A novel Silicon Photomultiplier with bulk integrated quench resistor – R&D progress

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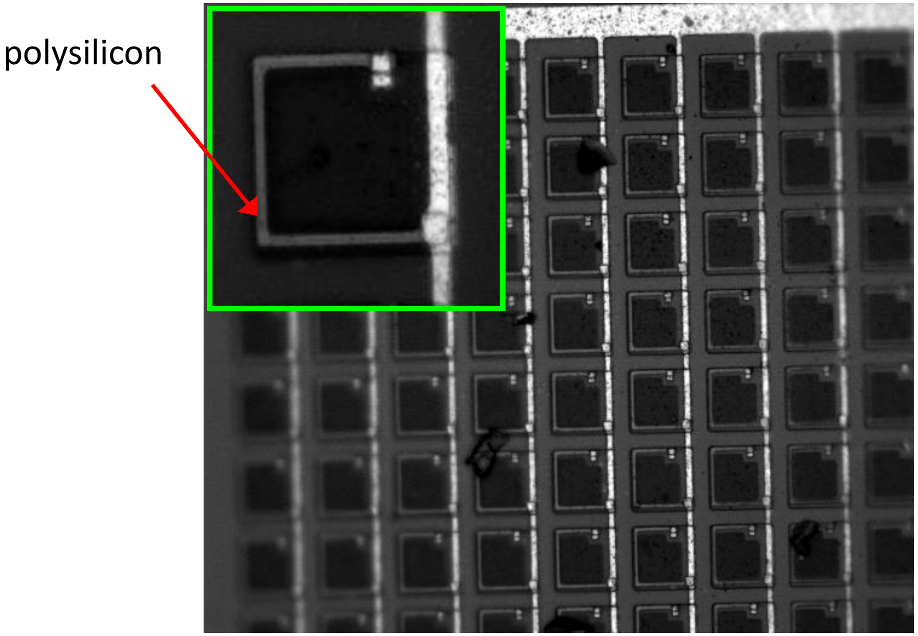
Conventional Silicon Photomultiplier (SiPM)

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>

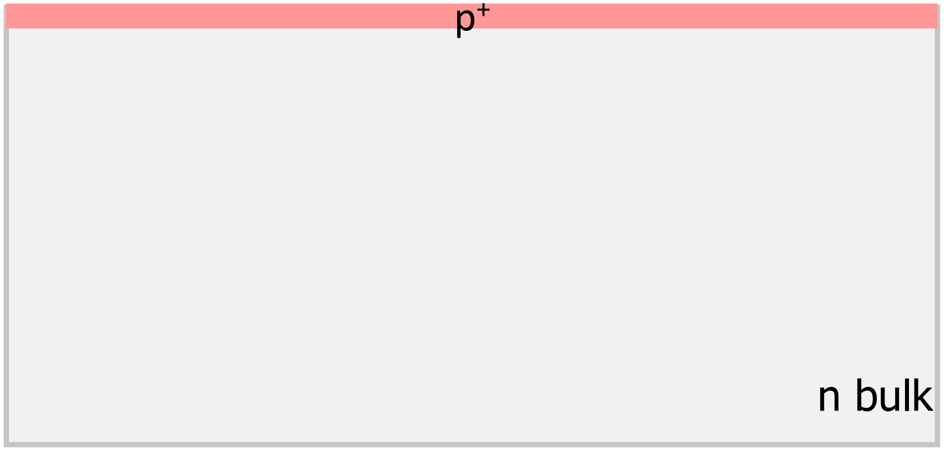
- Several additional process steps
- Increased stray capacitance
- Obstacles for light

→ limitation of the detection efficiency

SiMPl

SiMPl

SiMPl



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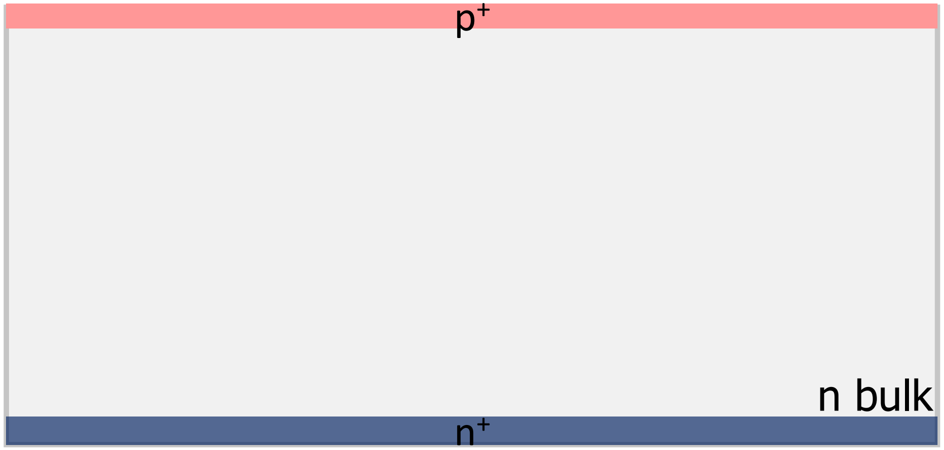

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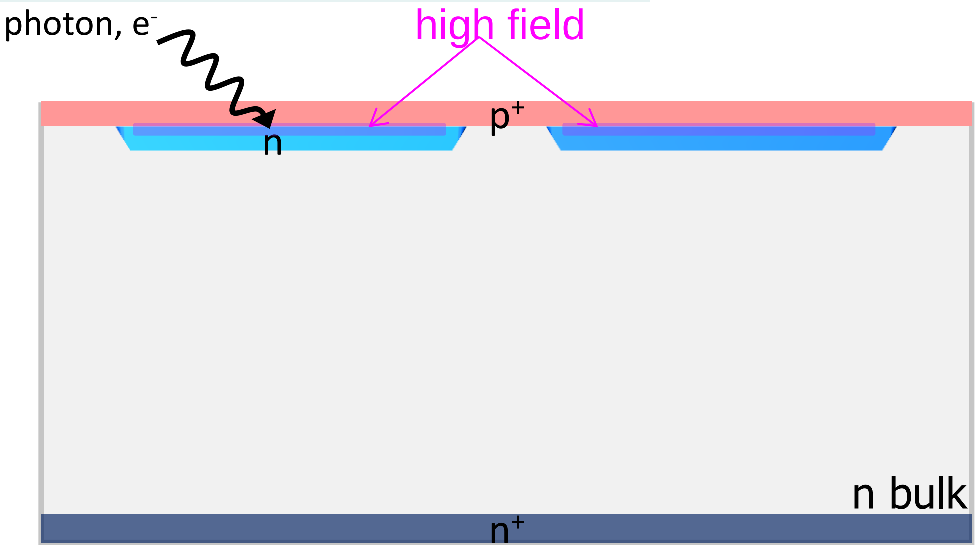

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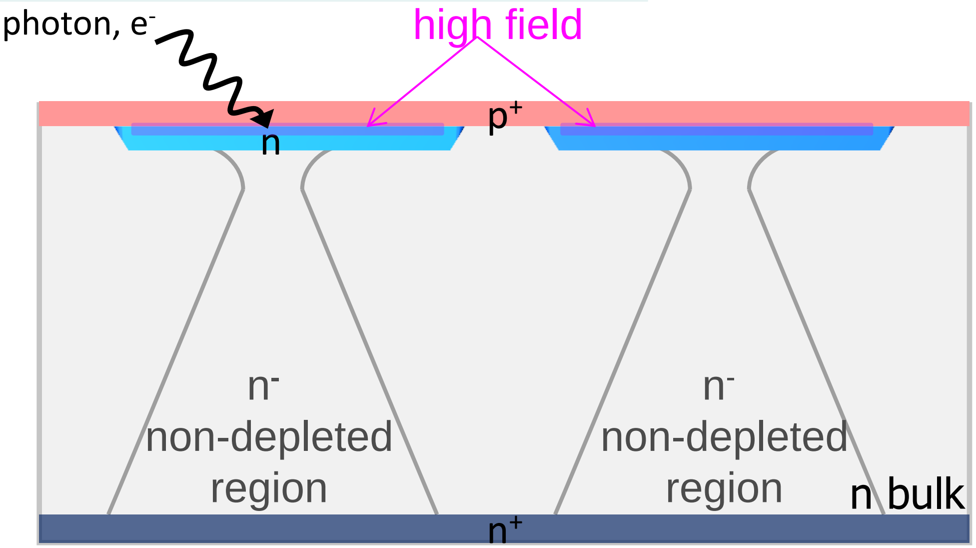
photon, e-
high field
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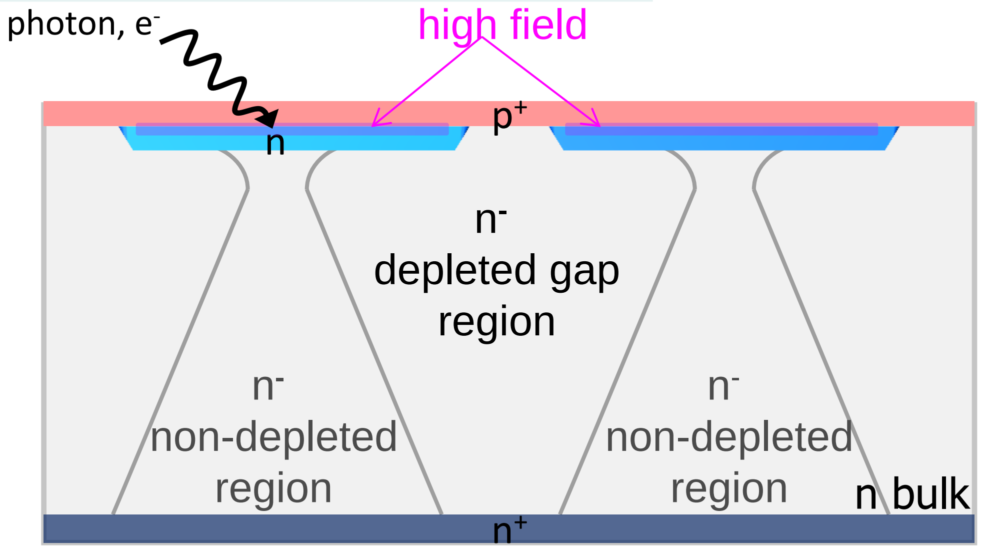
SiMPl



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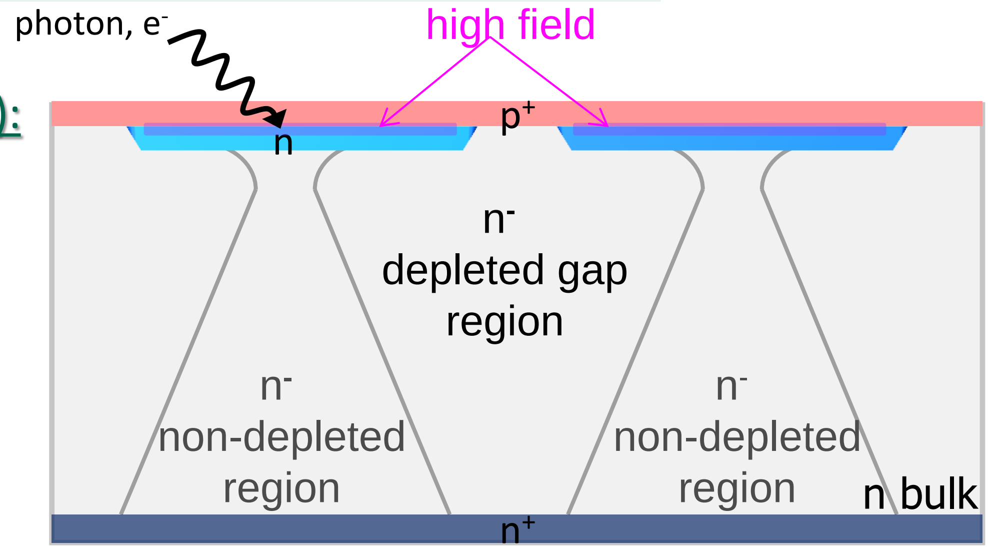
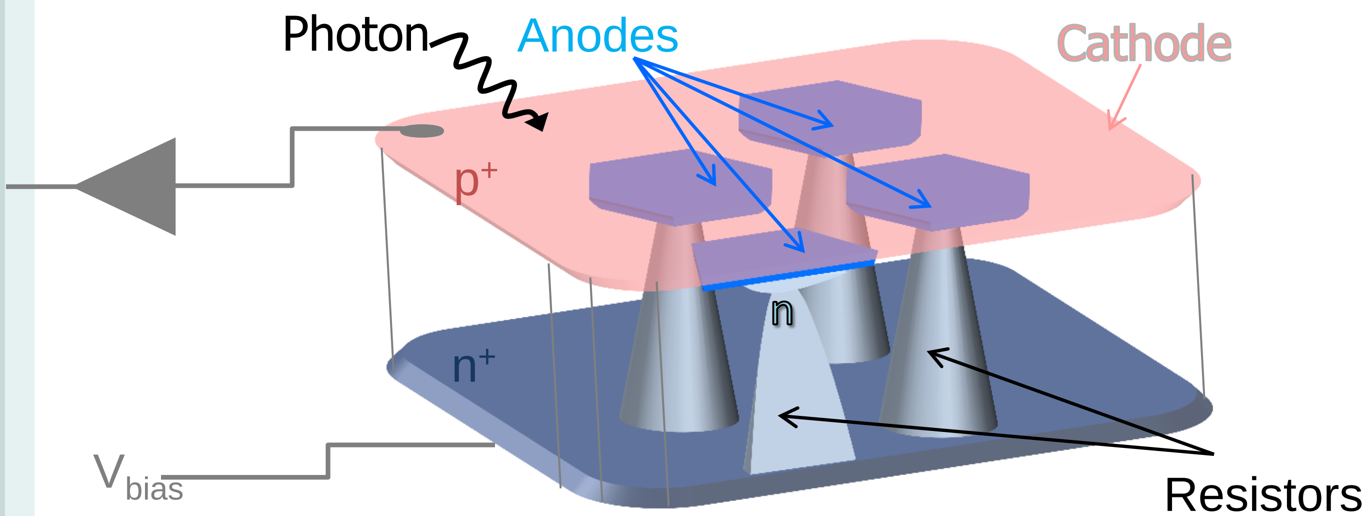
Silicon MultiPixel light detector (SiMPl):

- 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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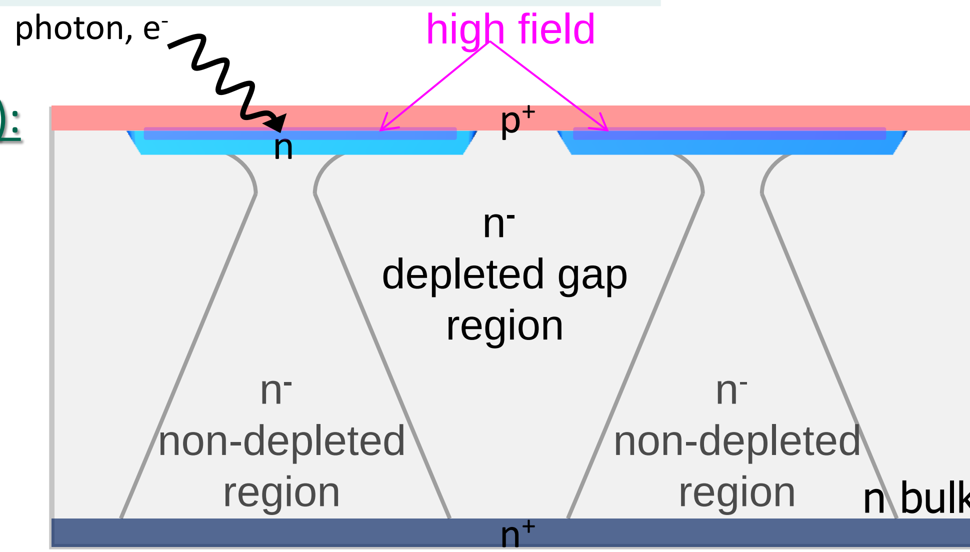

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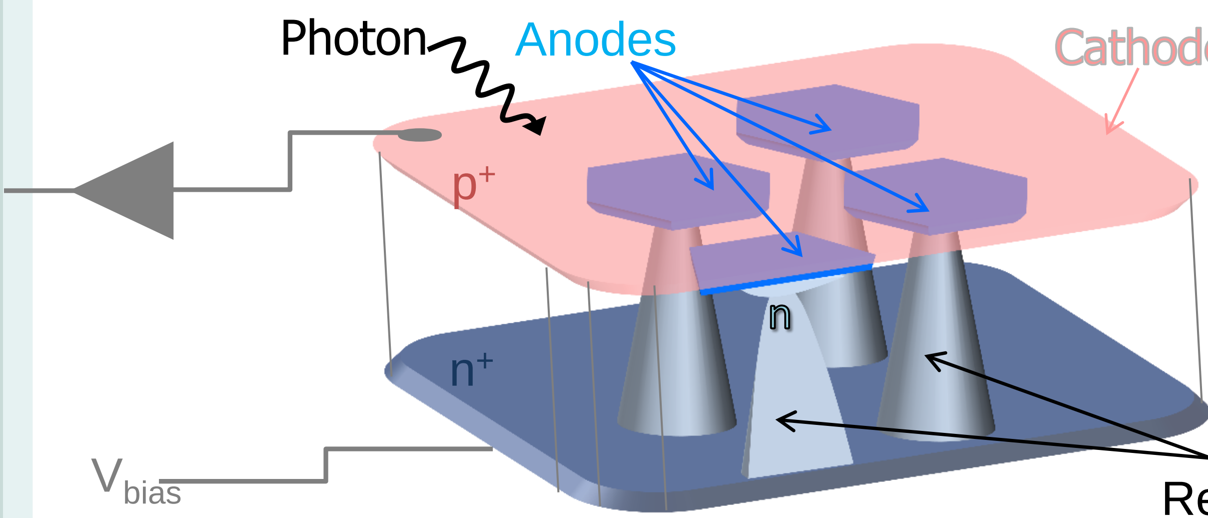

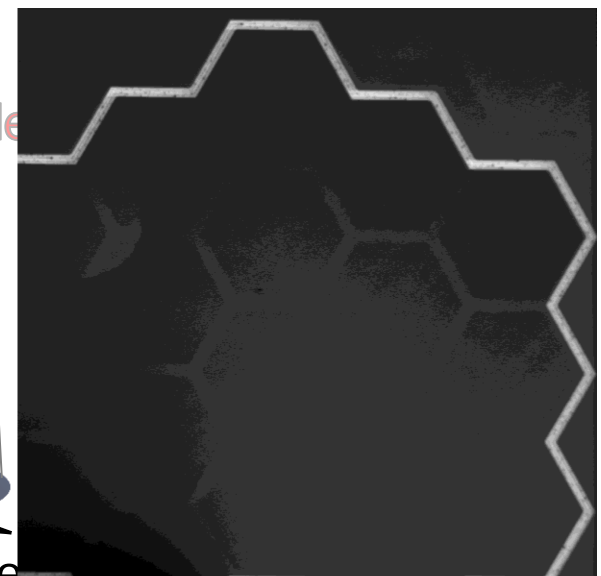

SiMPl – Advantages and Drawbacks

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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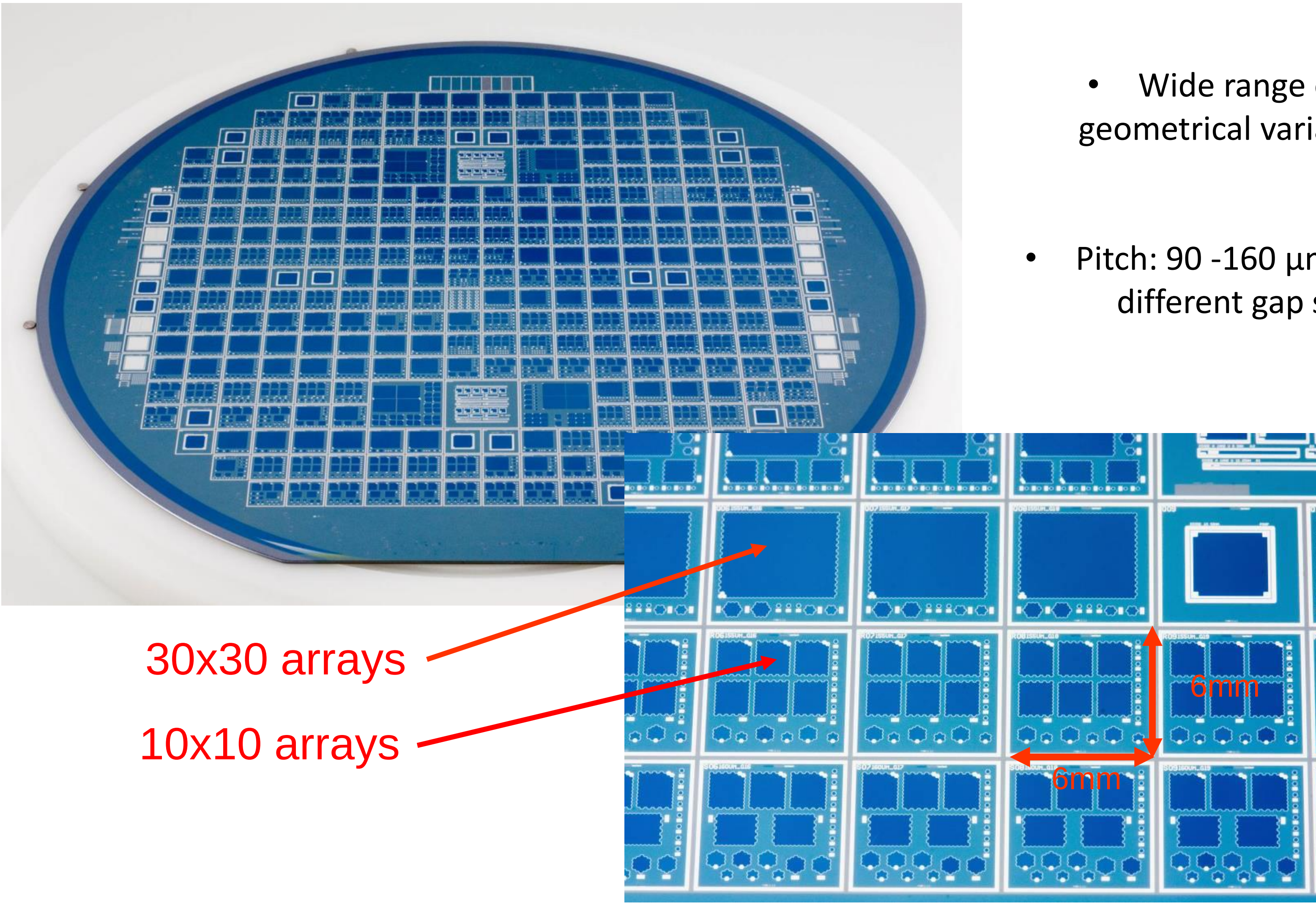
Drawbacks:

- 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 Prototype



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

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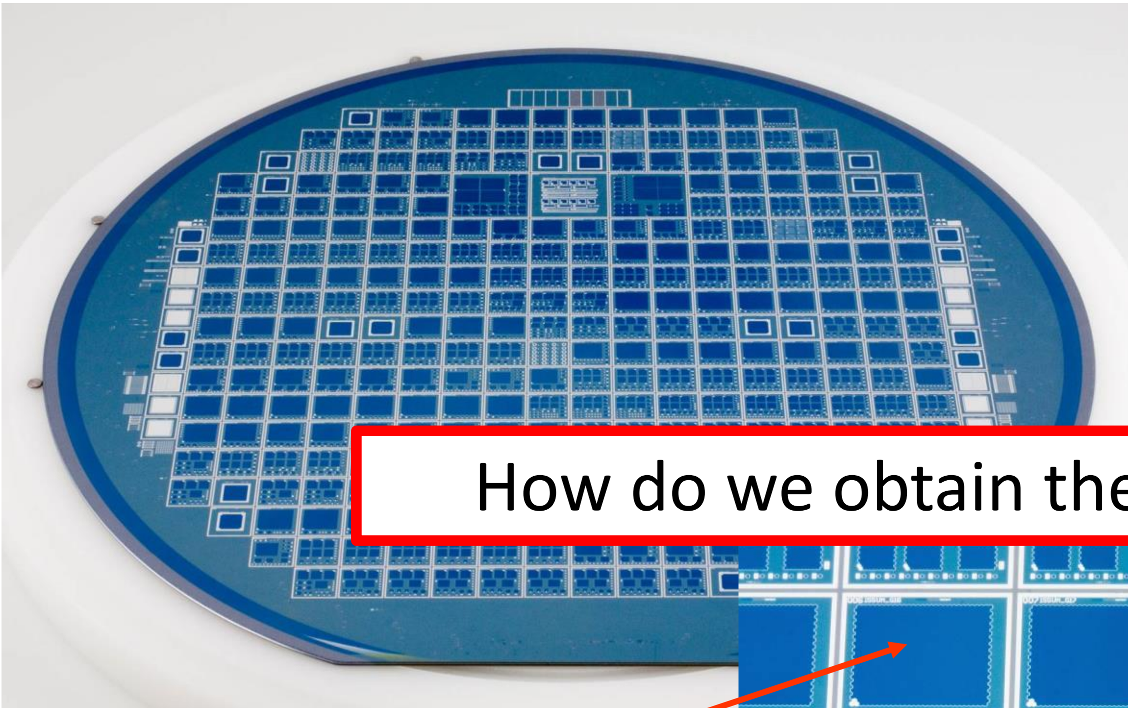

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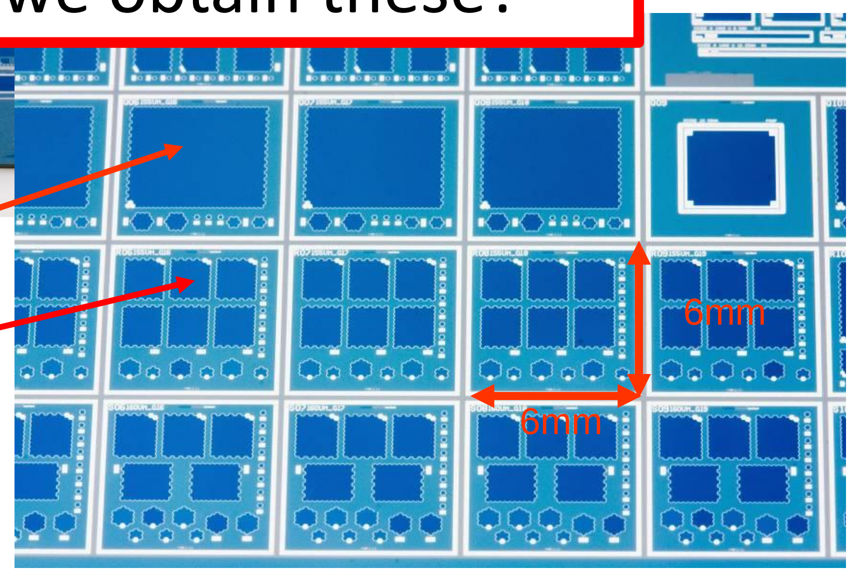
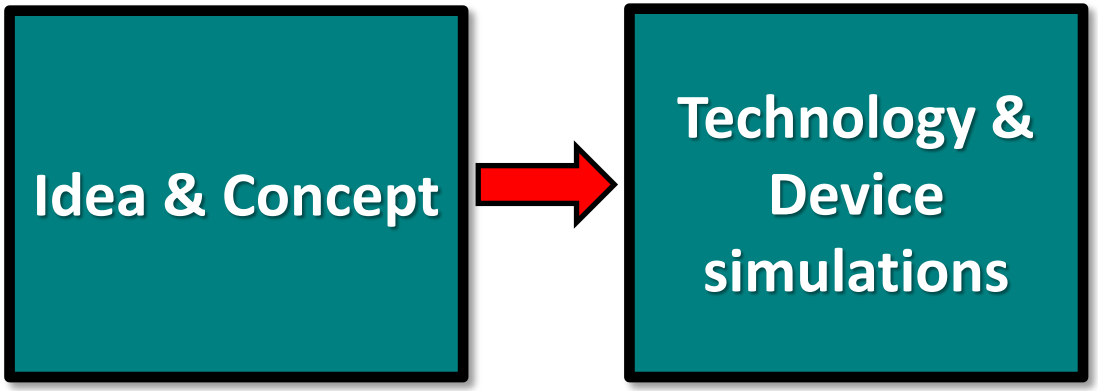
How do we obtain these?



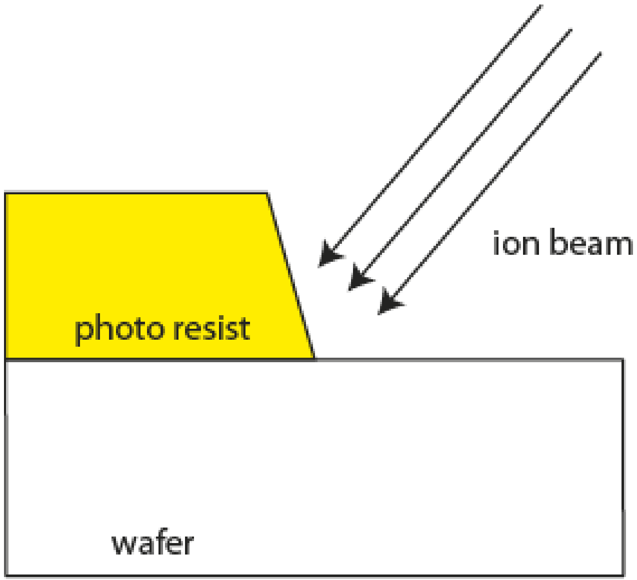
R&D of SiMPl

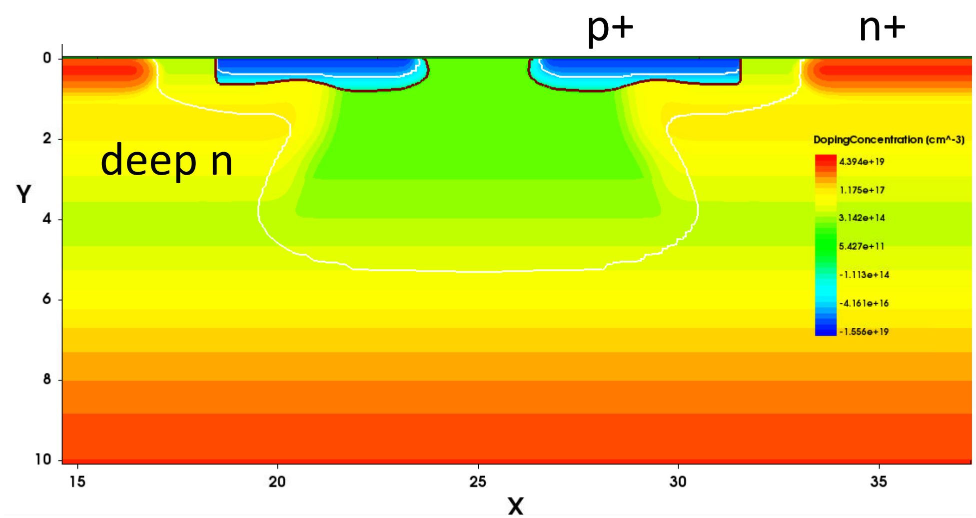
Idea & Concept

R&D of SiMPl



Technology & Device Simulations





Technology:

impact of parameters such as

- energy and dose of ion beam
- orientation of ion beam
- photo resist angle
- …

Device:

investigation of device behavior under operational conditions

→ electrical field distribution

→ electrical potential within

→ charge current densities

→ …

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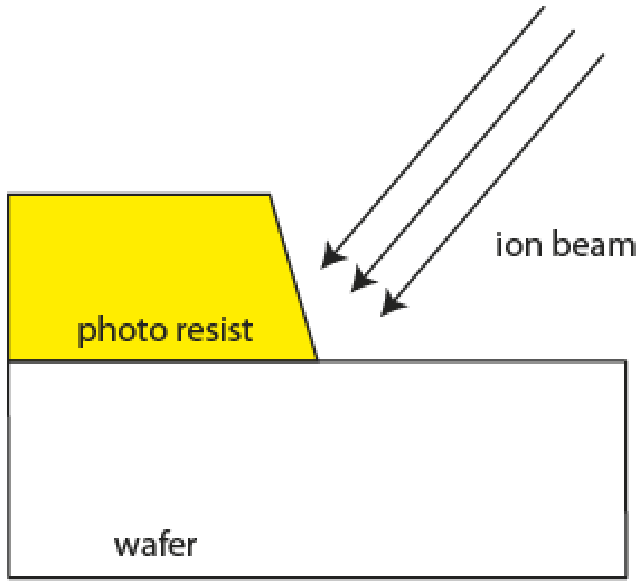

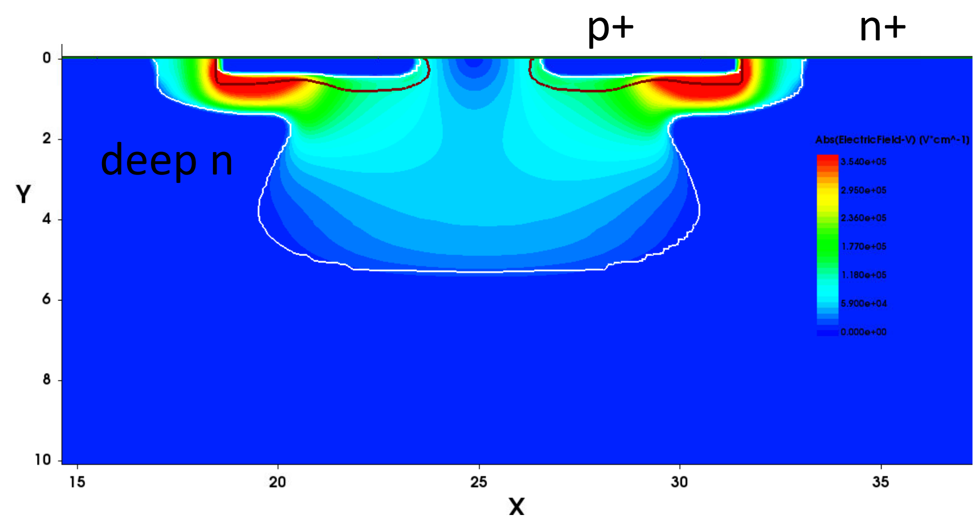

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R&D of SiMPl

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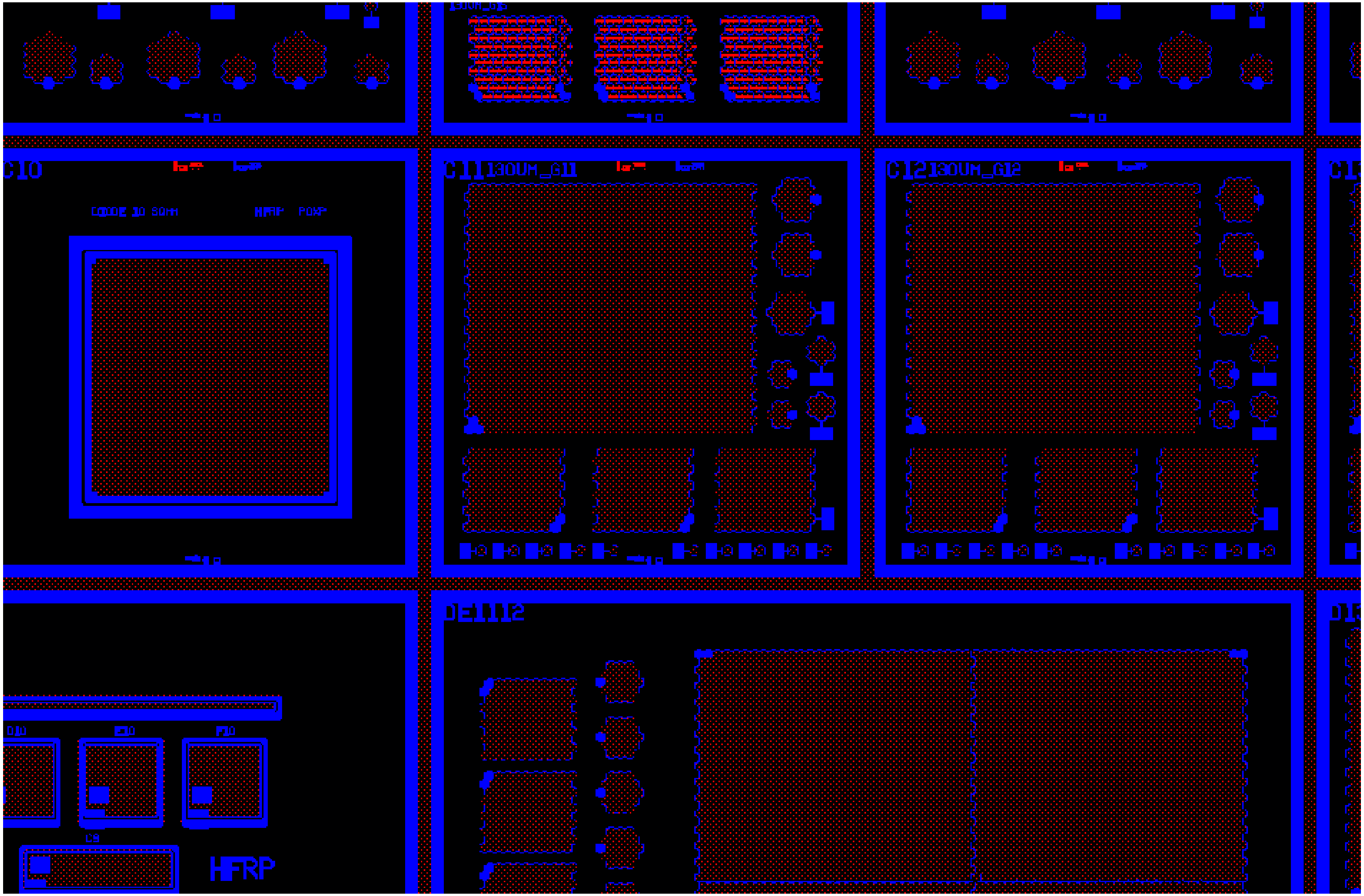

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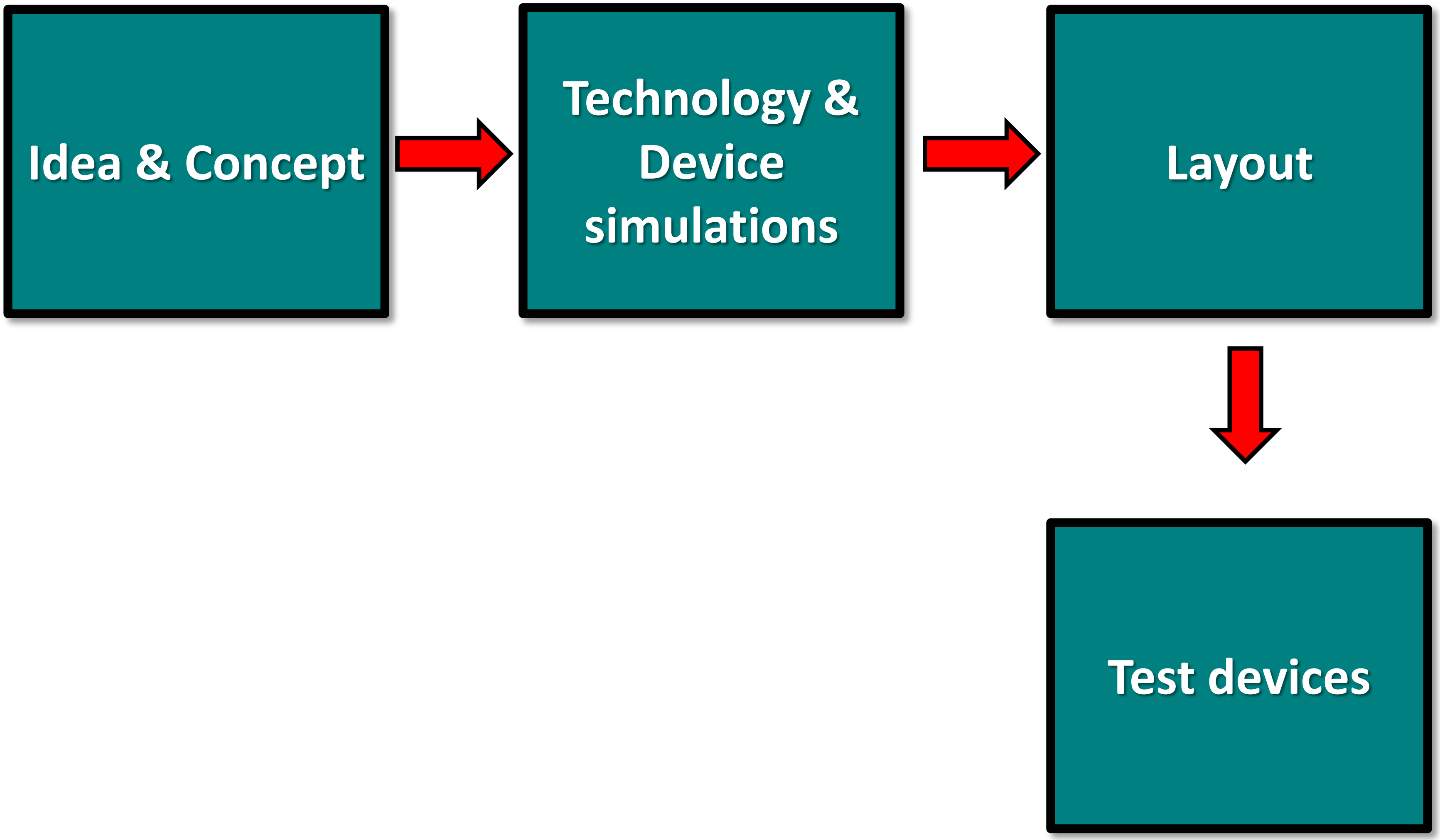
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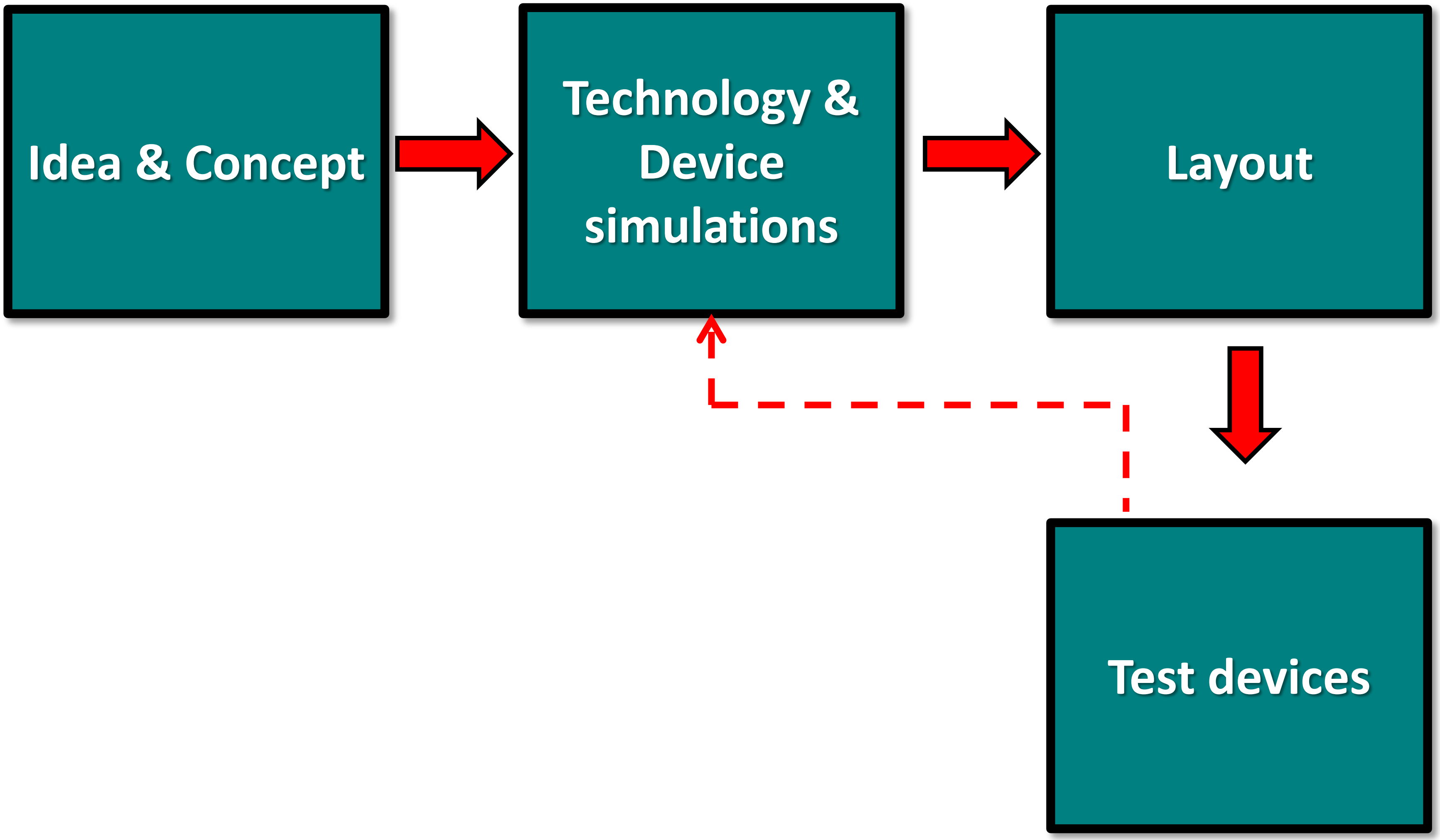

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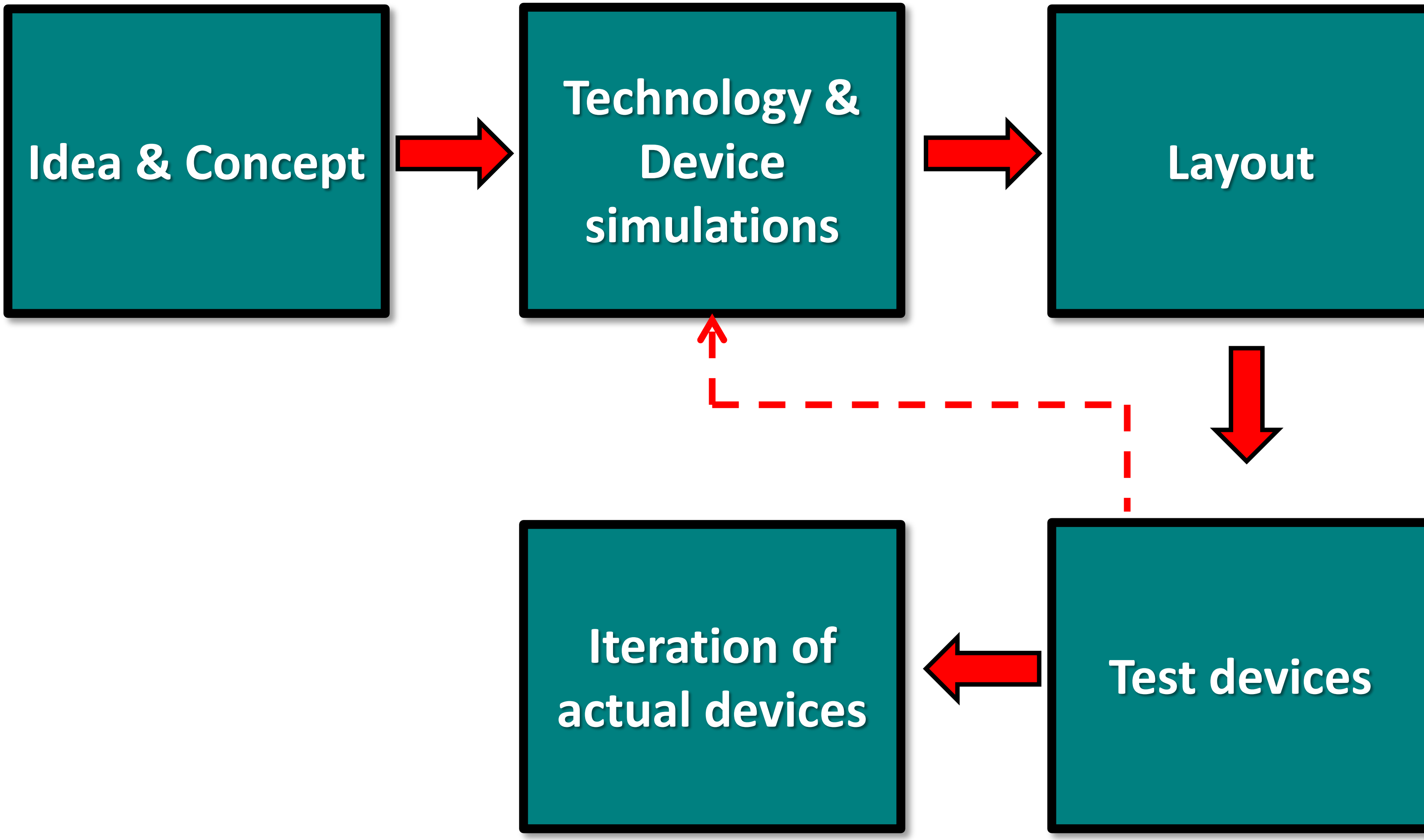
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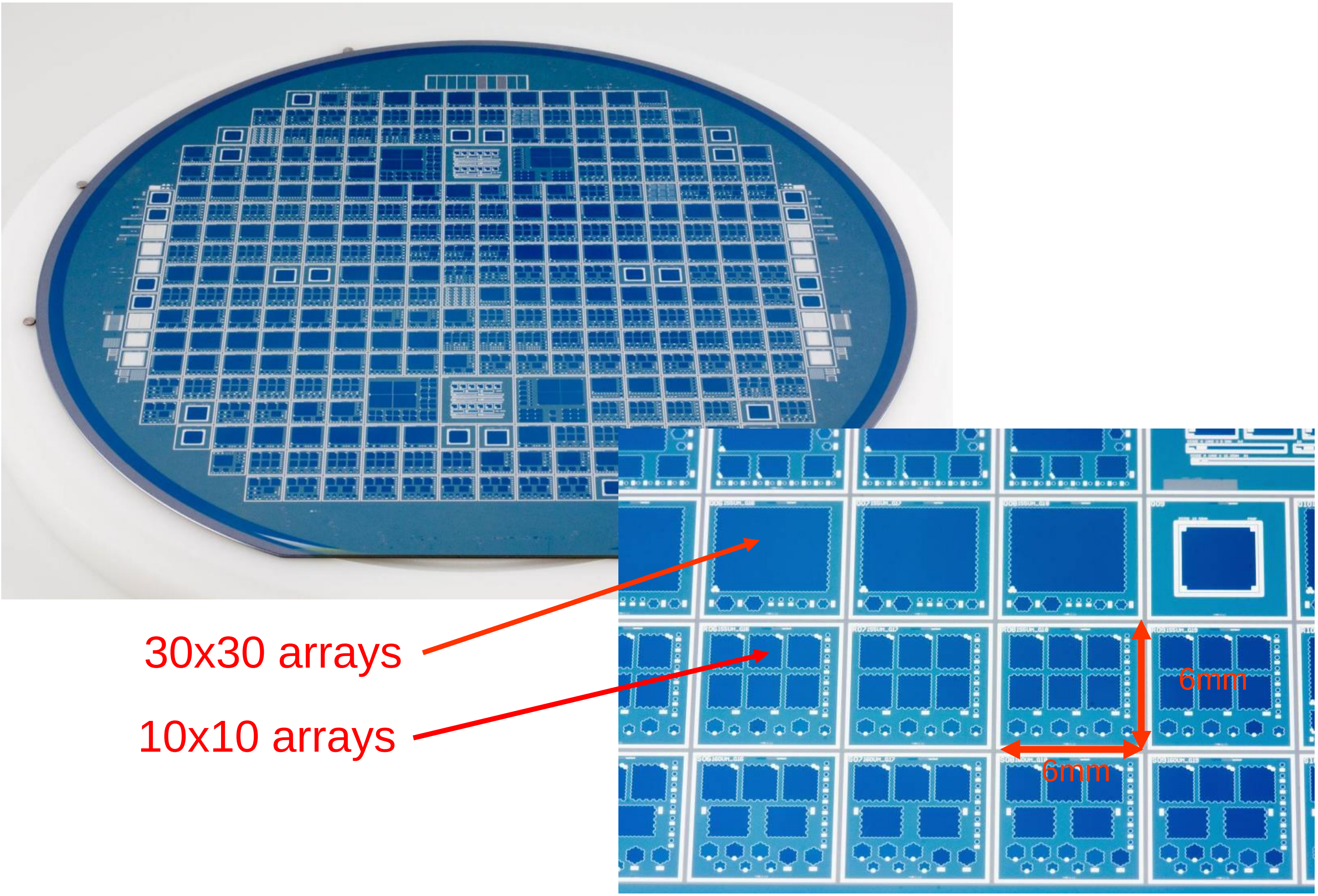

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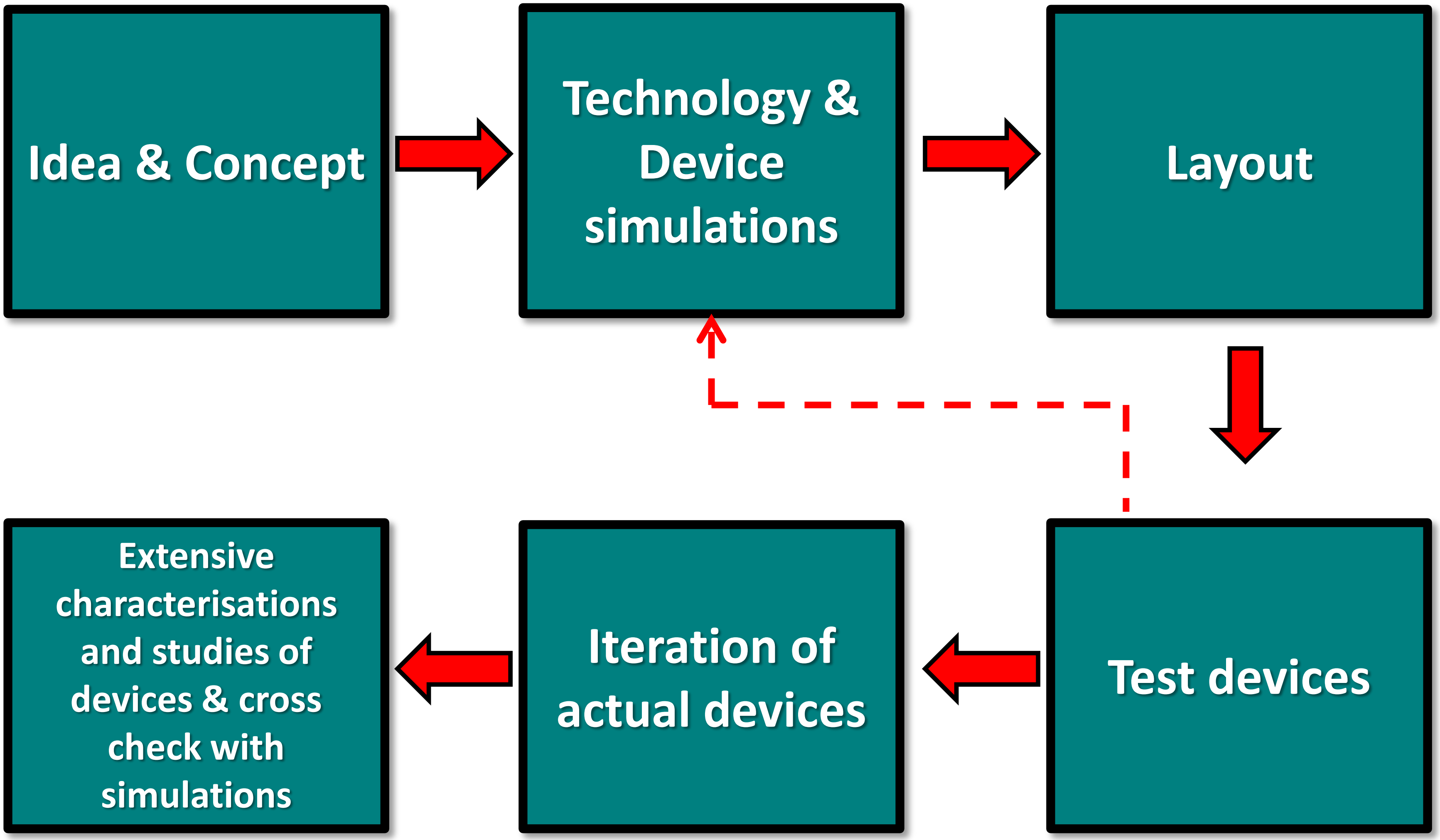
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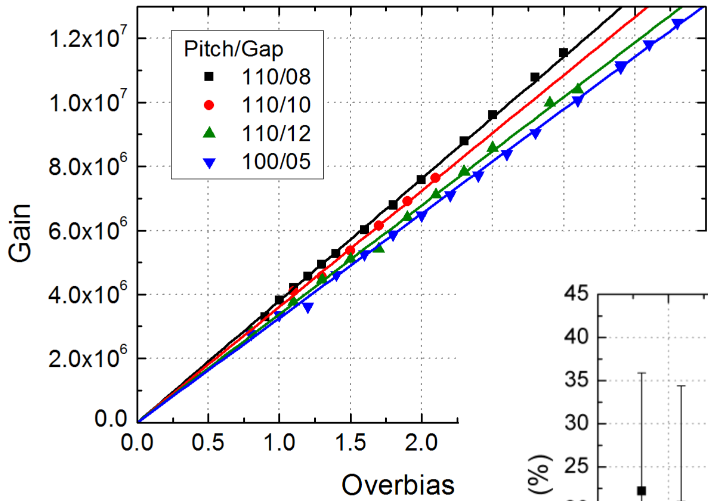
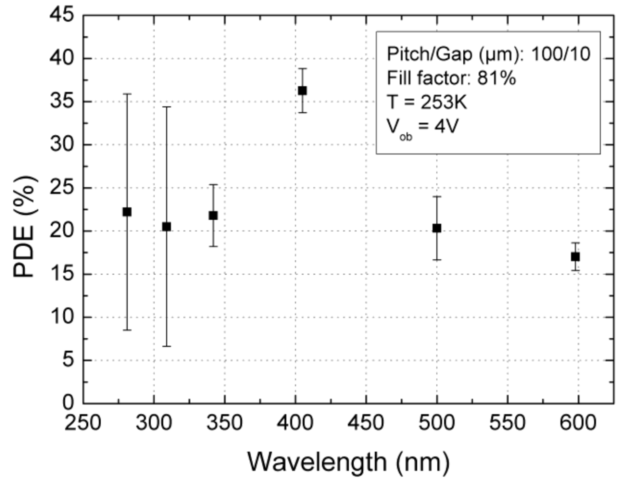
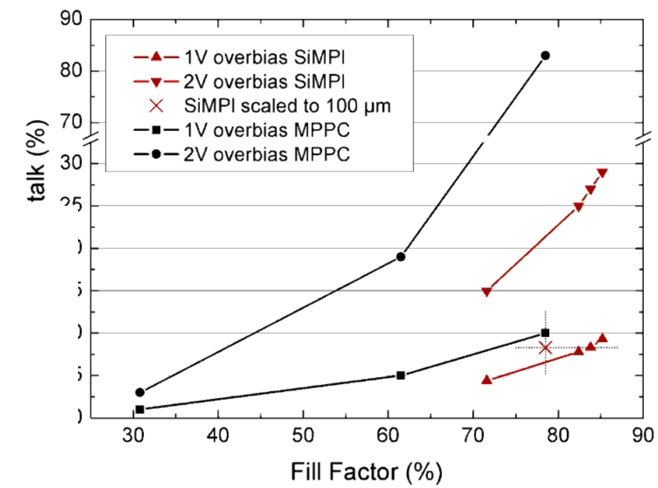
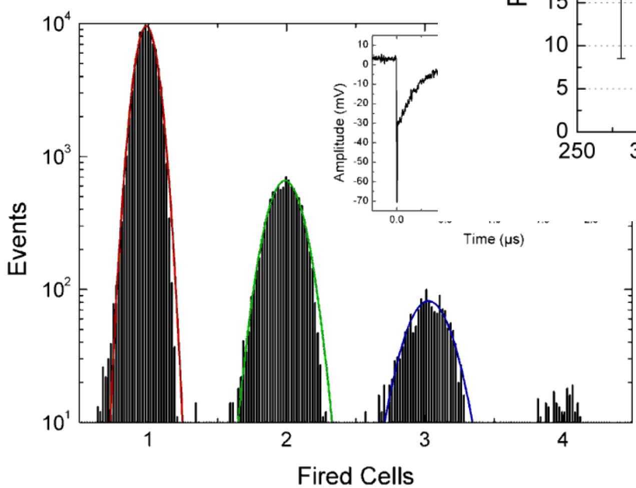
Characterisations & Studies of Devices

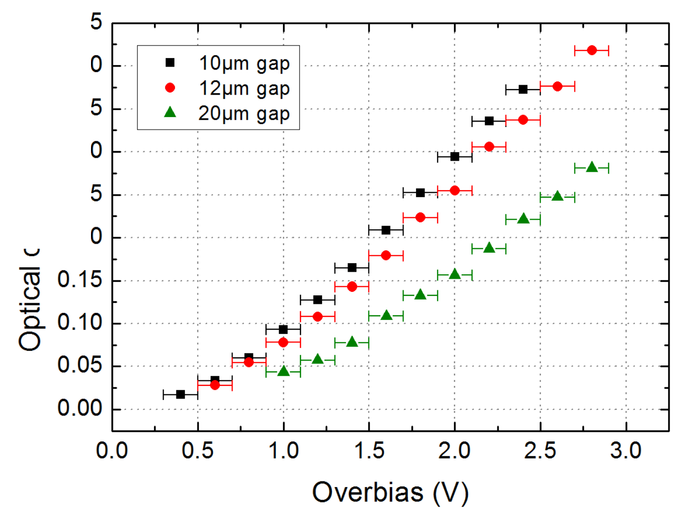
Measurement of dark counts, optical cross talk, after pulses, recovery time, gain, photon detection efficiency, …











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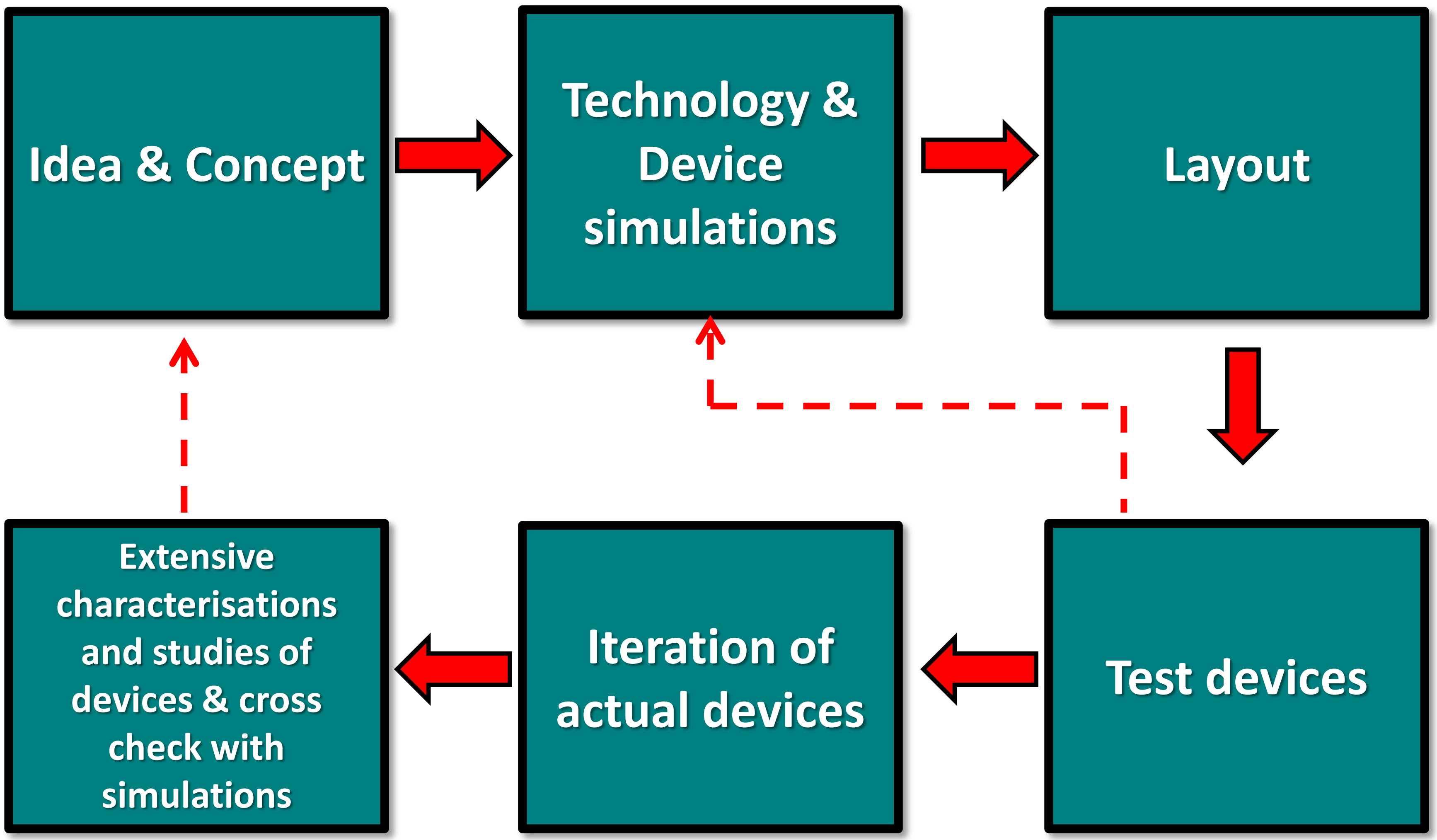
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Why use avalanche photodiodes for tracking ?

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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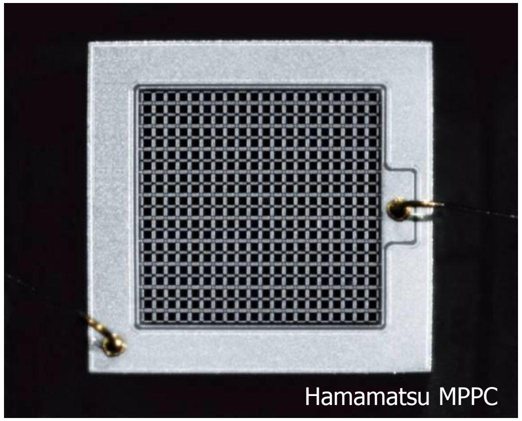
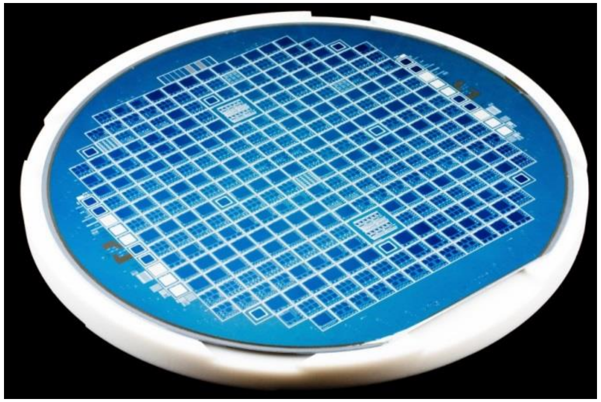
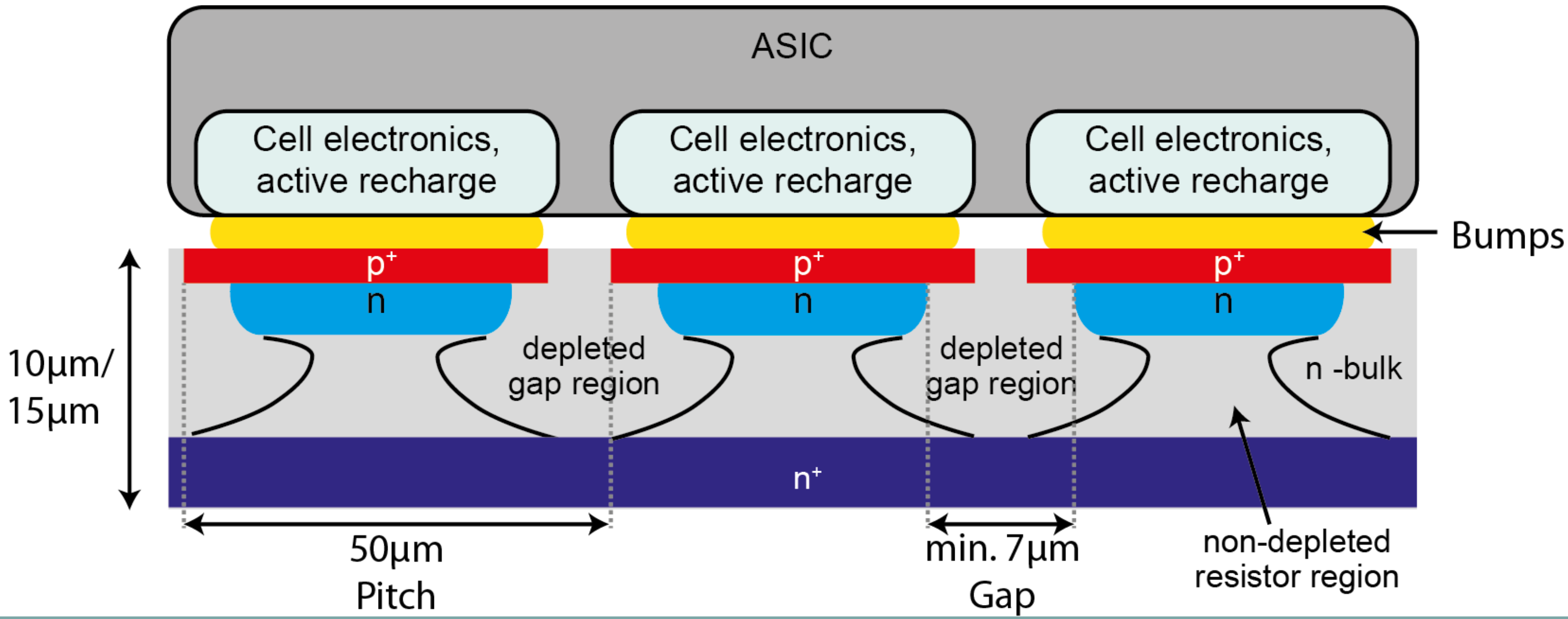


Accomplishable by Silicon Photomultipliers



Particle Tracking with SiMPl

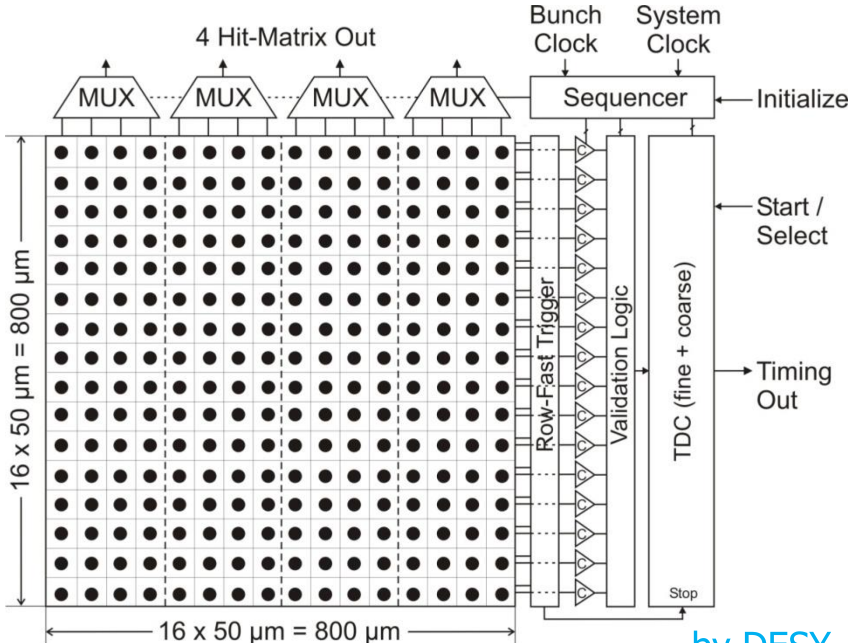
- Excellent time stamping due to fast avalanche (sub-ns)
- MIPs generate roughly 80 e-h-pairs/µm
- Inherently high trigger efficiency
  - → Allows operation at low overbias voltage
  - → Decrease of dark counts & optical cross talk
- Topologically flat surface → easy coupling to electronics
- High fill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



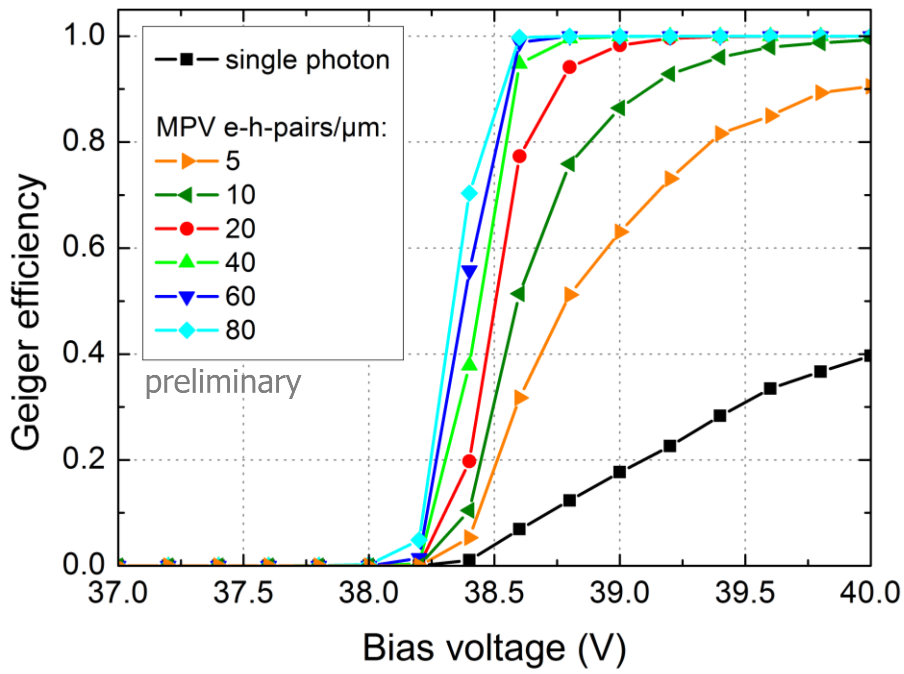
by DESY (Hamburg)

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

→ promising candidate for tracking

First Efficiency Simulations

→ Simulations: Small overbias voltages sufficient for high Geiger efficiency

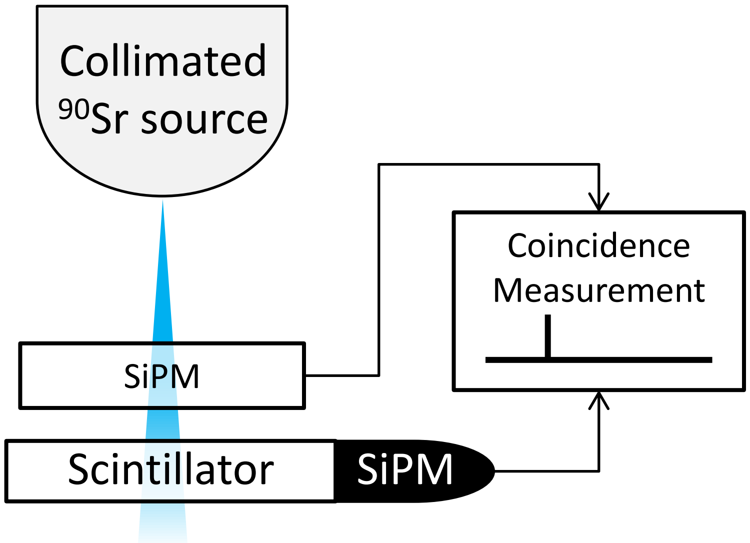


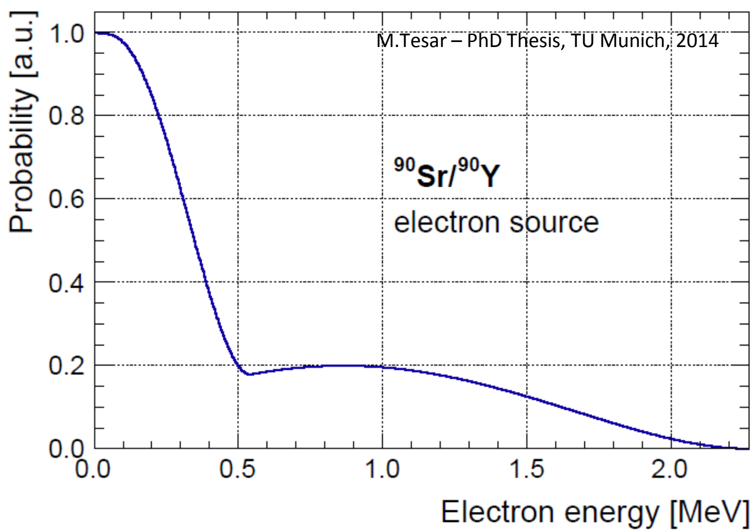
- Monte-Carlo simulations of ionisation probability (ionisation coefficients by Van Overstraeten) based on SiMPl device
  → Geiger efficiency for MIPs
- Overbias voltages ≈ 0.5 V should already provide Geiger efficiency ~ 1

→ 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

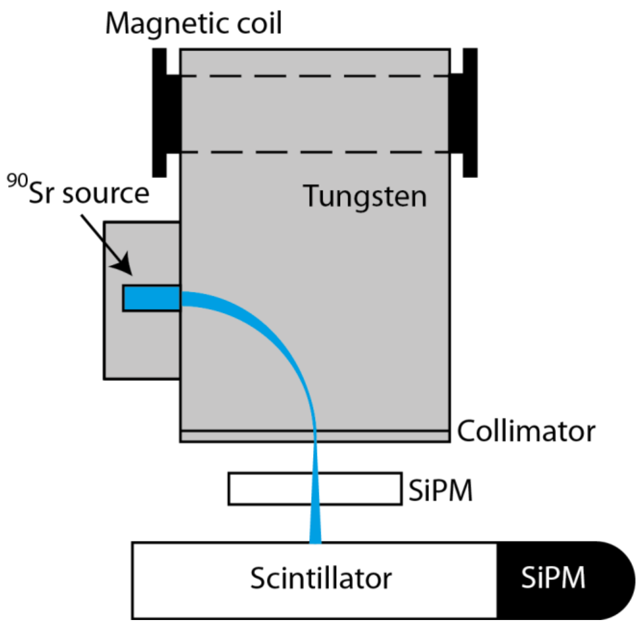
  → Broad energy spectrum and bremsstrahlung from shielding material
- Momentum selection by magnetic field
- Collimation down to spot sizes ~ 200 µm
- Determination of Geiger efficiency by measuring the signal coincidences between SiPM and scintillator
- But: extremely decreased rate of electrons with increasing collimation

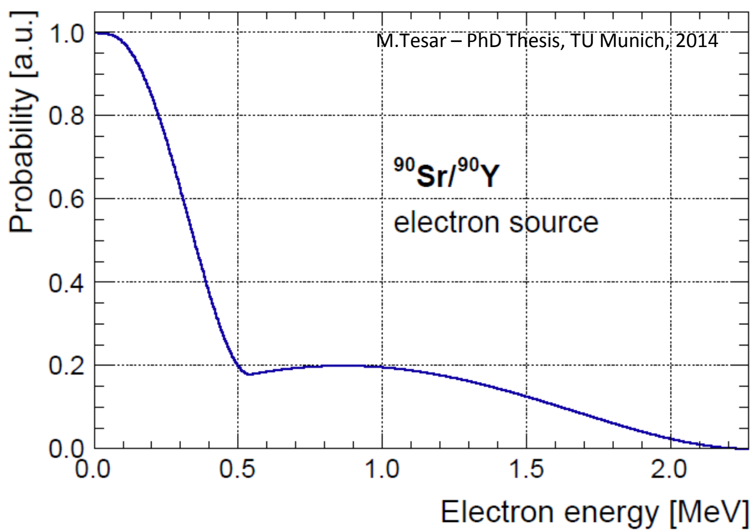
→ Obtaining high statistics very time consuming

→ Low energy electrons very susceptible to mounting material

- Also: Testbeam planned for efficiency measurements

First Efficiency Measurements





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Summary and Outlook

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  - No polysilicon resistors, no contacts necessary at the entrance window
  - Very simple processing
  - Topologically flat surface for easy coupling to electronics
- SiMPl prototype and characterisations
  - 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 with active quenching

Open questions & next steps

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- Implementation of optical trenches and devising active quenching readout electronics for light detection applications
- Particle detection efficiency measurements with improved setup
- Test beam with first prototypes
- Radiation hardness tests

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