Utilization of novel Silicon Photomultipliers with bulk integrated quench resistors in tracking applications for particle physics

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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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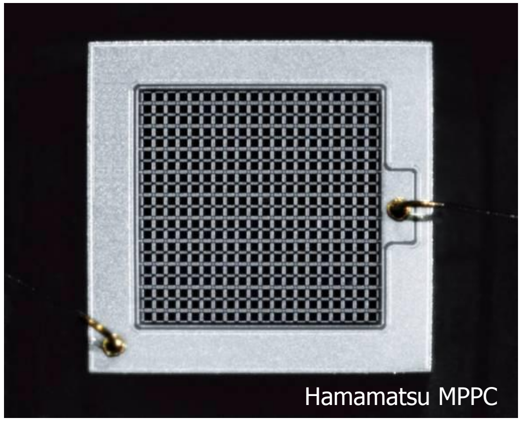
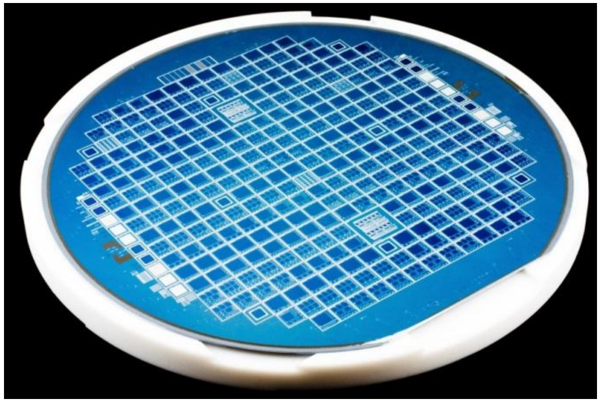


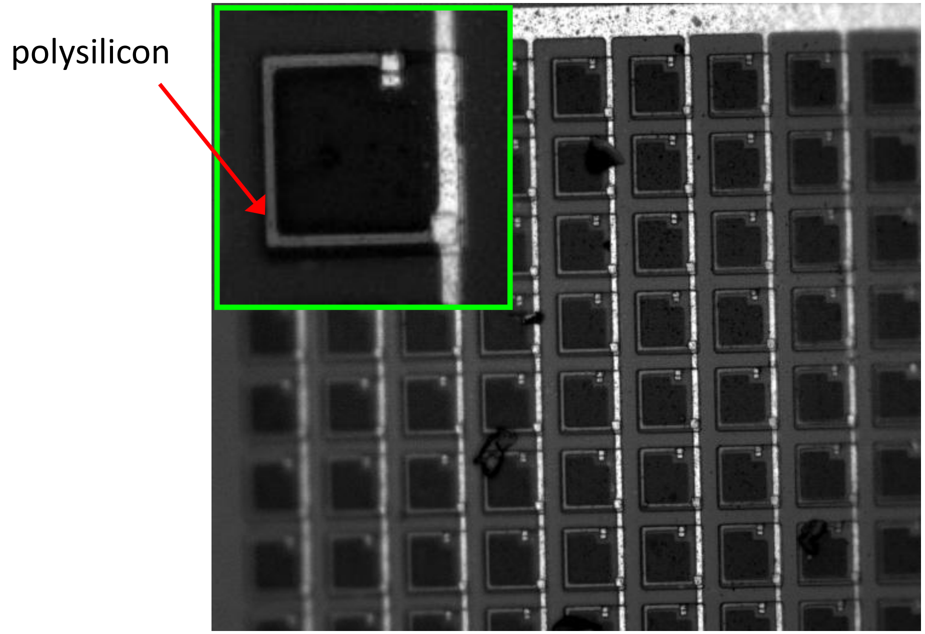
Accomplishable by Silicon Photomultipliers

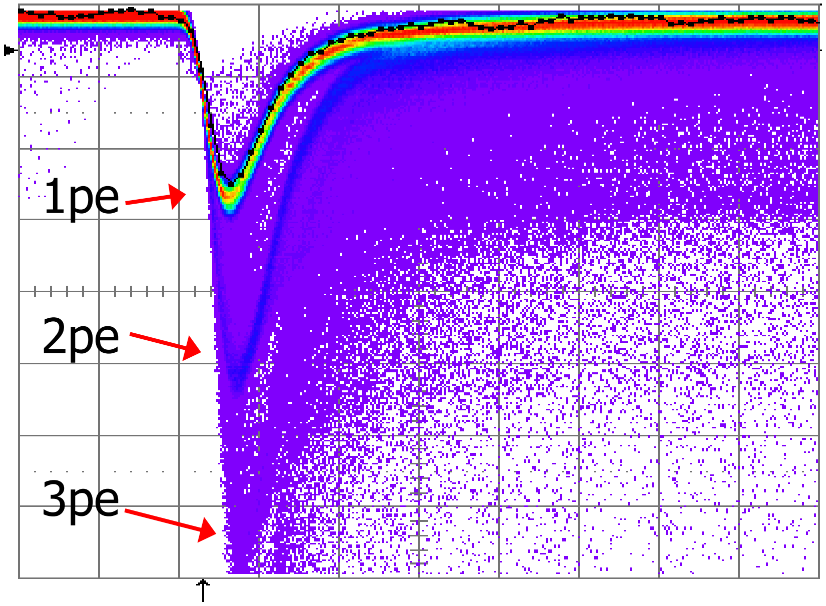


Silicon Photomultiplier

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





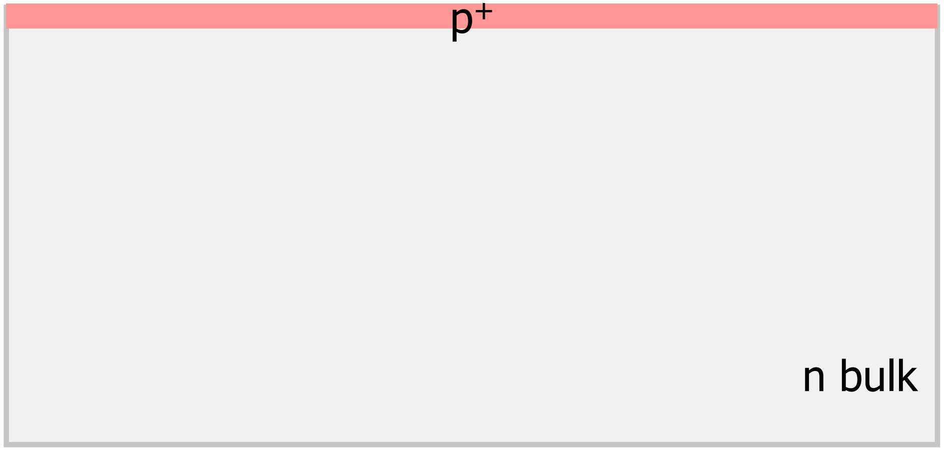
Polysilicon quench resistor:

- complex fabrication step
- limitation to fill factor for photon detection
- no flat surface within the array

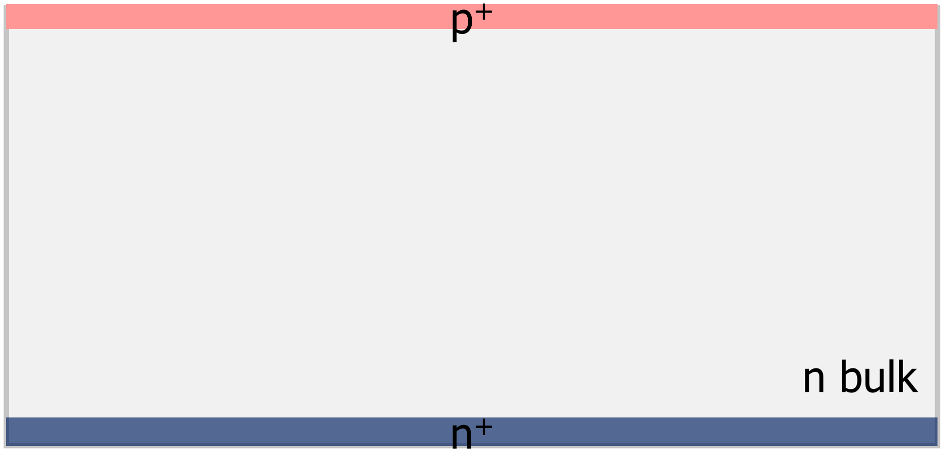
SiMPl

SiMPl

SiMPl



SiMPl



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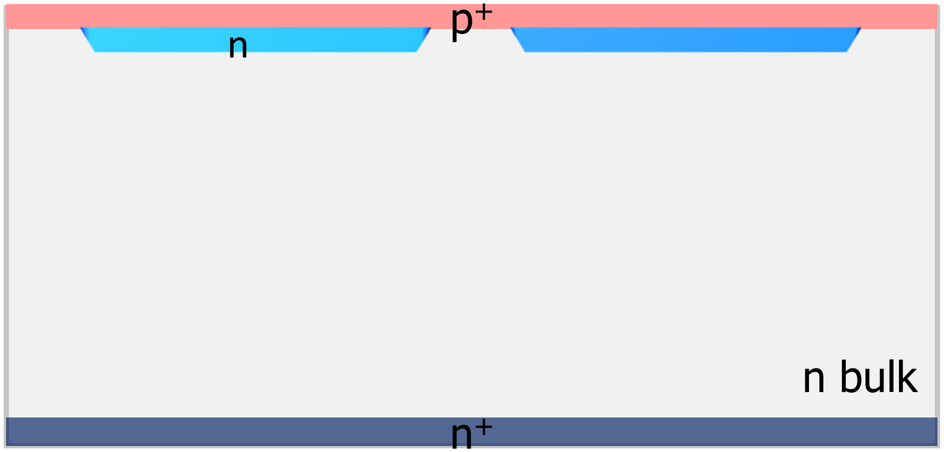

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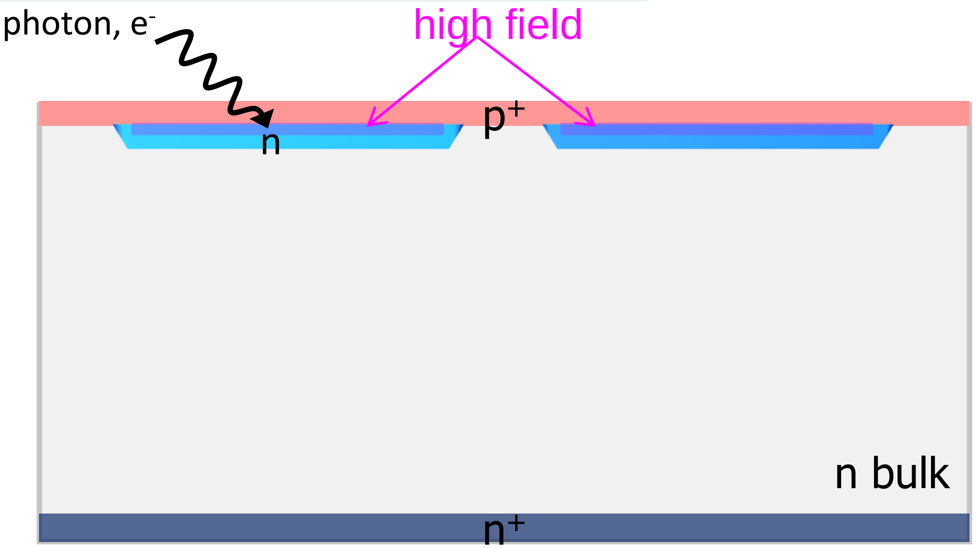

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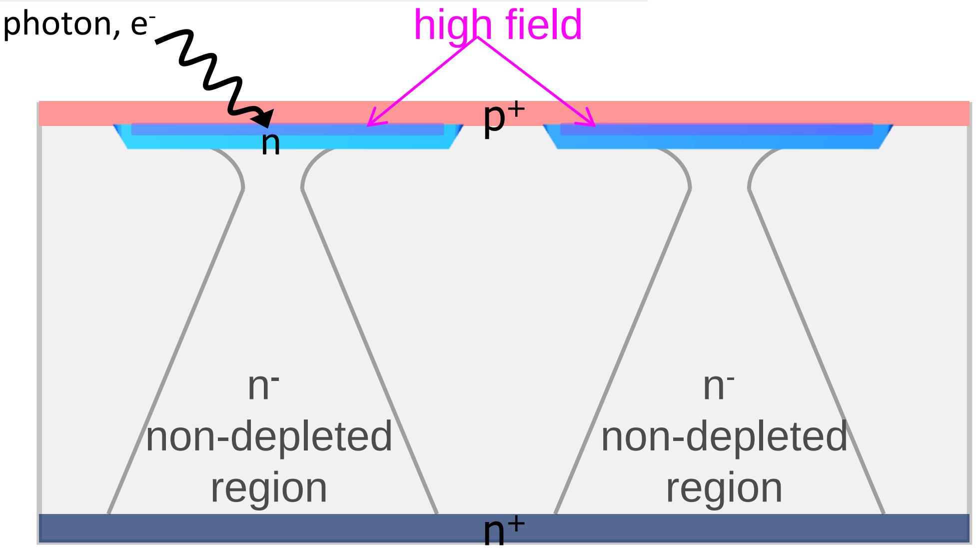
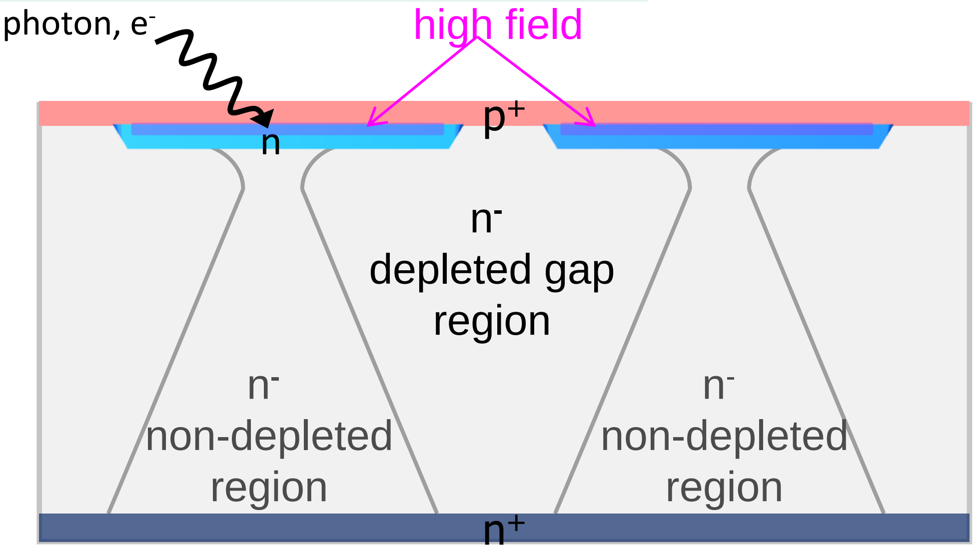


photon, e-
high field
p+
n
n-
non-depleted
region
n-
non-depleted
region
n+

SiMPl



photon, e-
high field
p+
n
n-
depleted gap
region
n-
non-depleted
region
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non-depleted
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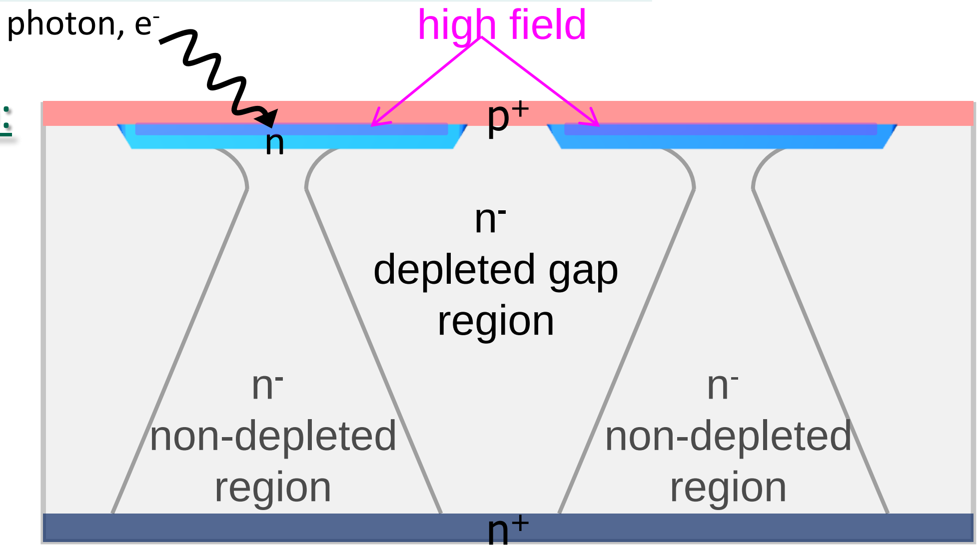
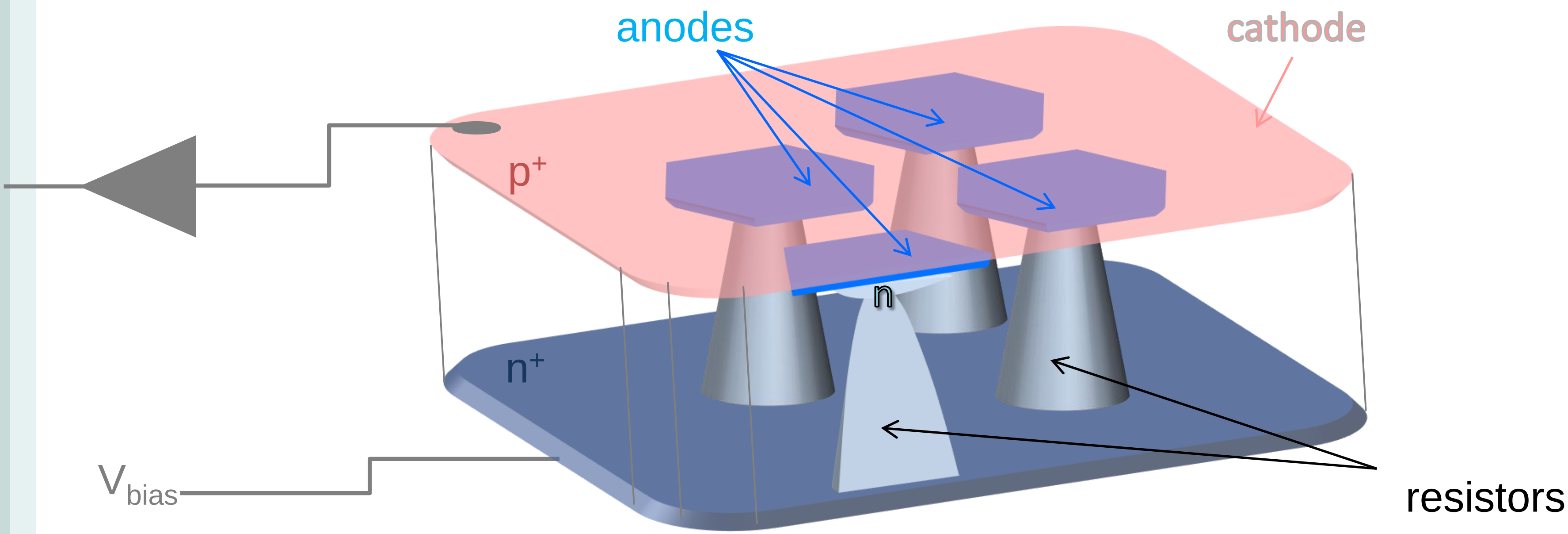
n+

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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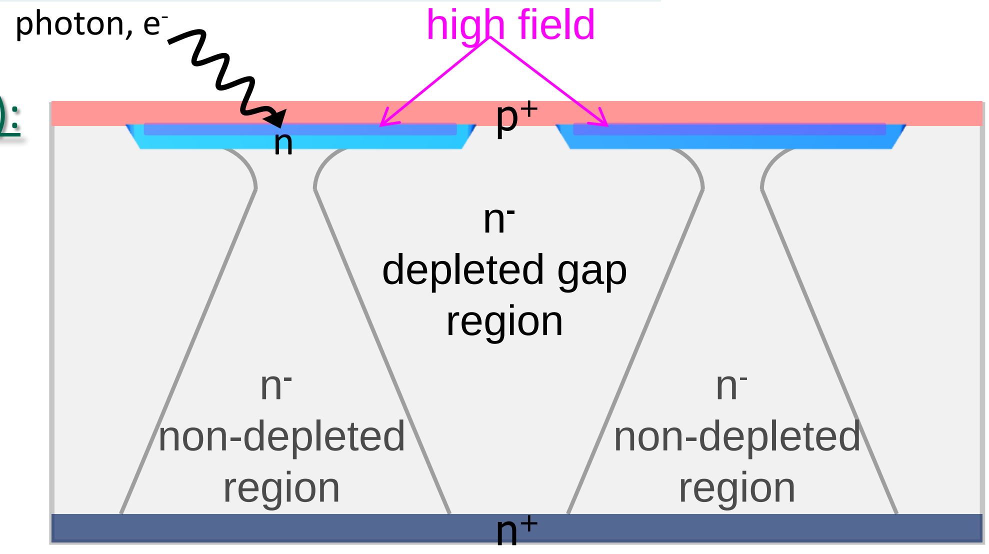

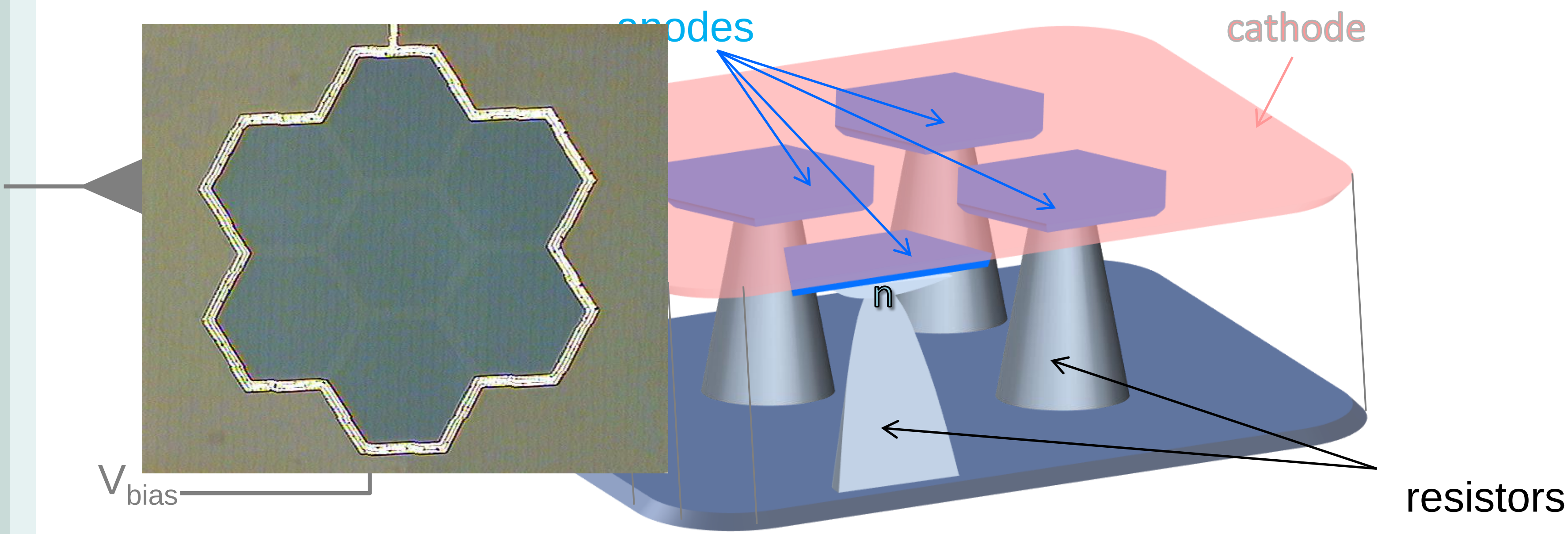

SiMPl – Advantages and Drawbacks

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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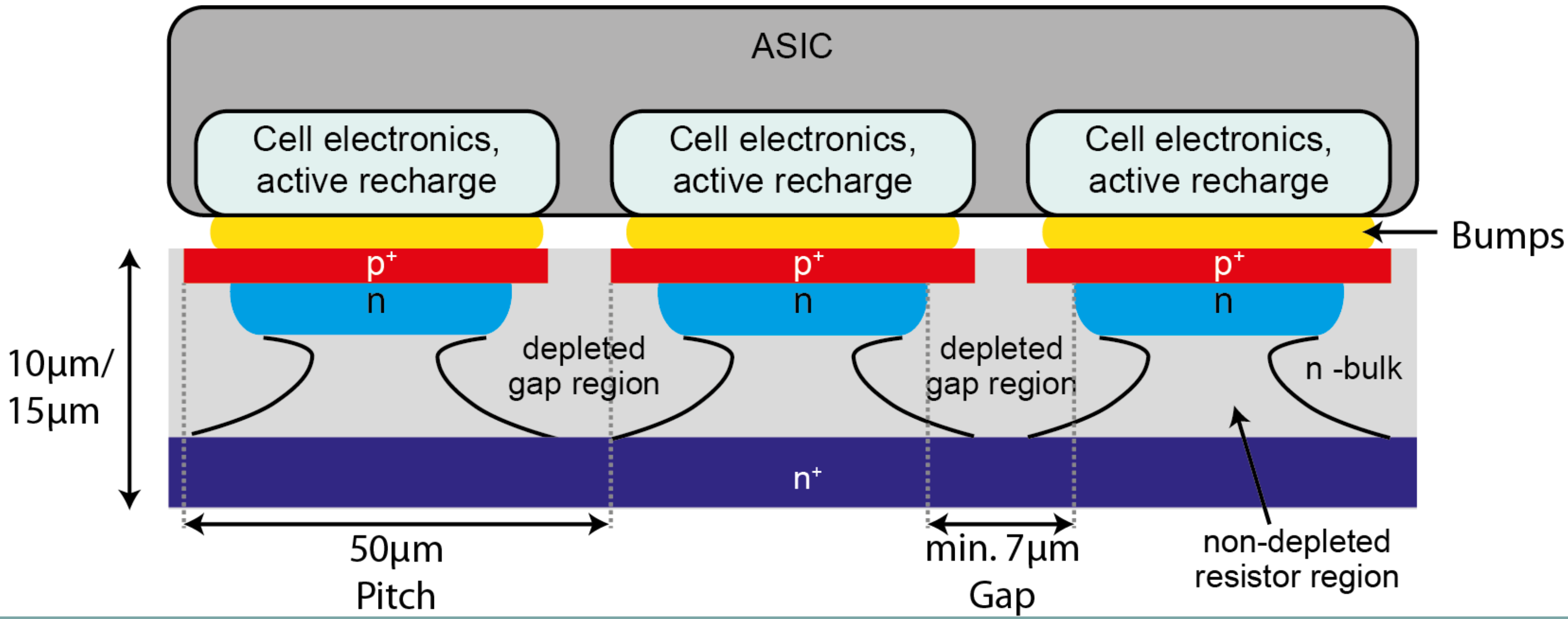
Drawbacks:

- 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

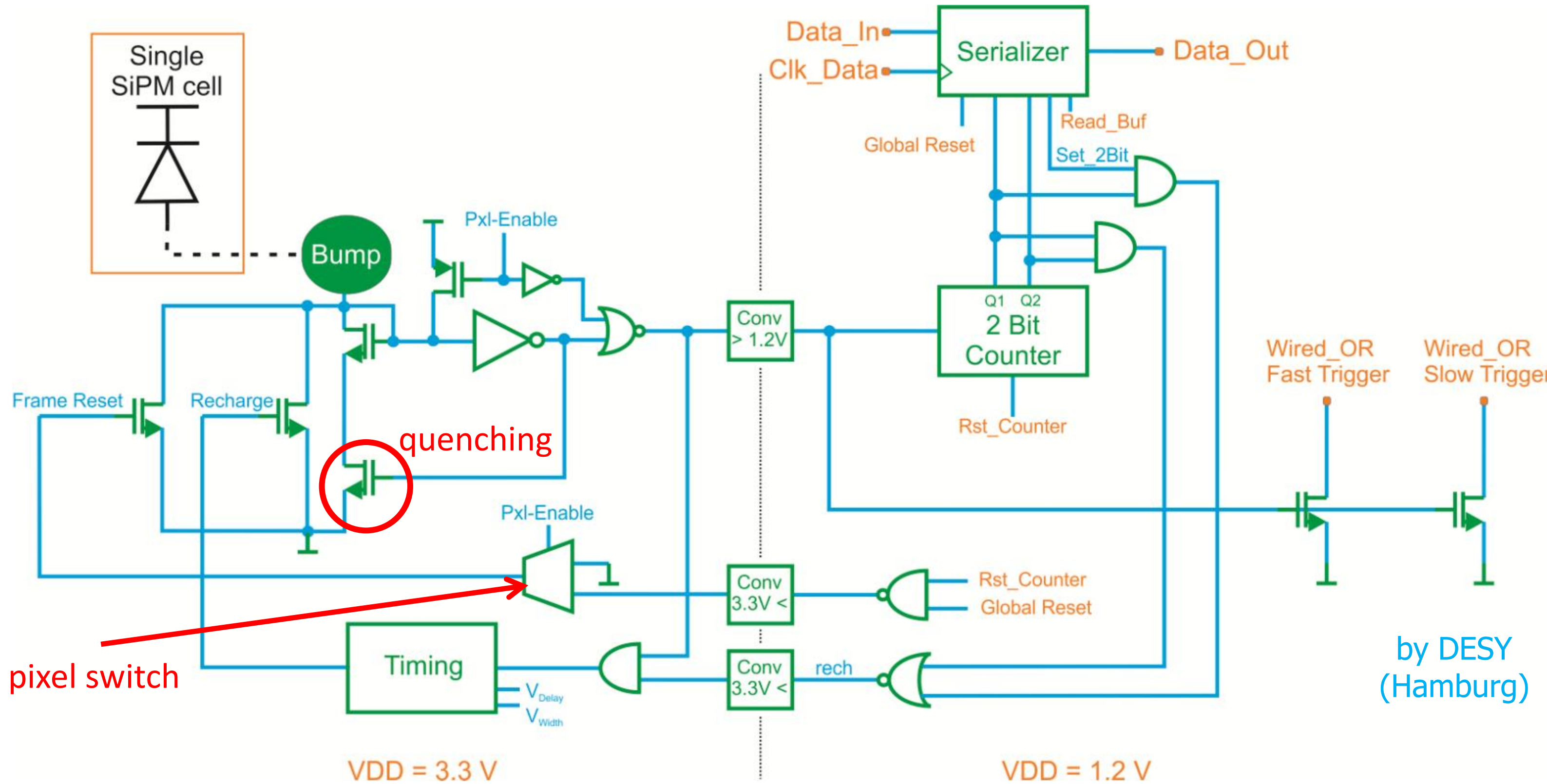
Particle Tracking with SiMPl

- 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

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

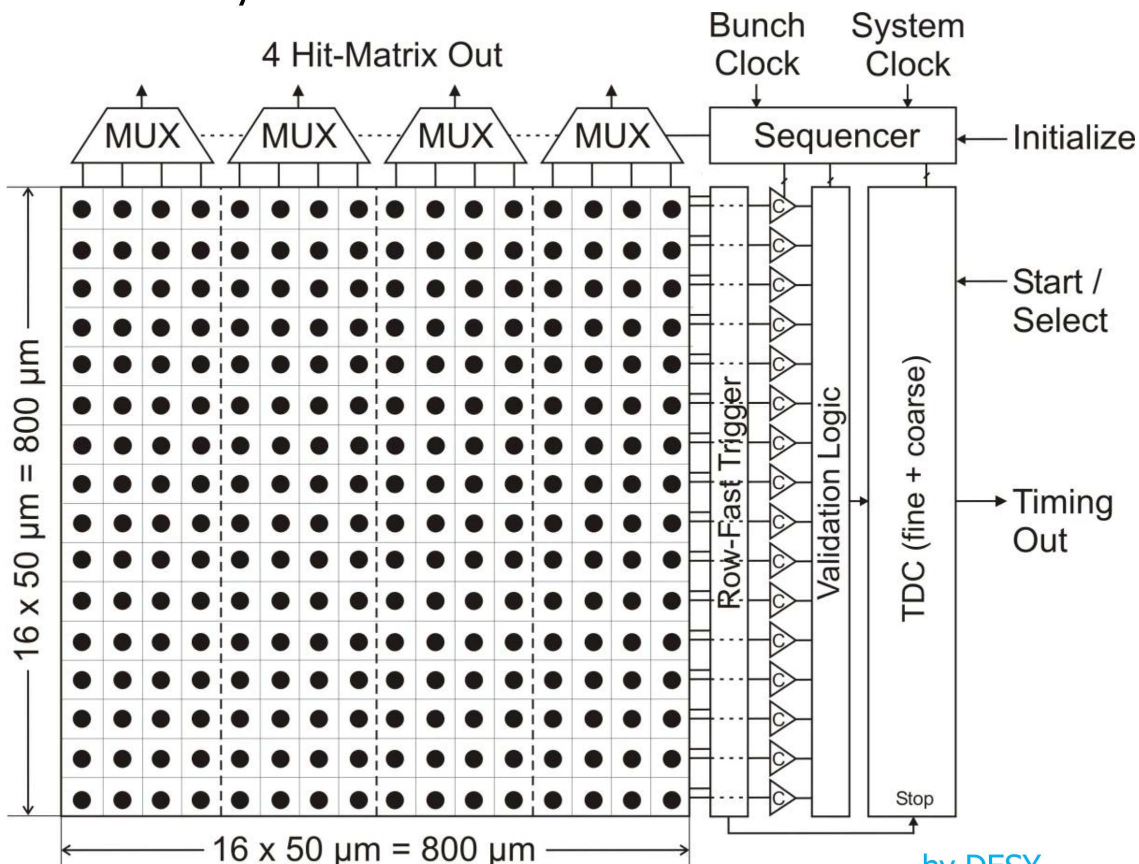


- overcome longer recovery times by implementing active quenching circuits
- uses current-mode approach
- active quenching for single pixels
- possibility to turn off individual pixels
- parallel readout and measurement possible

Active Quenching Concept

Possible layout

- 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

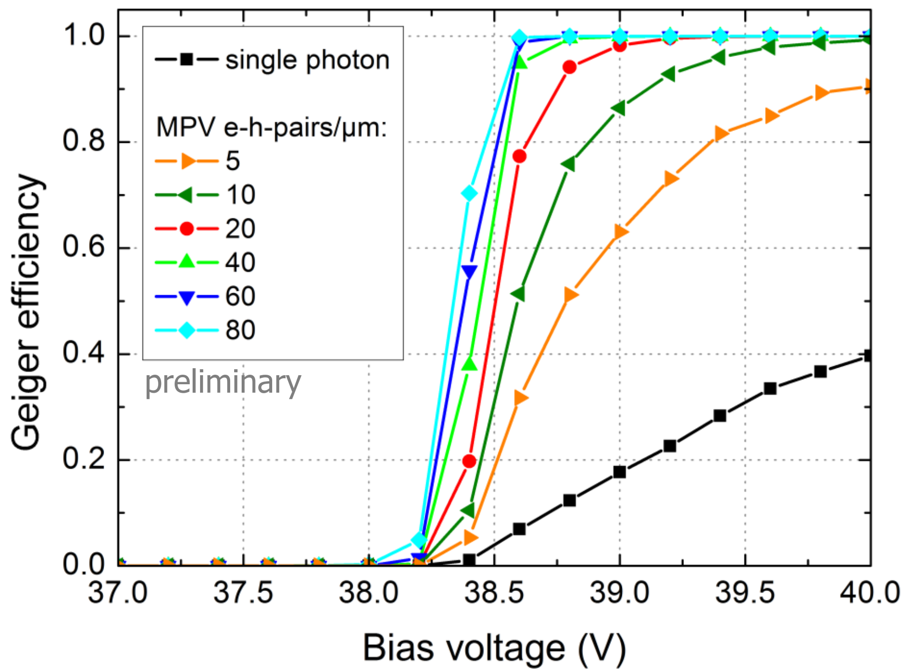


by DESY (Hamburg)

→ promising candidate for tracking

First Efficiency Simulations

→ Simulations: Small overbias voltages sufficient for high Geiger efficiency

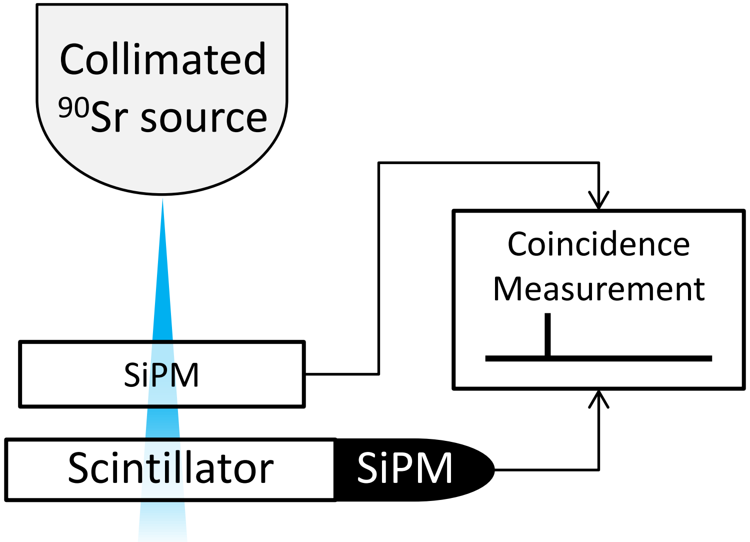


- Monte-Carlo simulations of ionisation probability (ionisation coefficients by Van Overstraeten) based on SiMPl device
  → Geiger efficiency for MIPs
- overbias voltages ≈ 0.5 V should already provide Geiger efficiency ~ 1

→ strongly decreased pile up with decreasing overbias voltage

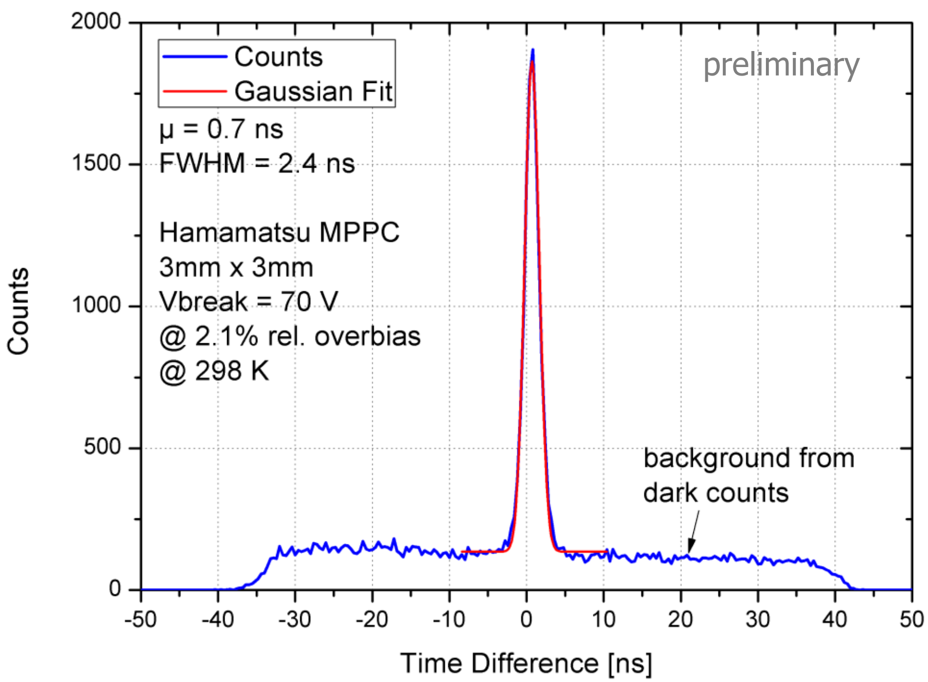
→ experimental validation required!

First Efficiency Measurements



→ 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 …

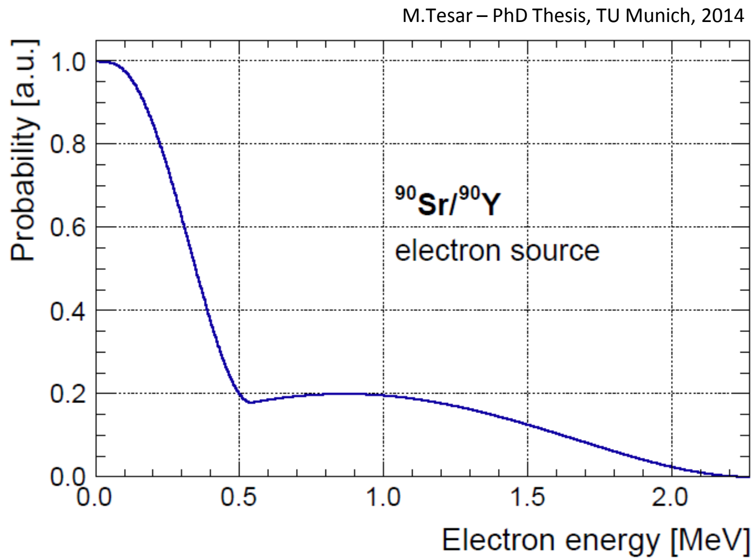
First Efficiency Measurements

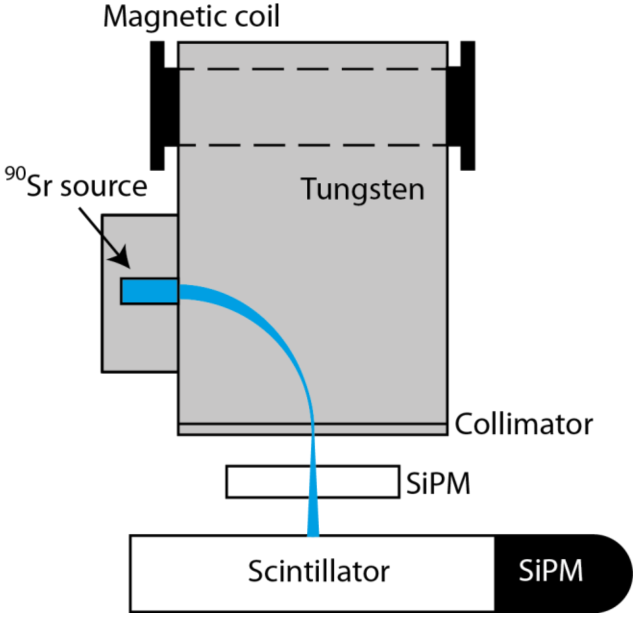
^{90}Sr signal rather 'unclean' (broad energy spectrum & bremsstrahlung from shielding material)

→ high number of missfires (triggers in scintillator) caused by bremsstrahlung

→ efficiency measurements not yet possible (falsified by missfires)

→ new experimental approach required





- sufficient shielding by high amount of tungsten
- momentum selection by magnetic field
- collimation down to spot sizes ~ 150 µm
- but: extremely decreased rate of electrons

→ new ^{90}Sr source with higher rate necessary (procurement in progress)

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

- 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 with active quenching

- first detection efficiency measurements
    - device operation at low overbias voltage with sufficient Geiger efficiency possible according to simulations
    - first measurements show clear coincidence

Open questions & next steps

- efficiency measurements with improved setup
- test beam with first prototypes
- radiation hardness tests

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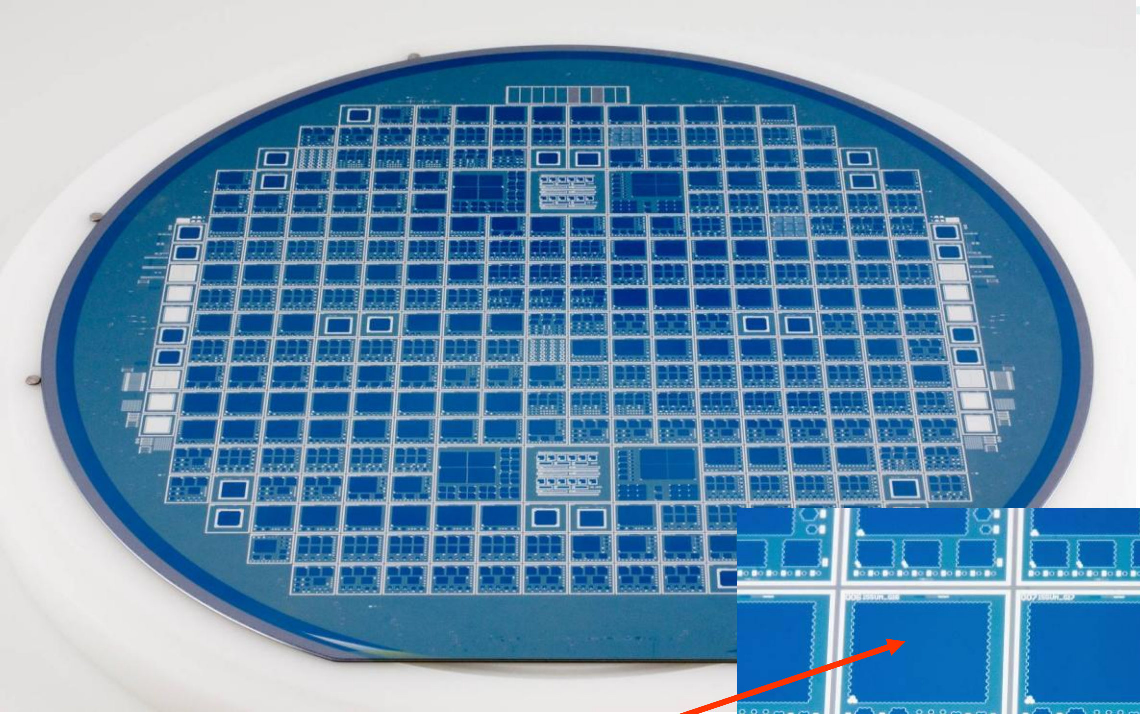
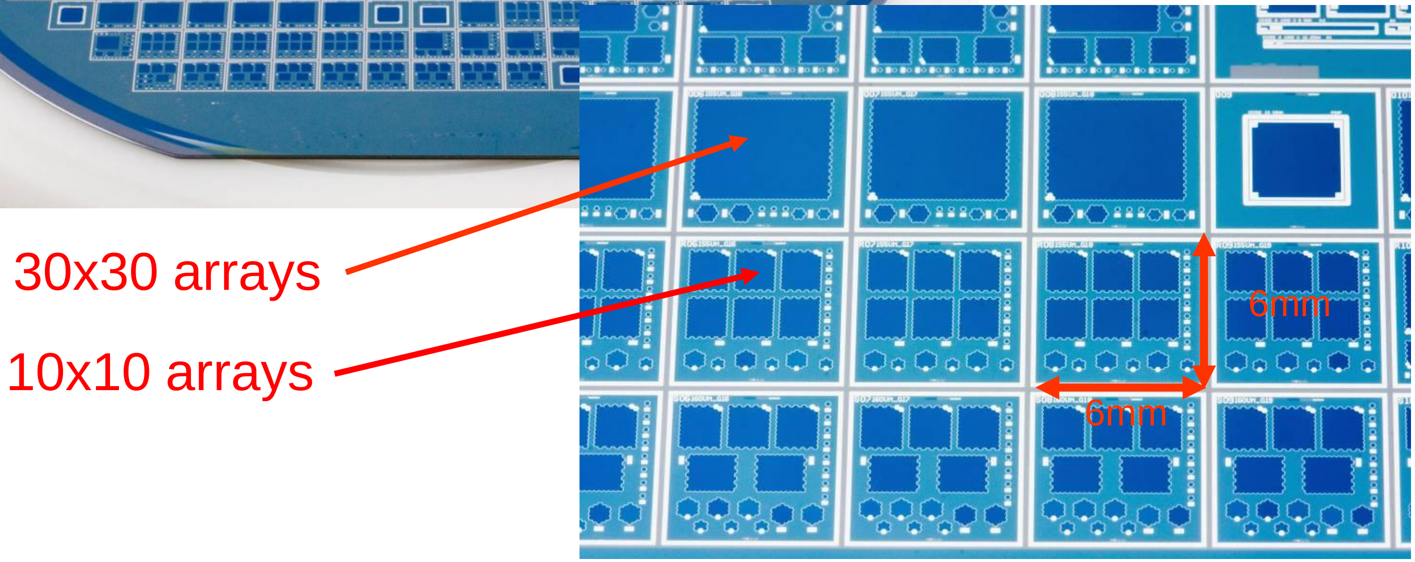
Thank you for your attention!

Backup

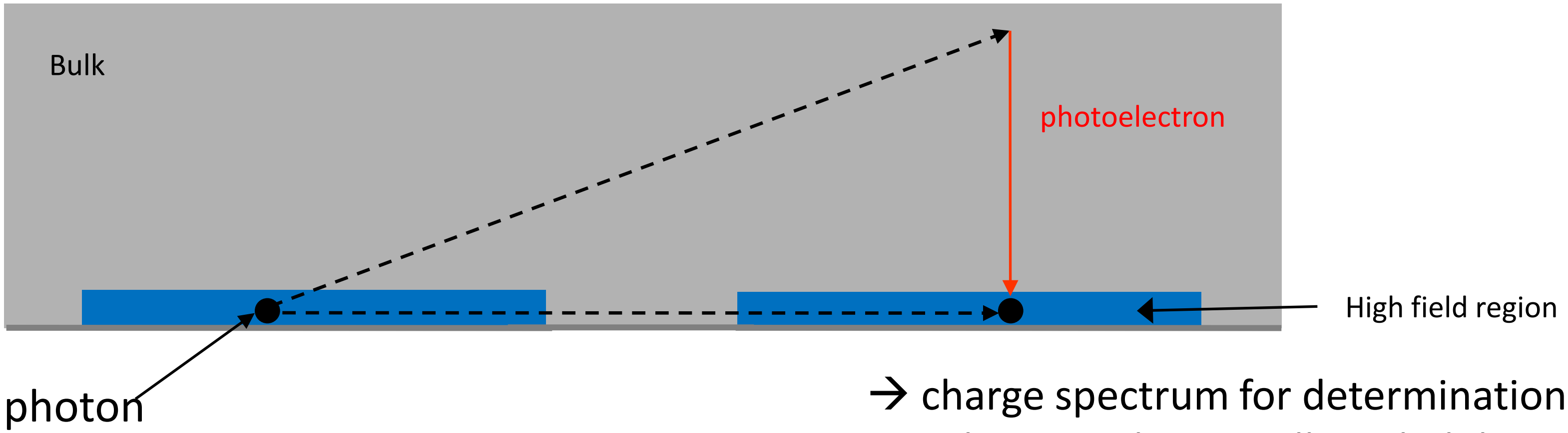
SiMPl prototype



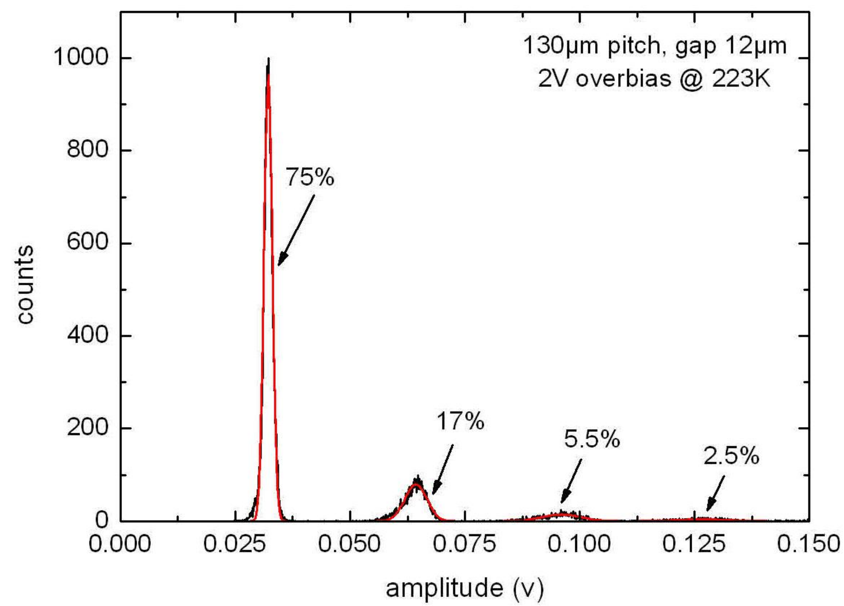


- Wide range of geometrical variations
- Pitch: 90 -160 µm with different gap size

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)

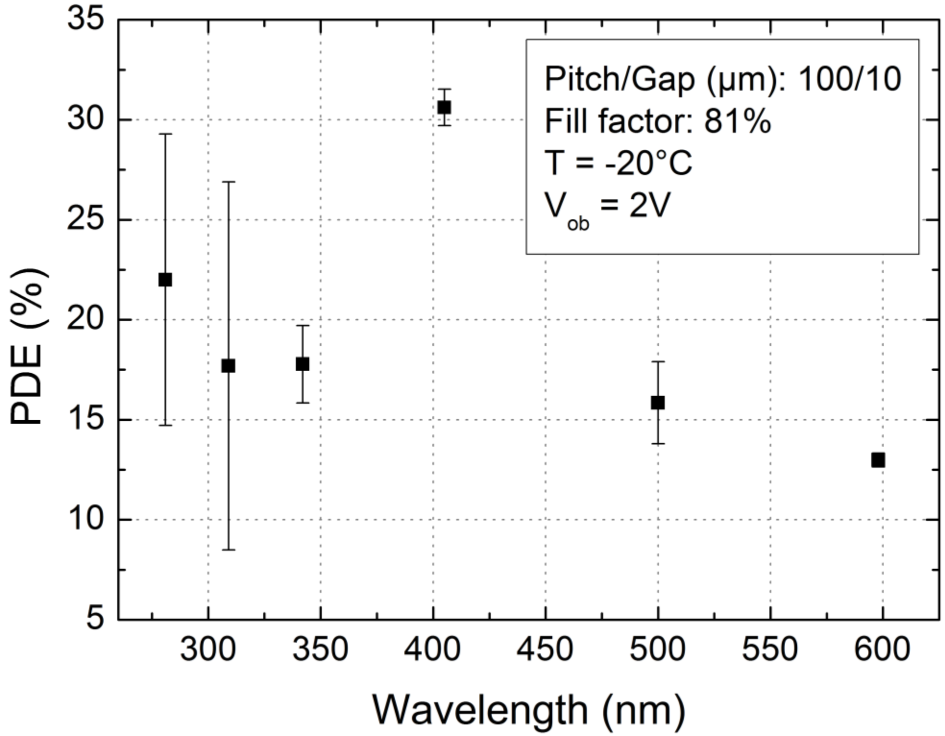
A. Lacaita et al, IEEE Trans. Elec. Dev.,Vol. 4, 1993

→ influence on photon counting statistics due to additionally fired cells

PDE

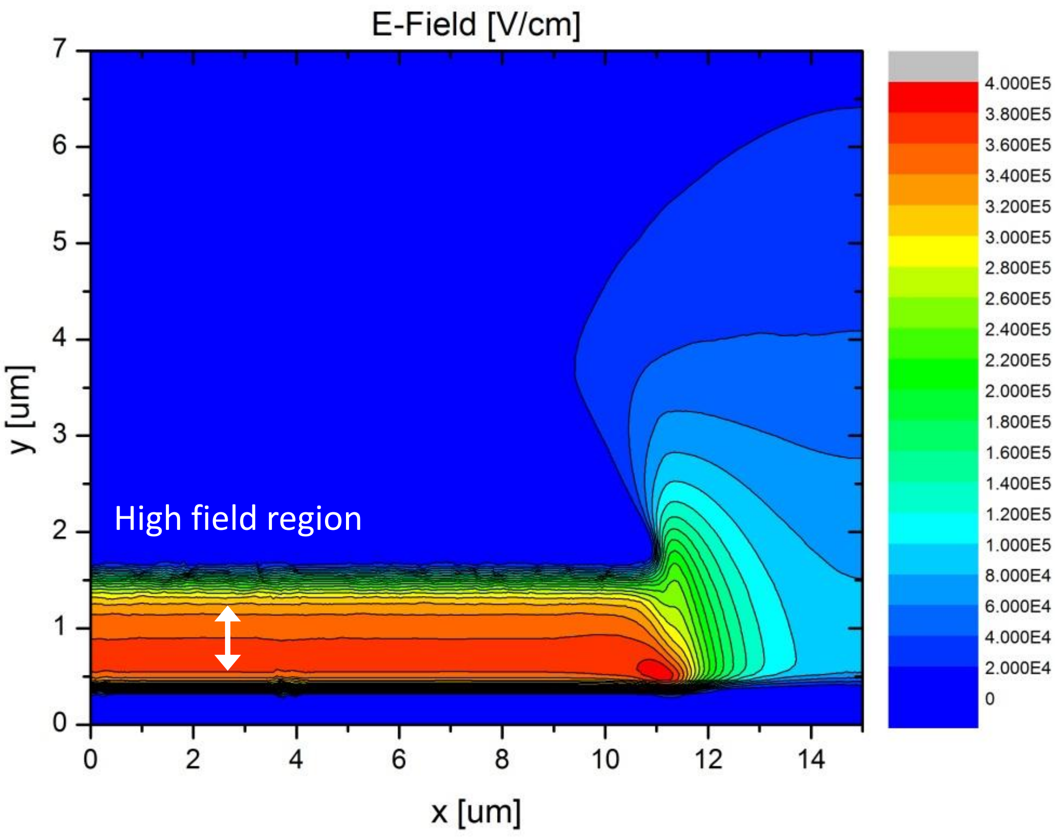
<u>Photon Detection Efficiency (PDE):</u>

Probability to detect incoming photons of certain wavelengths



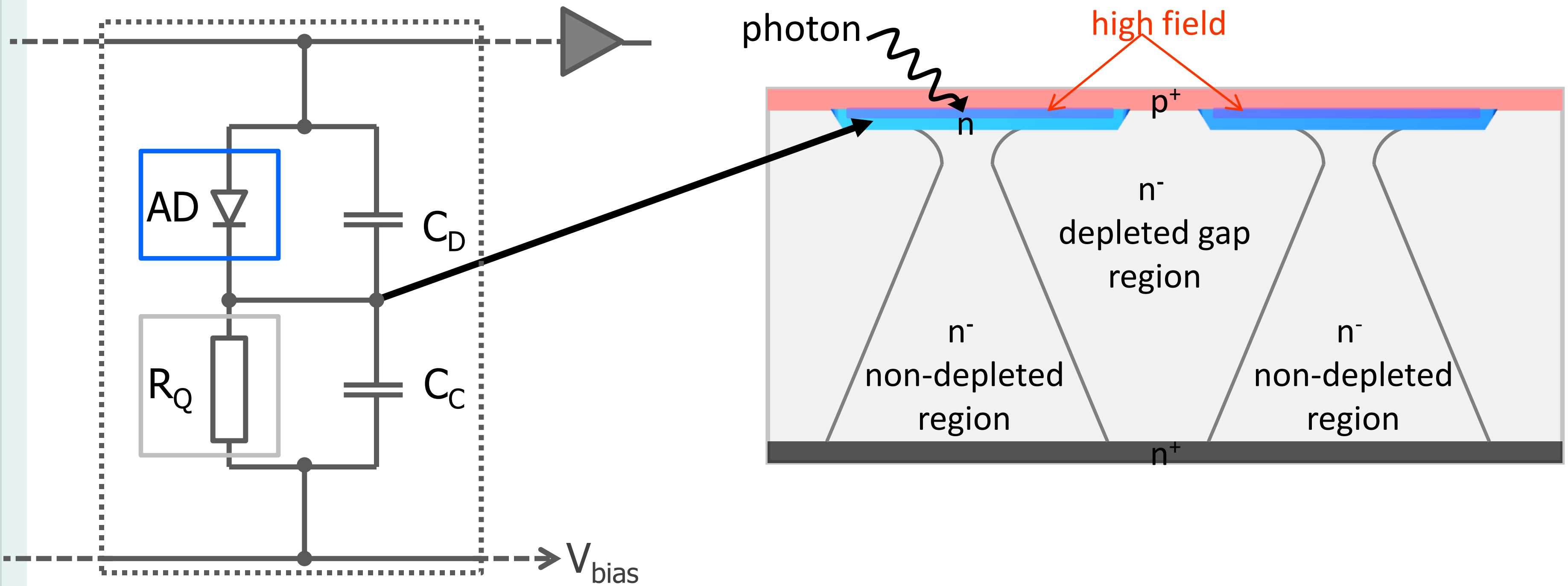
- measured PDE for different wavelengths
- peak efficiency around λ ≈ 405 nm
- sensitivity in the UV range observed

Device simulations



TCAD simulations for obtaining the electrical field

Equivalent circuit



Transient simulations