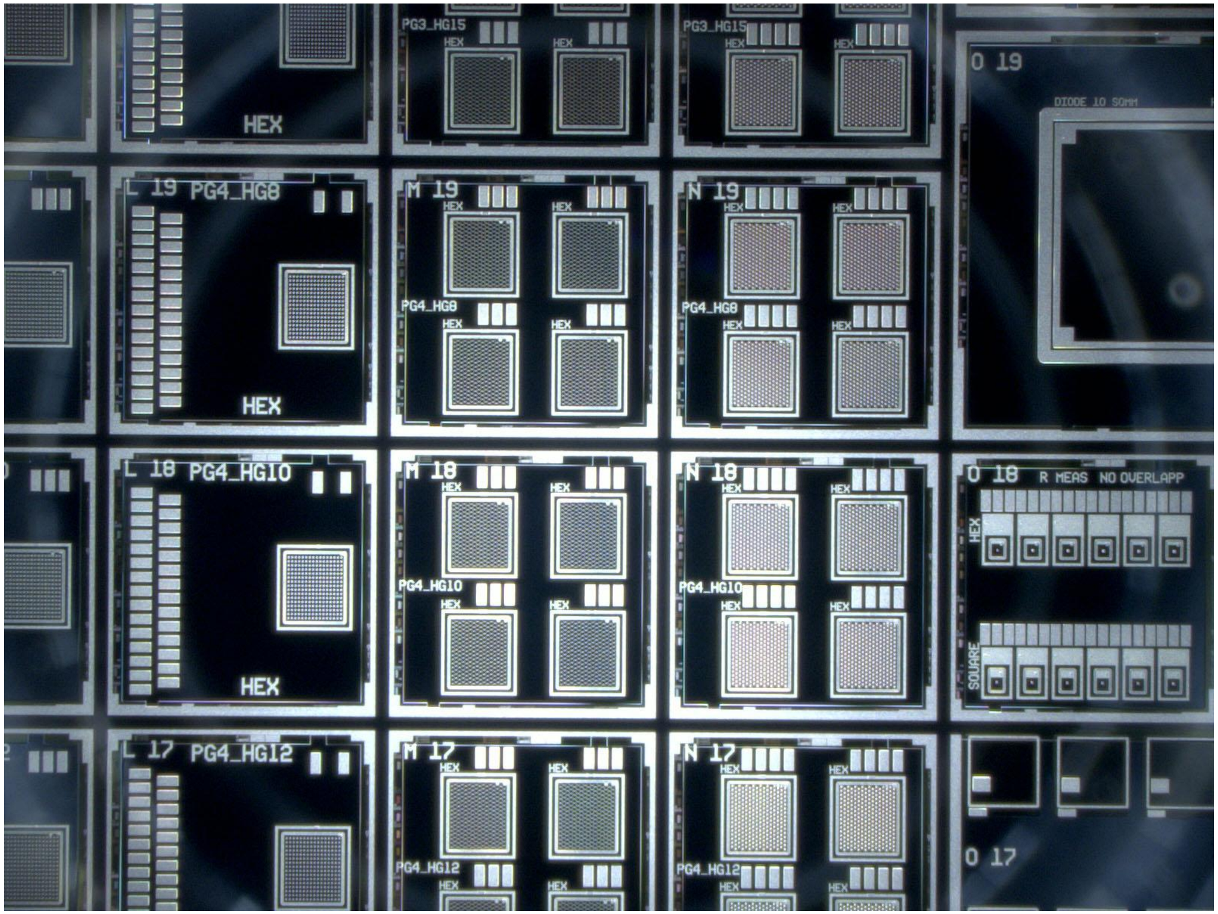


by DESY (Hamburg)

Inge Diehl, Karsten Hansen, Katja Krueger, Christian Reckleben, Felix Sefkow

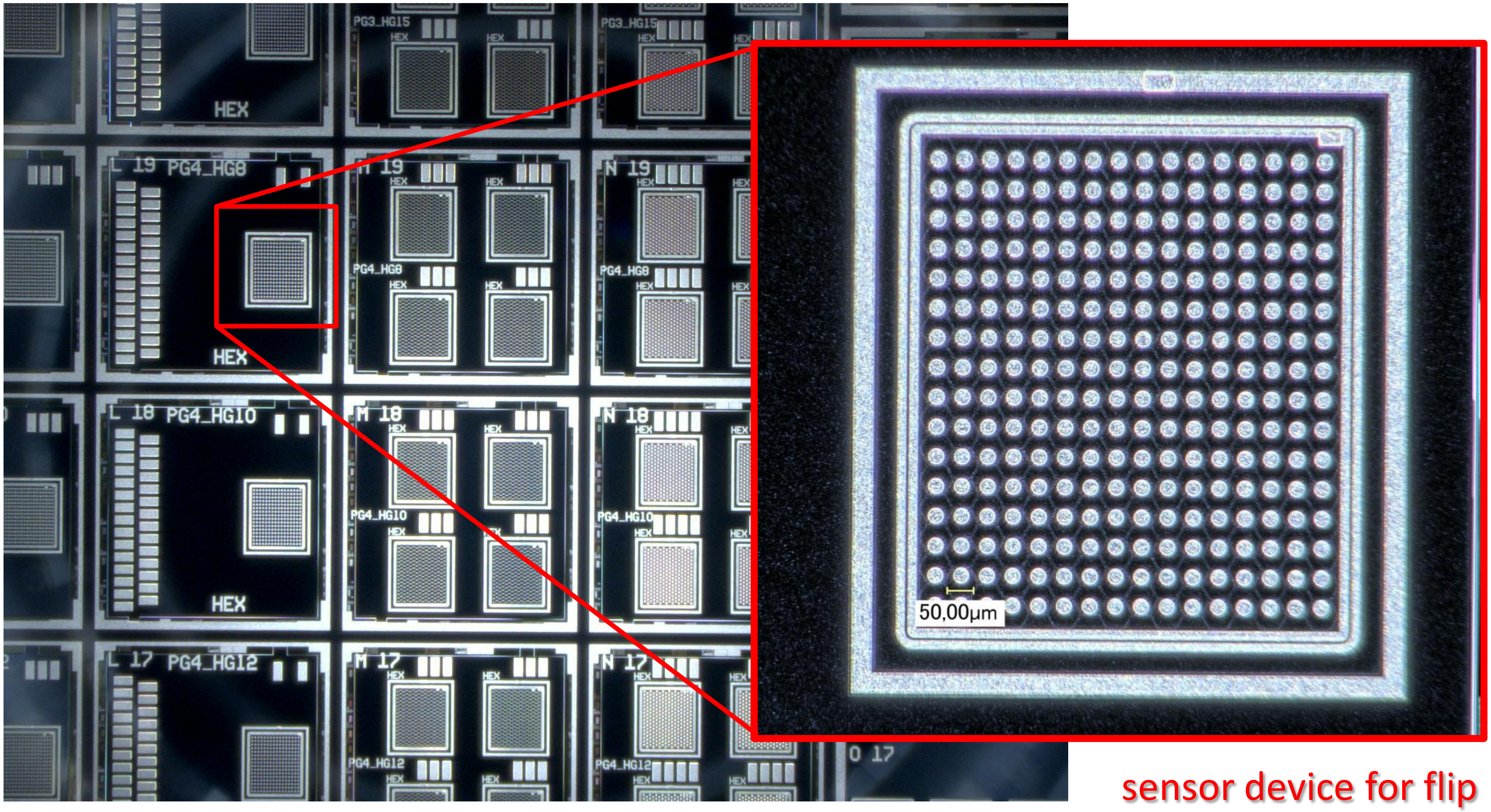
→ promising candidate for tracking

First DSiMPl Prototypes



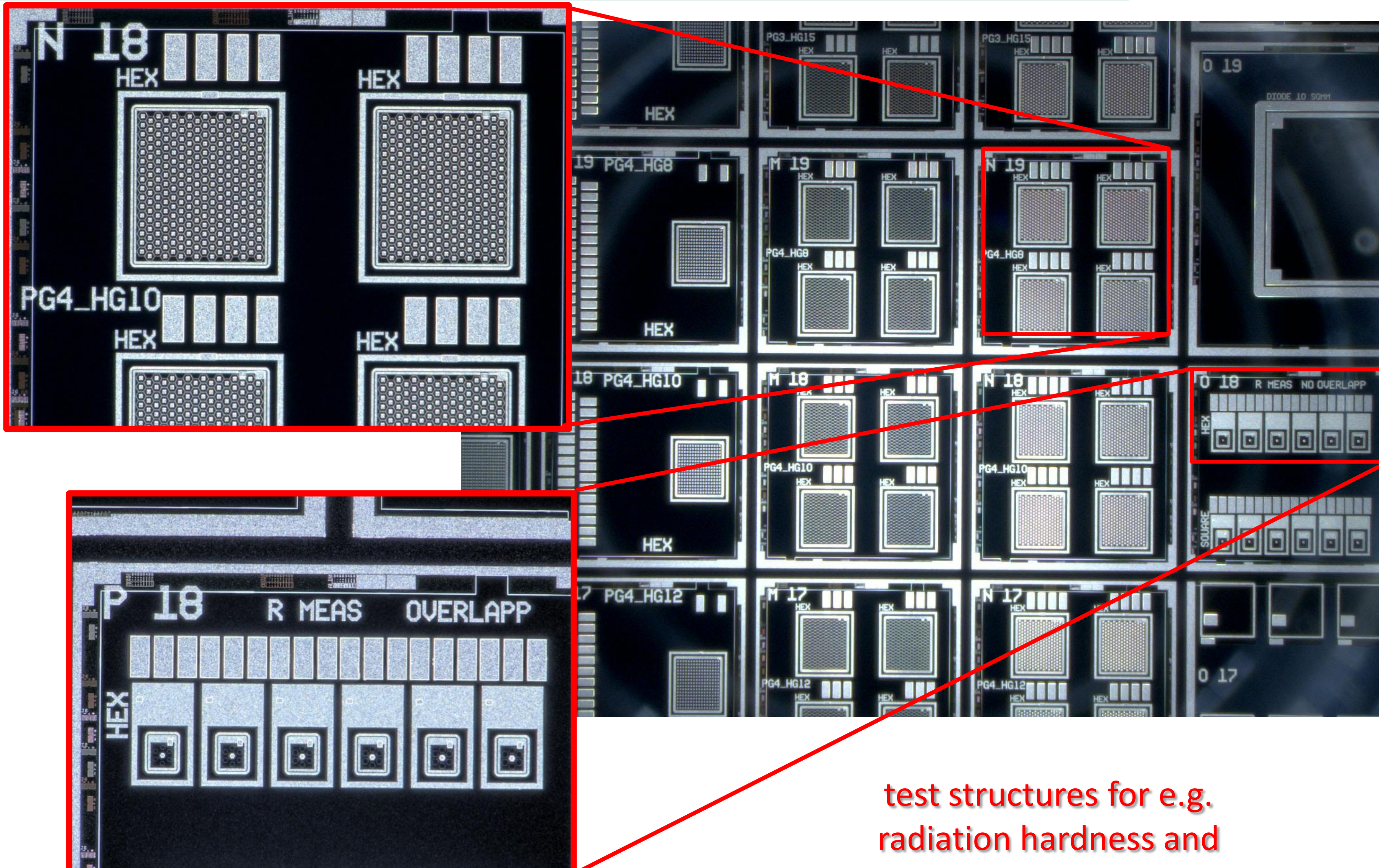
- geometrical variations of sensor devices
- different structures for test purposes
- first wafer-level test promising

First DSiMPl Prototypes



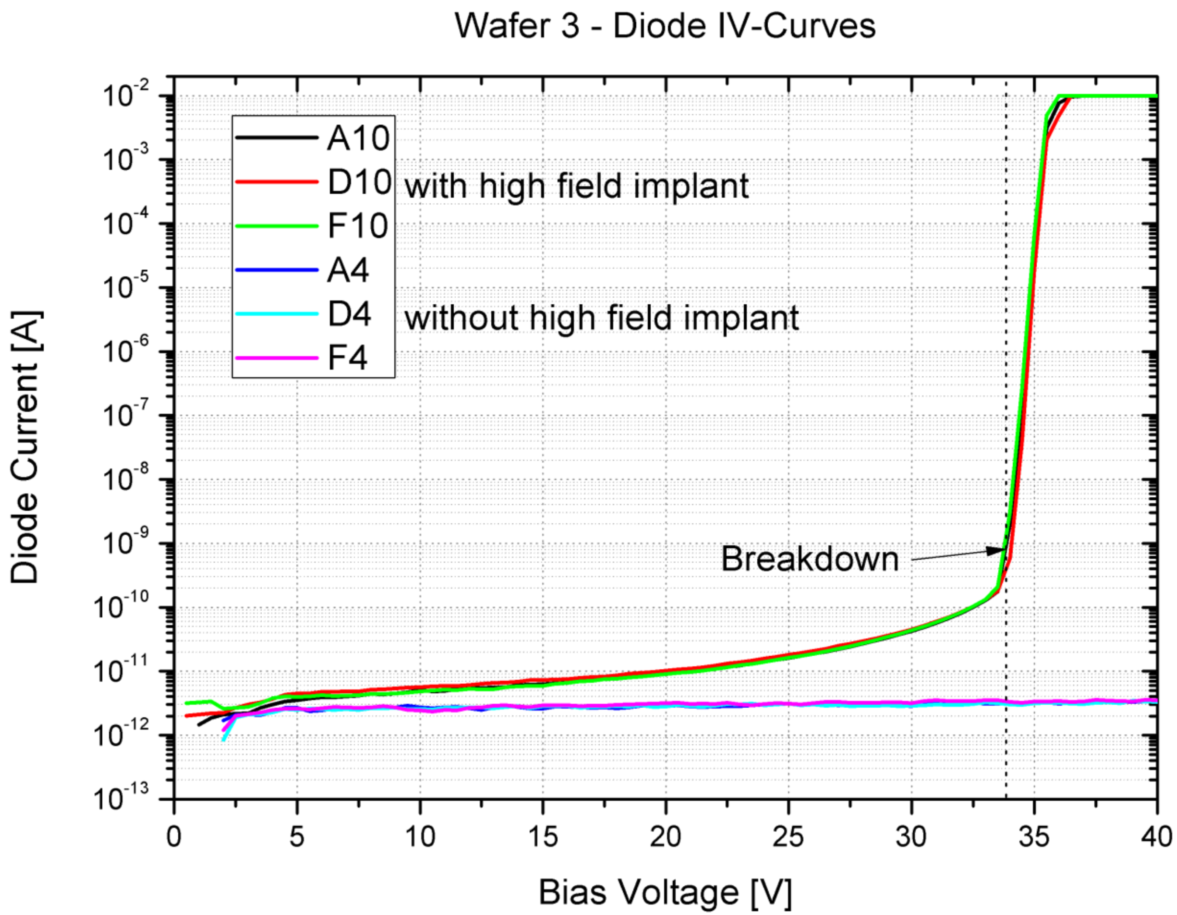
sensor device for flip chipping

First DSiMPl Prototypes



test structures for e.g. radiation hardness and quenching resistor

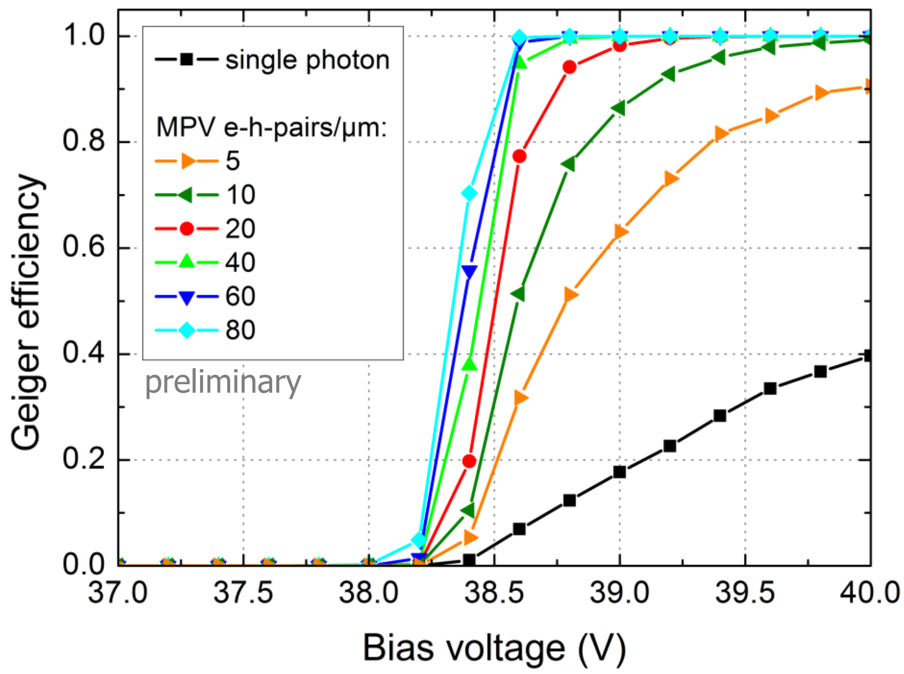
First DSiMPl Prototypes – Measurements



- IV-measurements of diodes with and without high field implants
- homogeneous behavior
- breakdown voltage in good agreement with TCAD and Monte Carlo simulations

First Efficiency Simulations

→ Simulations: Small overbias voltages sufficient for high Geiger efficiency

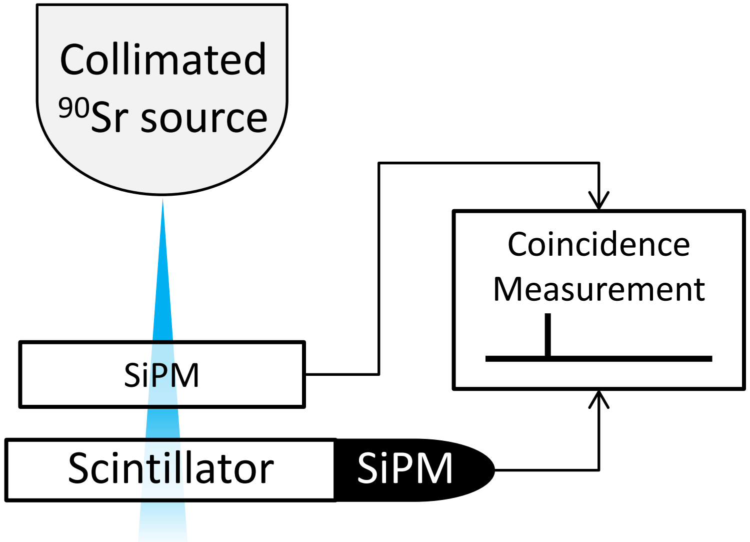


- Monte-Carlo simulations of ionisation probability (ionisation coefficients by Van Overstraeten) based on SiMPl device → Geiger efficiency for MIPs
- Overbias voltages ≈ 0.5 V should already provide Geiger efficiency ~ 1

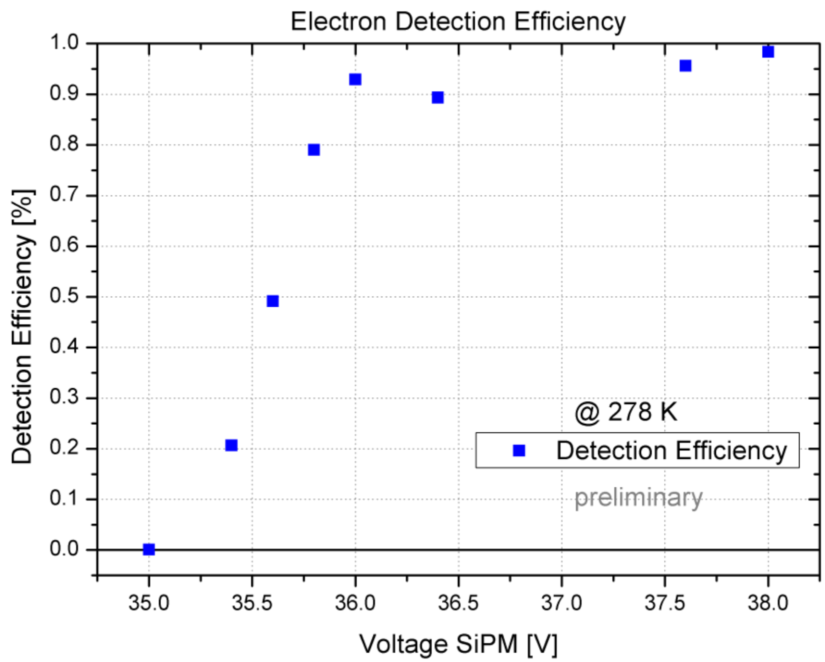
→ Strongly decreased pile up with decreasing overbias voltage

→ experimental validation required!

First Efficiency Measurements



- Experimental validation of Geiger efficiency simulation with ^{90}Sr electron beam
- Determination of Geiger efficiency by measuring the signal coincidences between SiPM and scintillator



- measured with 84% fill factor device
- in very good agreement with trend suggested by the simulations
- But: still missing a dark count correction and systematic error estimation

Summary and Outlook

Summary

- Novel detector concept for SiPMs with quench resistors integrated into the silicon bulk
  - No polysilicon resistors, no contacts necessary at the entrance window
  - Very simple processing
  - Topologically flat surface for easy coupling to electronics
  - Working quenching mechanism
  - Very promising results (high PDE, low cross talk)

- Particle tracking concept with active quenching circuits
  - SiMPl devices could fulfil detector requirements for tracking
  - Collaboration with DESY for active quenching circuits for SiMPl
  - Promising results from first simulations…
  - … and wafer level measurements of new batch
  - First detection efficiency results at low overbias voltages in very good agreement with simulations

Open questions & next steps

- Improvement of technology (e.g. optical trenches)
- Particle detection efficiency measurements with improved setup & improved corrections
- Test beam with first prototypes
- Radiation hardness tests

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Thank you for your attention!

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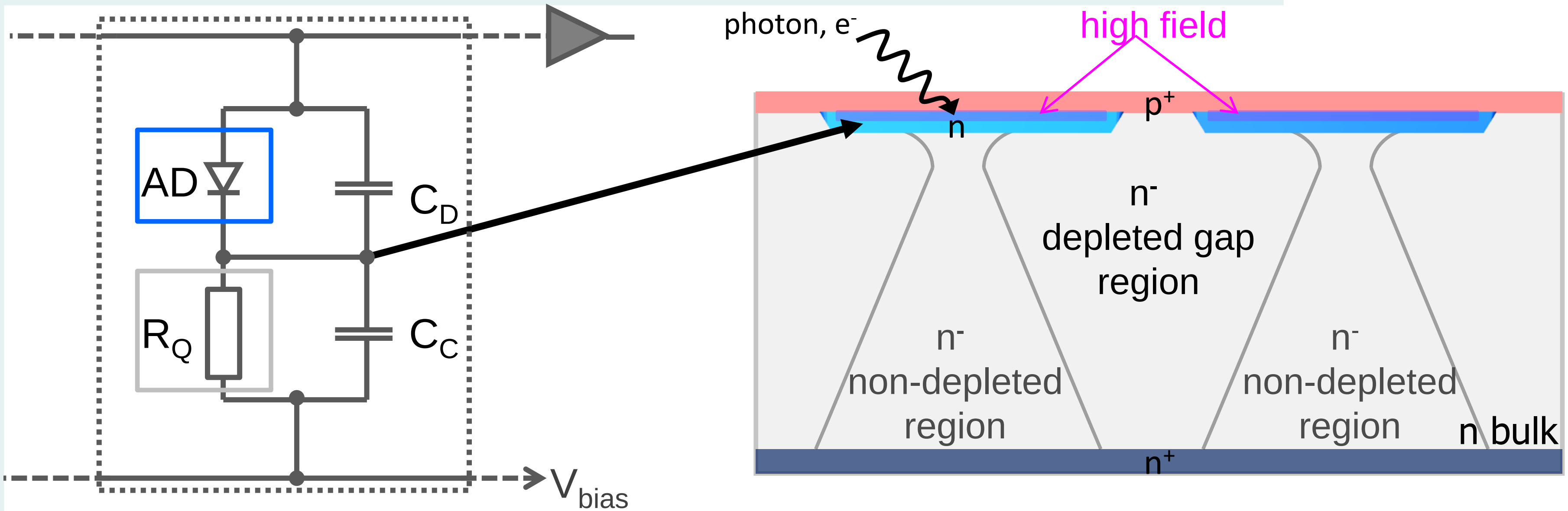
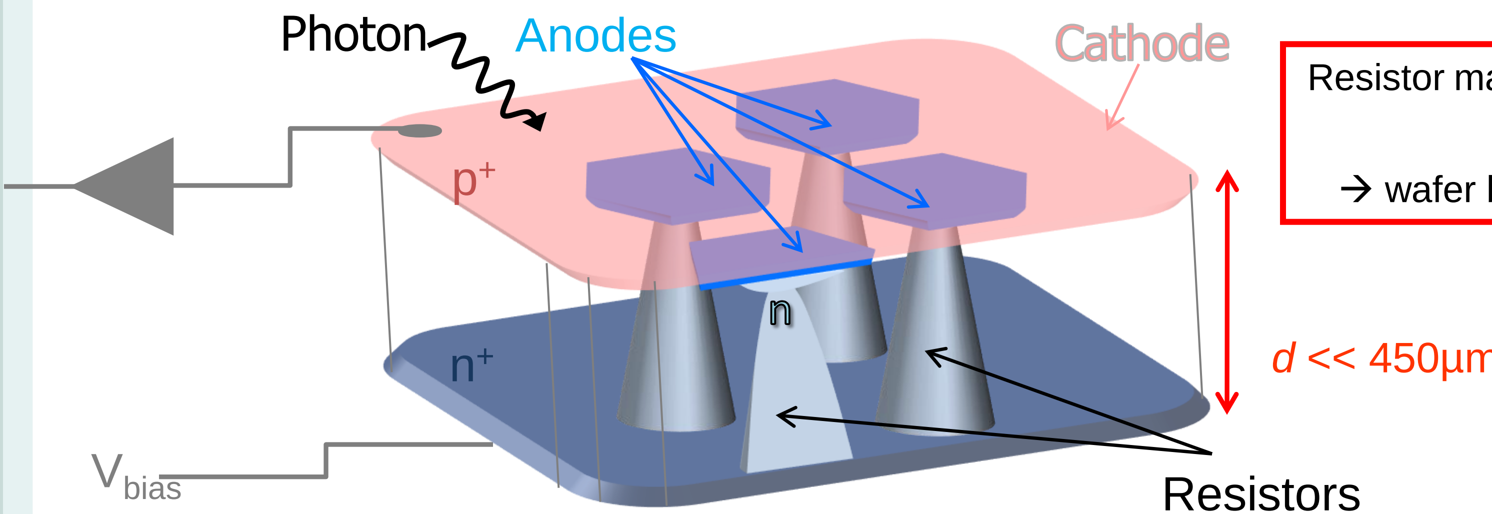
Backup

SiMPl

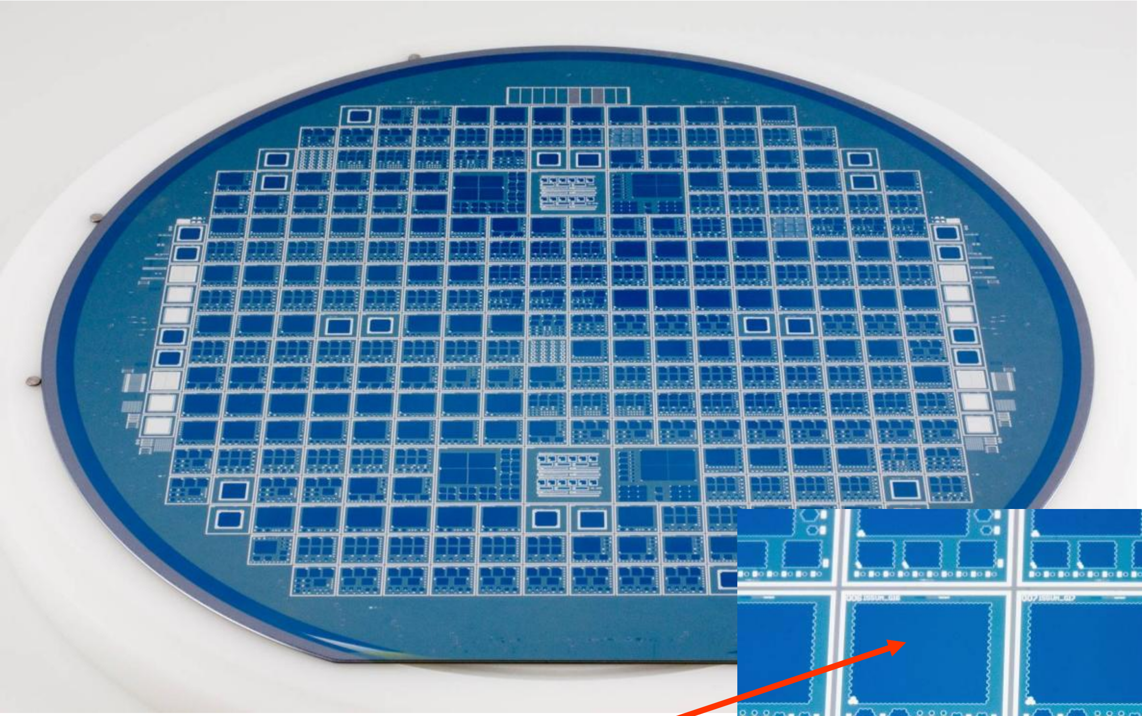


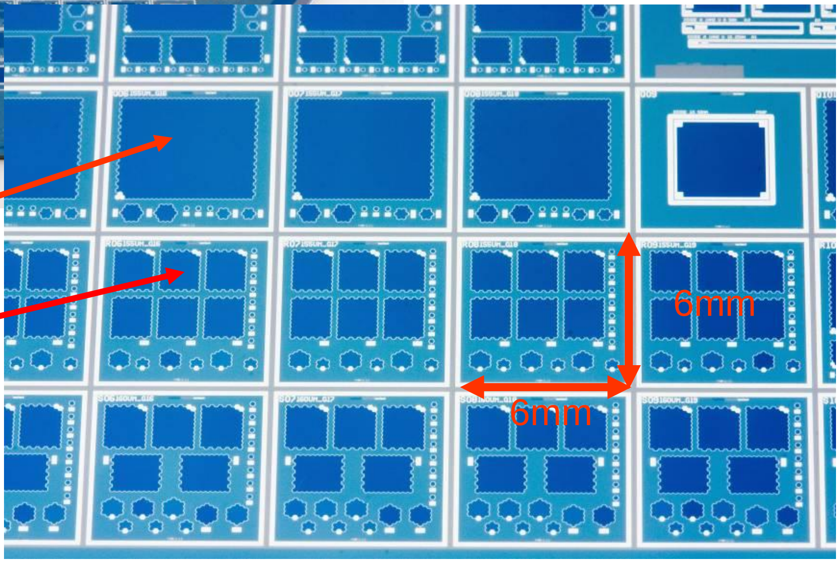


Resistor matching requires thin wafers!

→ wafer bonding or epitaxy

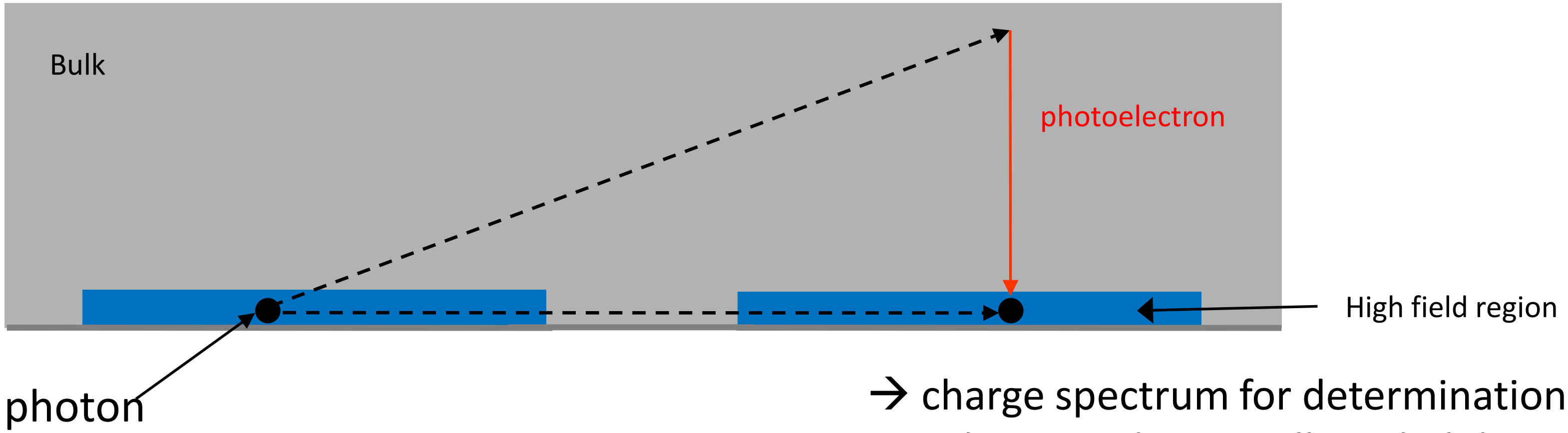
SiMPl Prototype



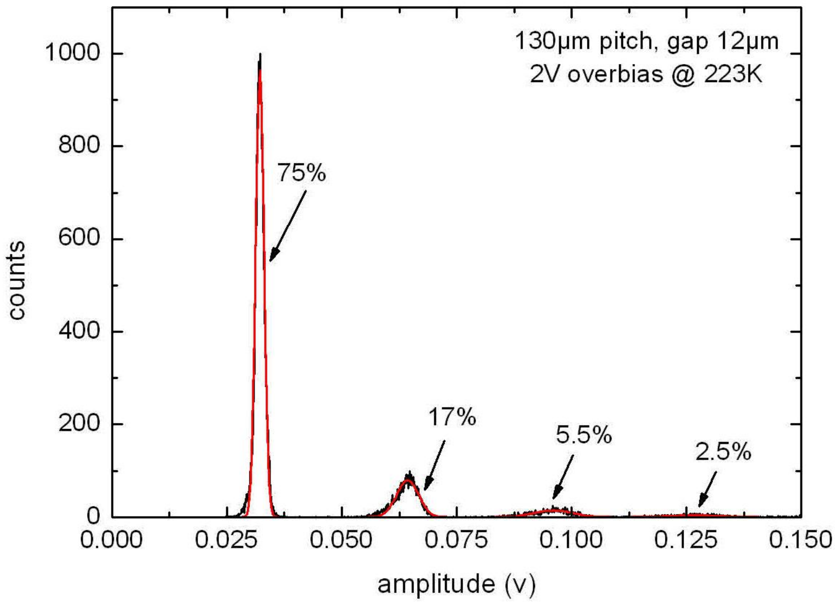


- Wide range of geometrical variations
- Pitch: 90 -160 µm with different gap size

Optical cross talk



→ charge spectrum for determination of the optical cross talk probability



hot-carrier luminescence:
in an avalanche breakdown 10^5 carriers emit in average

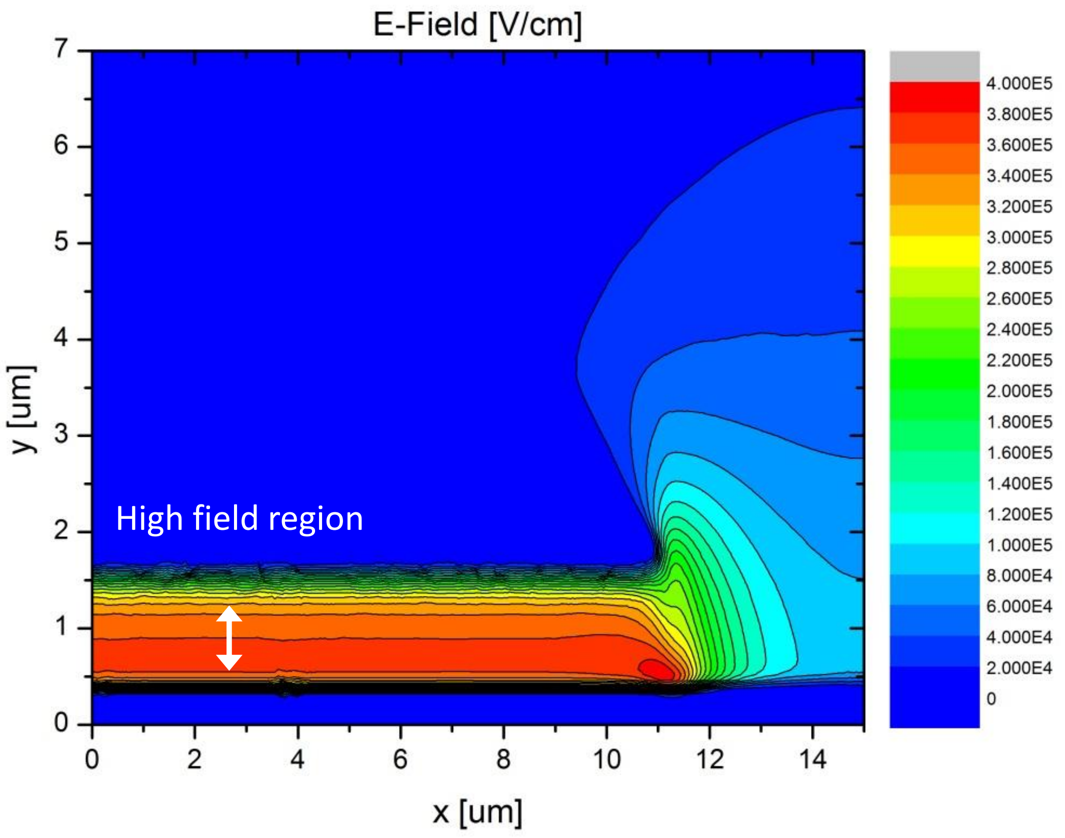
1 photon with E > 1.12 eV

→ trigger of neighbouring cells (fast & slow component)

A. Lacaita et al, IEEE Trans. Elec. Dev.,Vol. 4, 1993

→ influence on photon counting statistics due to additionally fired cells

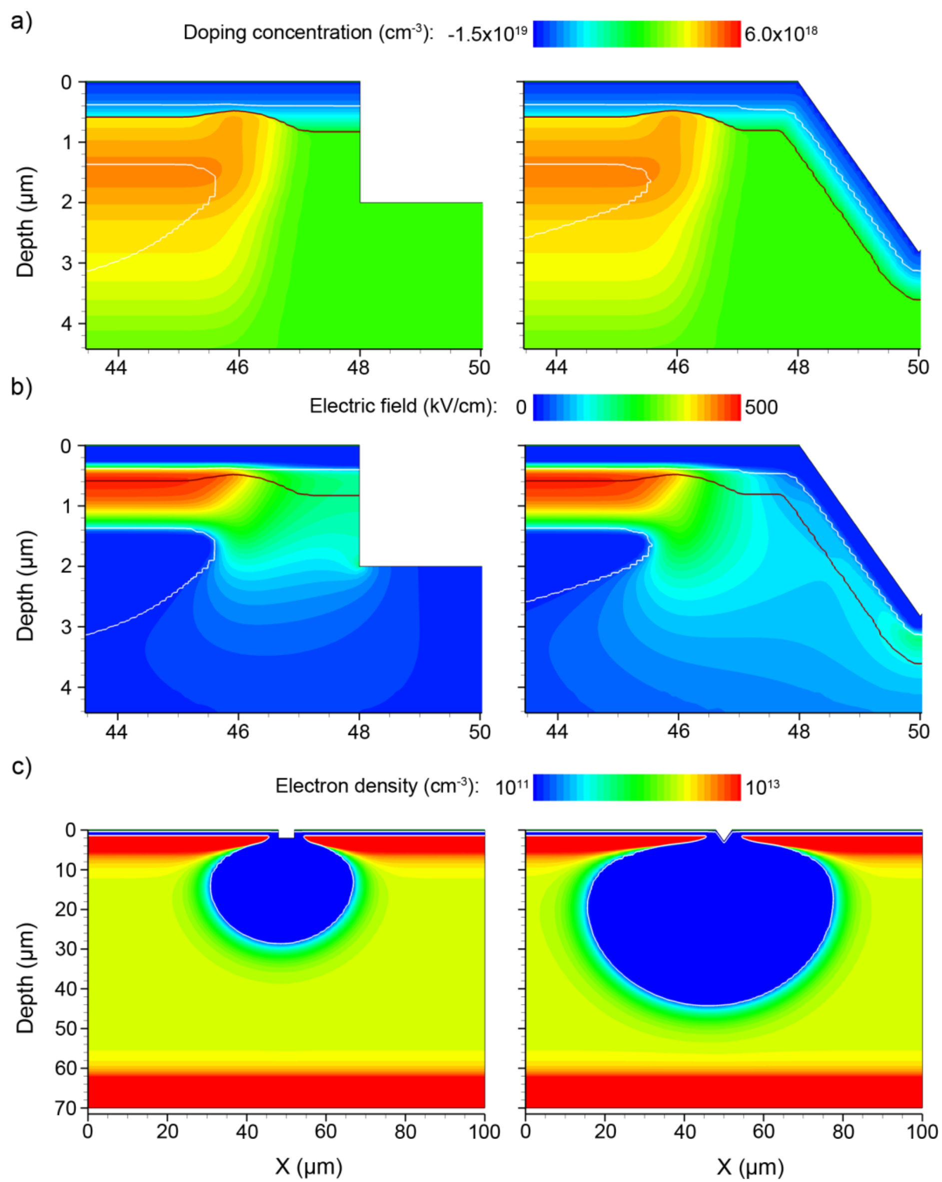
Device simulations



TCAD simulations for obtaining the electrical field

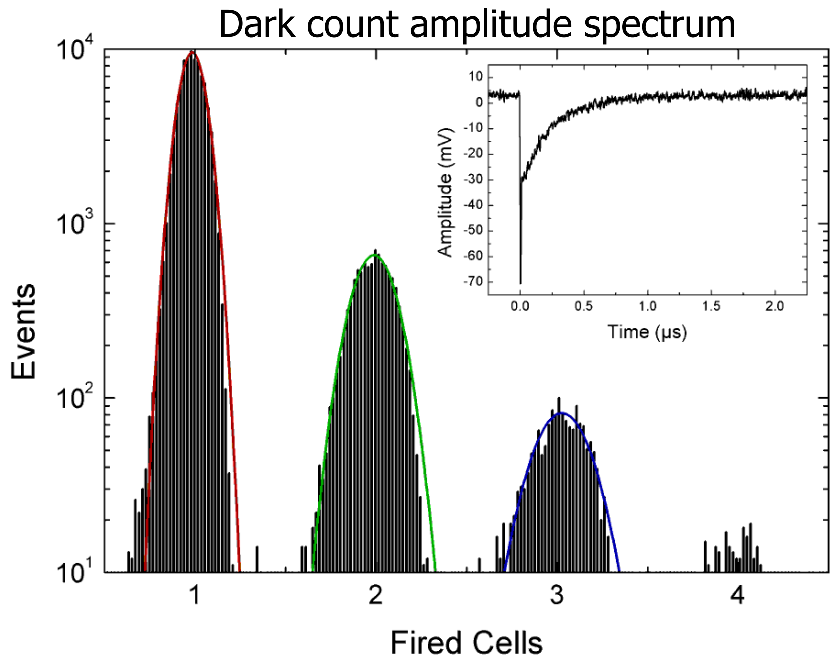
Optical Trenches

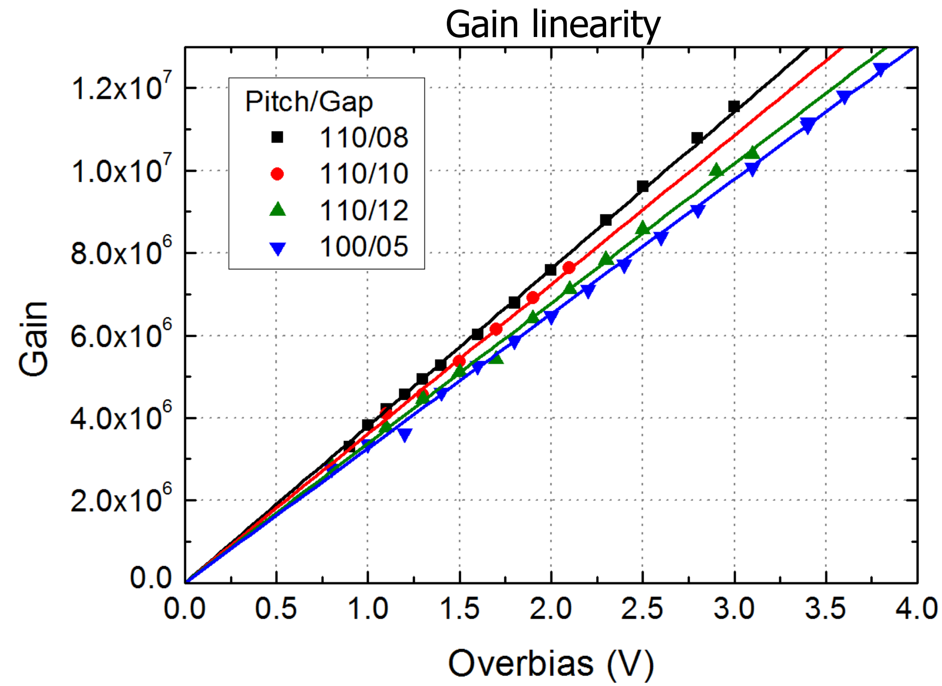
plasma etching



anisotropic wet chemical etching

SiMPl – General Characterisation





Dark count amplitude spectrum:

10x10 array of 135µm pitch @ 253K

Indicates normal quenching operation

<u>Dark counts:</u>

Due to non-optimised process sequence ~ 10 MHz/mm² @ 300K & 4V overbias voltage

→ Cooling required

→ Dark count rate 100 kHz/mm² @ 253K & 2V overbias voltage

SiMPl characterisation – Optical cross talk

Pitch / Gap	Fill factor	Cross talk (2V V_{ob})
130µm / 10µm	85.2%	29%
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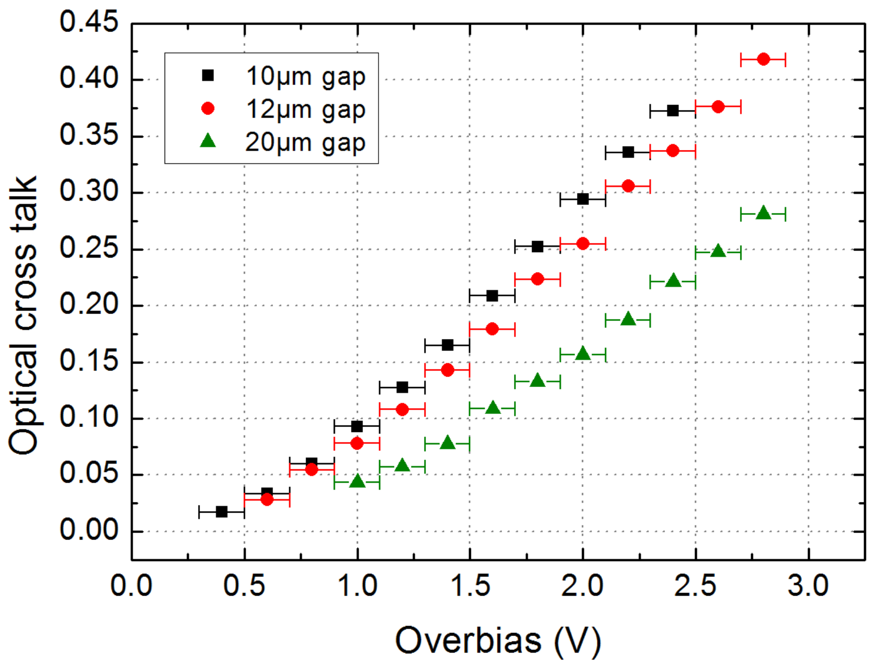
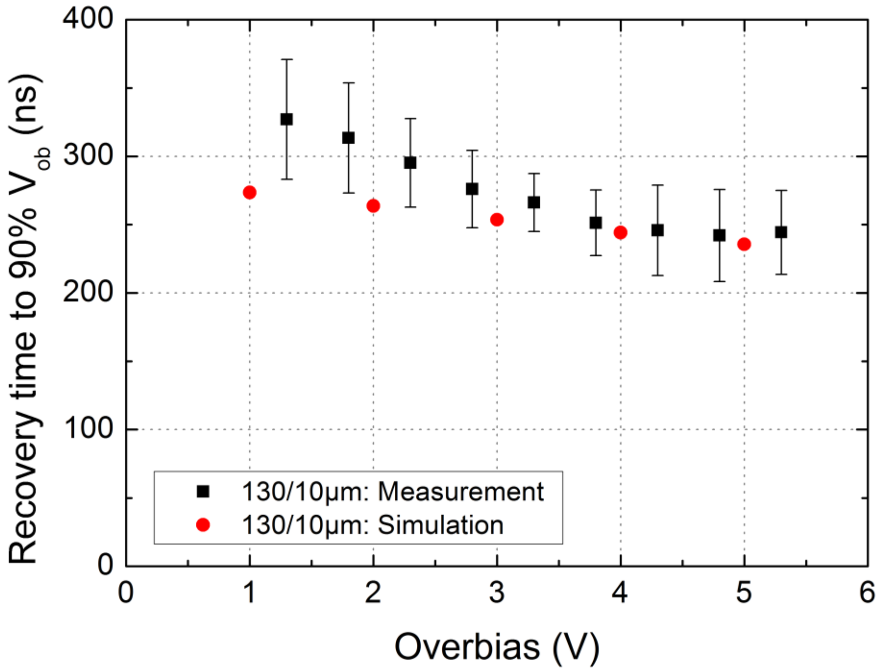


- Increasing overbias
  - → Increasing gain
  - → Increasing trigger efficiency
- Non-linear dependency on overbias

Recovery Time



- measurement @ 253K
- simulations with TCAD
- good agreement
- uncertainties due to exact doping profiles

Afterpulsing

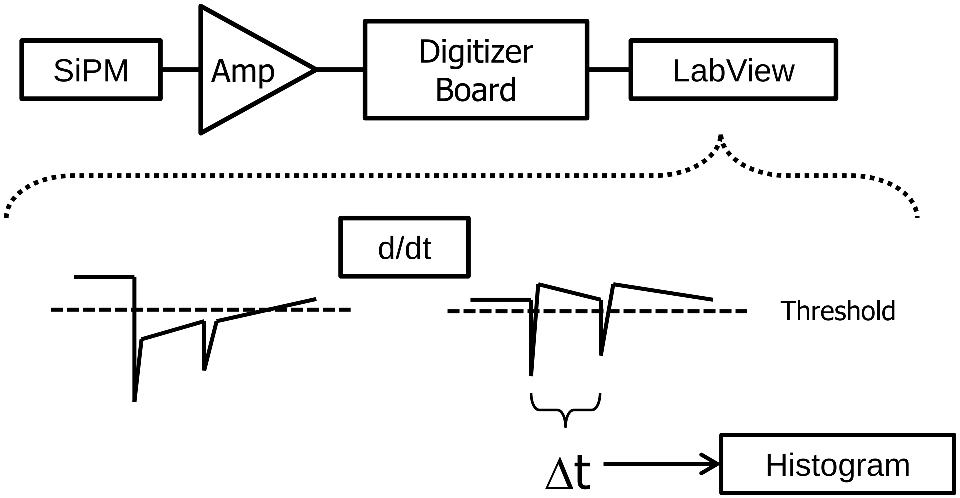
Trapping of charge carriers caused by crystal defects

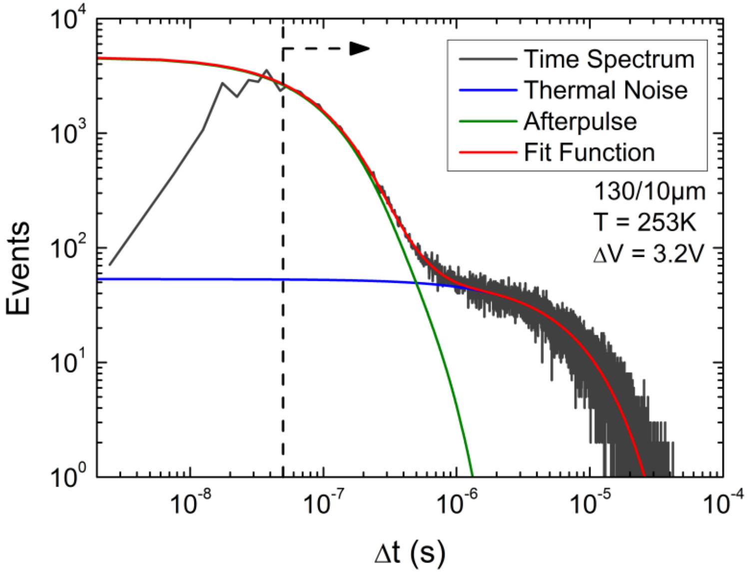
→ delayed second pulse with characteristic time constant

→ additional noise (correlated)

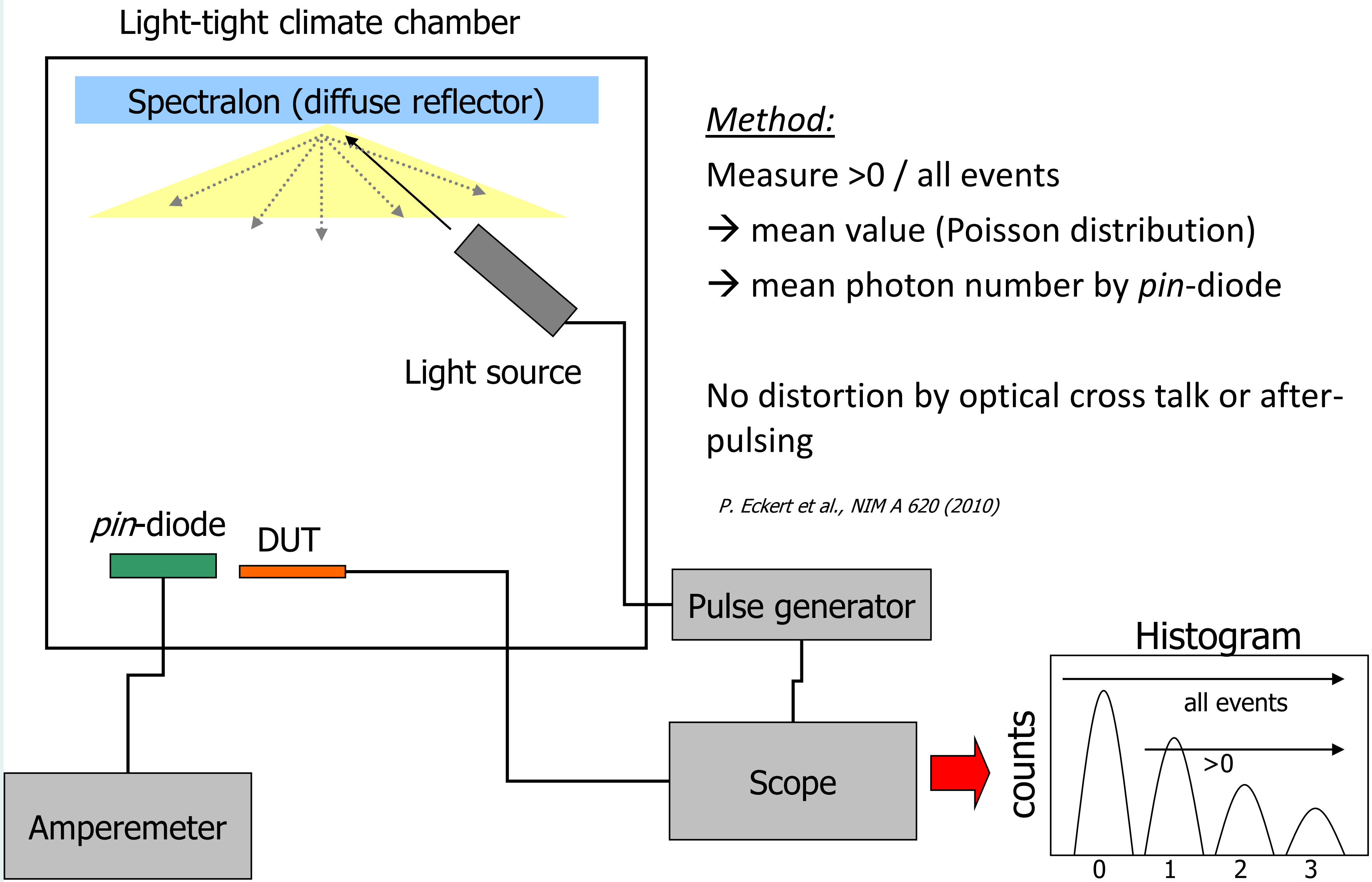
Afterpulsing (AP) measurements:

- time-distribution of consecutive pulses
- fit with sum of exponential distributions for afterpulsing and thermal noise
- 15% - 20% afterpulsing probability





PDE Setup



Method:

Measure >0 / all events

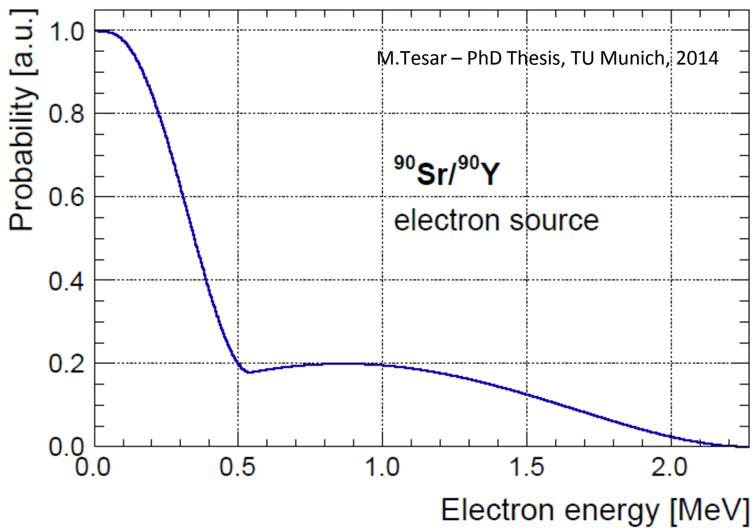
→ mean value (Poisson distribution)

→ mean photon number by *pin*-diode

No distortion by optical cross talk or after-pulsing

P. Eckert et al., NIM A 620 (2010)

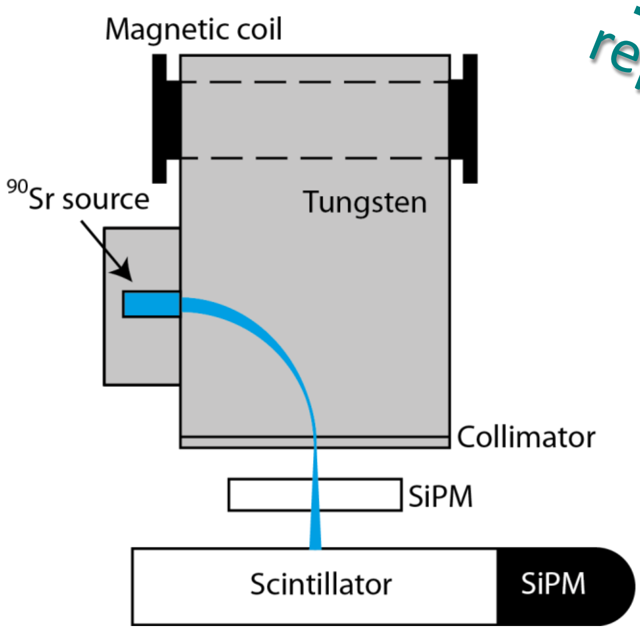
First Efficiency Measurements



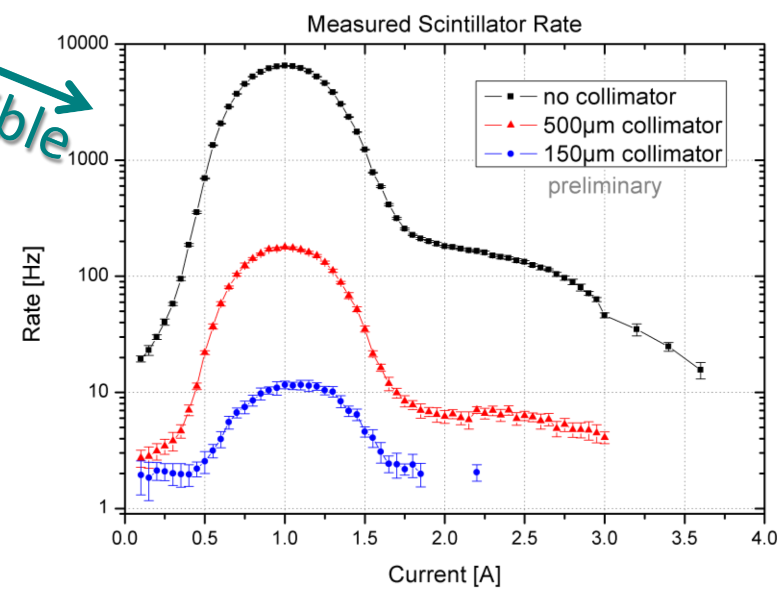
^{90}Sr signal 'unclean' (broad energy spectrum & bremsstrahlung from shielding material)

→ new experimental approach

- Momentum selection by magnetic field
- improved shielding by high amount of tungsten
- Collimation down to spot sizes ~ 150 µm
- But: extremely decreased rate of electrons



reproducible



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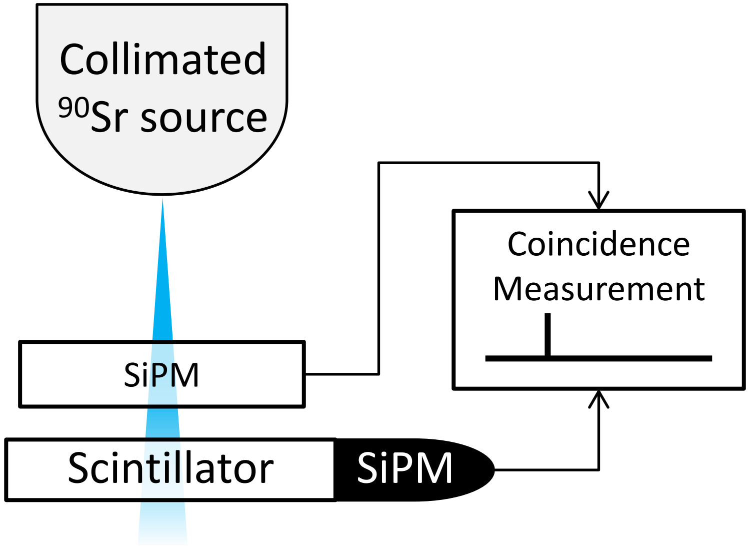
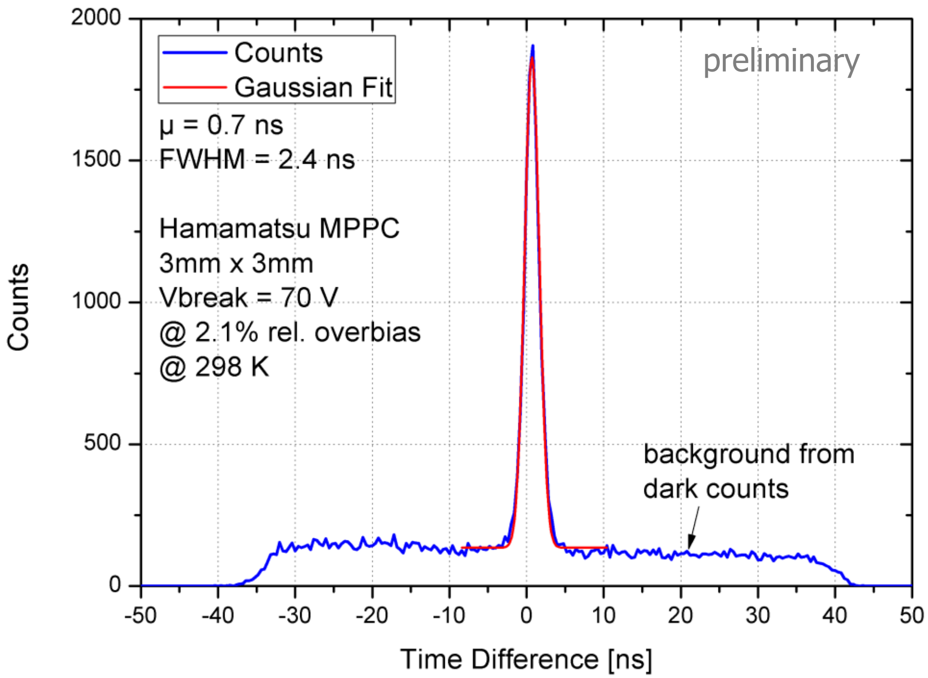


→ first coincidence measurements with a collimated ^{90}Sr source and coincidence unit (scintillator coupled to SiPM)

- MIP signal in scintillator >> dark counts of SiPM → clear background separation
- measurement of time difference between both signals within a predefined time window

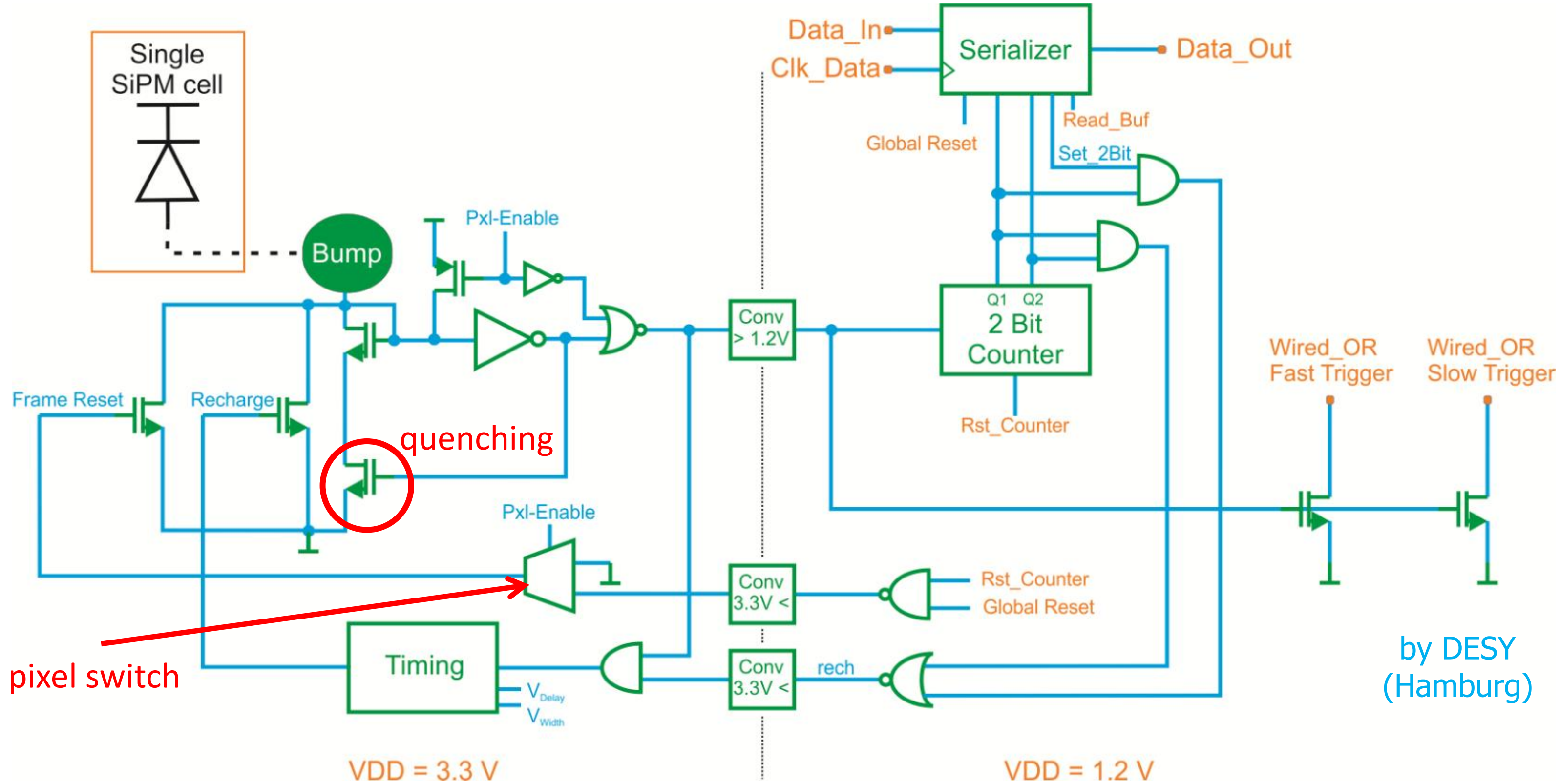


→ clear coincidence peak visible!

further measurements possible, but …

Active Quenching Concept

Collaboration with DESY (Hamburg): Active quenching circuits for SiMPl



- Overcome longer recovery times by implementing active quenching circuits
- Uses current-mode approach
- Active quenching for single pixels
- Possibility to turn off individual pixels
- Parallel readout and measurement possible