Possible application of SiMPl devices for particle tracking
&
Latest SiMPl simulation results

IMPRS Young Scientist Workshop

Ringberg, 22th – 26th July 2013

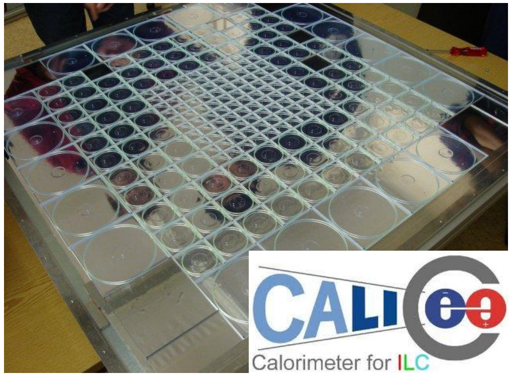
Stefan Petrovics

Motivation for novel photon detectors

cta
cherenkov telescope array

Low light level → High Detection Efficiency
Large detector area → low costs & power consumption

Large number of detectors → low costs & power consumption
Single tile readout → compact devices



Other requirements:
fast timing & insensitivity to magnetic fields

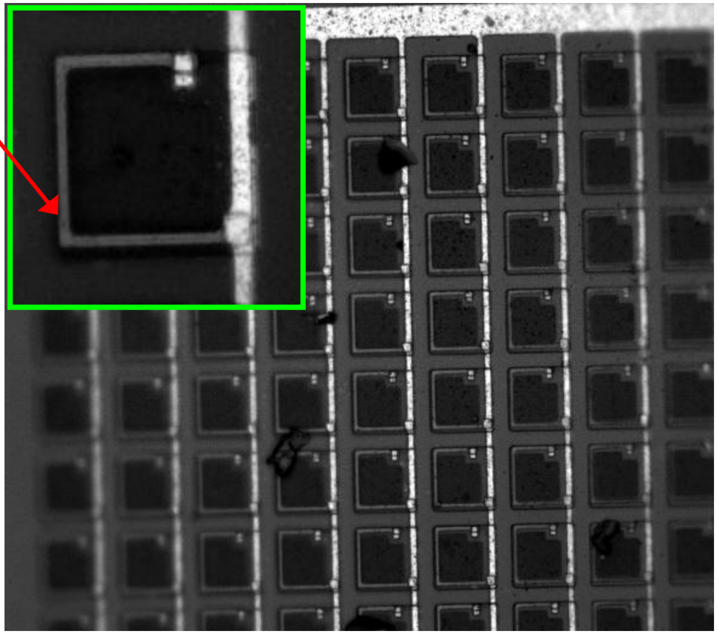
Silicon Photomultiplier promising candidate

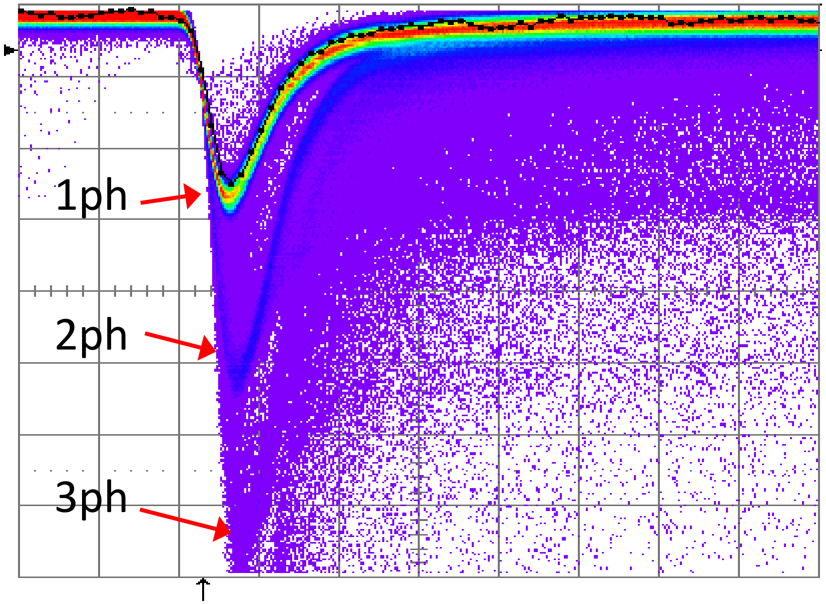
Silicon Photomultiplier

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





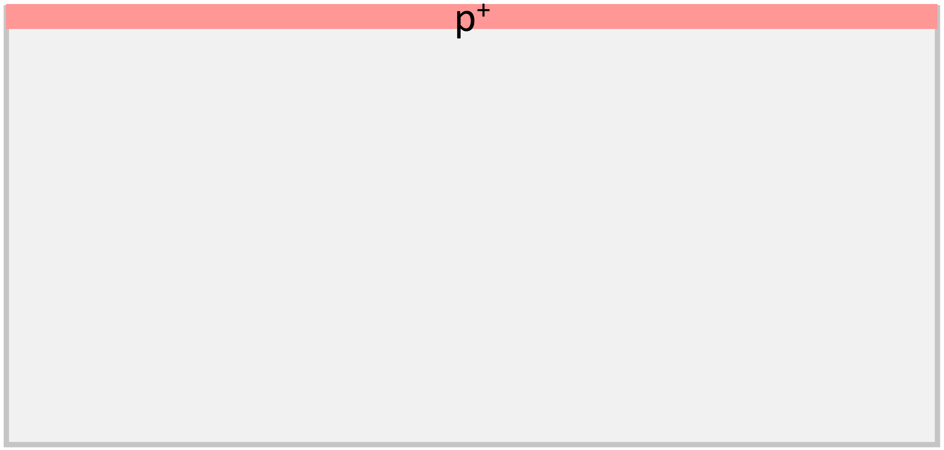
Polysilicon quench resistor:

- complex fabrication step
- limitation to fill factor

SiMPl

SiMPl

SiMPl



SiMPl

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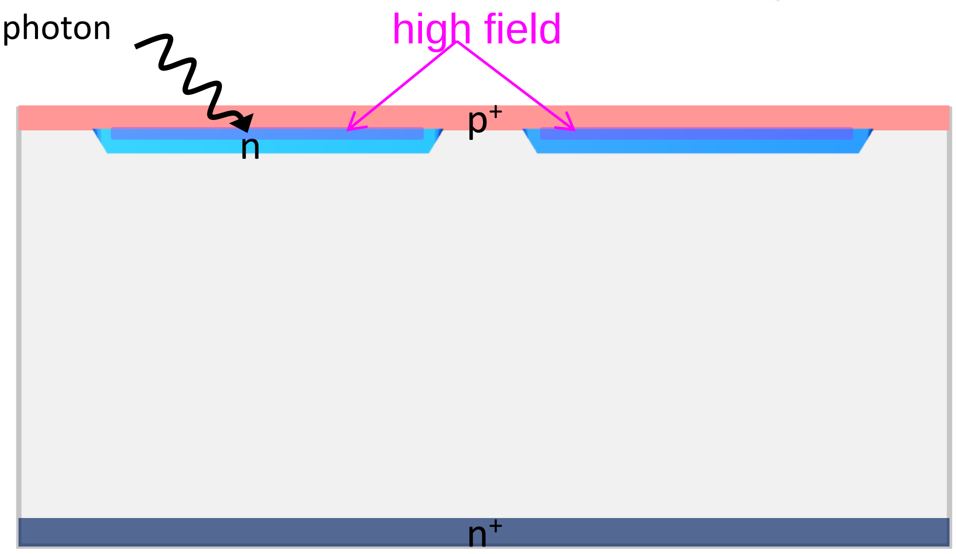

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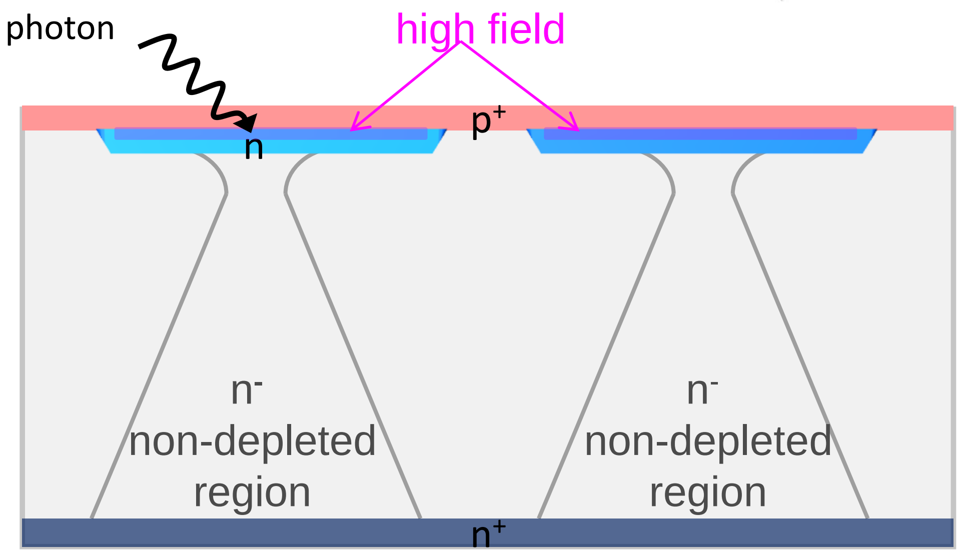
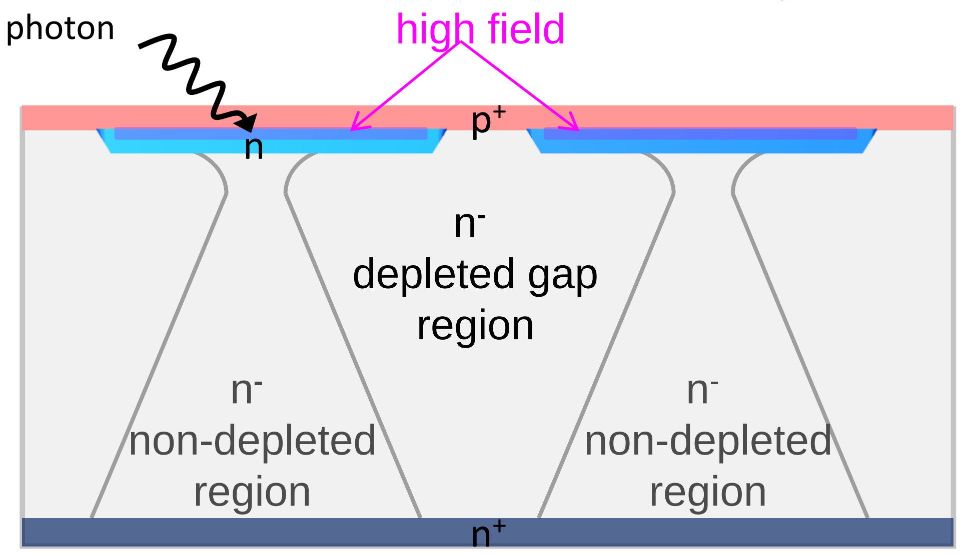

photon
high field
p^+
n
n^-
non-depleted
region
n^-
non-depleted
region
n^+

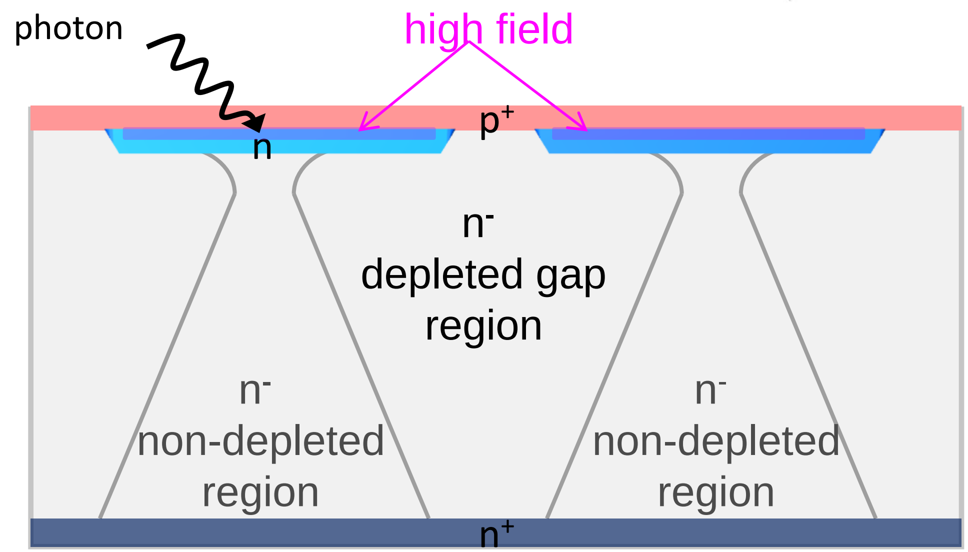
SiMPl

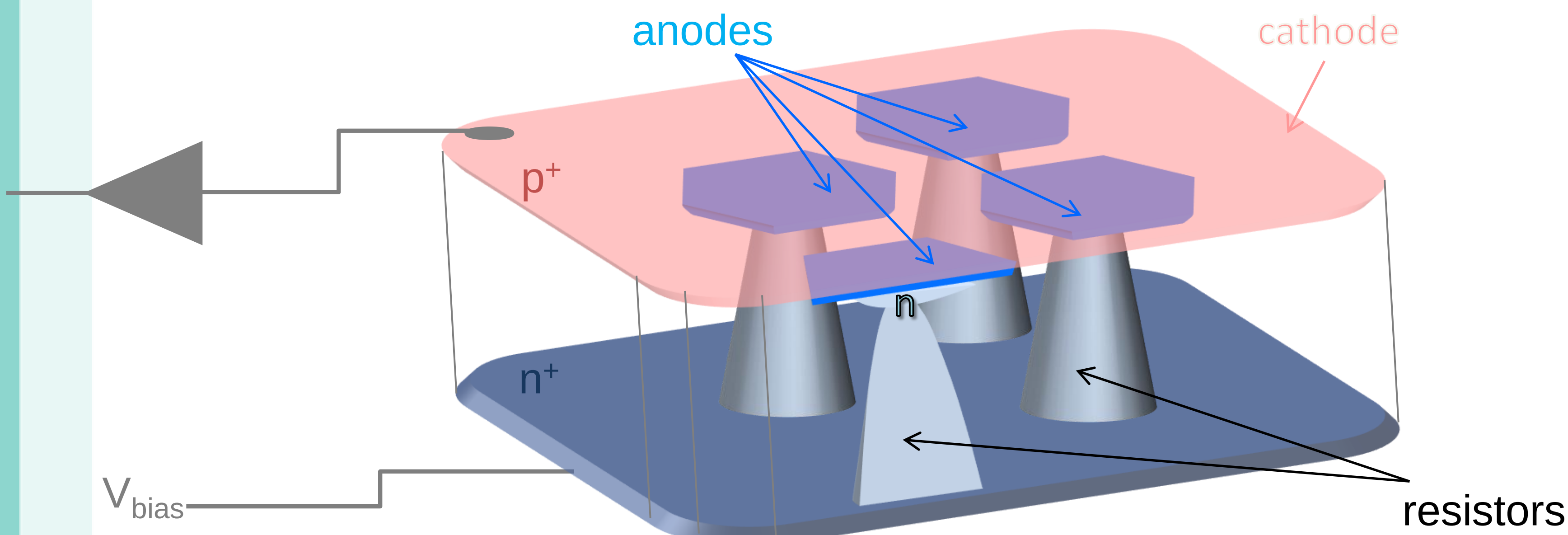

photon
high field
p+
n
n-
depleted gap
region
n-
non-depleted
region
n-
non-depleted
region
n+

SiMPl

<u>Silicon MultiPixel light detector (SiMPl):</u>

- 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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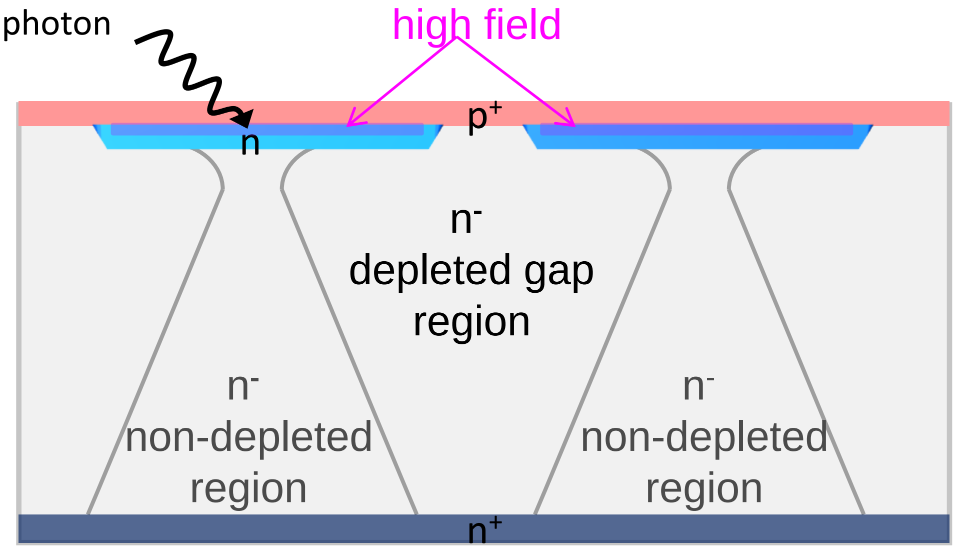

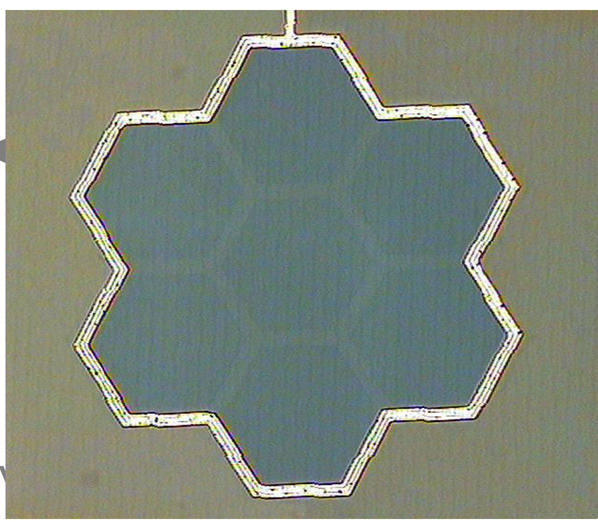

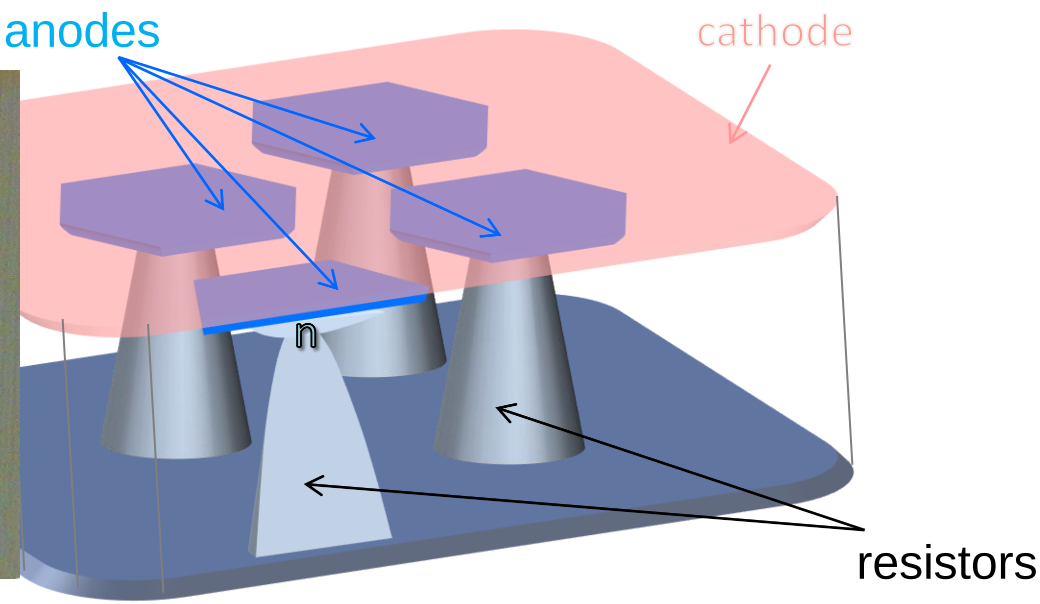

SiMPl – Advantages and Drawbacks

Advantages:

- no need of polysilicon
- no metal necessary within the array → free entrance window for light → higher fill factor
- simple technology → lower costs
- inherent diffusion barrier against minorities in the bulk → less optical cross talk

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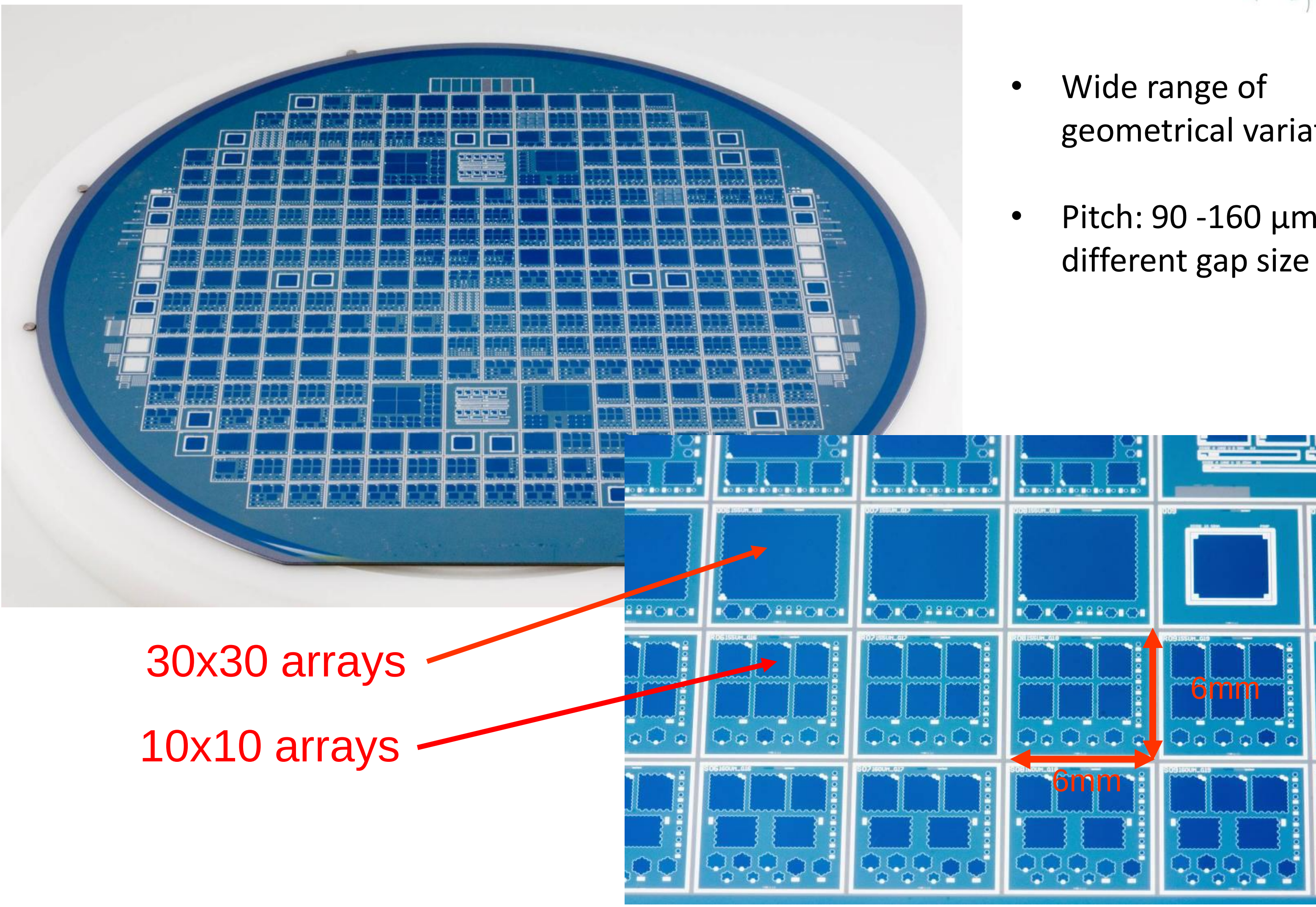
Drawbacks:

- 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 Prototypes



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

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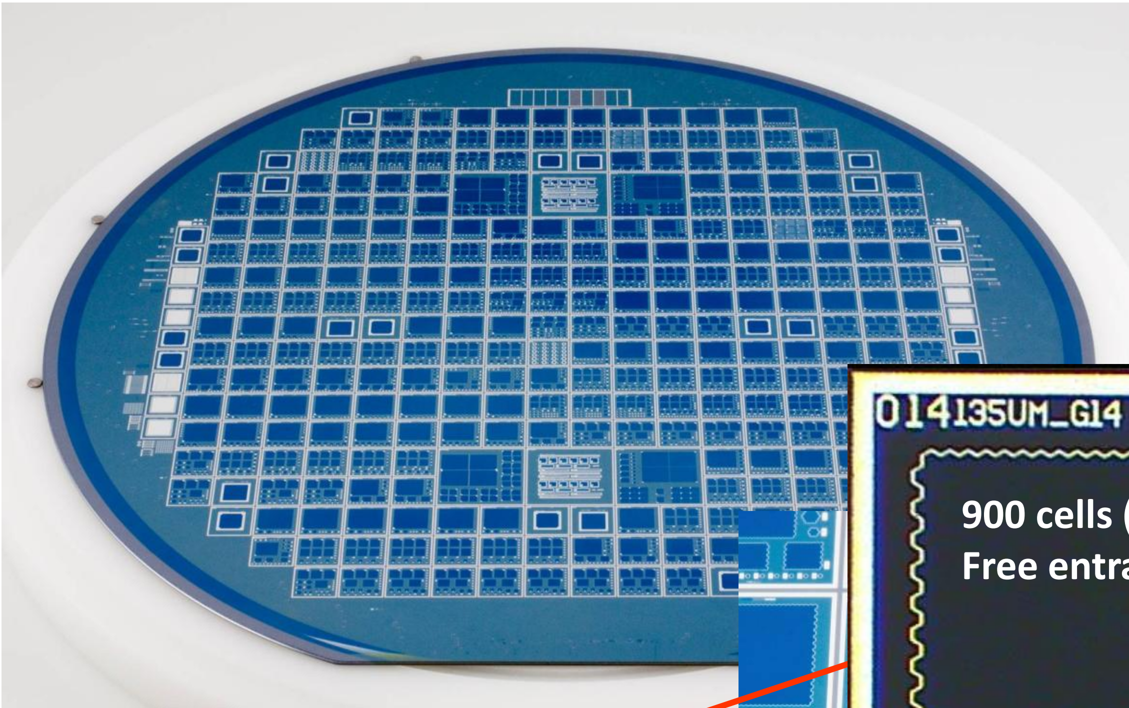

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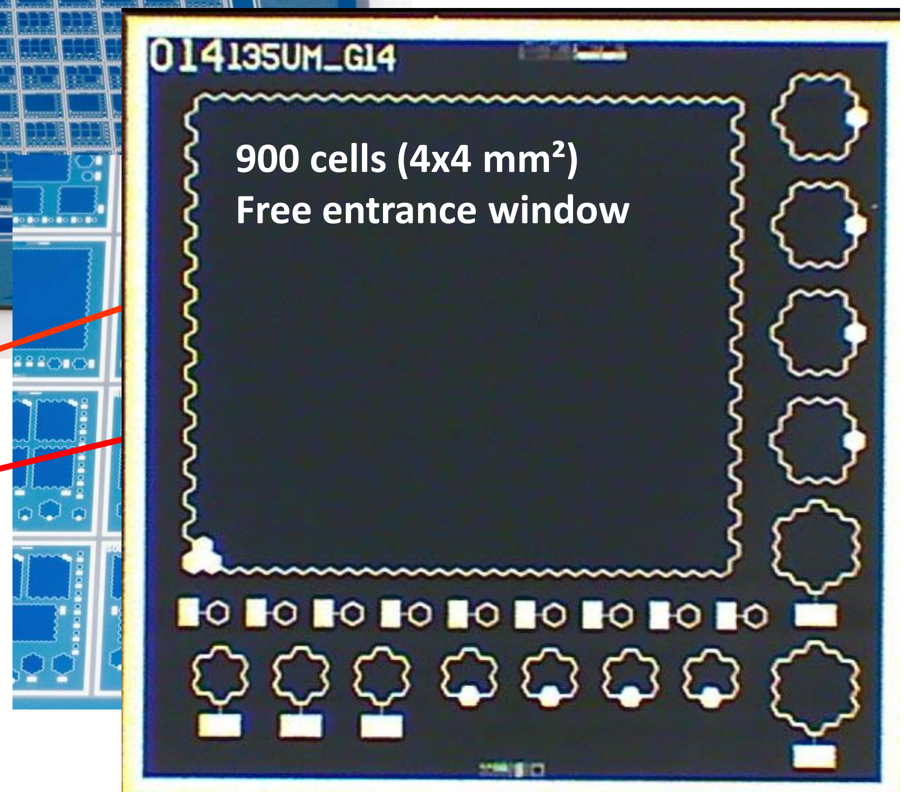

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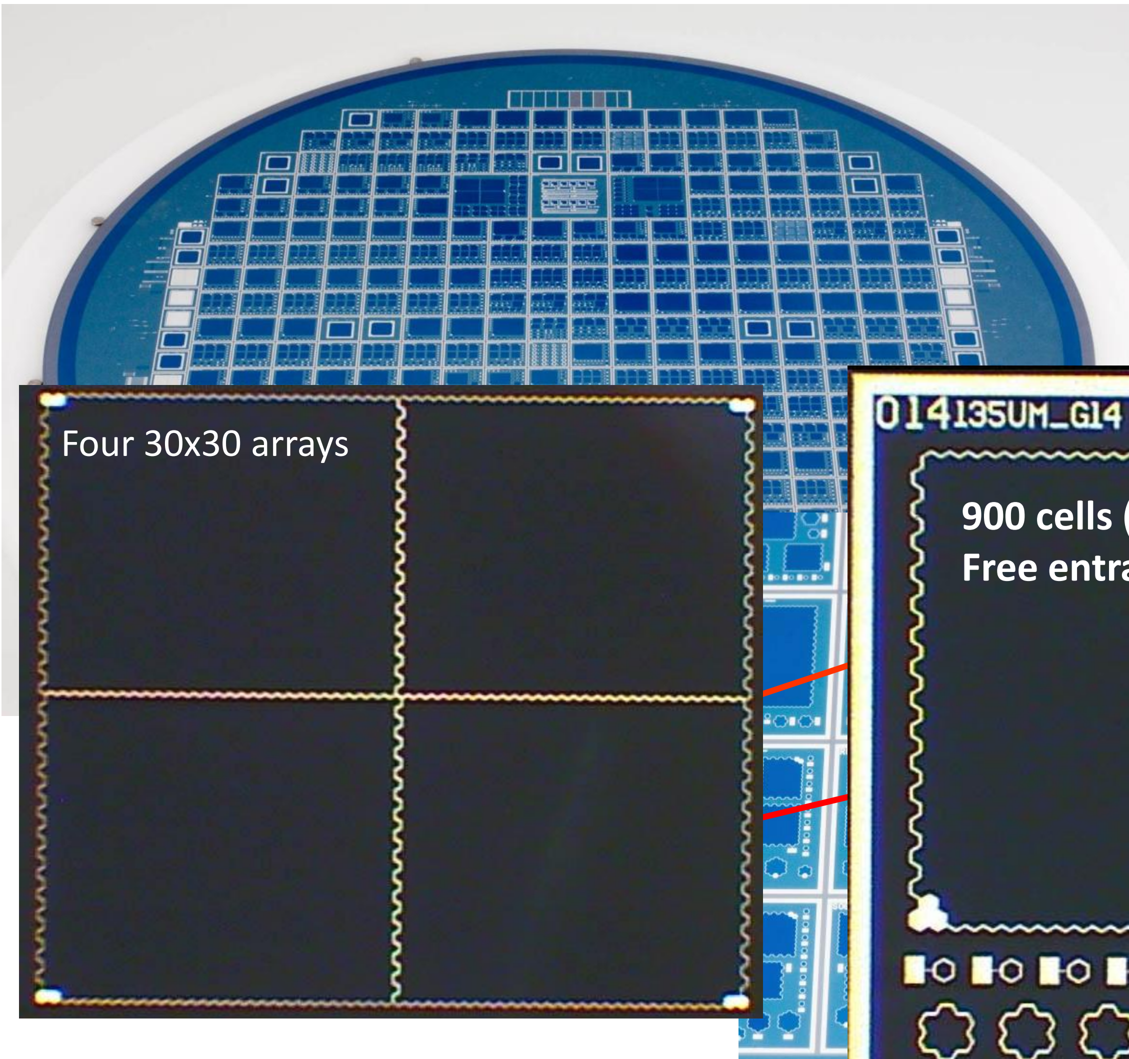
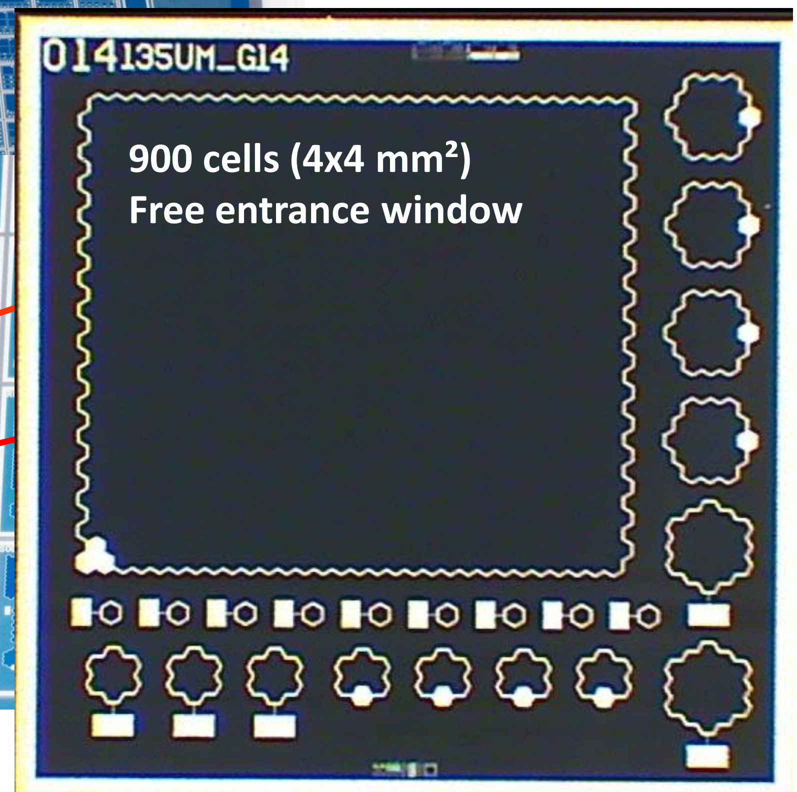
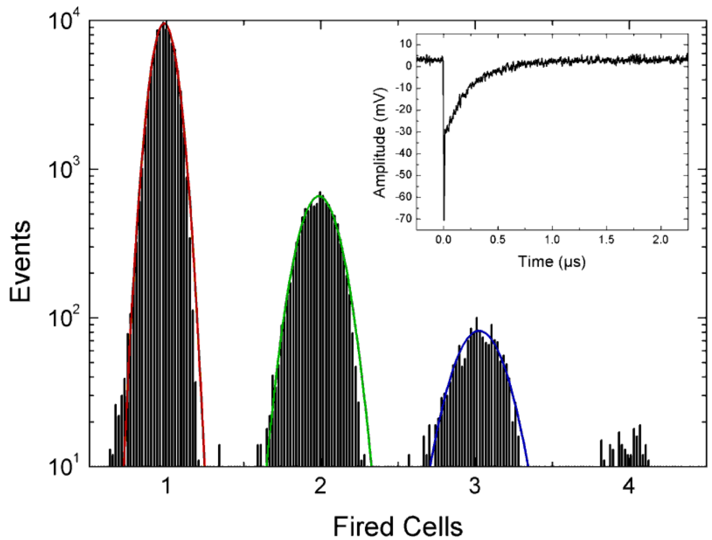




SiMPl Measurements

Characterization of devices: measurement of

- amplitude/charge spectra → photon resolution, gain, cross talk, …
- dark counts
- after-pulsing
- recovery time
- photoemission response
- Photon Detection Efficiency (PDE)



10x10 array of 135µm pitch @ 253K @2V overbias

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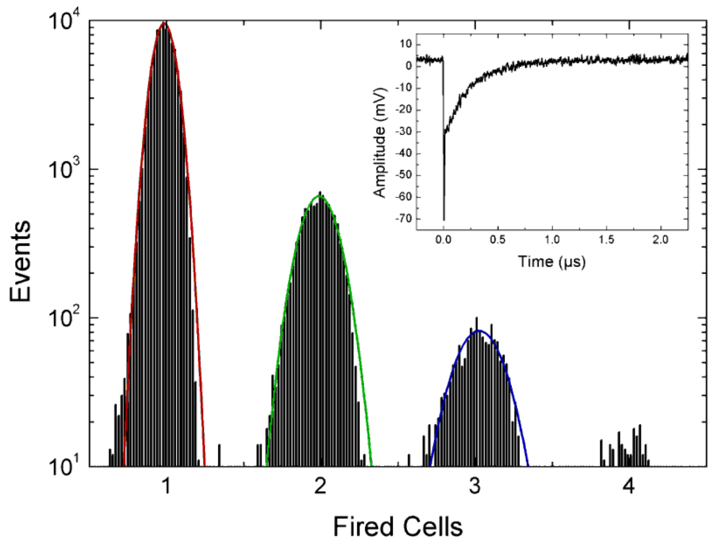

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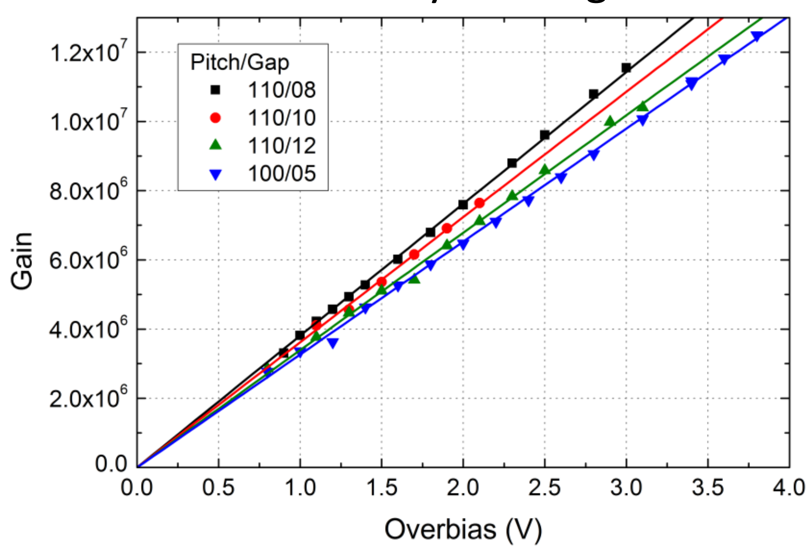
Linearity of the gain



SiMPl Measurements: Cross Talk

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

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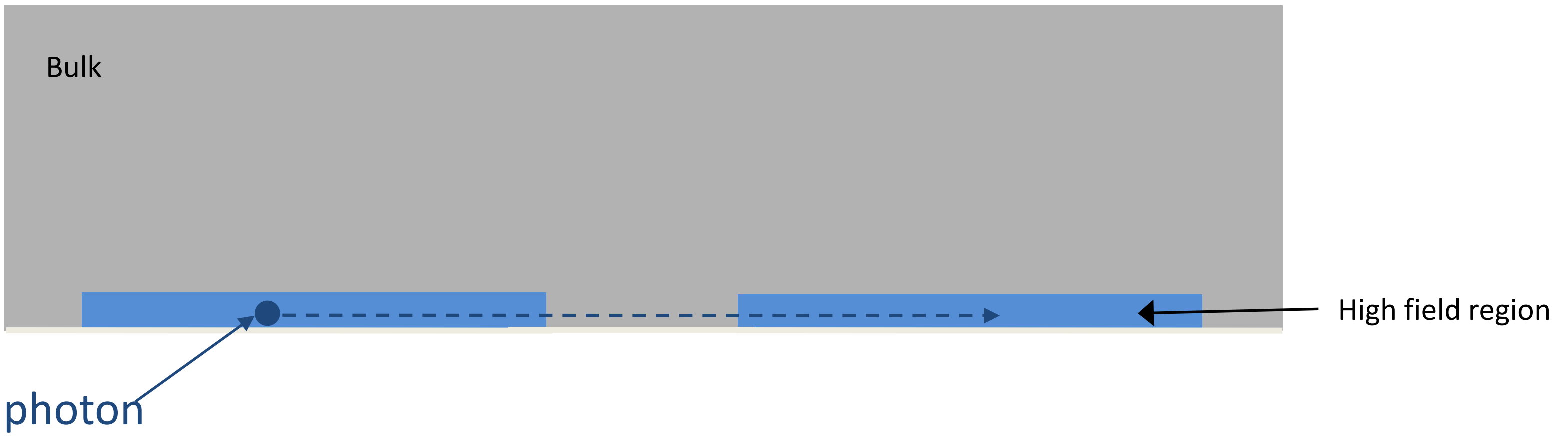

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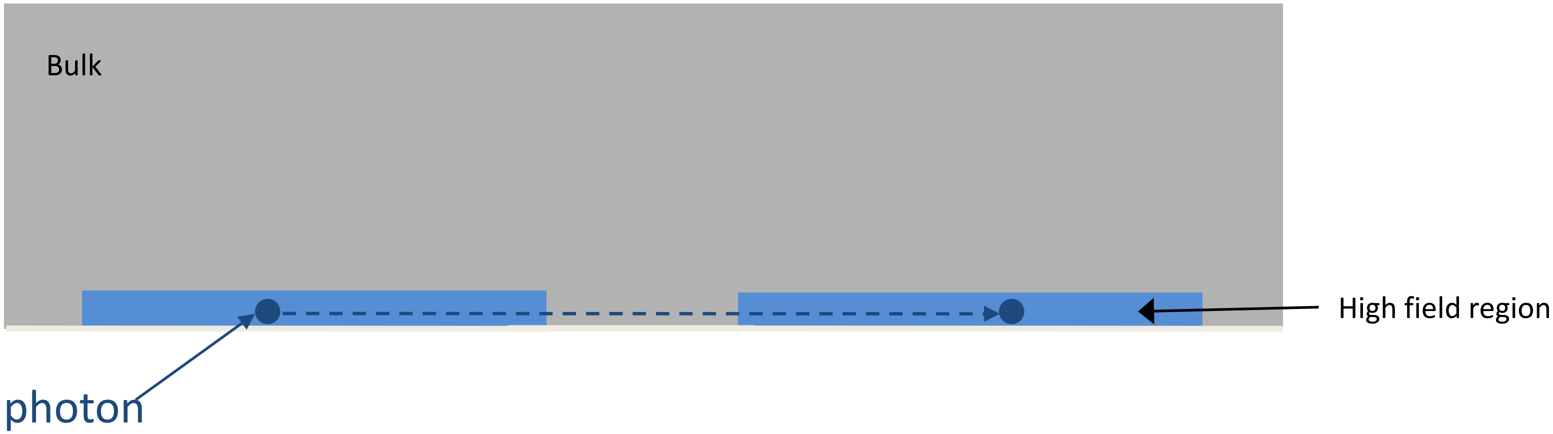

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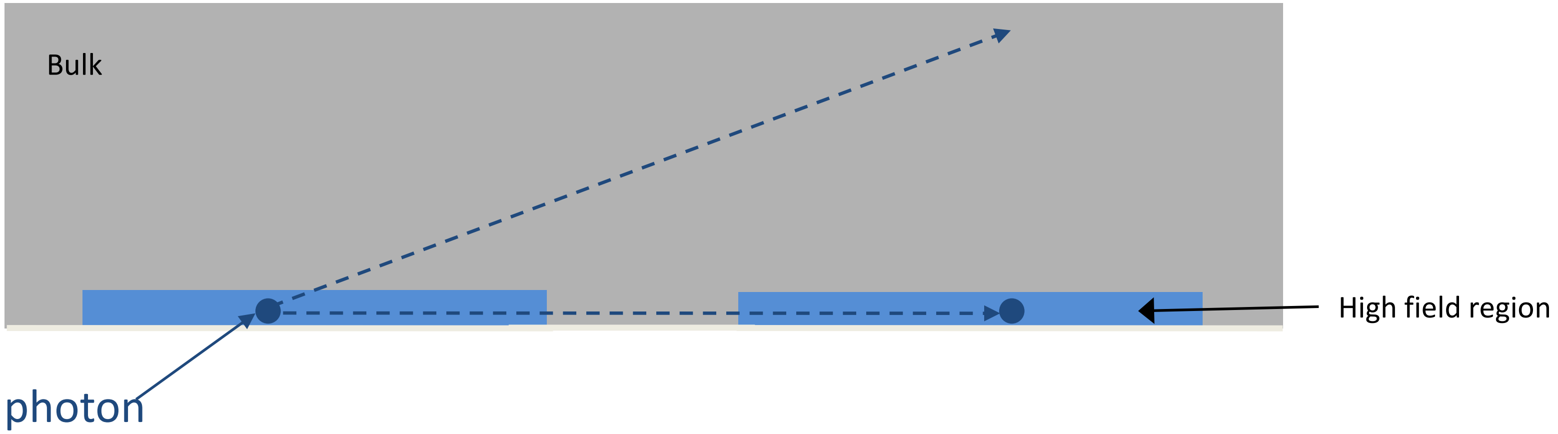

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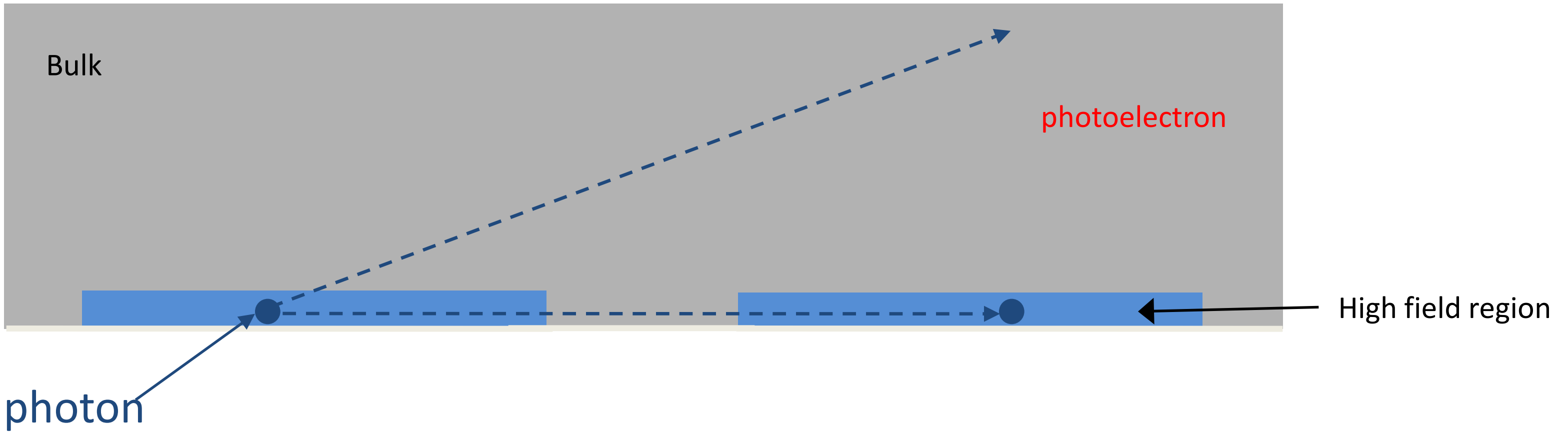

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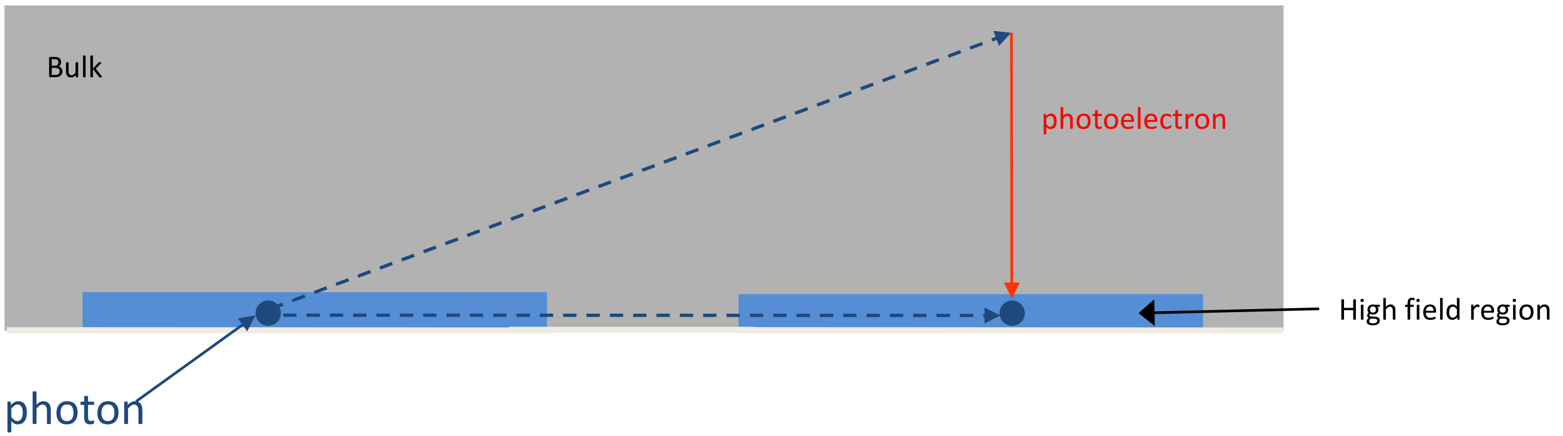

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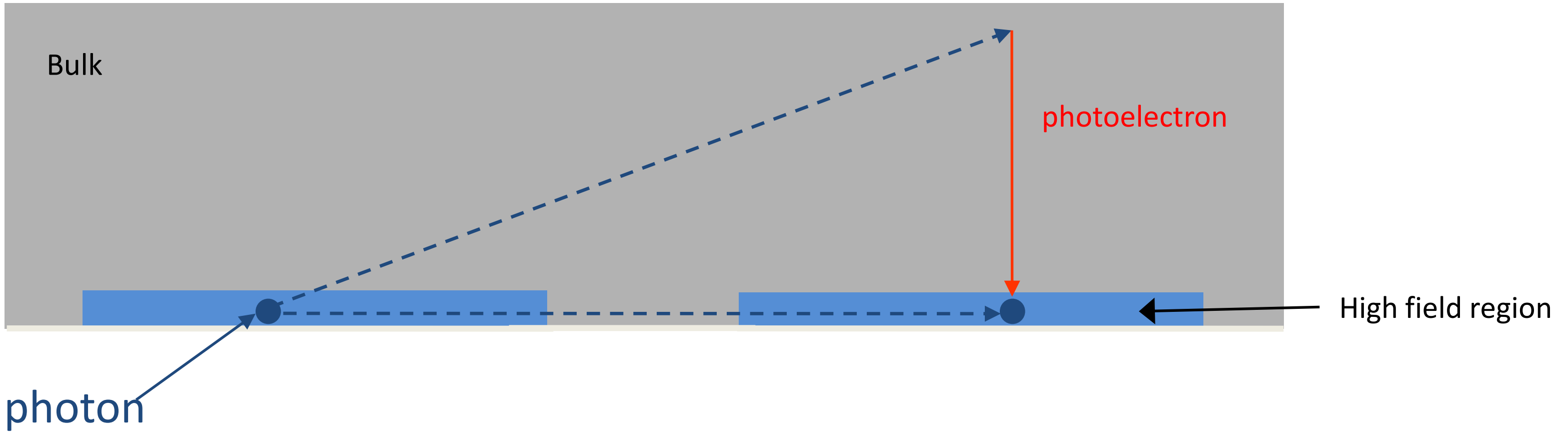

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→ influence on photon counting statistics due to additionally fired cells

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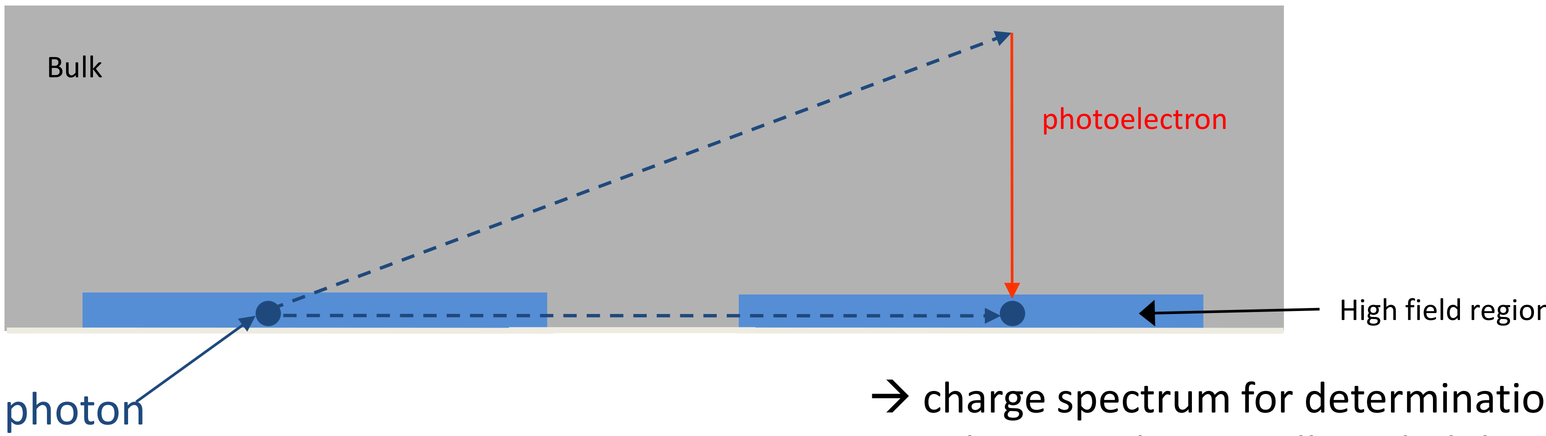
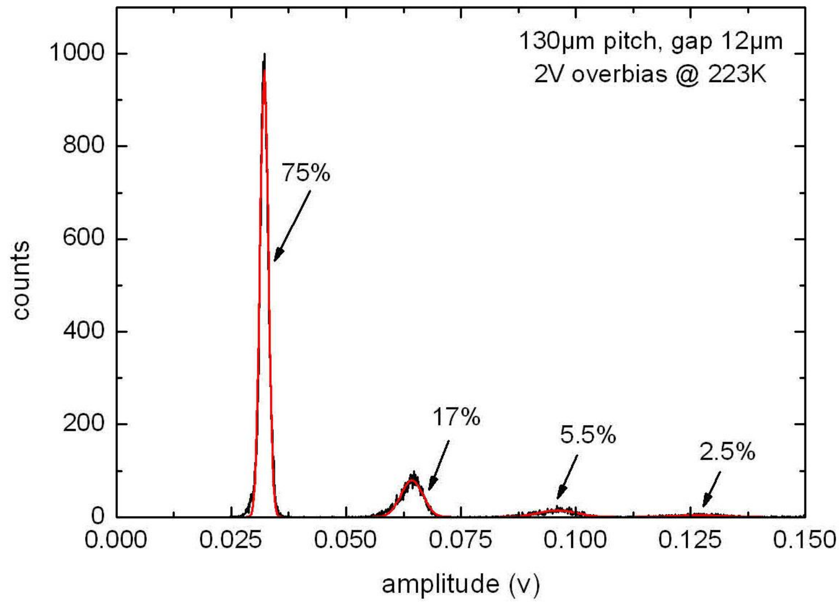


→ charge spectrum for determination of the optical cross talk probability



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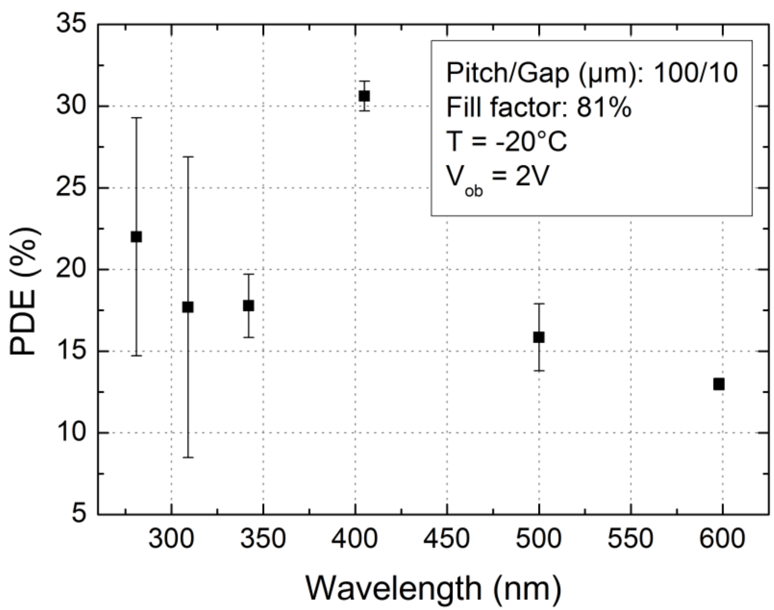
SiMPl Measurements: PDE

Photon Detection Efficiency (PDE):

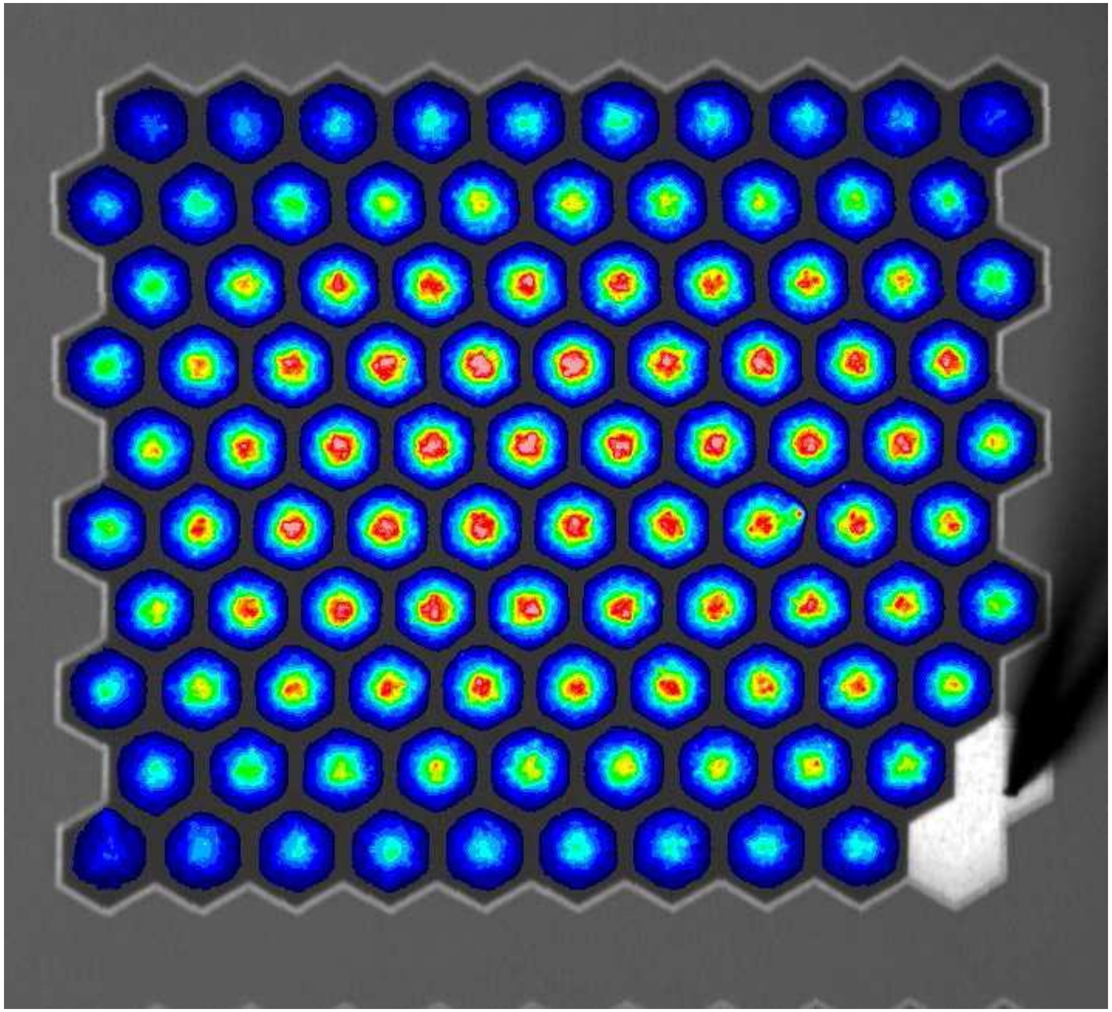
Probability to detect incoming photons of certain wavelengths



- measured PDE for different wavelengths
- peak efficiency around $\lambda \approx 405$ nm
- sensitivity in the UV range observed

SiMPl Measurements: Photoemission

Measurement of the photoemission response of SiMPl devices in Geiger mode



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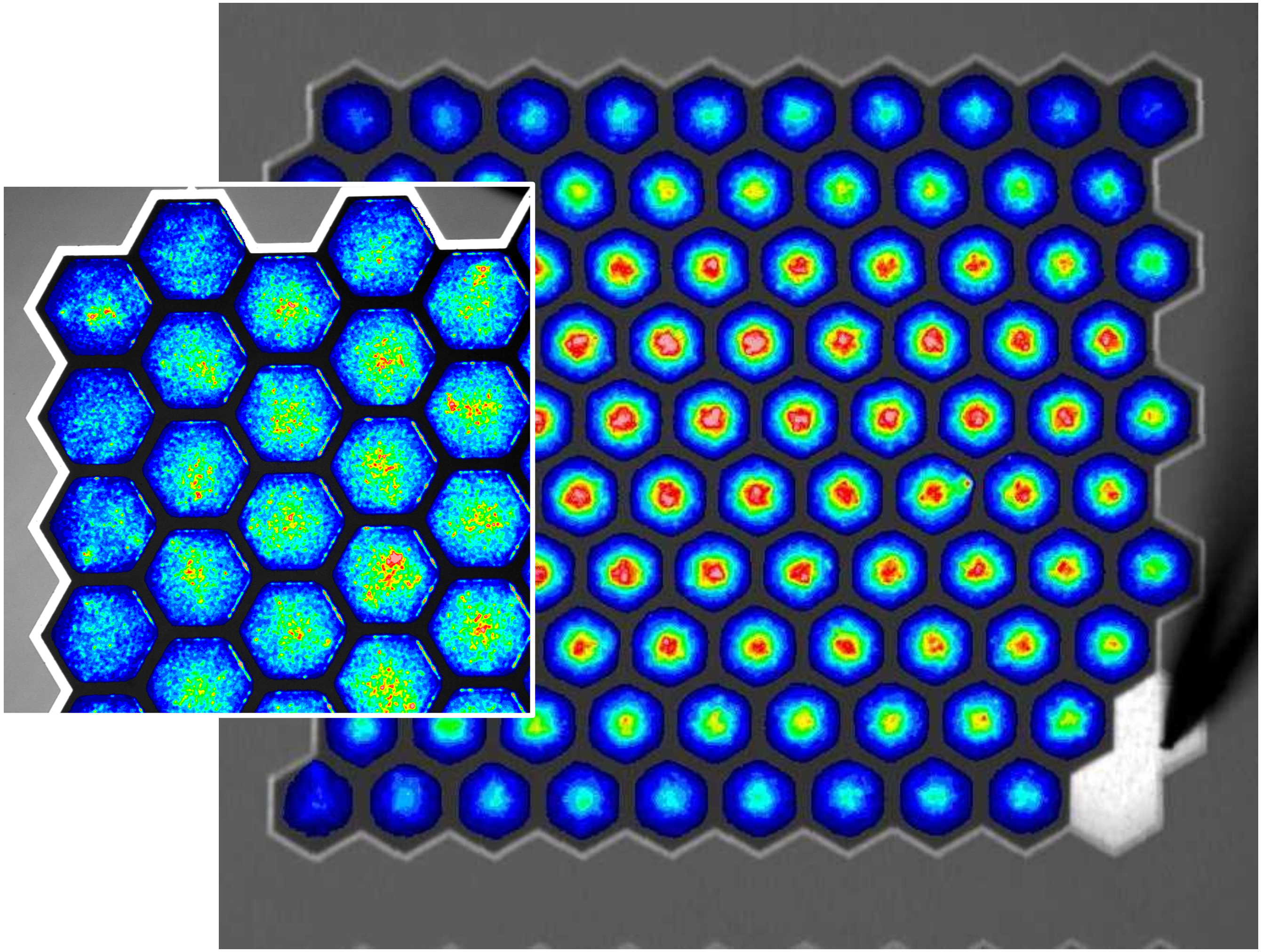

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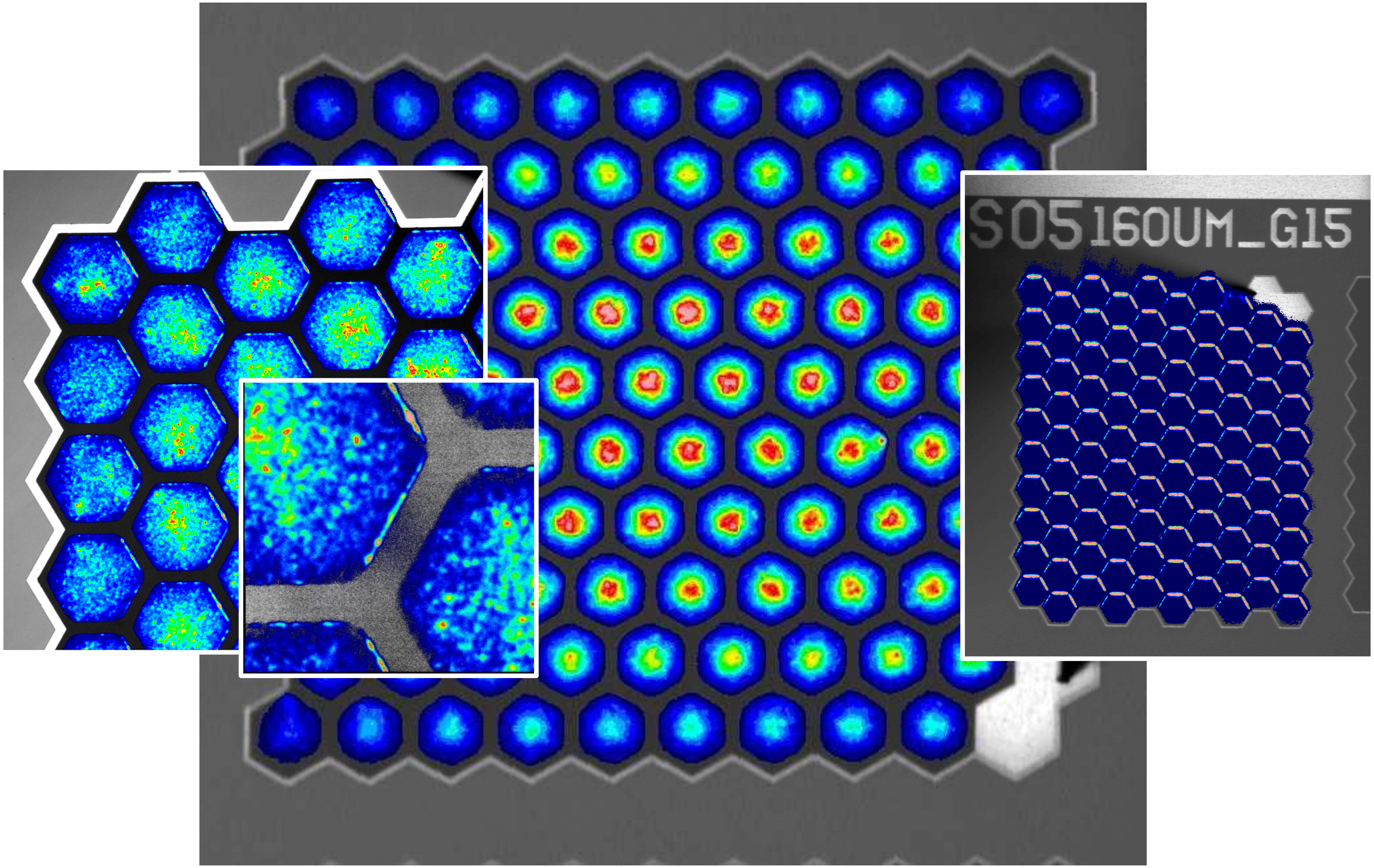

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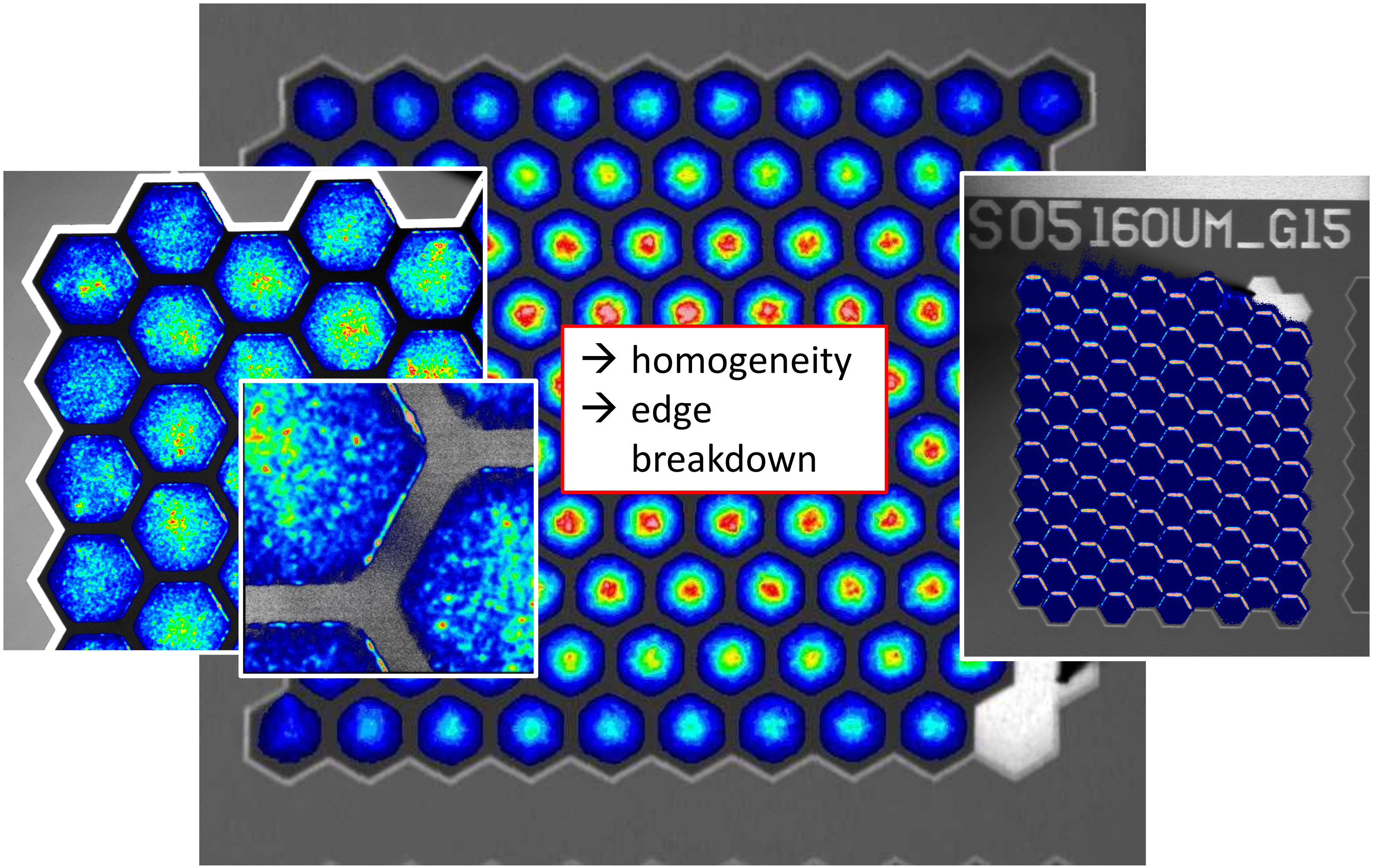
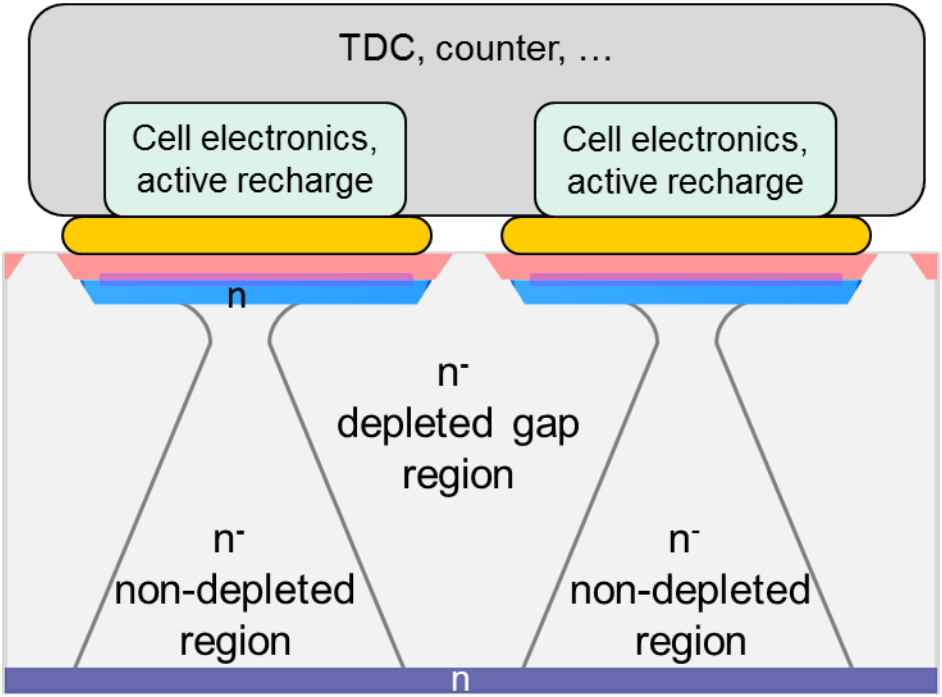


Particle Tracking

Particle tracking with SiMPl devices

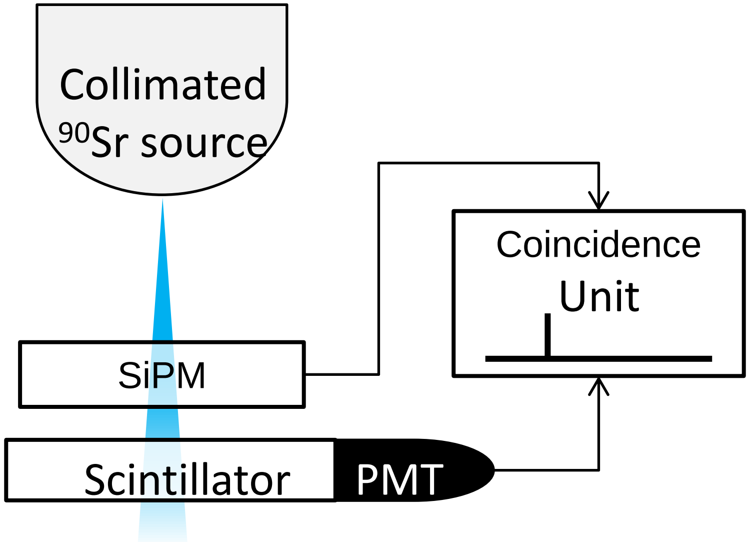
- excellent time stamping due to fast avalanche (sub-ns)
- MIPs generate roughly 80 e-h-pairs/µm
- no need for high trigger efficiency

→ allows operation at low overbias voltage
→ decrease of dark counts & optical cross talk



- Topologically flat surface
- High fill factor
- Pitch limited by bump bonding

Particle Tracking: First Measurements



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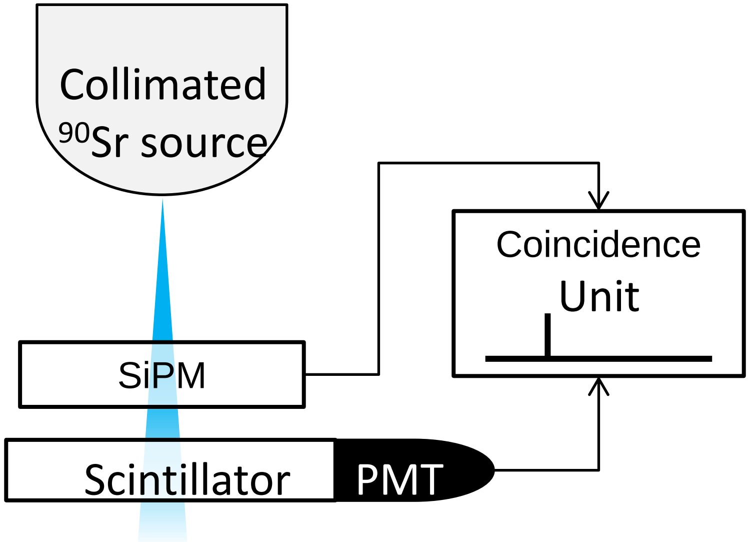

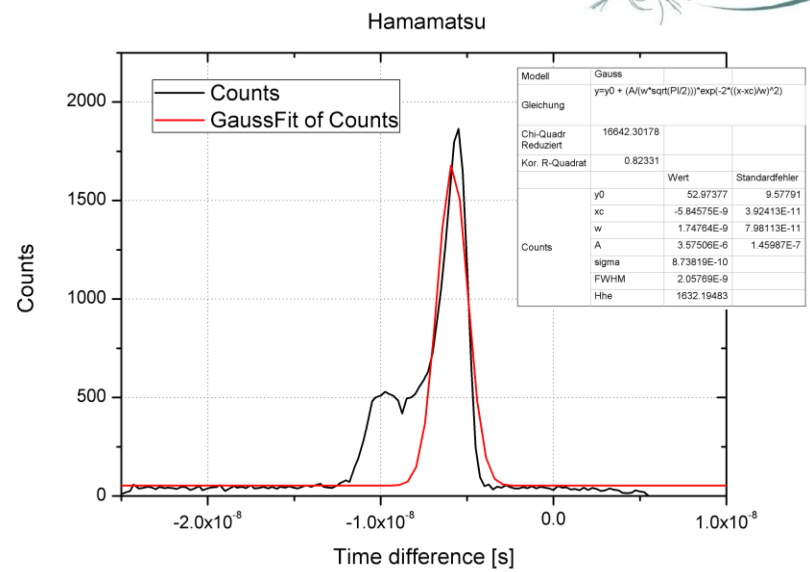

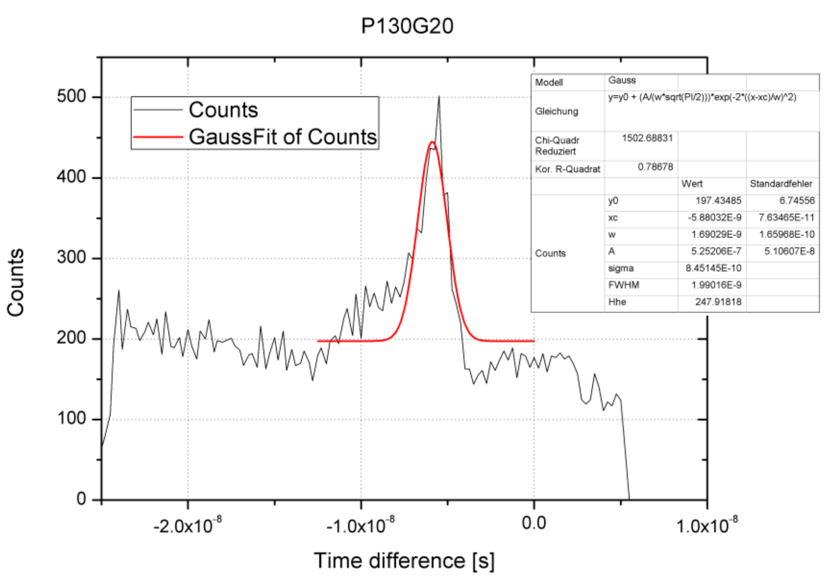

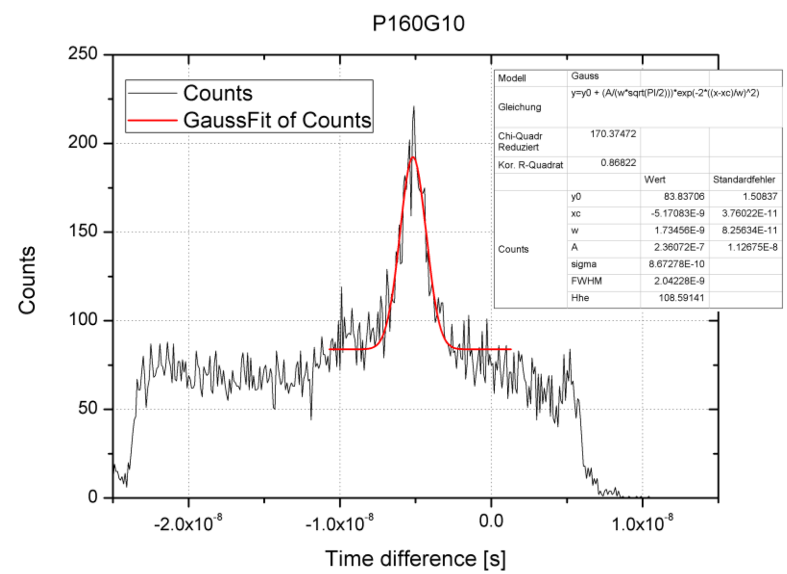

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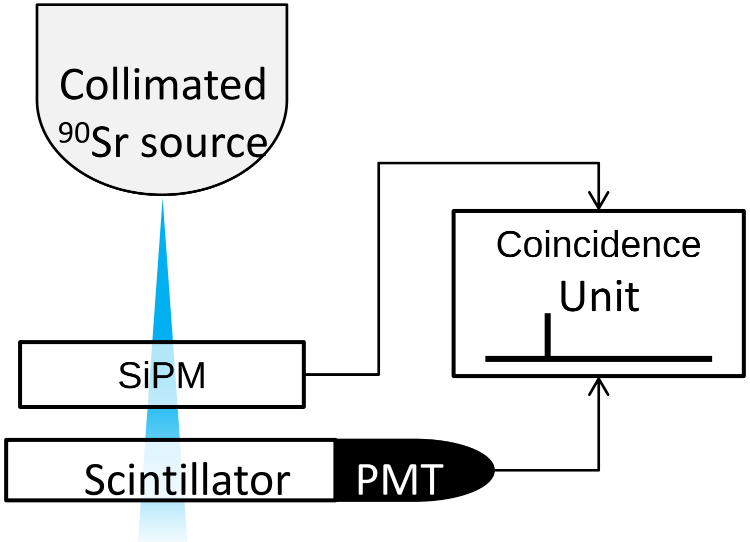
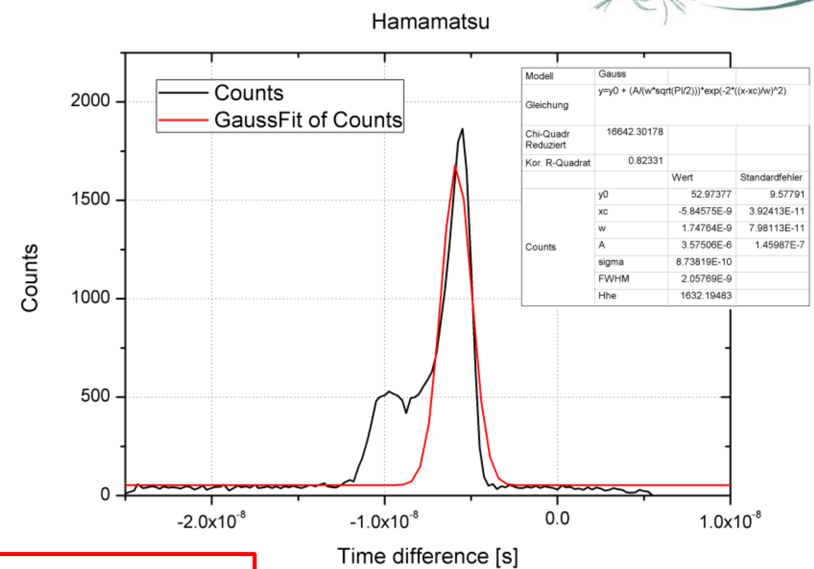
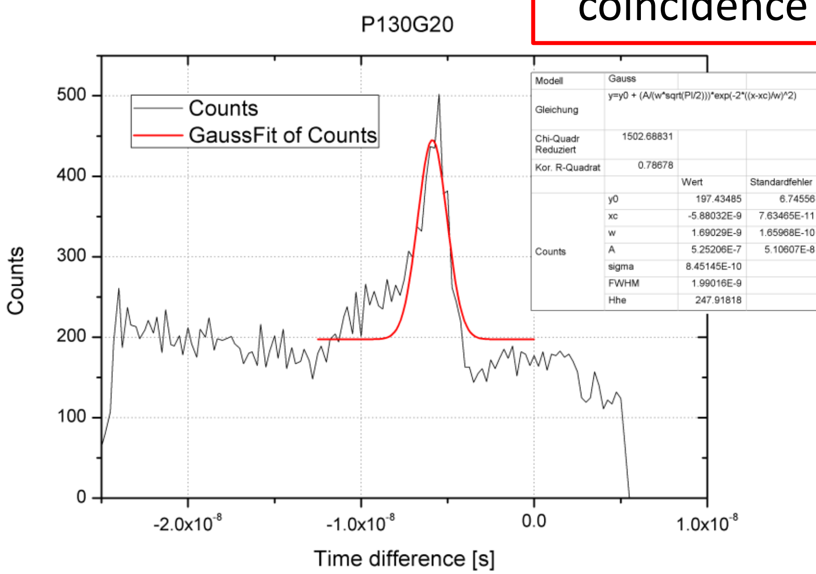
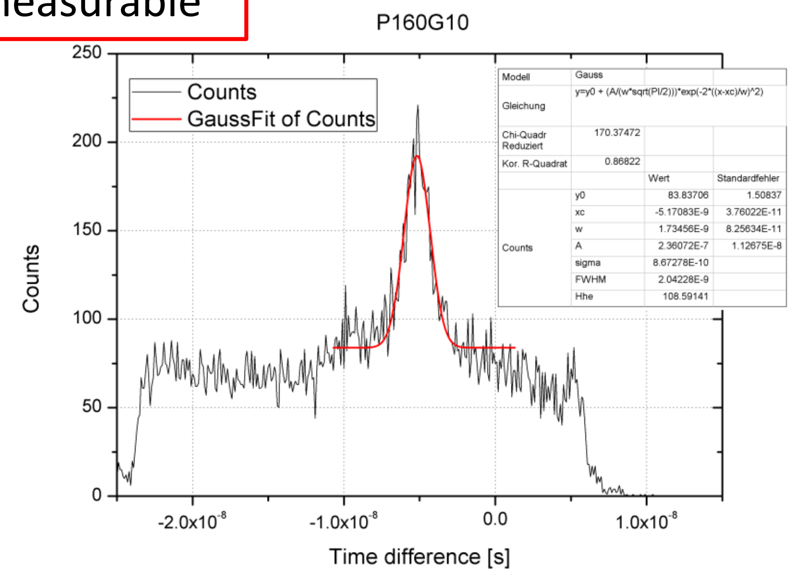




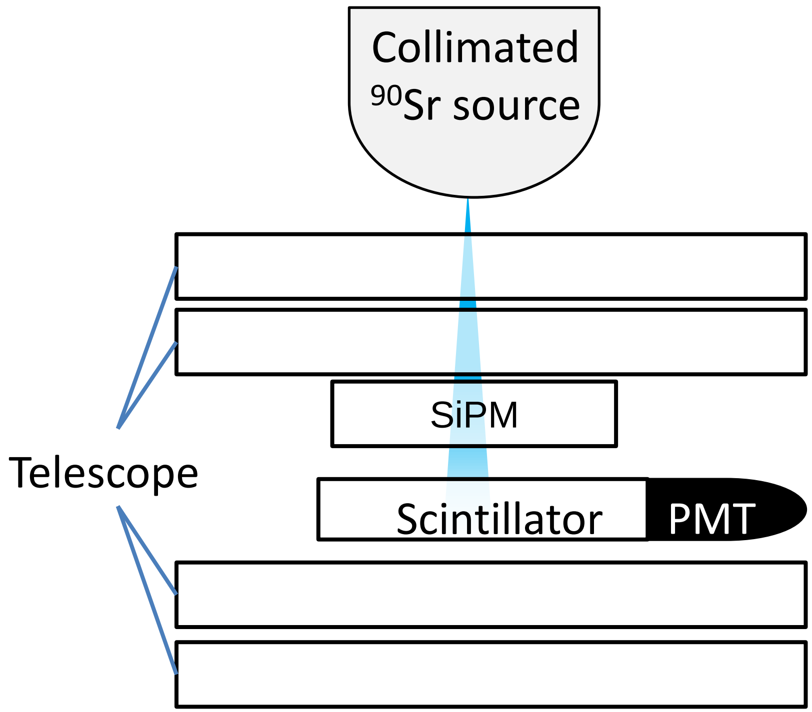
coincidence measurable





Particle Tracking: New Setup

Particle tracking setup concept:
Need to measure particle detection efficiency for lower overbias



→ use telescope or laser (similar to microscope revolver) for alignment of Sr source to SiMPl device

→ electron spot should be sufficiently small (< array/pixel size)

→ technical difficulties in producing a small but deep hole of d ≈ 100µm (mechanical/laserdrilling not up to the task)

→ sufficient collimation leads to extremely low particle rate (≈10/s) (→ cooling)

Technology & Device Simulations

Problems:

edge breakdown, new material for smaller cells, …

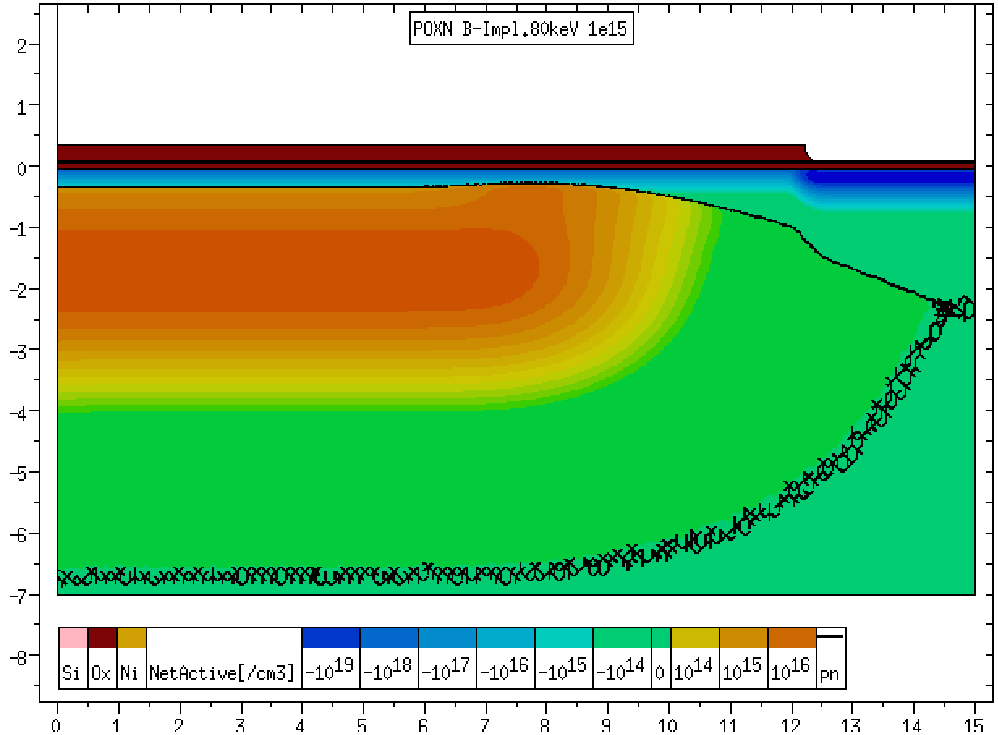
before new production

Technology & Device Simulations:

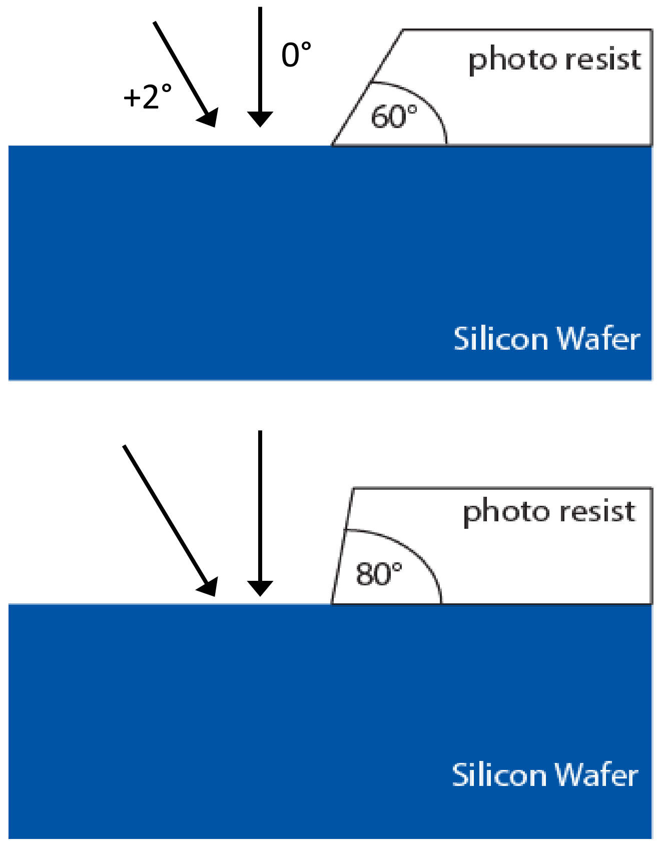
→ optimization of the parameter space

Technology & Device Simulations

Technology simulations with Dios



Direction of ion implantation (tilt)



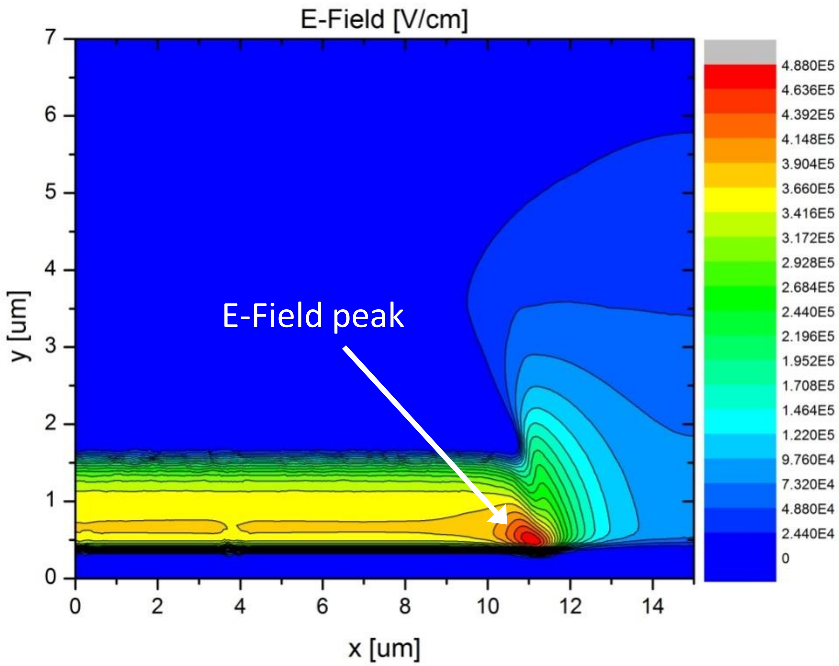
Possibilties in the simulations:

- variation of the photo resist and tilt angle
- tuning of annealing scenario (time, temperature, atmosphere)
- change of implantation dose and energy for E-field optimization

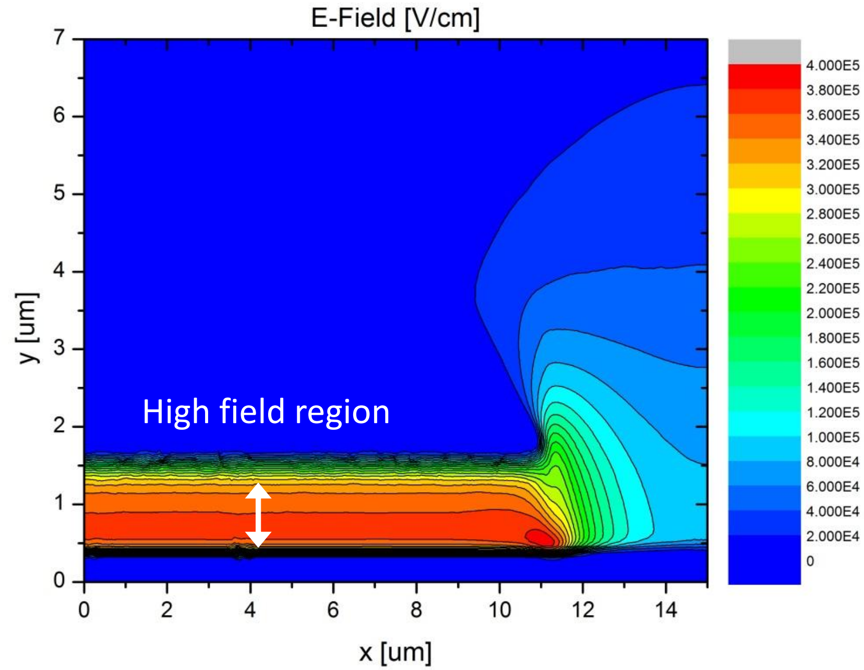
Technology & Device Simulations

Impact on electrical field of the high field region

smaller photo resist angle



larger photo resist angle

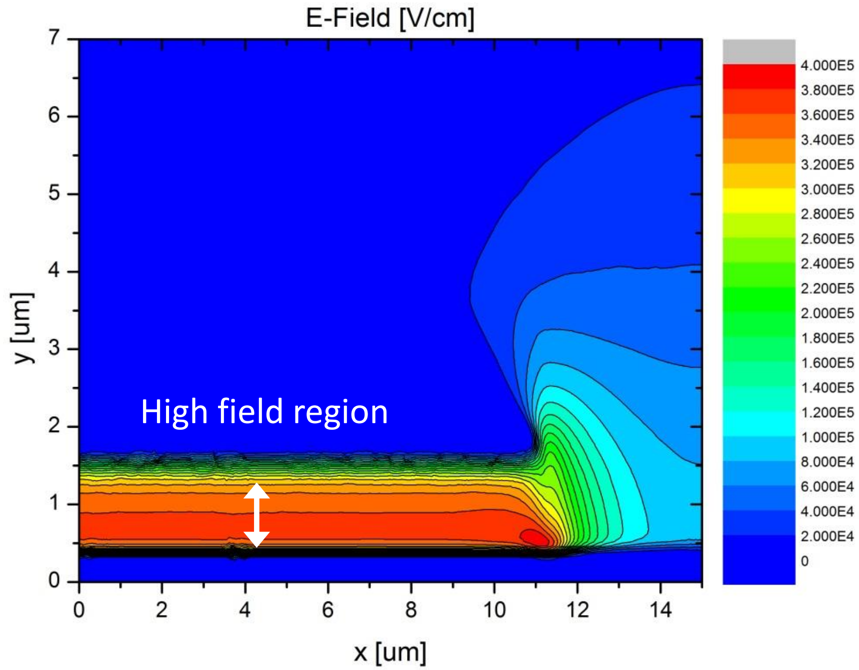


- peak of the electrical field on the edge of the high field region can cause edge breakdown

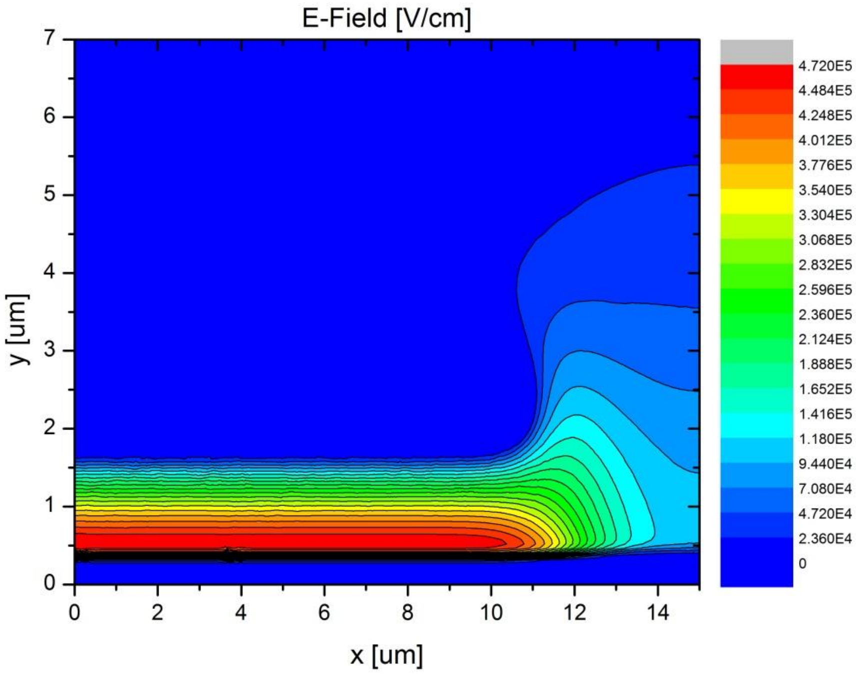
Technology & Device Simulations

Impact on electrical field of the high field region

shorter annealing @ lower temperature



longer annealing @ higher temperature



- peak of the electrical field on the edge of the high field region can cause edge breakdown
- inhomogeneous field in y-direction due to diffusions

→ affected by various parameters (photo resist angle, tilt angle, annealing scenario)

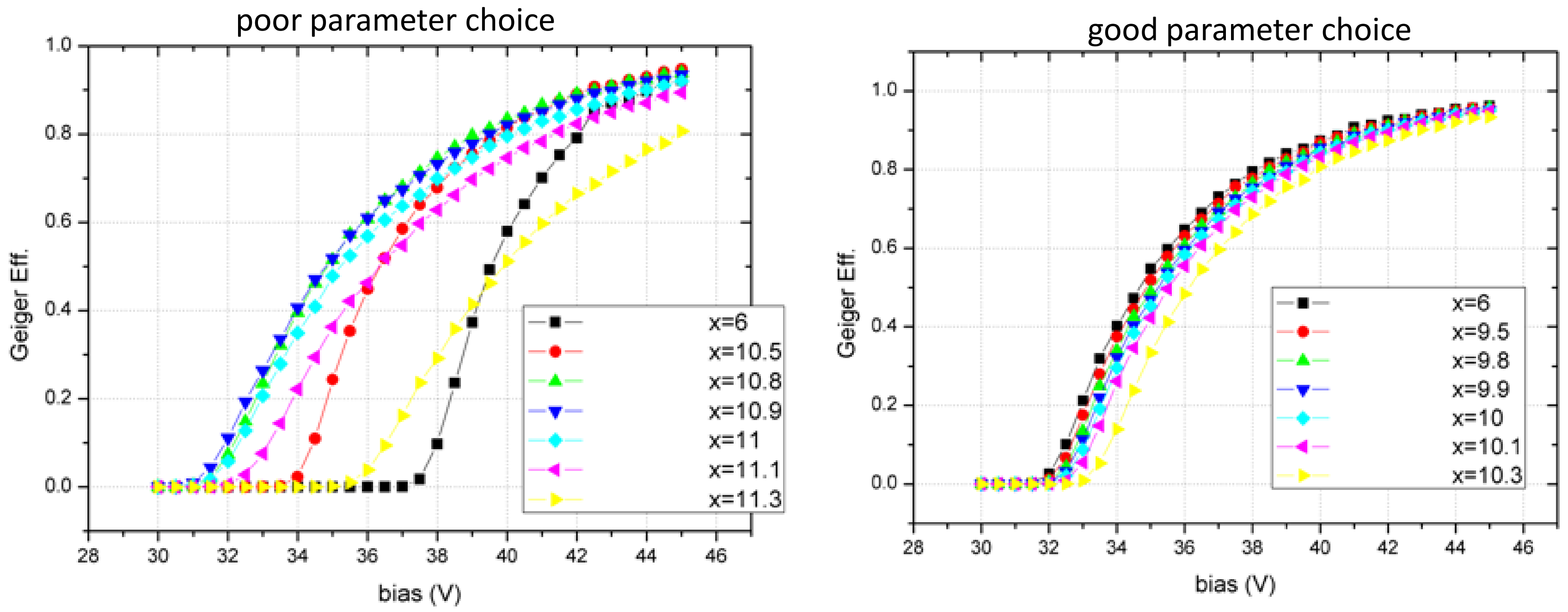
→ find optimum parameters for edge breakdown suppression and homogeneity of E_y

Technology & Device Simulations

Electrical field and edge breakdown

→ decrease the E-field peak → reduce chance of edge breakdown

→ Monte-Carlo simulations for determining the trigger efficiency for different parameters



Technology & Device Simulations

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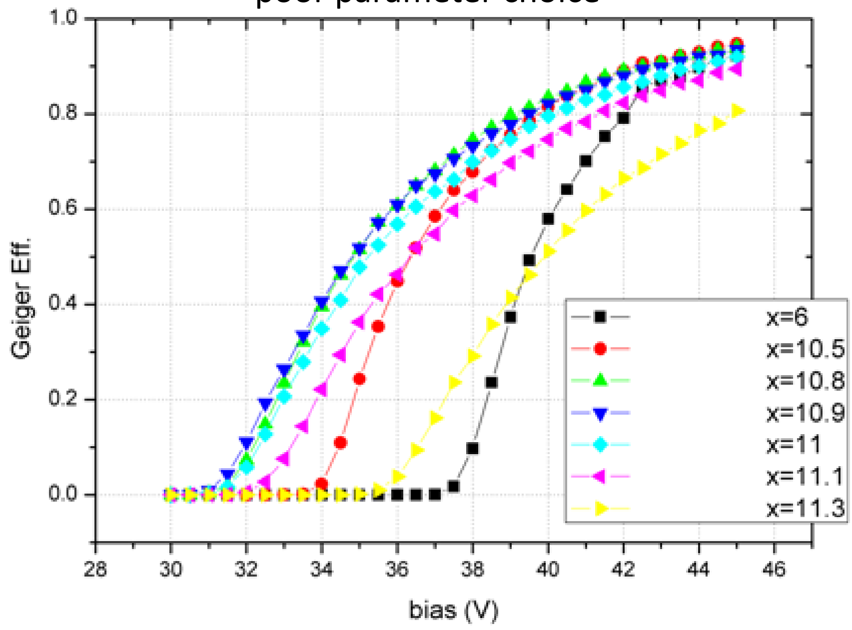
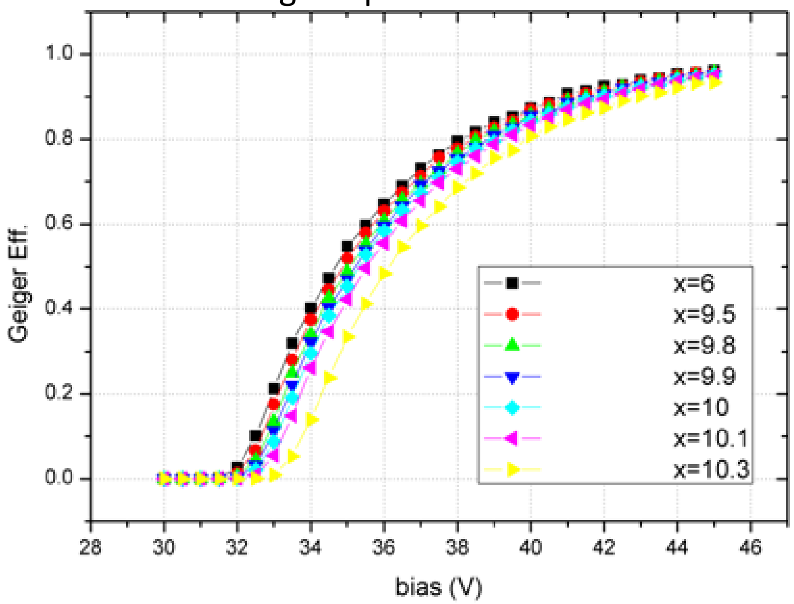
poor parameter choice



good parameter choice

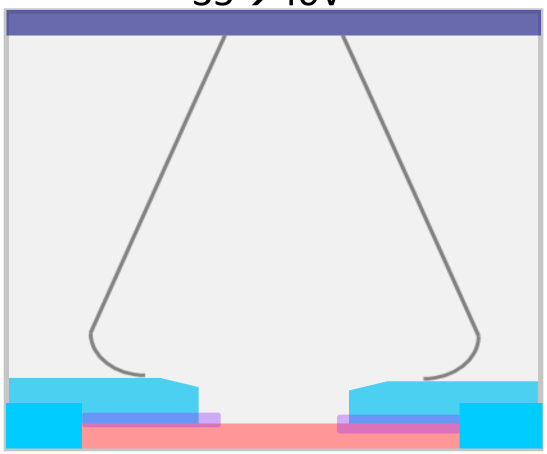


→ probability of edge breakdown can be estimated

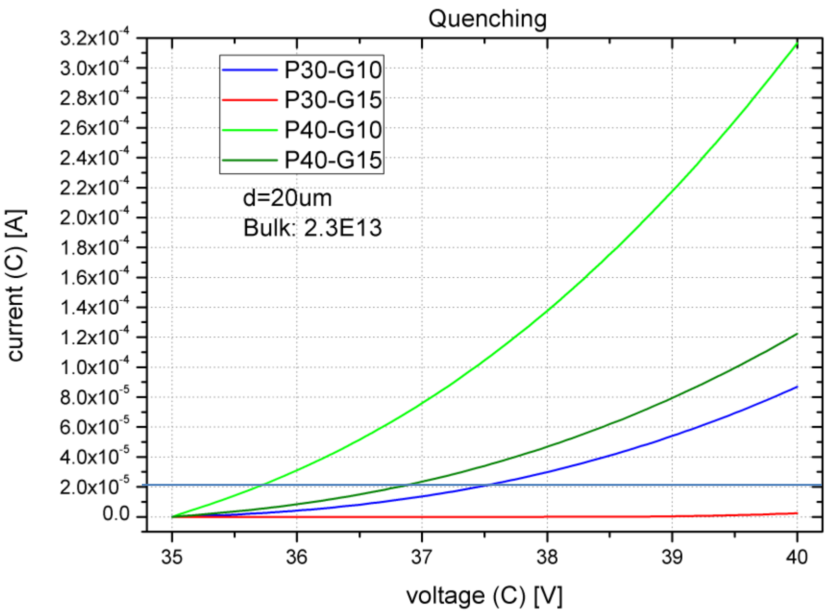
→ parameters can be optimized

Technology & Device Simulations

Recovery & Quenching: static simulations



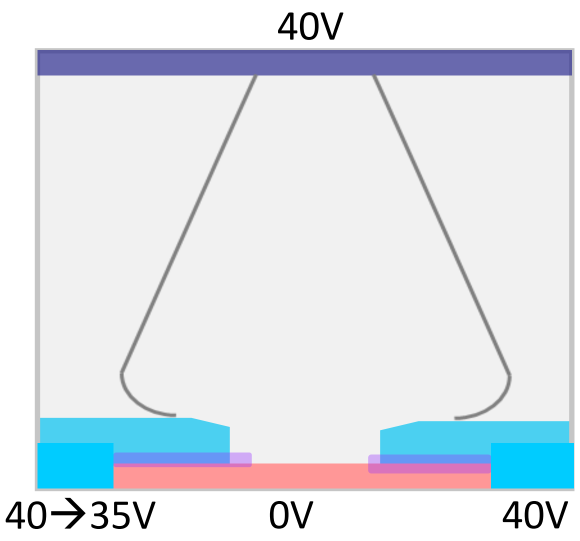
- breakdown voltage @ 35V
- increase overbias
- obtain IV-curve, which should simulate the moment of the avalanche breakdown



rule of thumb:
current limit for quenching @
I_{max} = 20 µA

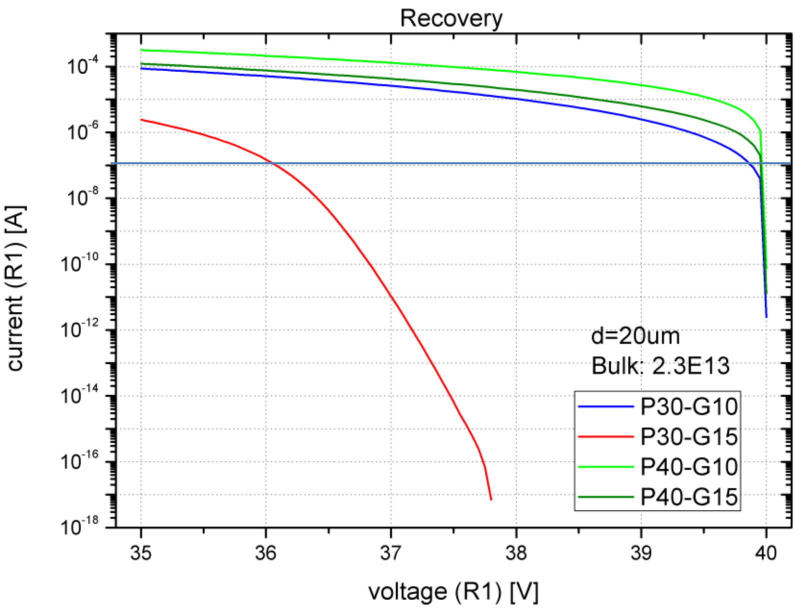
Technology & Device Simulations

Recovery & Quenching: static simulations



- overbias voltage @ 40V
- decrease voltage of internal anode to breakdown
- obtain IV-curve, which should simulate the recovery process of the cell

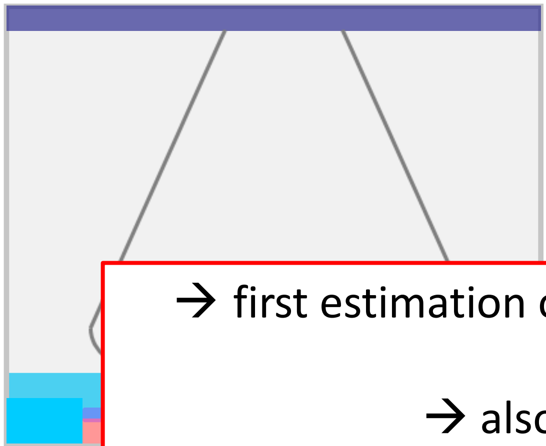
rule of thumb:
current limit for acceptable cell recovery time @ I_{max} = 100 nA



Technology & Device Simulations

Recovery & Quenching: static simulations

40V

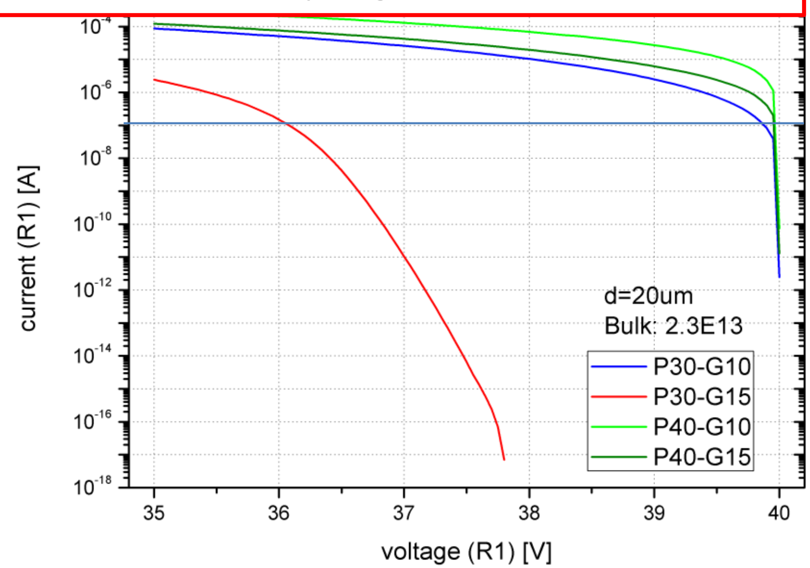


40→35V 0V 40V

- overbias voltage @ 40V
- decrease voltage of internal anode to breakdown
- obtain IV-curve, which should simulate the recovery process of the cell

→ first estimation of parameter space for different pixel structures possible

→ also dynamic simulations (in progress)



rule of thumb:
current limit for acceptable cell recovery time @ I_{max} = 100 nA

Summary and Outlook

- New detector concept for SiPMs with quench resistors integrated into the silicon bulk
  - no polysilicon resistors, no contacts necessary at the entrance window
  - geometrical fill factor is given by the need of cross talk suppression only
  - very simple process

- Prototype production
  - first results very promising → quenching works
  - problems encountered → optimization necessary

- Technology & Device Simulations
  - tackling of various problems (e.g. edge breakdown)
  - simulation of new production, including small pixels

→ New production to reduce dark counts and implement small pixels

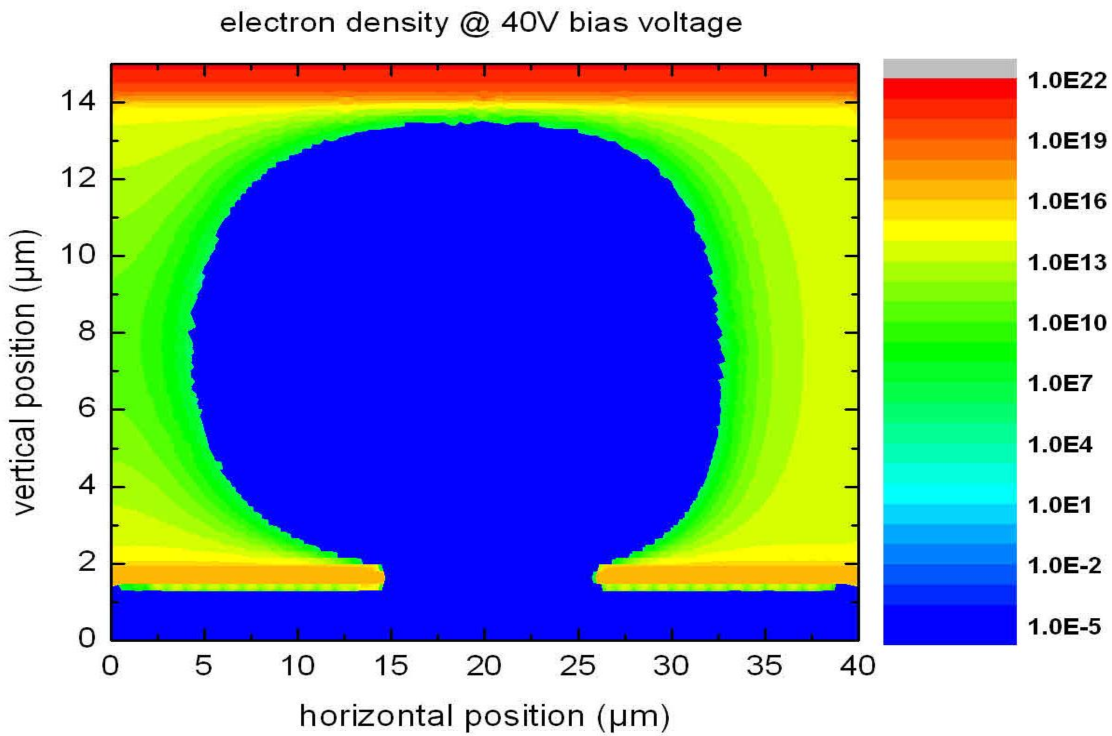
→ Further investigation in particle tracking application
  - new measurement setup
  - investigation of radiation hardness
  - test of new electronics
  - test beam measurements

The End

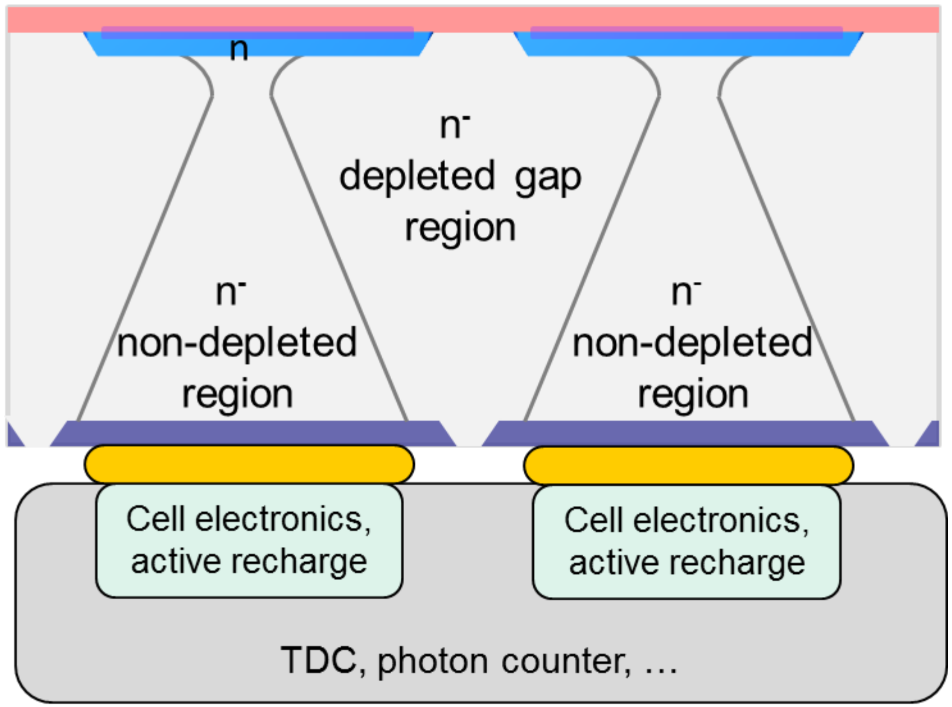
Thank You For Your Attention!

Backup

Backup

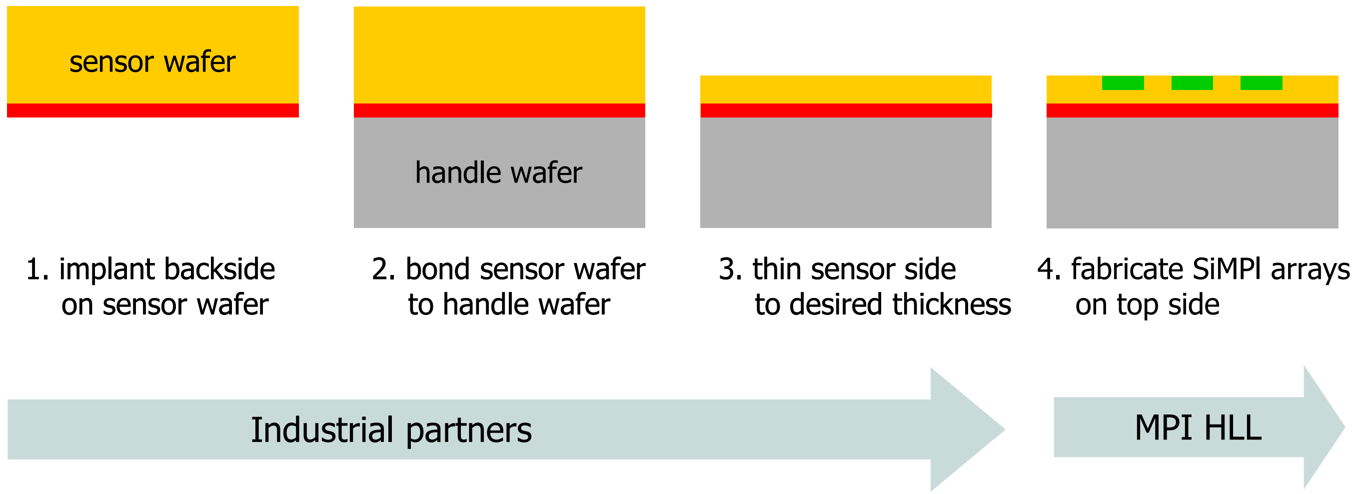

electron density @ 40V bias voltage
vertical position (μm)
horizontal position (μm)
0
2
4
6
8
10
12
14
0
5
10
15
20
25
30
35
40
1.0E22
1.0E19
1.0E16
1.0E13
1.0E10
1.0E7
1.0E4
1.0E1
1.0E-2
1.0E-5

Backup



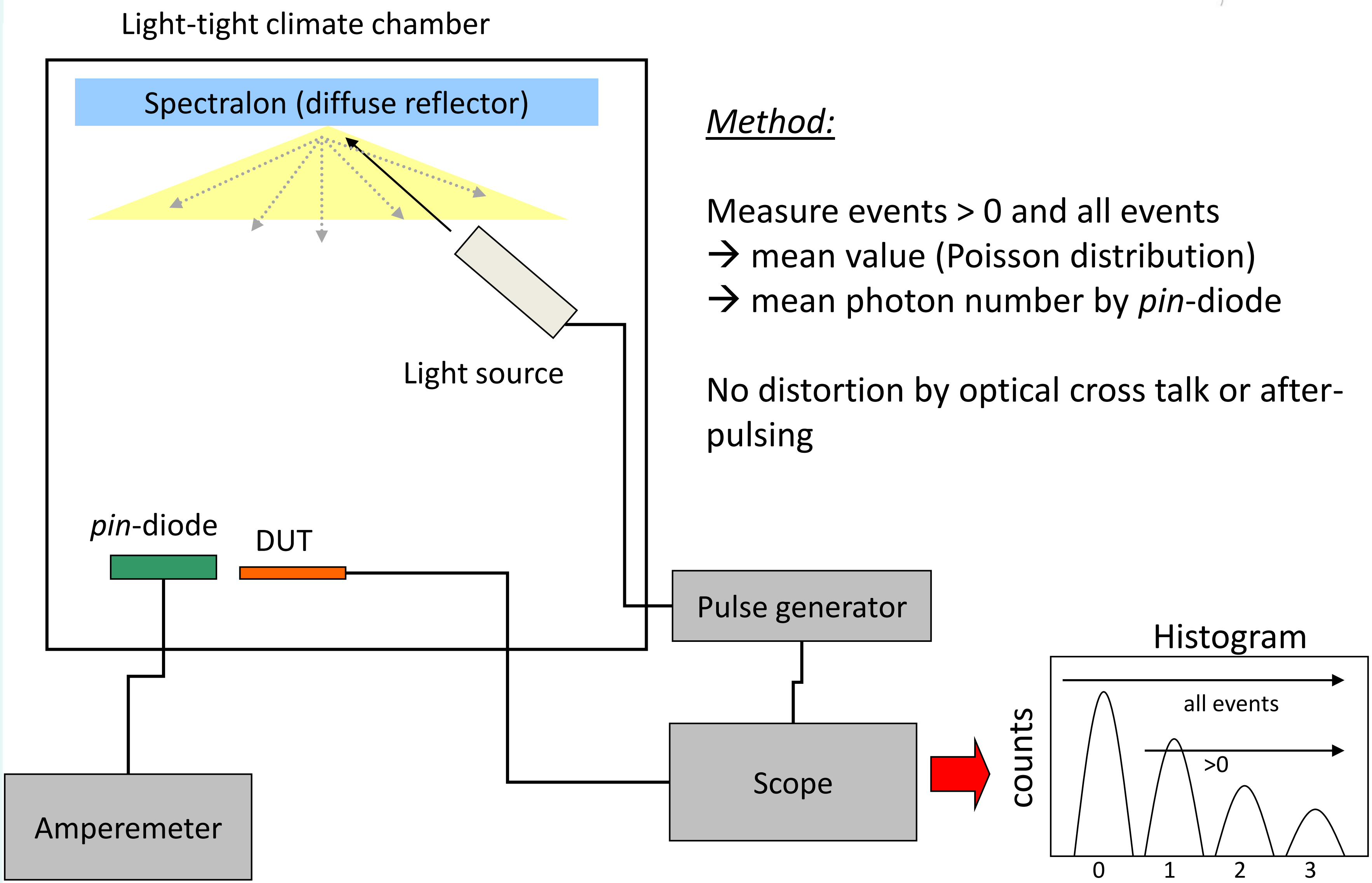
1. Structured implant on backside on sensor wafer
2. bond sensor wafer to handle wafer
3. thin sensor side to desired thickness
4. process SiMPl arrays on top side
5. Etching backside & flip chipping on back side

Backup



sensor wafer
handle wafer
1. implant backside on sensor wafer
2. bond sensor wafer to handle wafer
3. thin sensor side to desired thickness
4. fabricate SiMPl arrays on top side
Industrial partners
MPI HLL

Backup



Method:

Measure events > 0 and all events
→ mean value (Poisson distribution)
→ mean photon number by *pin*-diode

No distortion by optical cross talk or after-pulsing

Backup

due to non-optimized process sequence
~10MHz/mm² @300K for 4V overbias

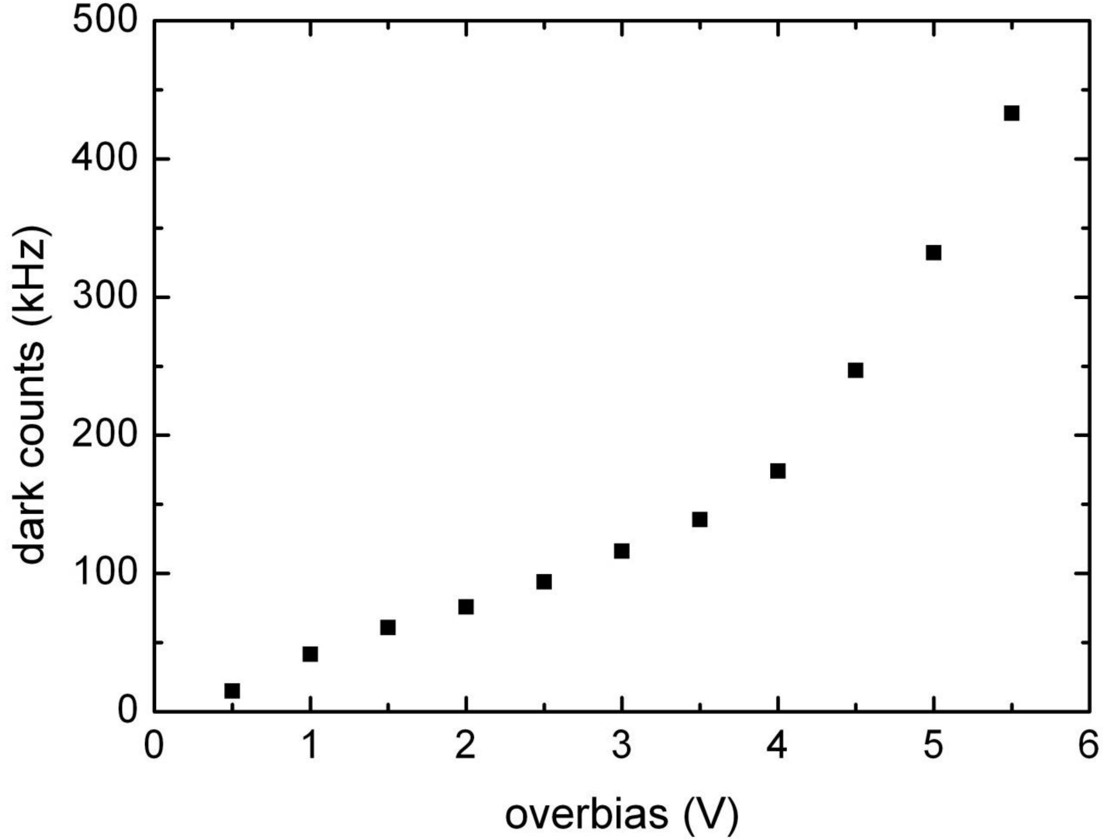
Thermal generation

→ cooling helps

normal operation up to
4V overbias @233K

overbias > 4V
→ non-quench condition

10x10 array of 130µm pitch @ 233K



Backup

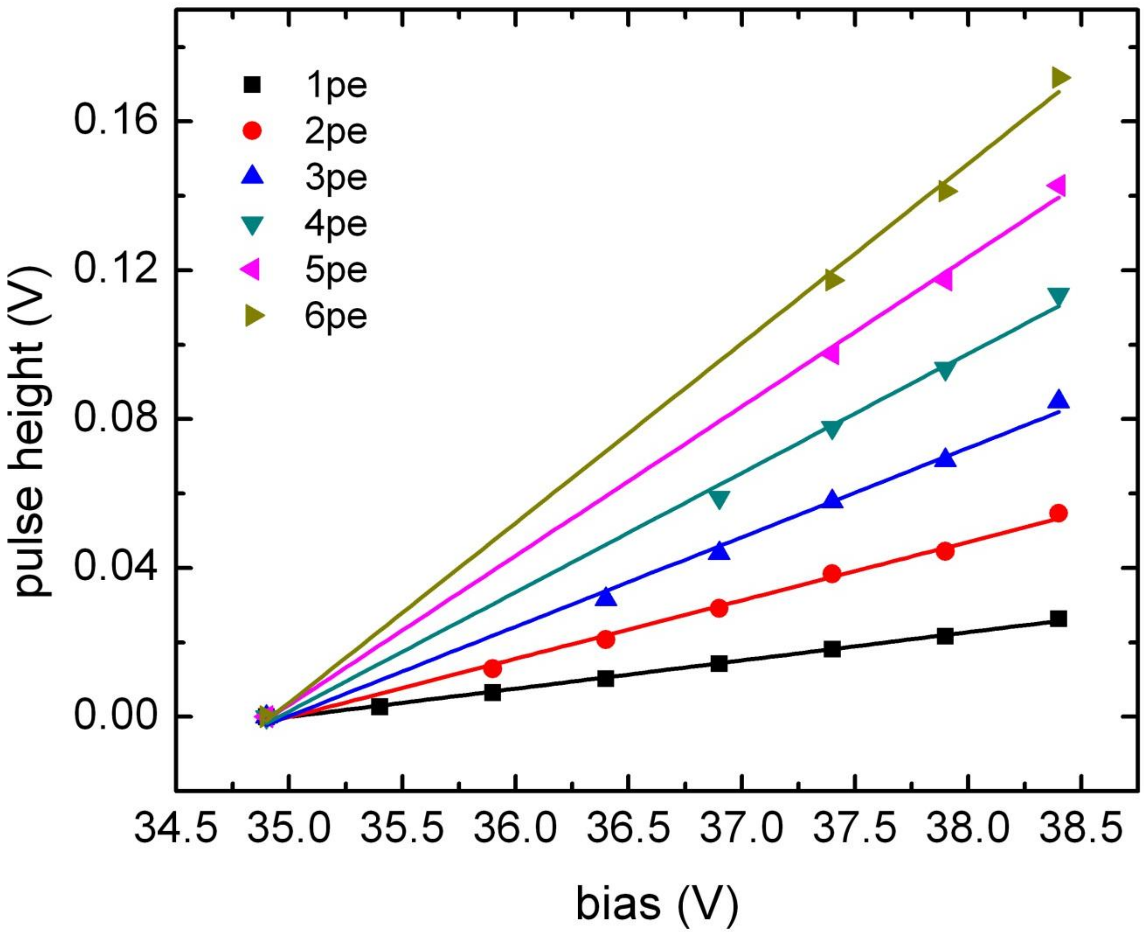
10x10 array of 135µm pitch @ 253K

pulse height ∝ Q

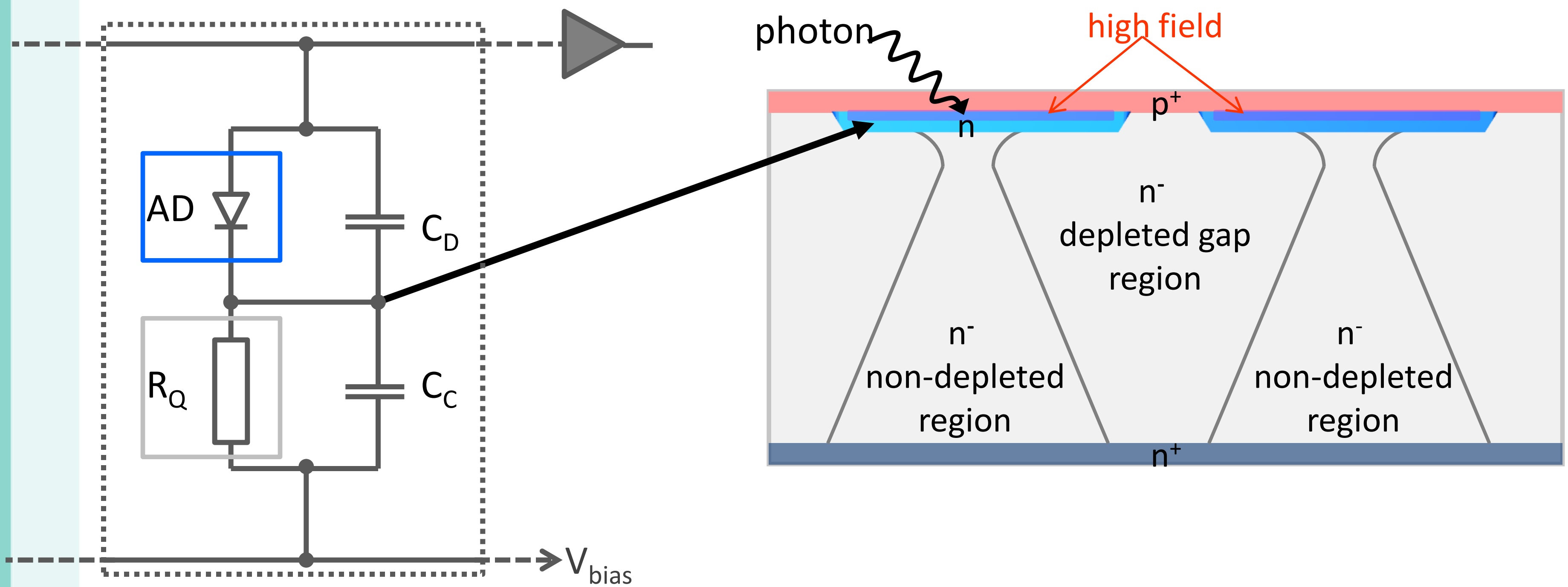
$Q = e \cdot G = C \cdot \Delta U$

linear

normal operation

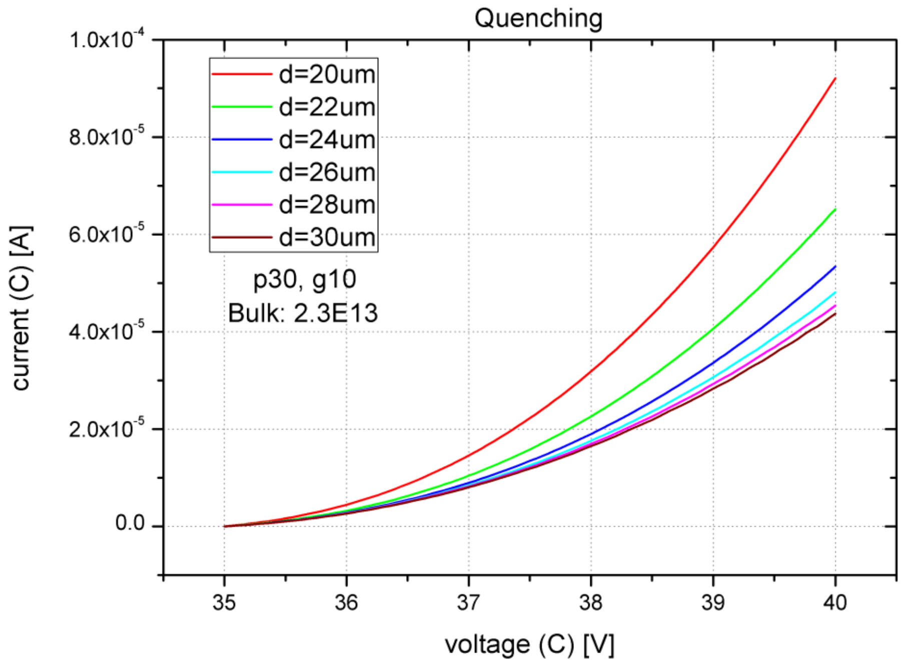


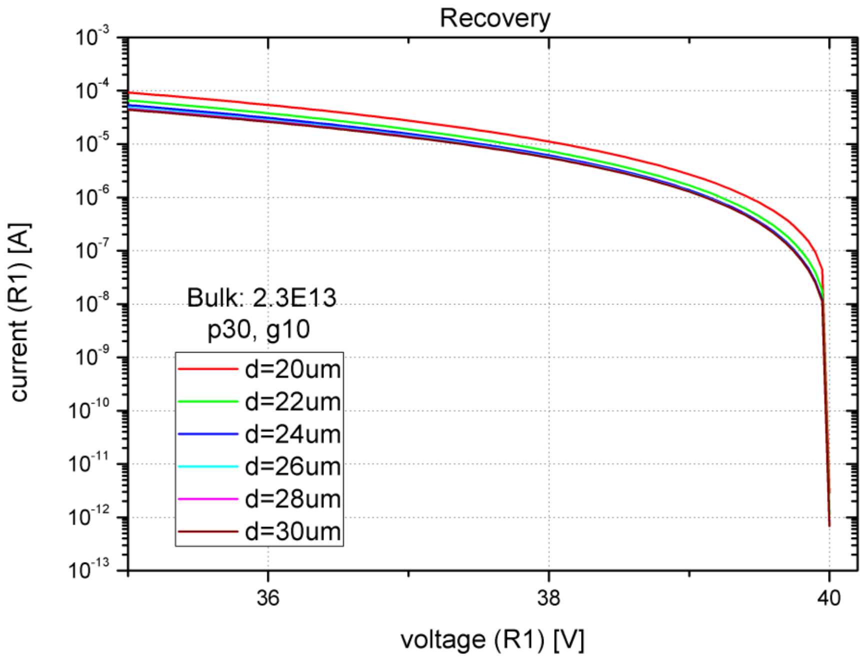
Backup



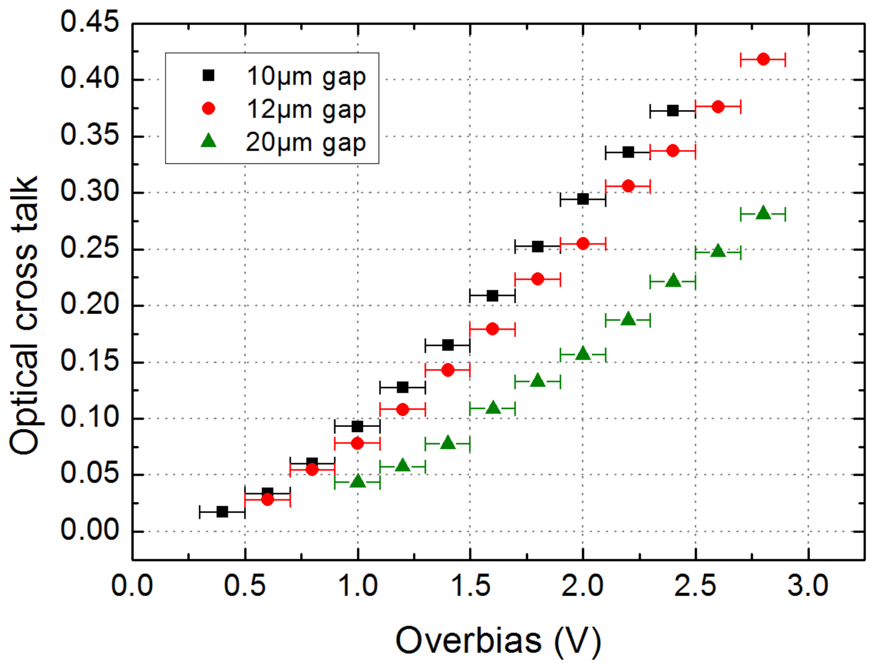
AD
C_D
R_Q
C_C
V_{bias}
photon
high field
p^+
n
n^-
depleted gap
region
n^-
non-depleted
region
n^-
non-depleted
region
n^+

Backup


Quenching
current (C) [A]
voltage (C) [V]
d=20um
d=22um
d=24um
d=26um
d=28um
d=30um
p30, g10
Bulk: 2.3E13


Recovery
current (R1) [A]
voltage (R1) [V]
Bulk: 2.3E13
p30, g10
d=20um
d=22um
d=24um
d=26um
d=28um
d=30um

Backup



- Increasing overbias
  ~ increasing gain
  ~ increasing trigger efficiency

- Non-linear dependency on overbias

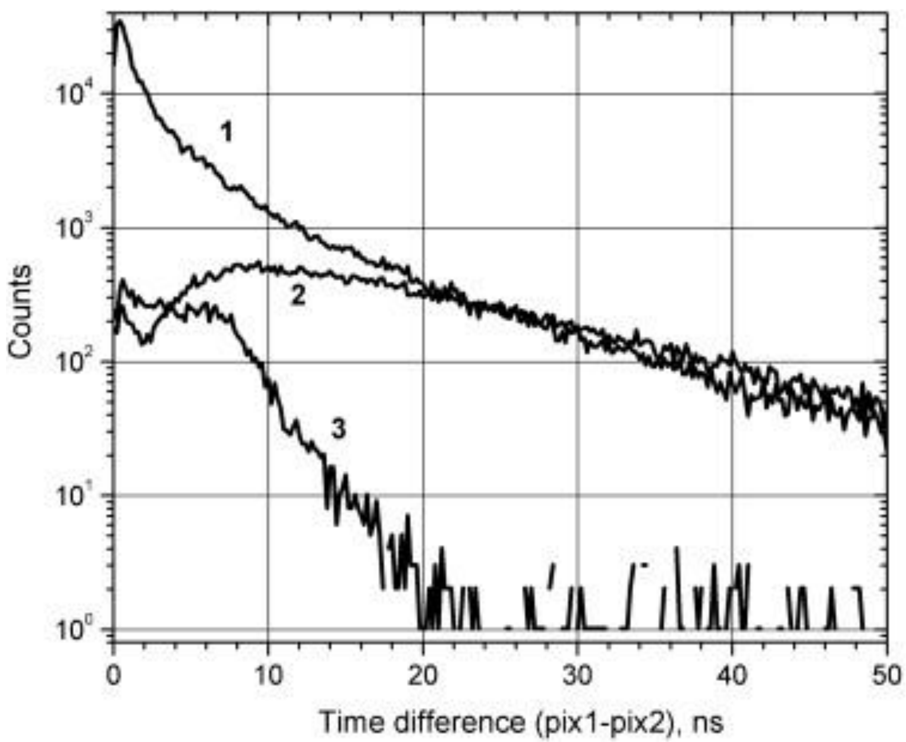
Backup

__Distribution of time difference between two neighboring cells:__

1: without optical crosstalk suppression

2: suppression by optical barrier

3: suppression by optical barrier and second *pn*-junction



Backup

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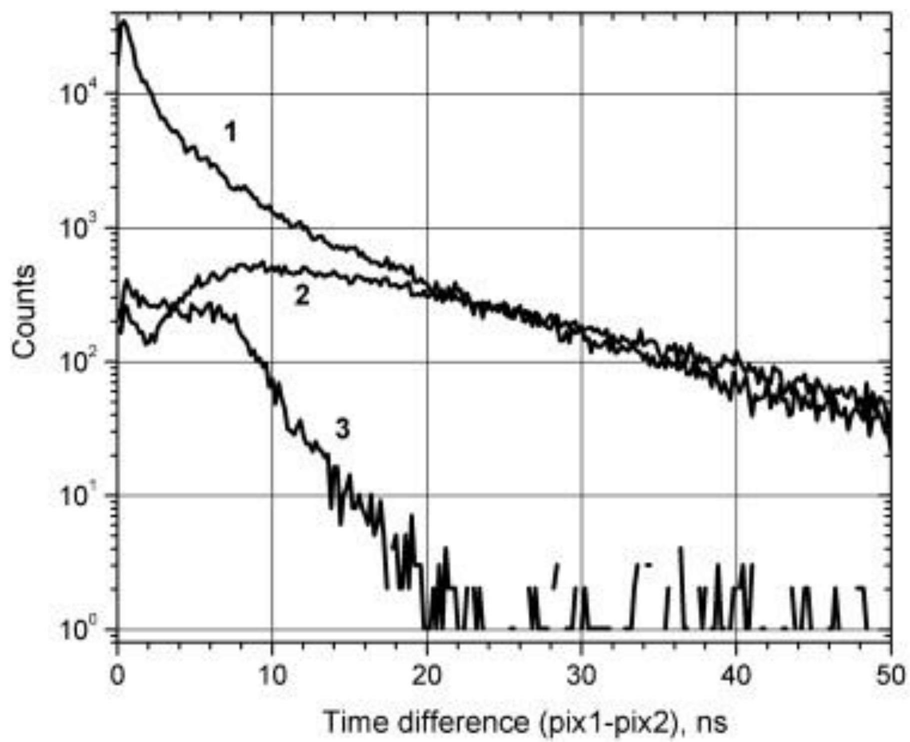
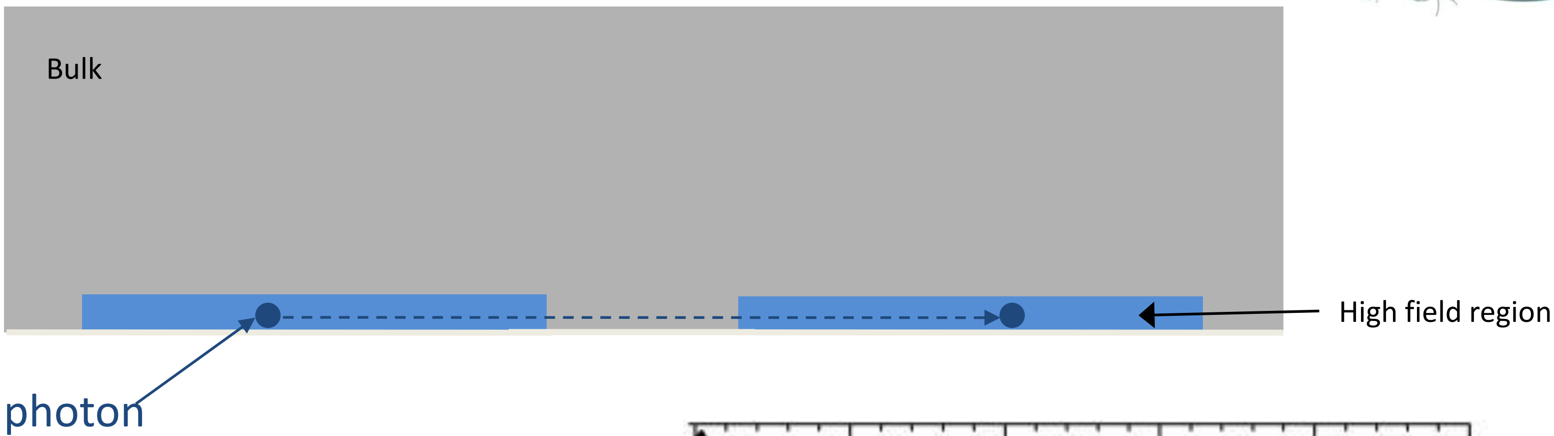
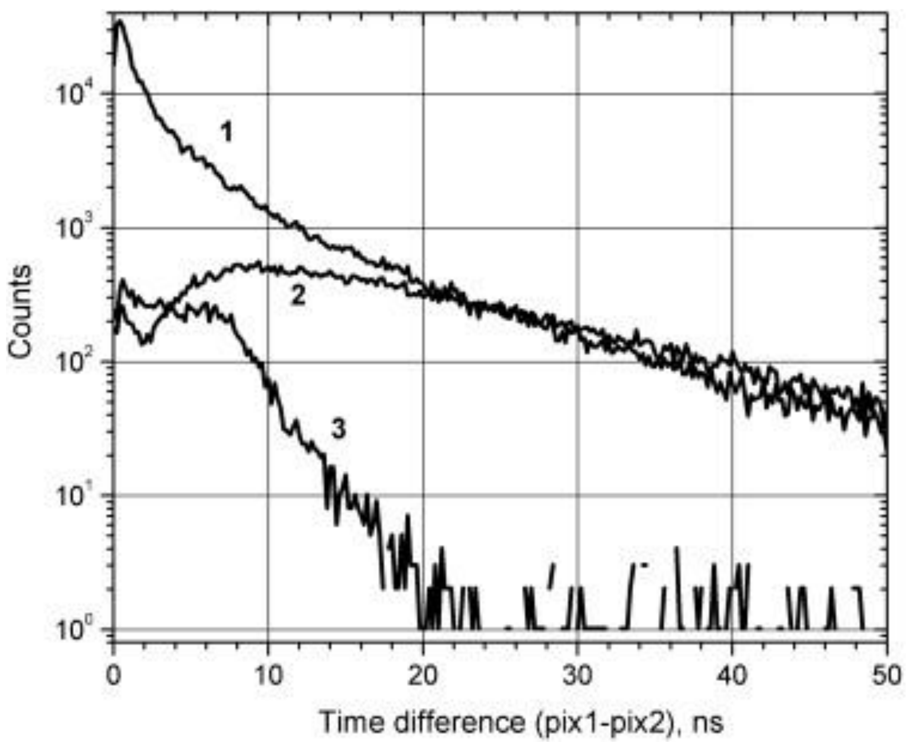


Backup





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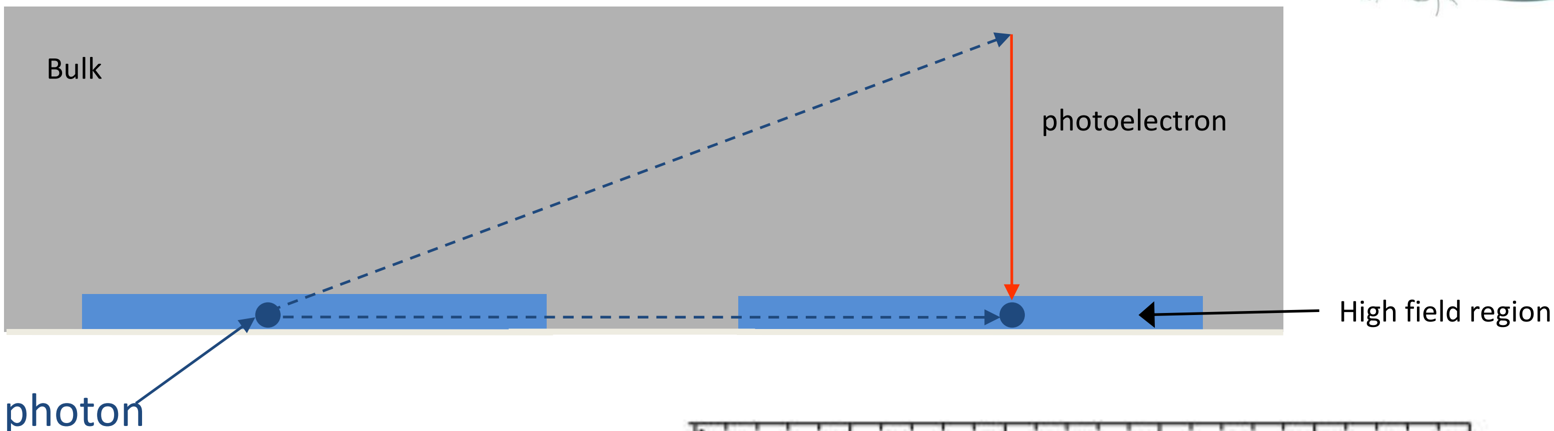

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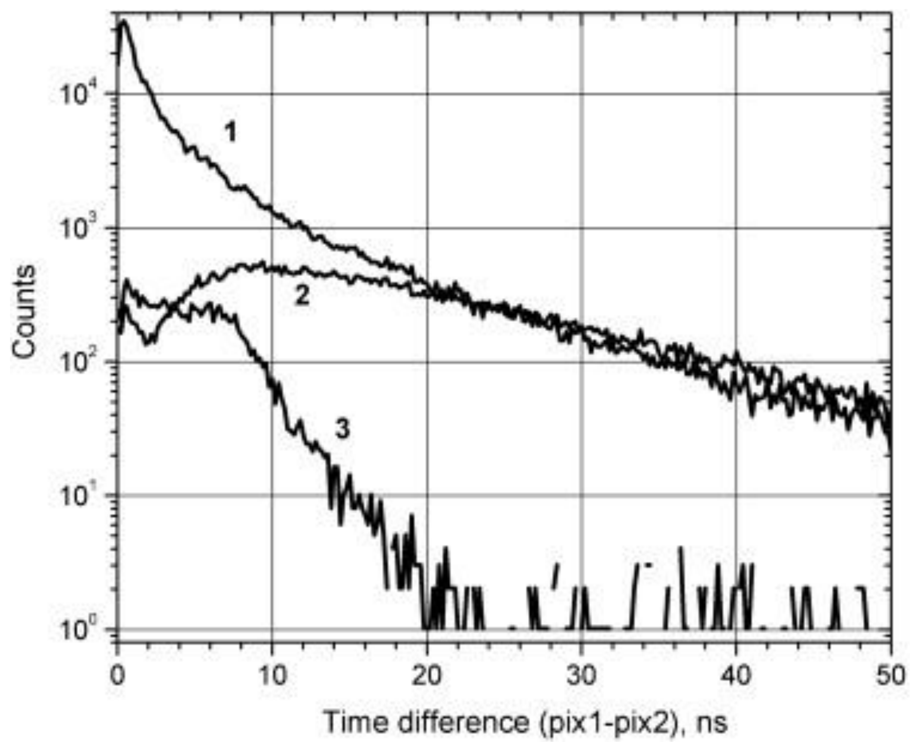
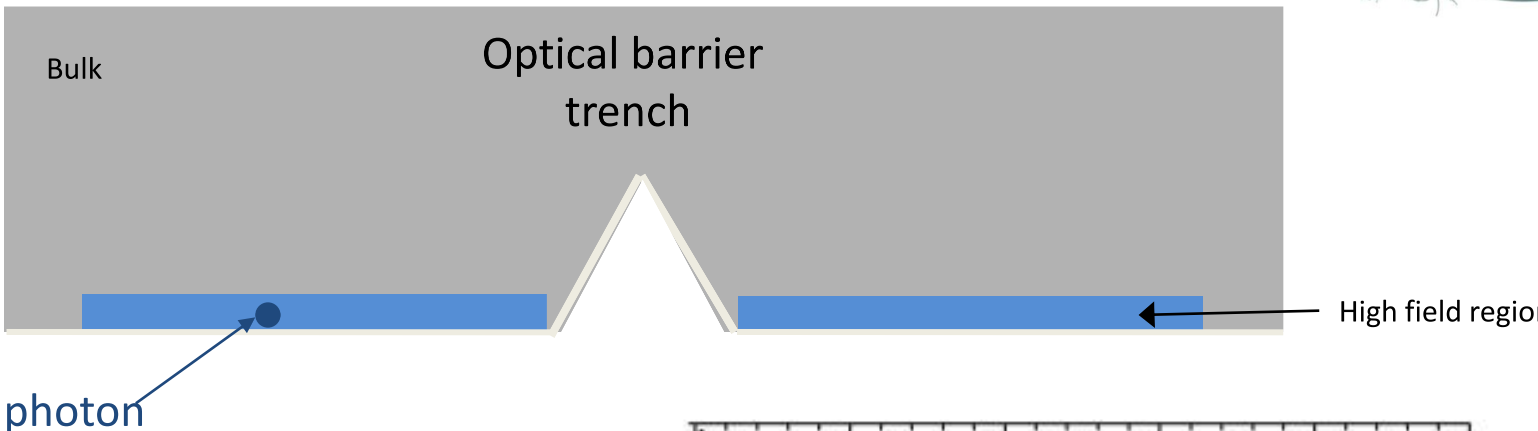


Backup



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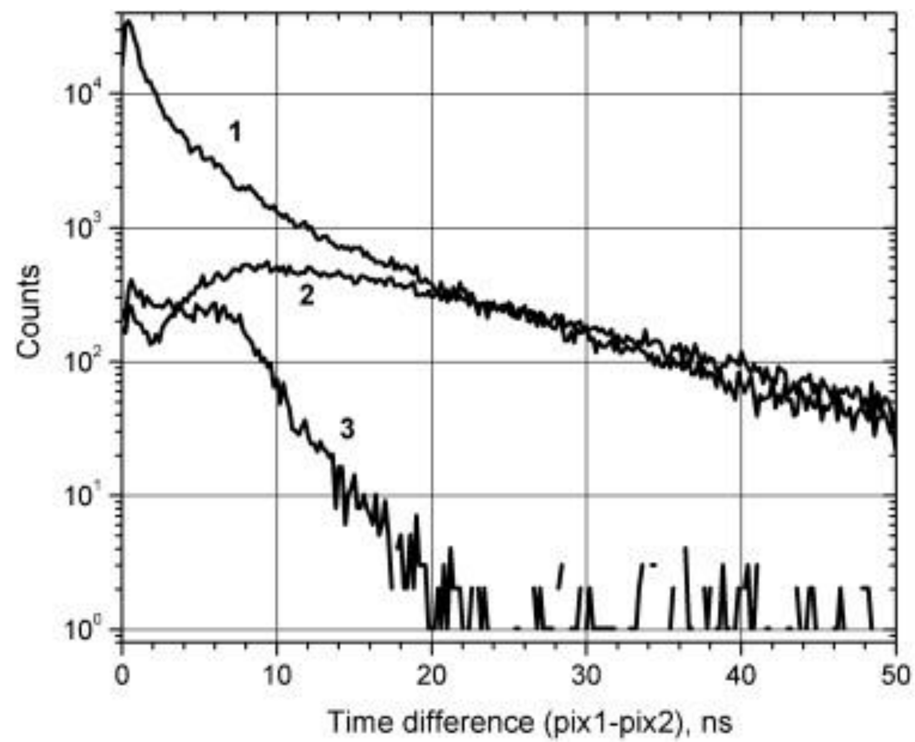
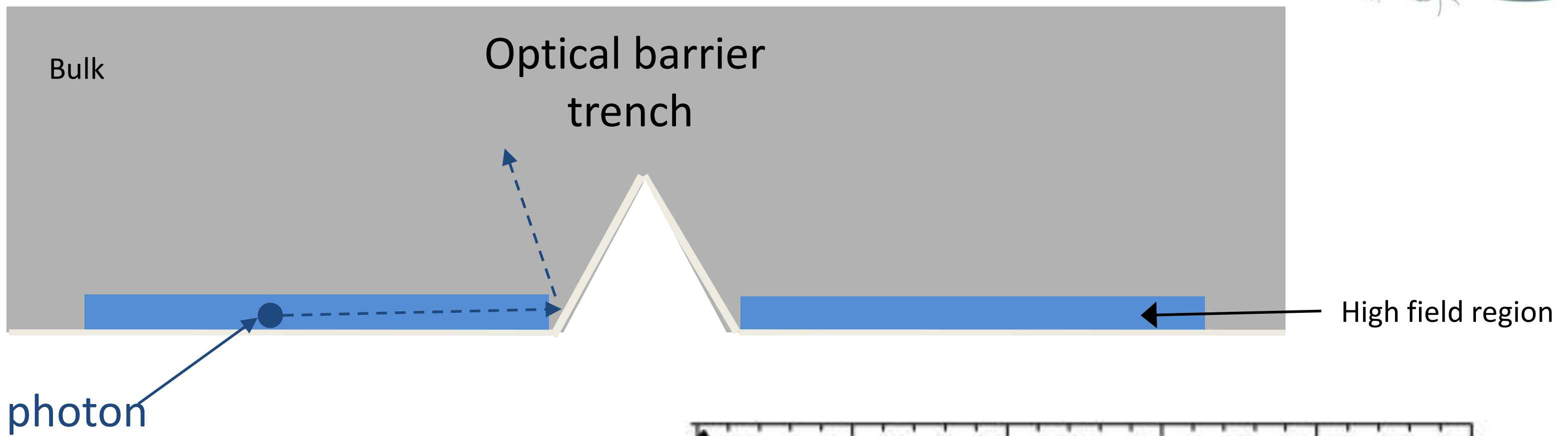


Backup



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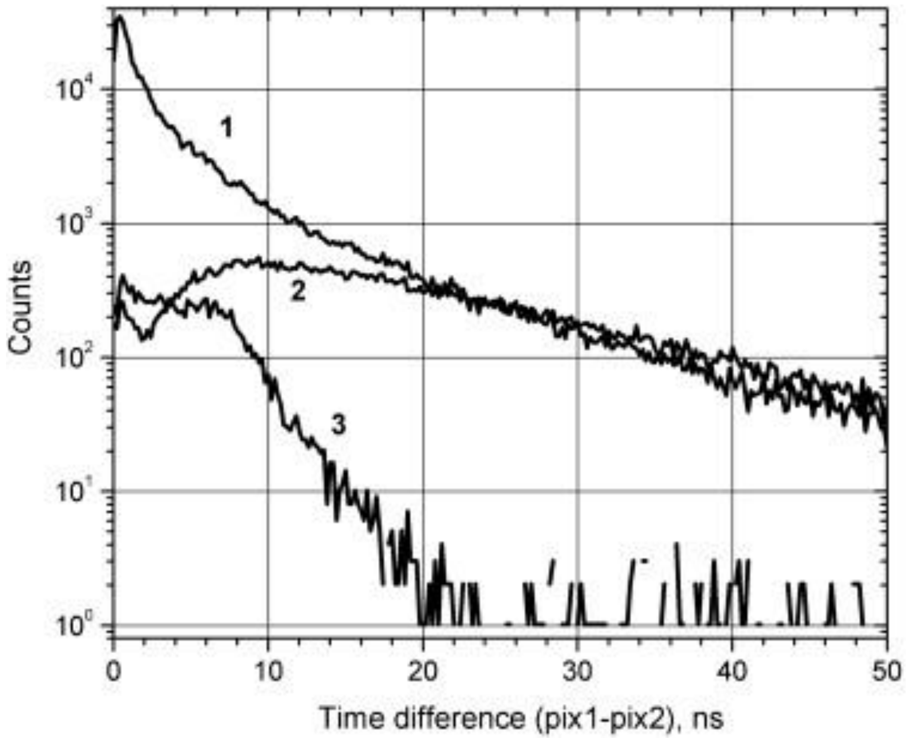
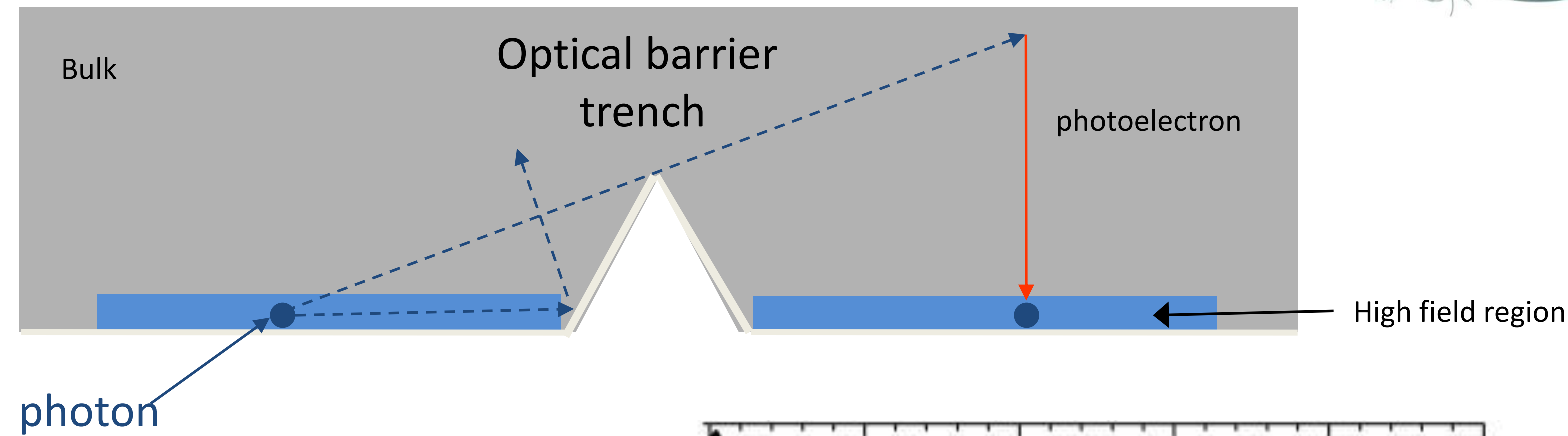


Backup



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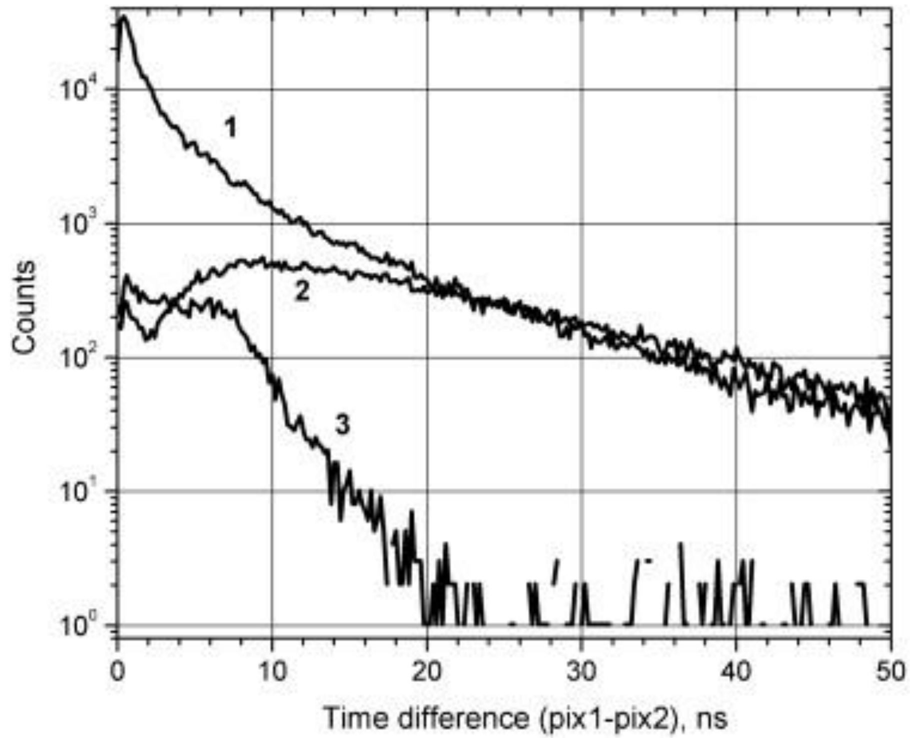
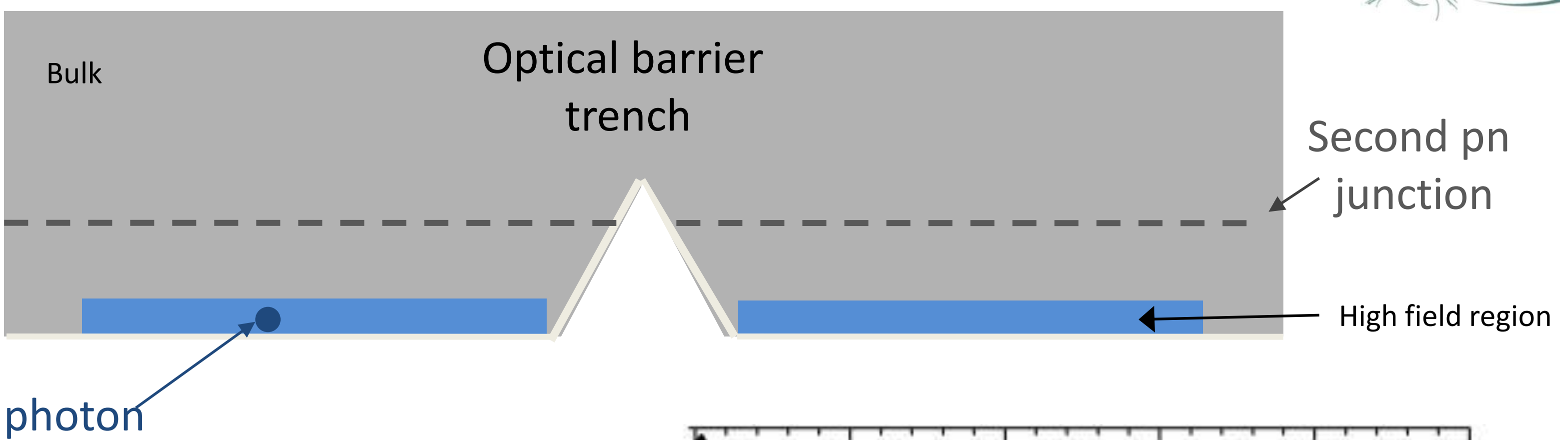


Backup



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