Silicon Photomultipliers with bulk-integrated quench resistor fabricated at MPI semiconductor laboratory

IMPRS Young Scientist Workshop

Ringberg, 2012

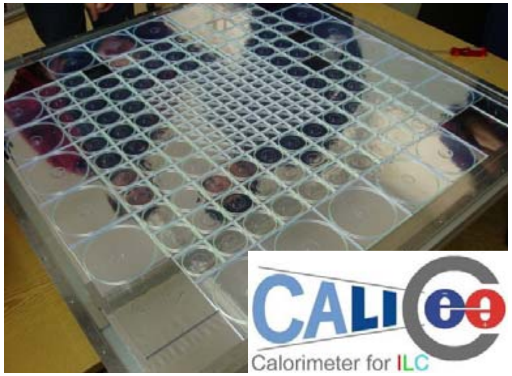
Christian Jendrysik

Outline

- motivation & introduction to silicon photomultipliers
- SiMPl concept: **S**ilicon **M**ulti**P**ixel **l**ight detector
- results of SiMPl characterization
- summary & outlook

Motivation for novel photon detectors

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

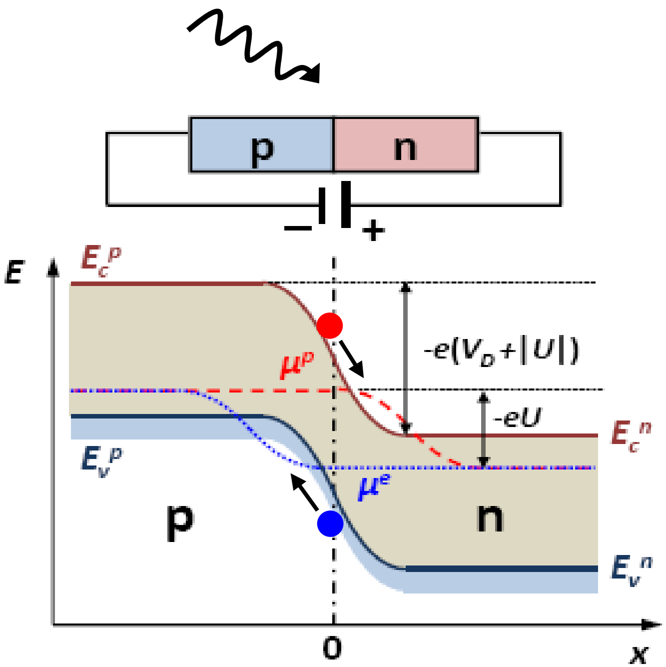


Large number of detectors → low costs & power consumption
Single tile readout → compact devices

Other requirements:
fast timing & insensitivity to magnetic fields

promising candidate: Silicon Photomultiplier

Semiconductor photodetectors



- *pn-junction in reverse bias*

incident photon creates e-h-pair

photocurrent ∝ incident photons

- *avalanche photodiode (APD)*

biased slightly below breakdown voltage

high electric field → single electron can trigger an avalanche

linear mode → amplifier

gain ~ 500

Semiconductor photodetectors

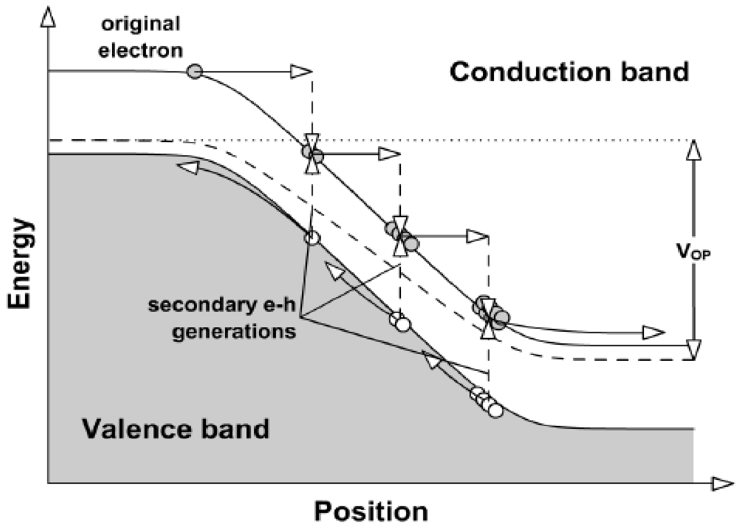
- Geiger-APD ($U_{bias} > U_{breakdown}$)

also holes contribute to avalanche generation → single photon detection

gain ~ $10^5 – 10^6$

quenching resistor stops discharge

BUT: binary device → no information about number of incident photons



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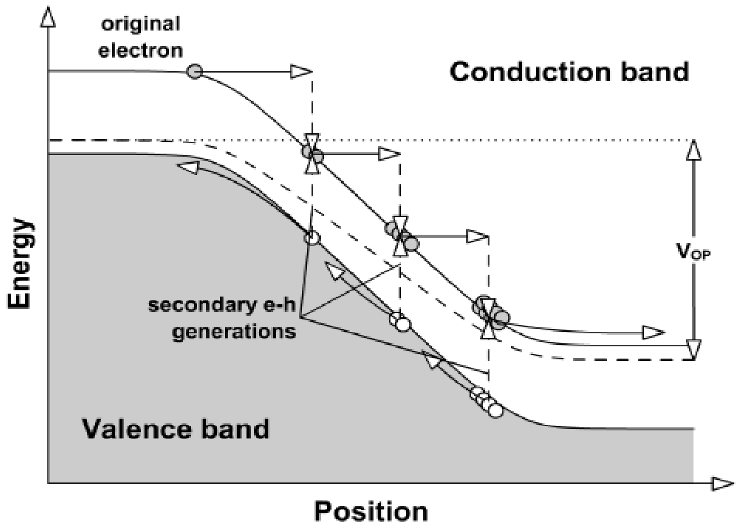
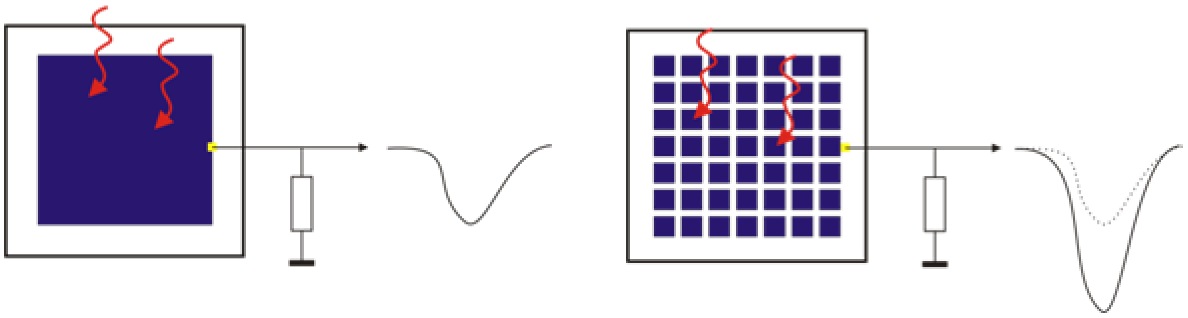


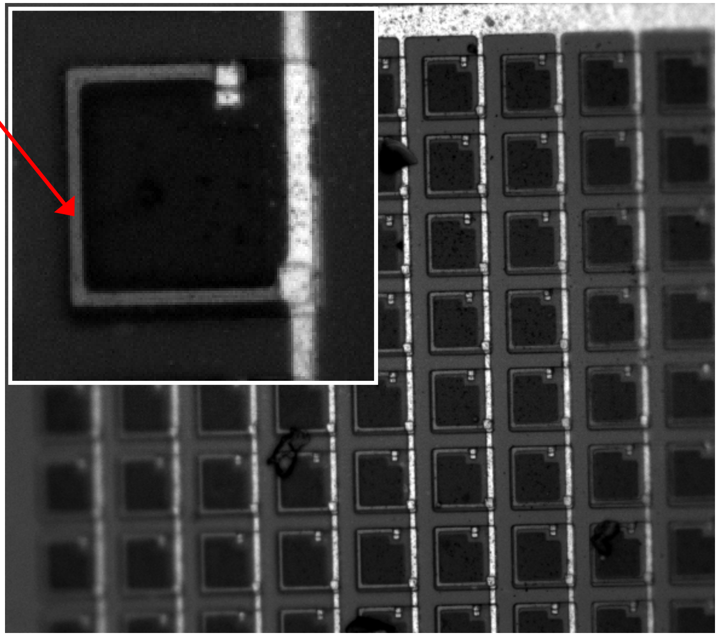
→ Silicon photomultipliers



Conventional Silicon Photomultiplier – SiPM

- an array of avalanche photodiodes
  - operated in Geiger mode
  - passive quenching by integrated resistor
  - read out in parallel → signal is sum of all fired cells

polysilicon



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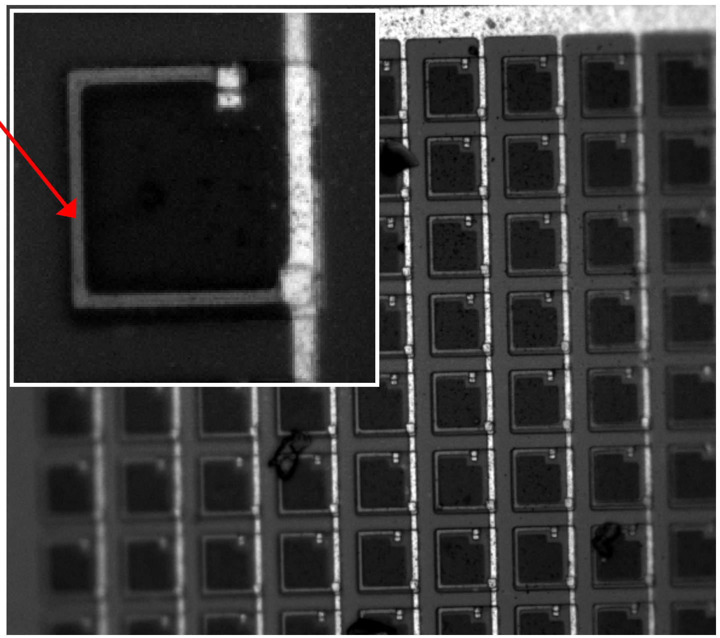

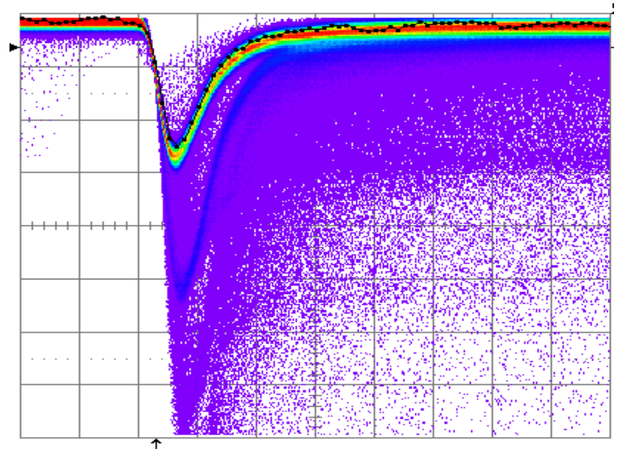

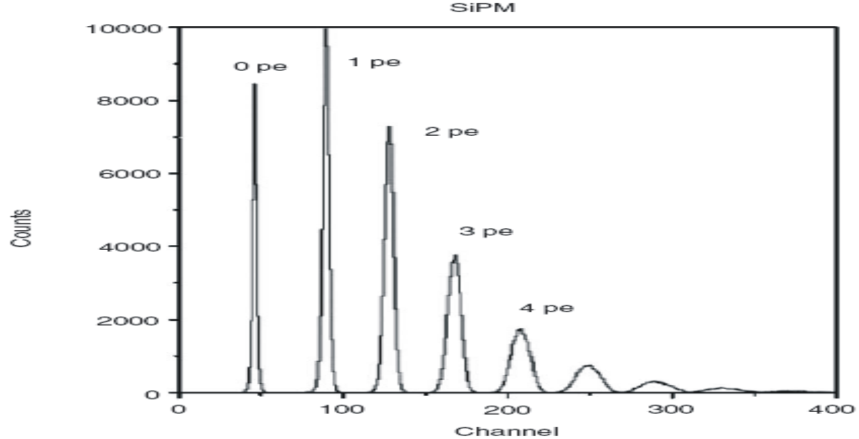

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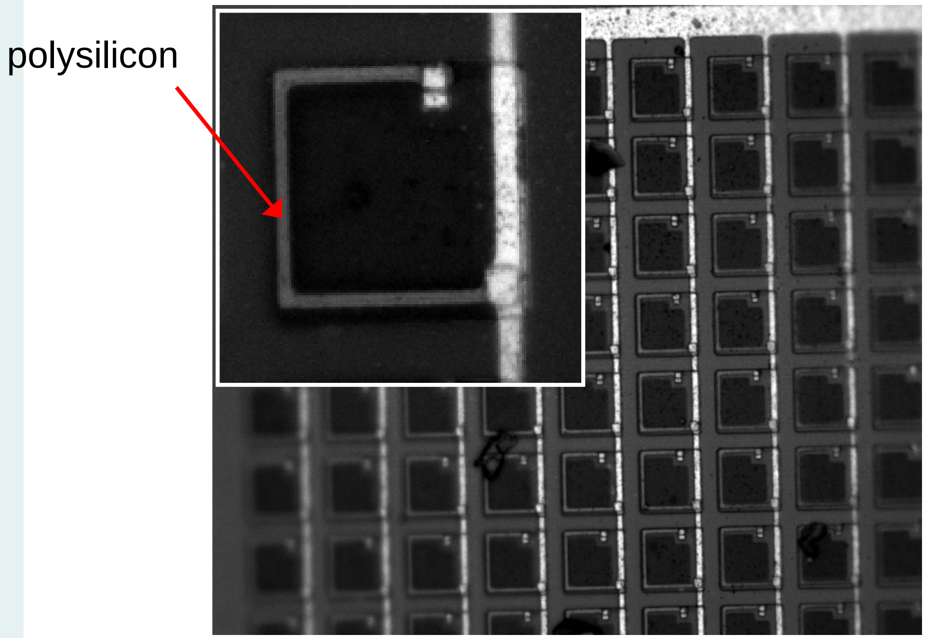
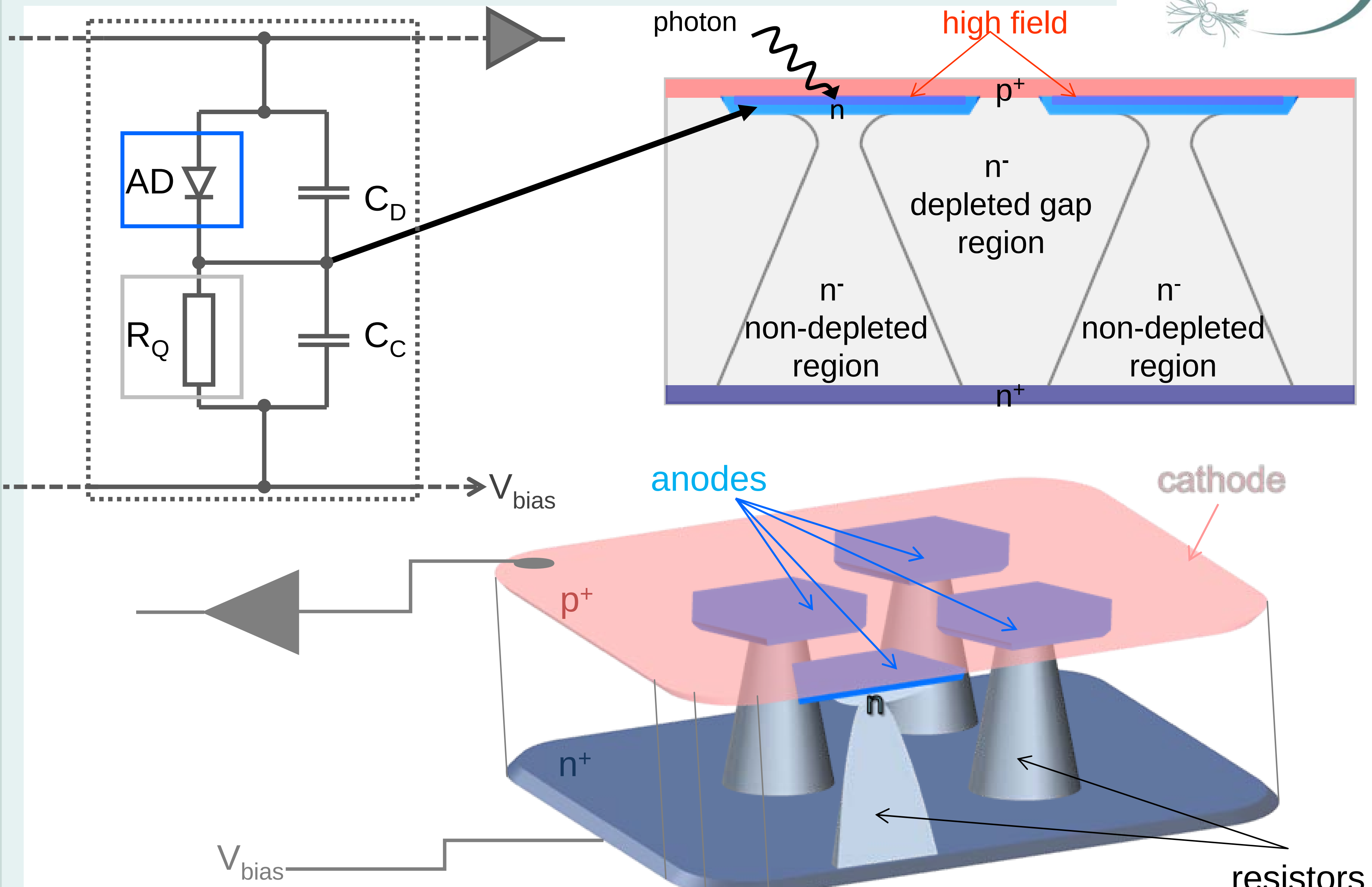


polysilicon resistor:

→ obstacle for light

→ limitation of PDE

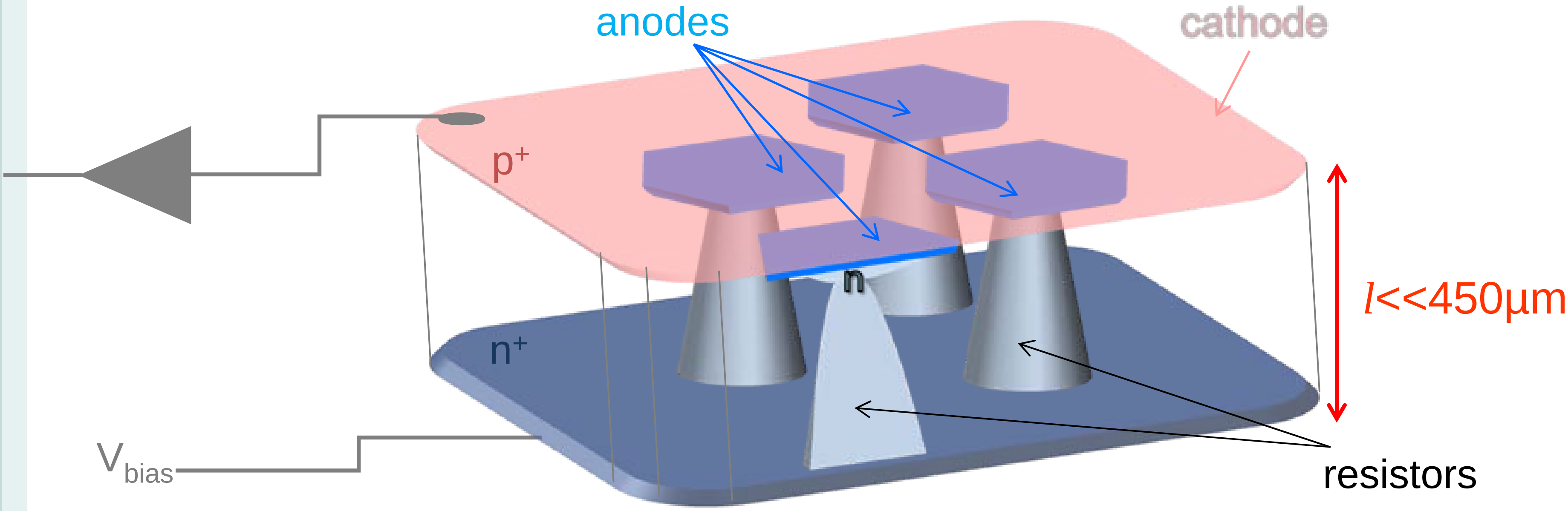
SiPM cell components → SiMPl approach



SiPM cell components → SiMPl approach

Resistor matching requires thin wafers !

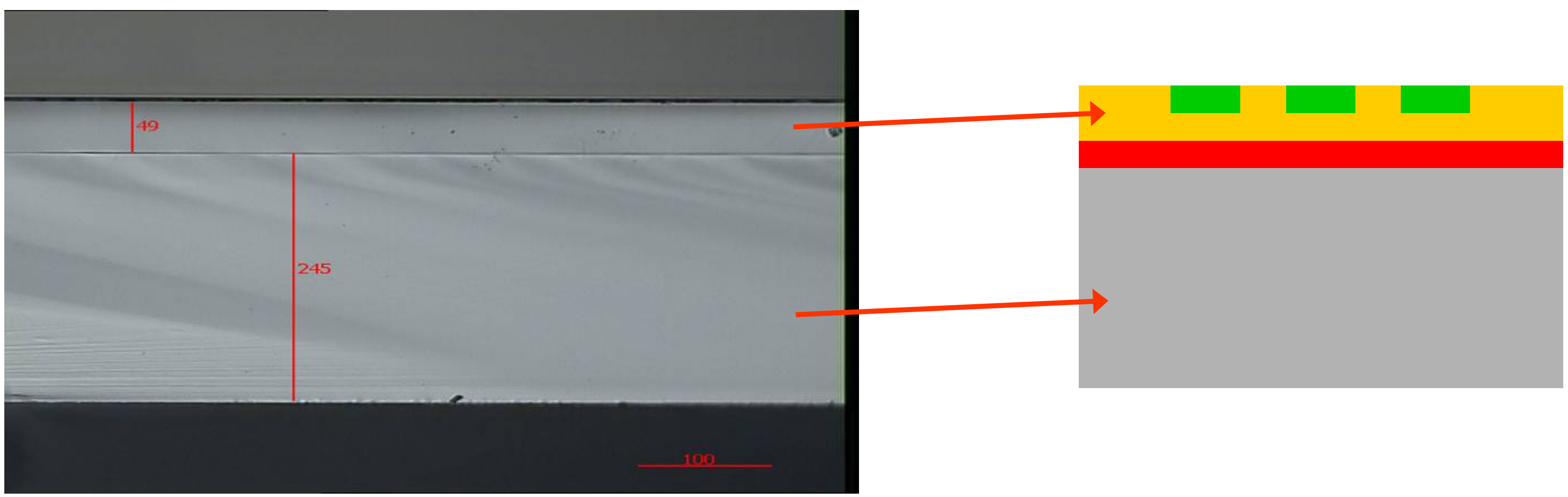
→ wafer bonding



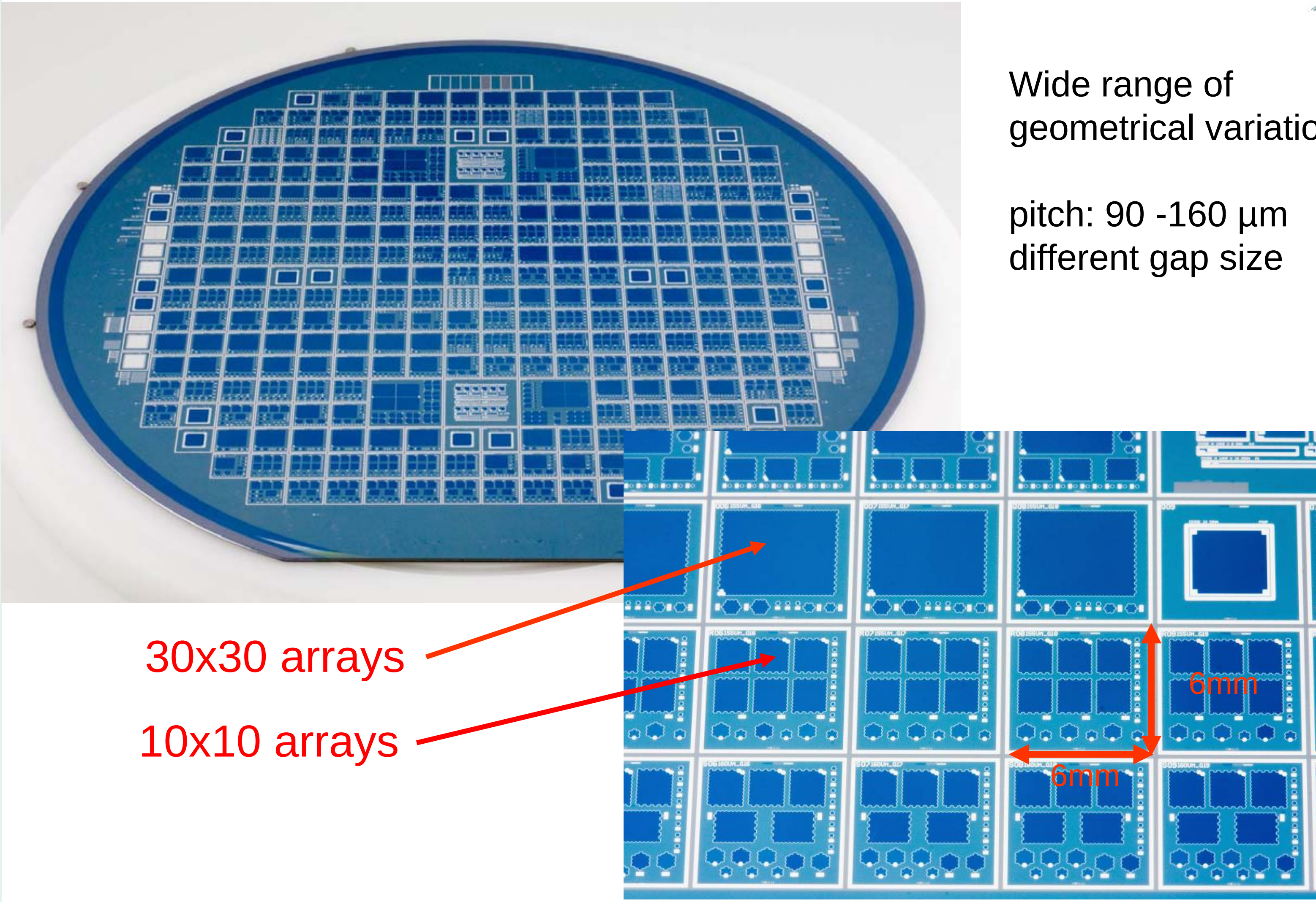
$$R = \rho \frac{l}{A}$$

Wafer bonding – Silicon On Insulator wafers

1. implant backside on sensor wafer
2. bond sensor wafer to handle wafer
3. thin sensor side to desired thickness
4. fabricate SiMPI arrays on top side



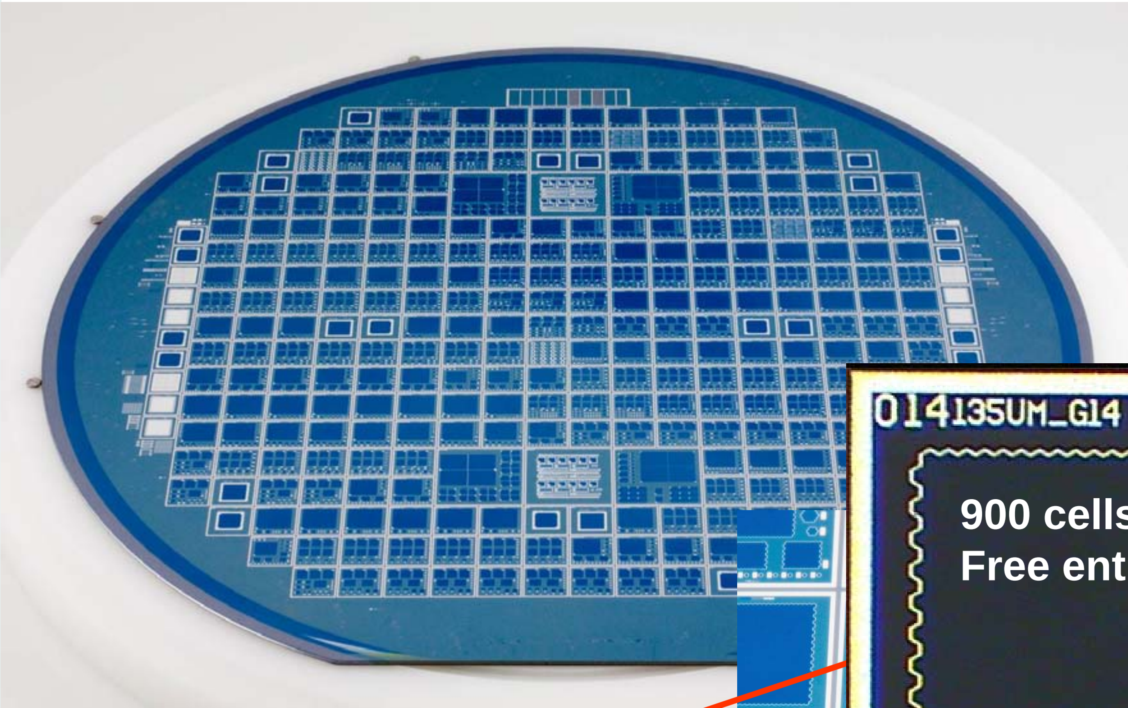
SiMPl prototype



Wide range of geometrical variations

pitch: 90 -160 µm
different gap size

SiMPl prototype



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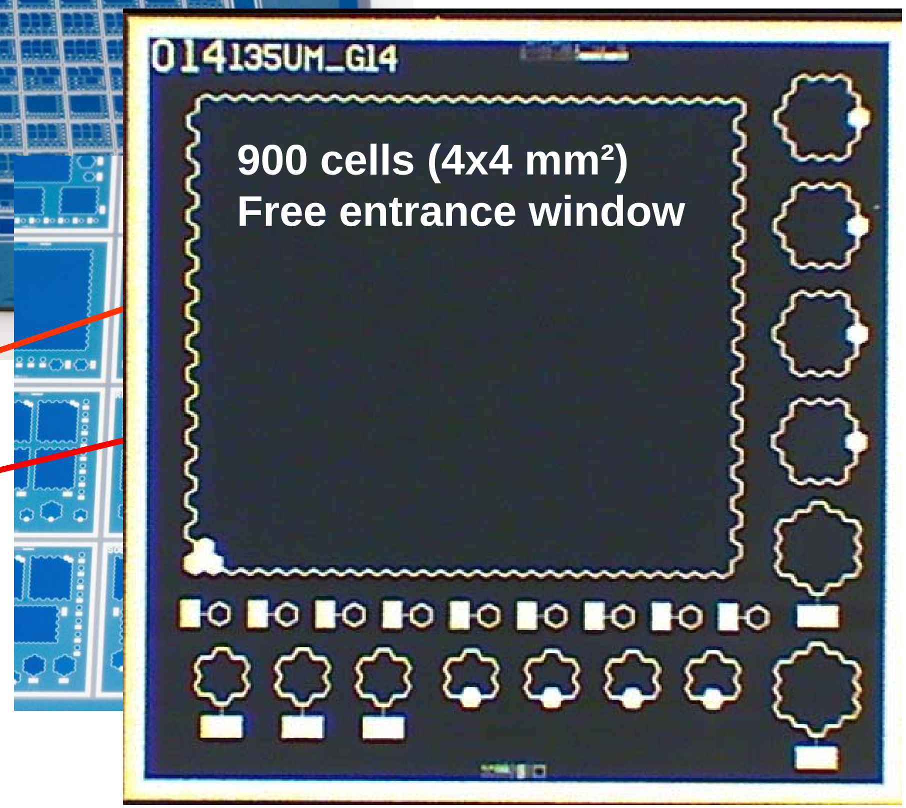
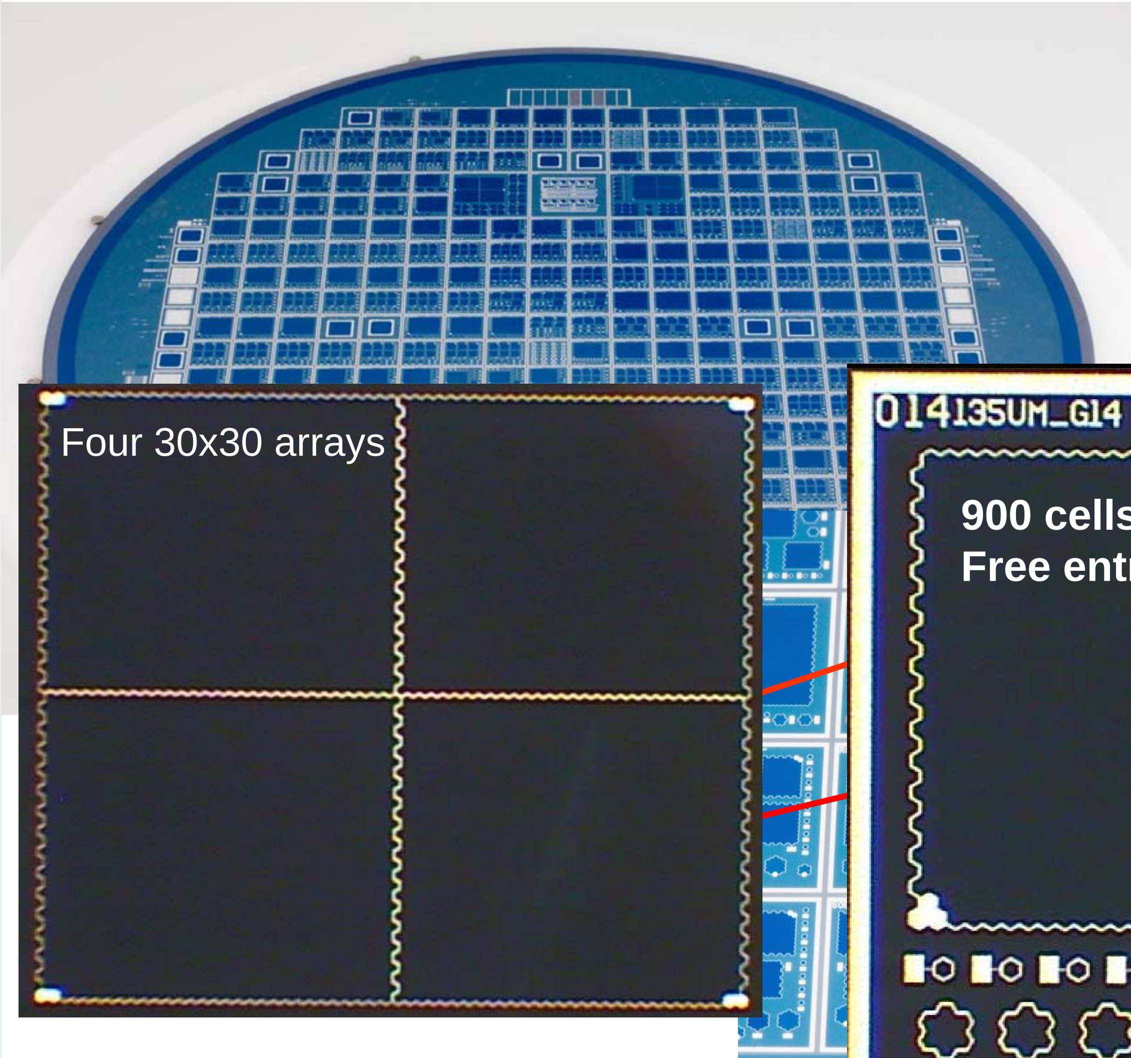


30x30 arrays

10x10 arrays

SiMPl prototype



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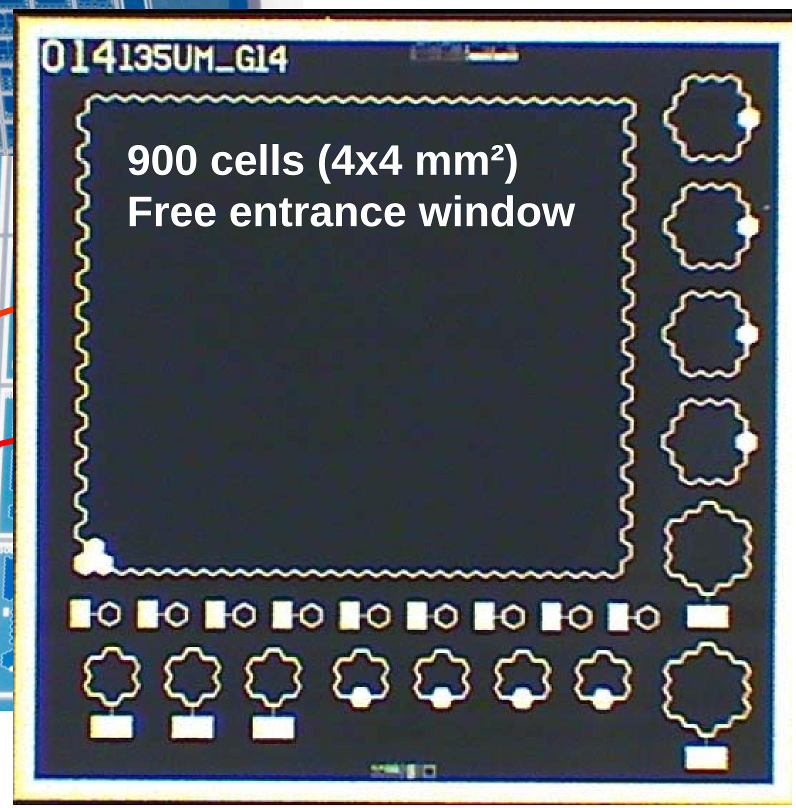

Advantages and Disadvantages

Advantages:

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

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mpi halbleiterlabor

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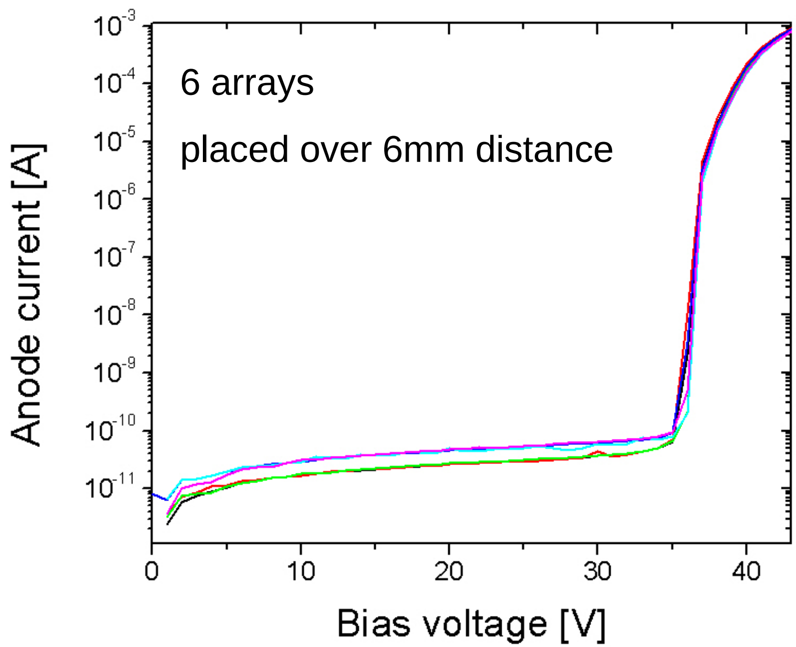
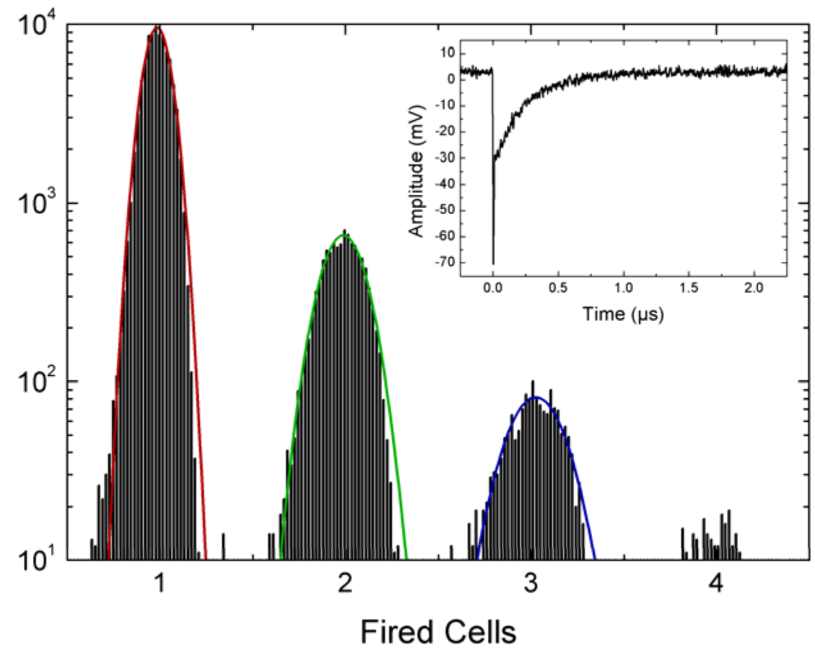
Drawbacks:

- required depth for vertical resistors does not match wafer thickness
- wafer bonding is necessary for big pixel sizes
- significant changes of cell size requires change of the material
- vertical ‘resistor‘ is a JFET → non-linear IV → longer recovery times

IV-measurement & amplitude spectrum



homogeneous breakdown voltage



10x10 array of 135µm pitch @ 253K

(dark count spectrum)

Dark counts

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

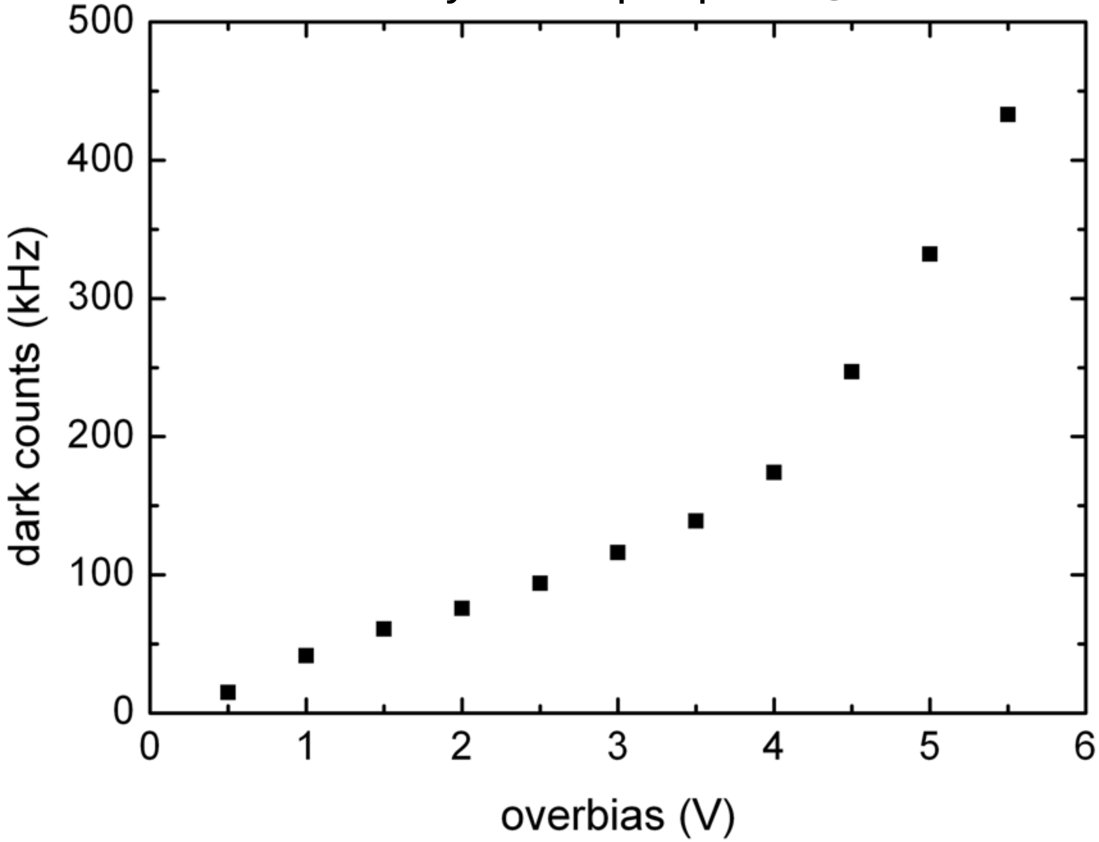
Thermal generation

→ cooling helps

normal operation up to
4V overbias @233K

overbias > 4V
→ non-quench condition

10x10 array of 130µm pitch @ 233K



Temperature dependence of quench resistor

Resistors designed for room temperature operation

→ limitation of operation voltage (non-quenching)

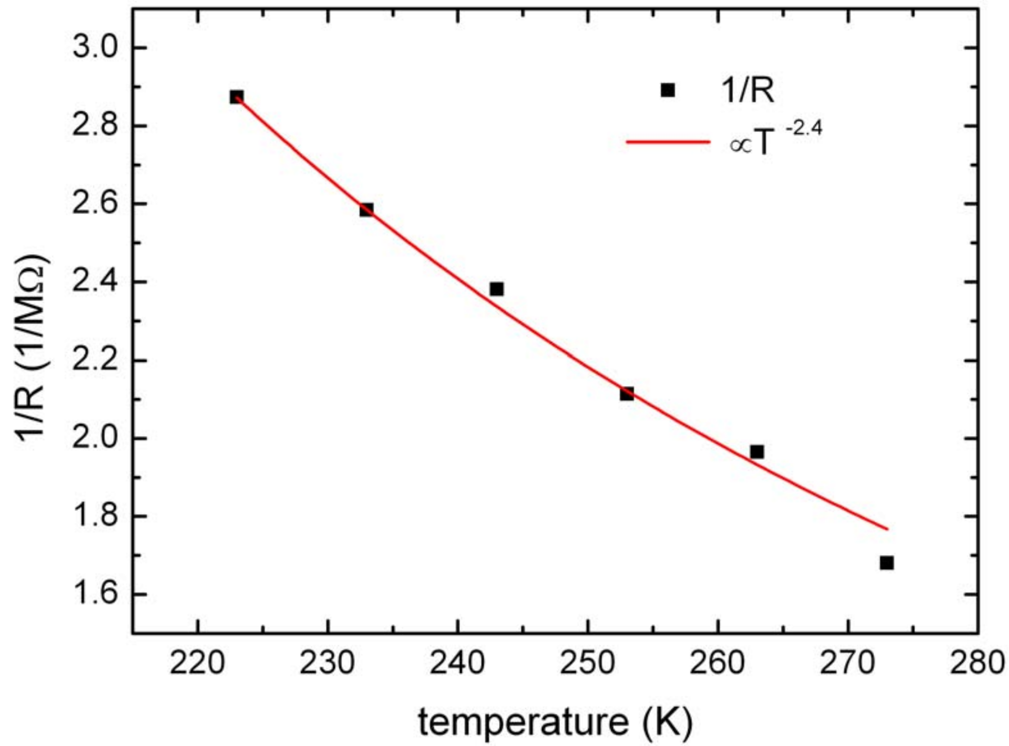
S. Cova et al., Appl. Opt. 35 (1996)

T (°C)	0	-10	-20	-30	-40	-50
R (kΩ)	595	509	473	420	387	348

$\tau = R_Q \cdot C_D$

mobility:

$\mu_n(\mathrm{Si}) \propto T^{-2.4}$



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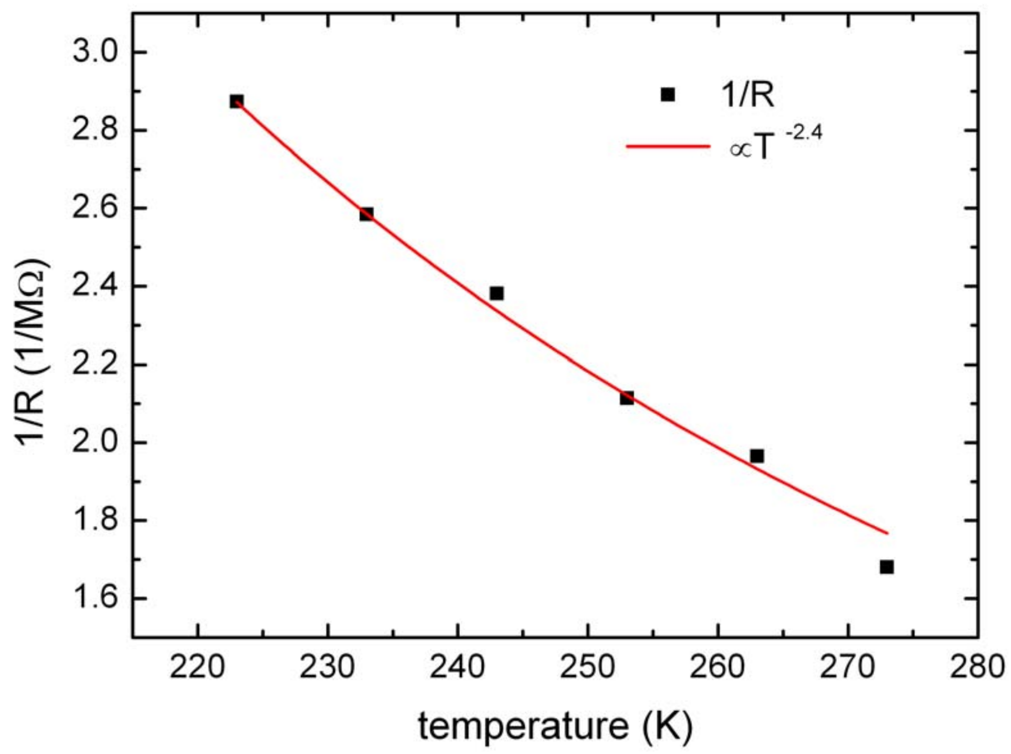


JFET behaviour → also dependent on $V_{bias}(T)$ → $T^{??}$

New results on quenching and recovery soon!

Optical cross talk

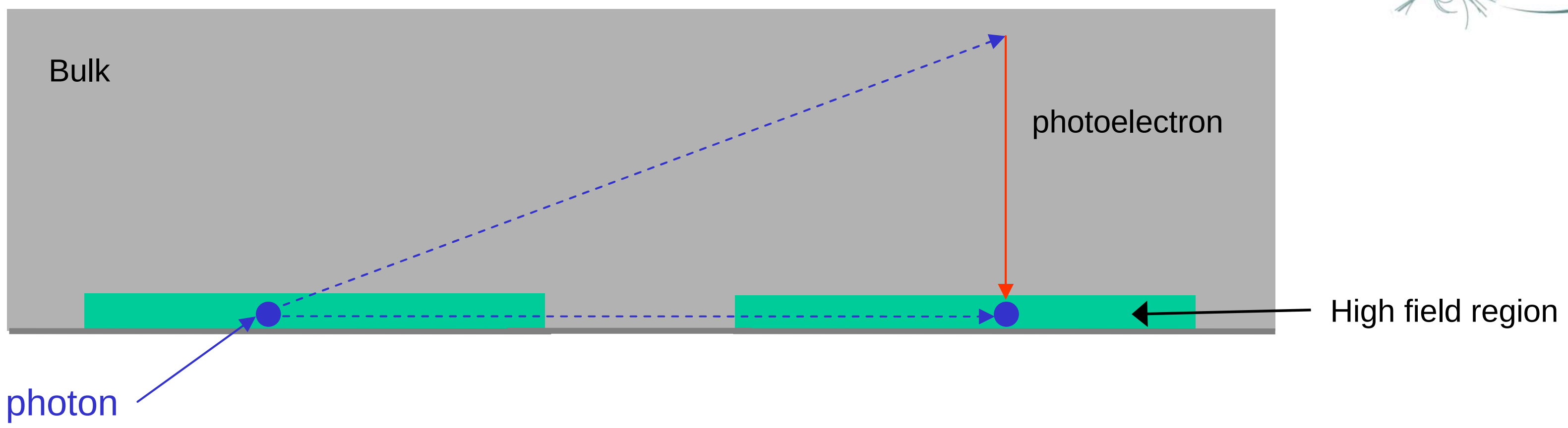
hot-carrier luminescence:

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

Optical cross talk



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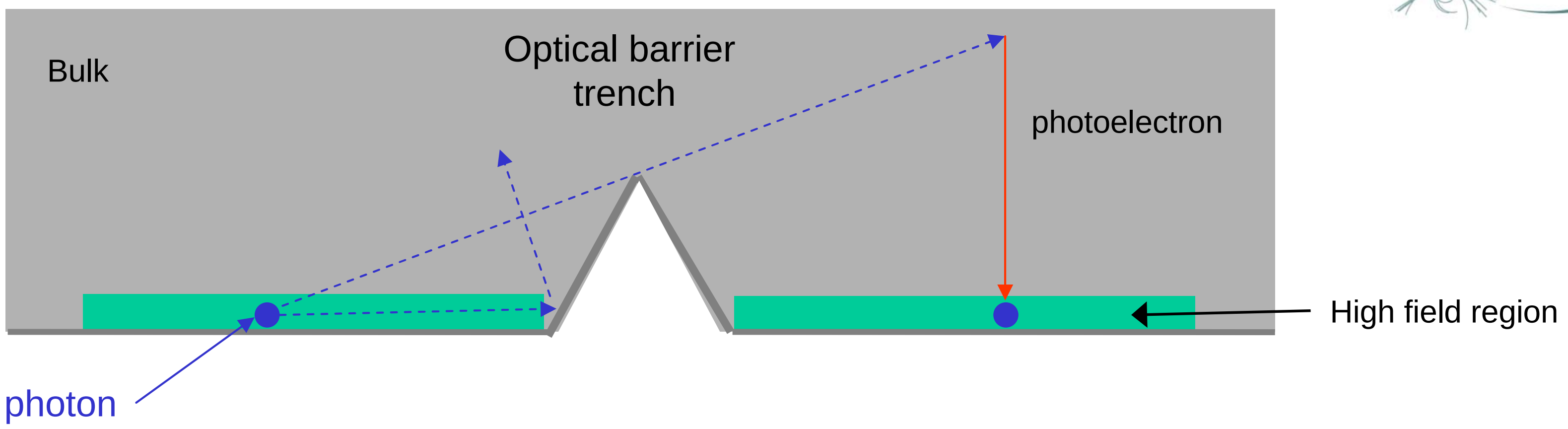

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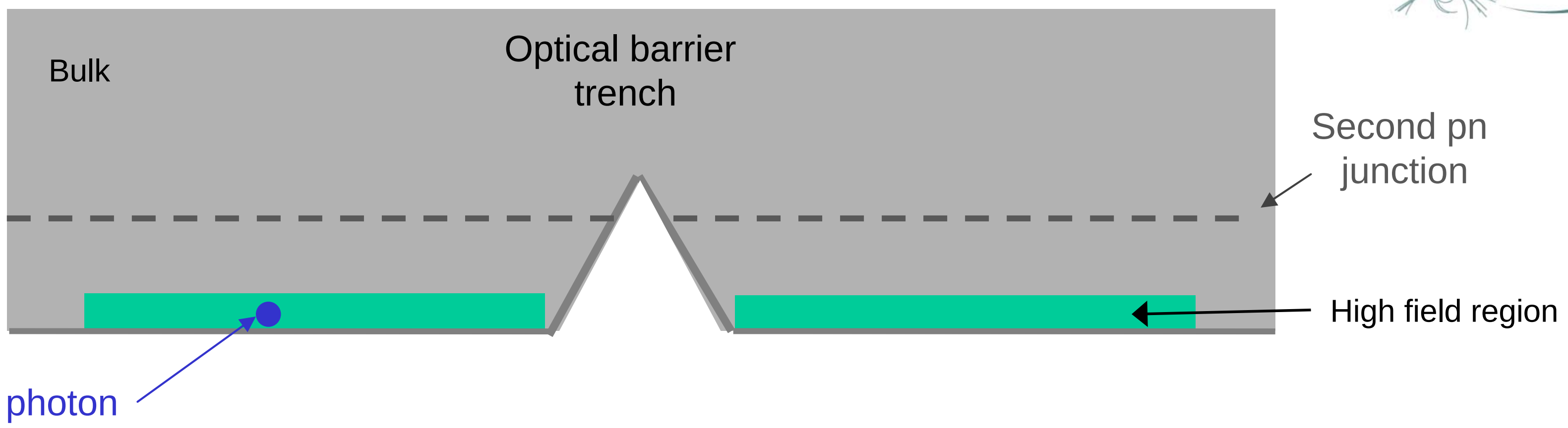

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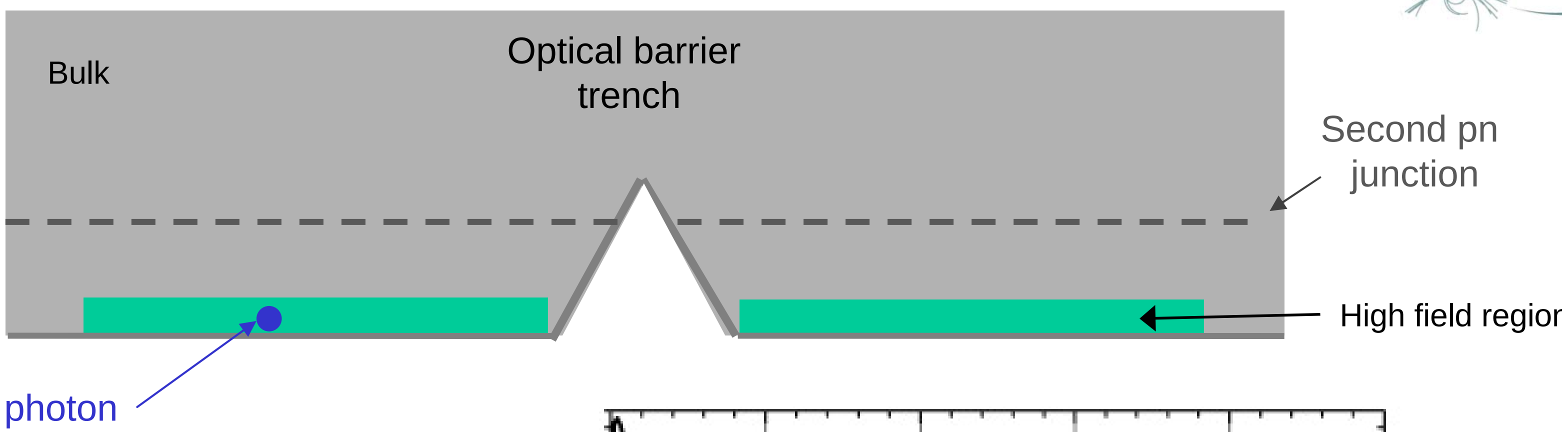
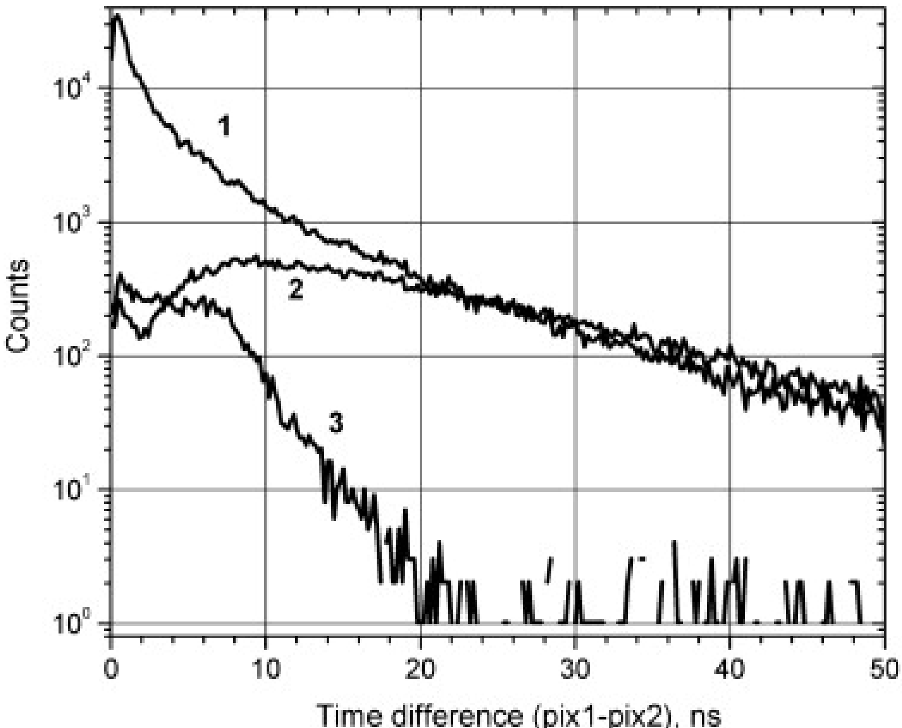




P. Buzhan et al., NIM A 610 (2009)

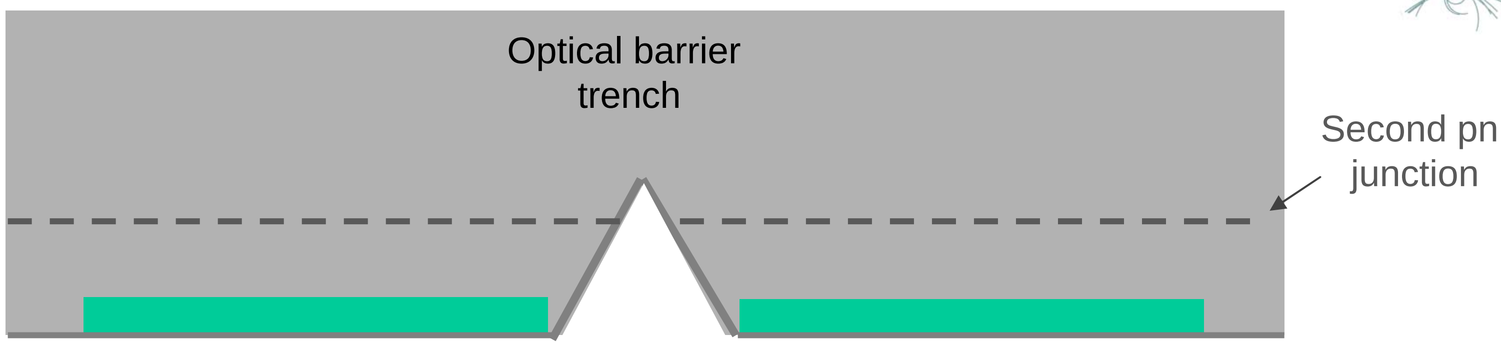
<u>*Distribution of time difference between two neighbouring cells:*</u>

1: without optical crosstalk suppression

2: suppression by optical barrier

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

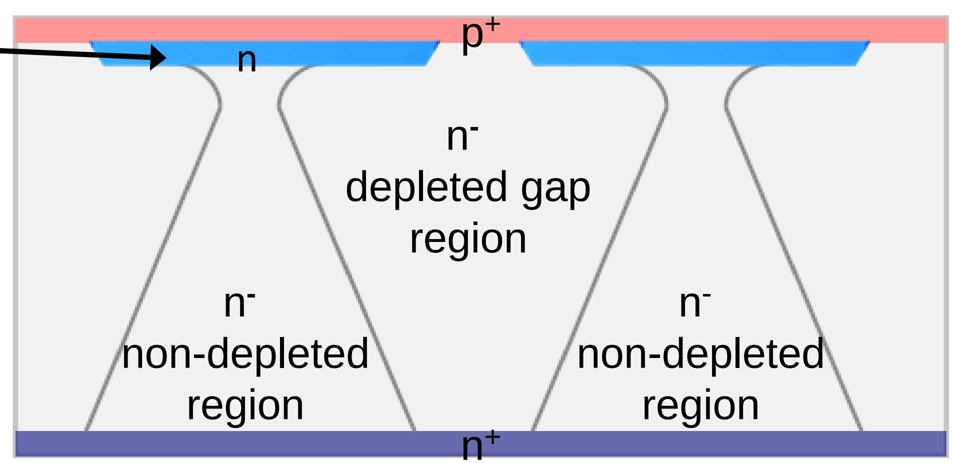
Optical cross talk



Internal anode as diffusion barrier:

Corresponds to second pn-junction

Inherent for SiMPl



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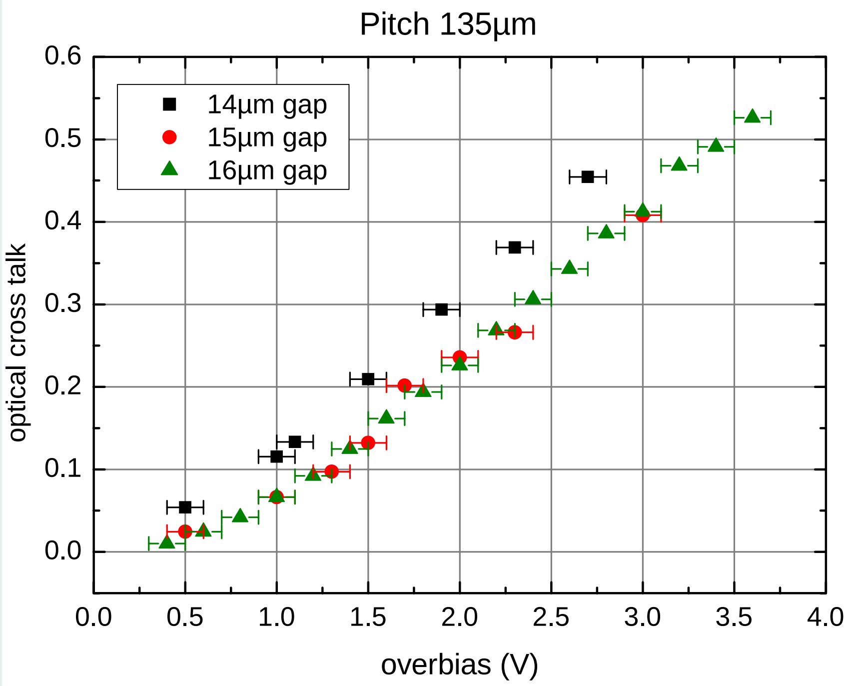
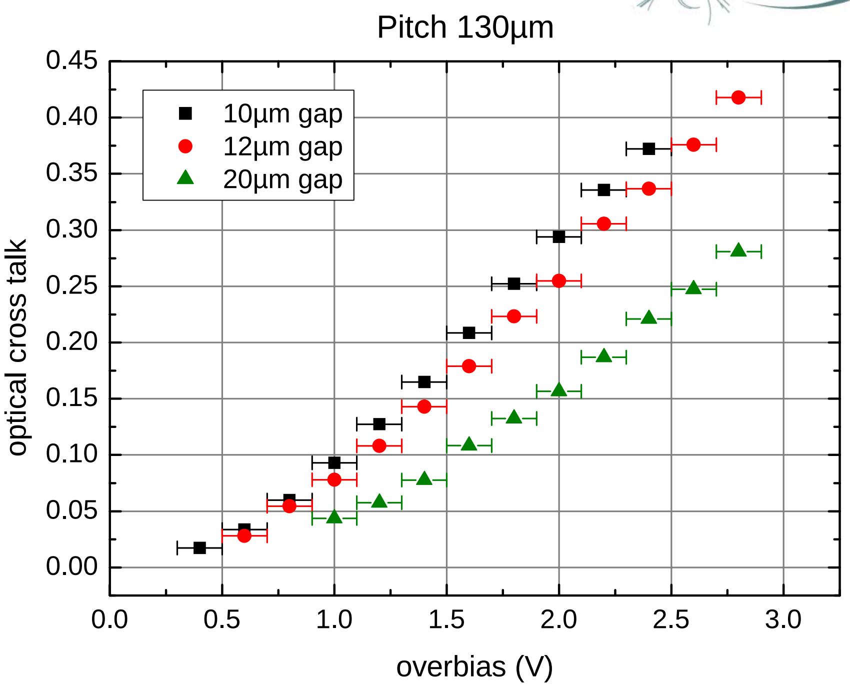


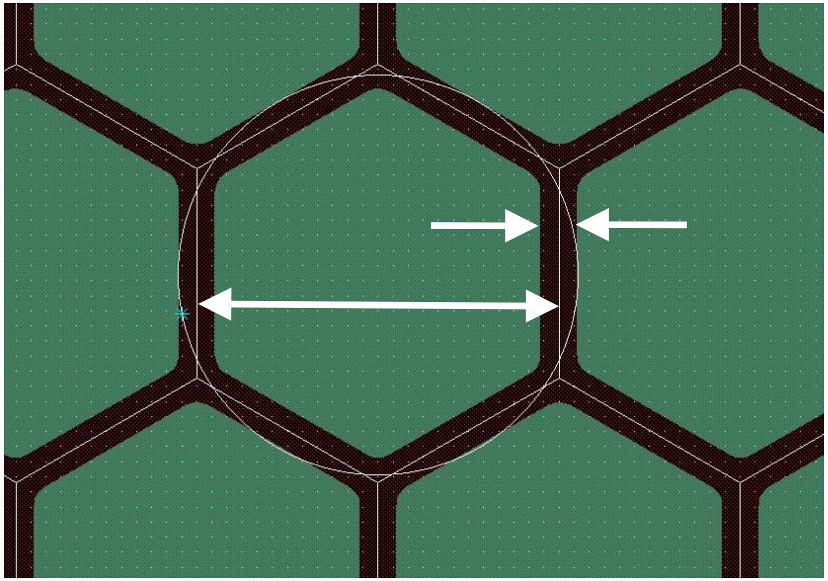


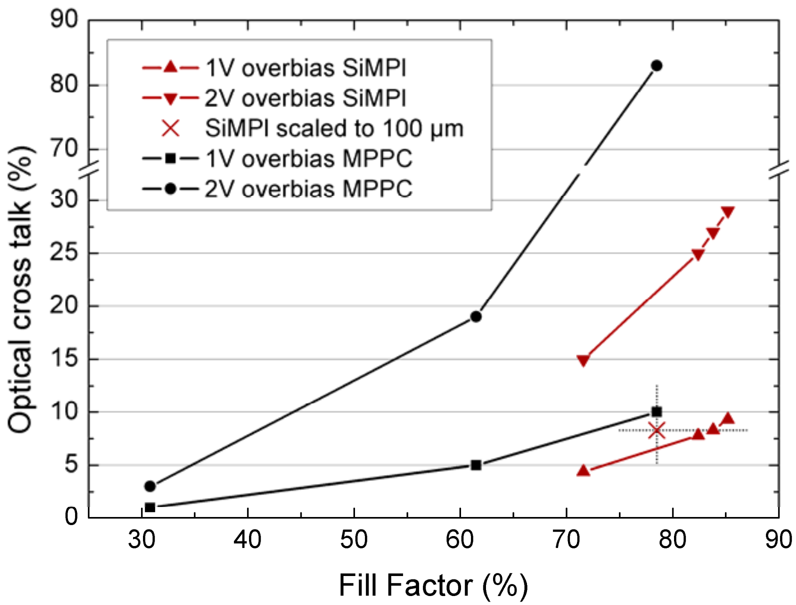
Increasing overbias
~ increasing gain
~ increasing trigger efficiency

Non-linear dependency on overbias

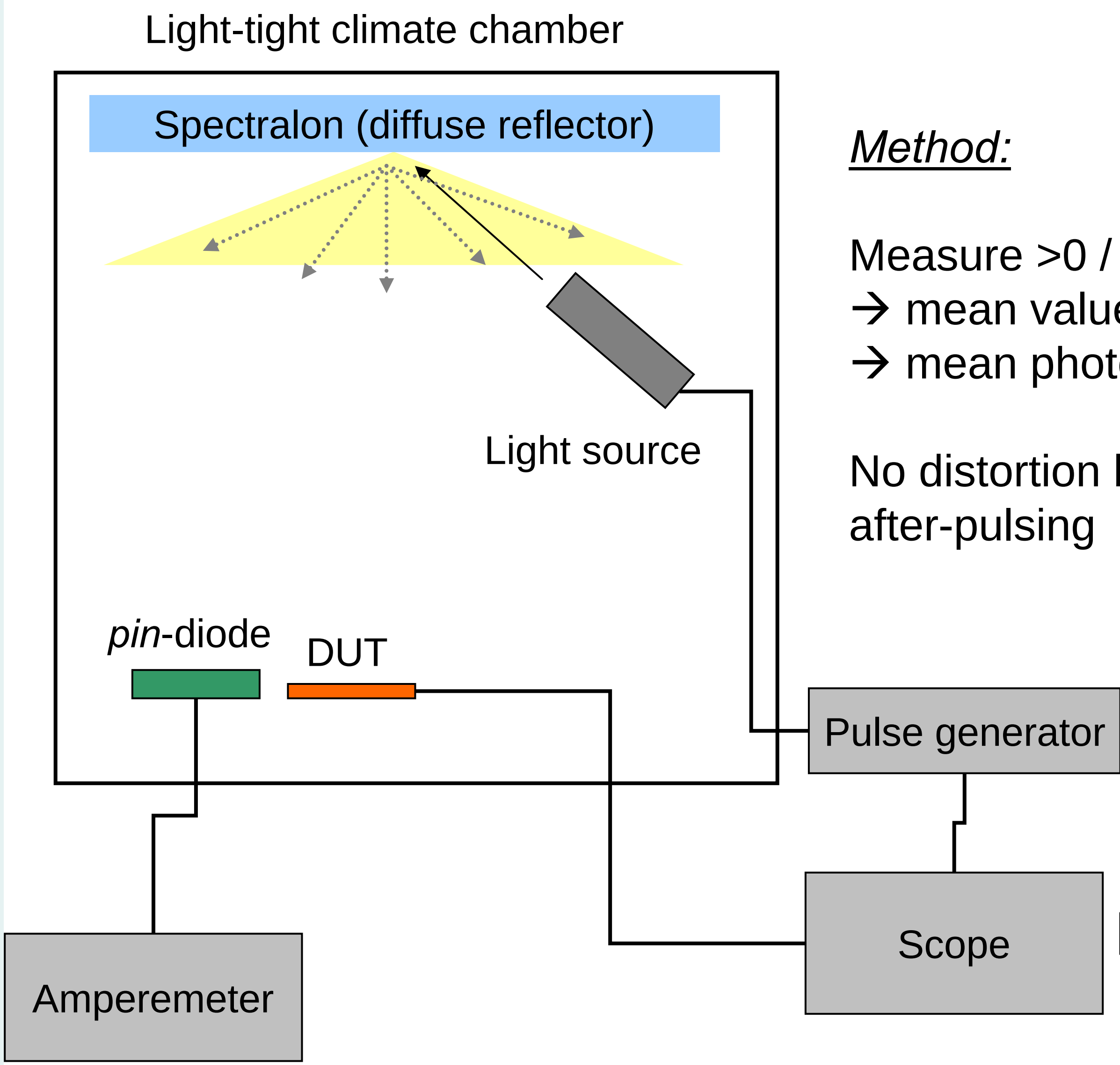
Optical cross talk

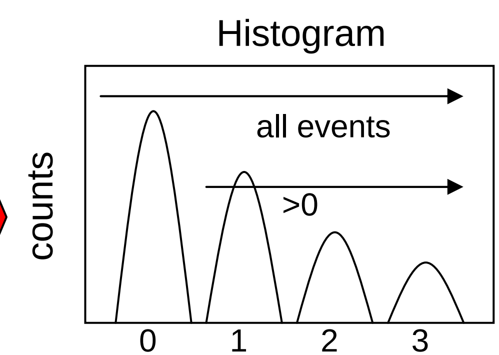
Pitch / Gap	Fill factor	Cross talk (2V V_{ob})
130µm / 10µm	85.2%	29%
130µm / 11µm	83.8%	27%
130µm / 12µm	82.4%	25%
130µm / 20µm	71.6%	15%





PDE measurements - setup





Method:

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

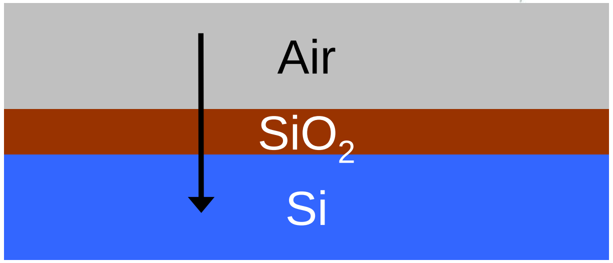
No distortion by optical cross talk or after-pulsing

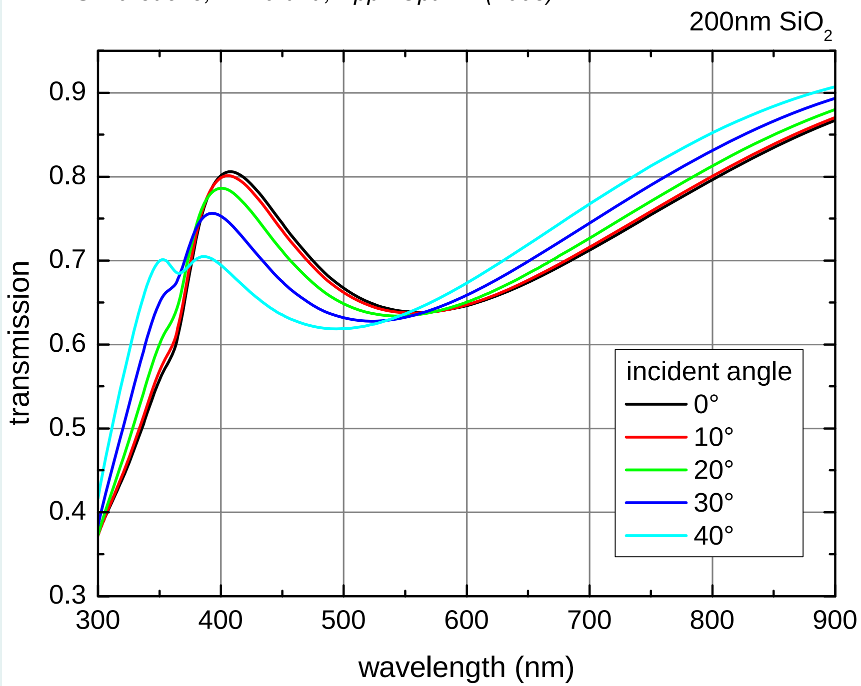
Transmission to silicon

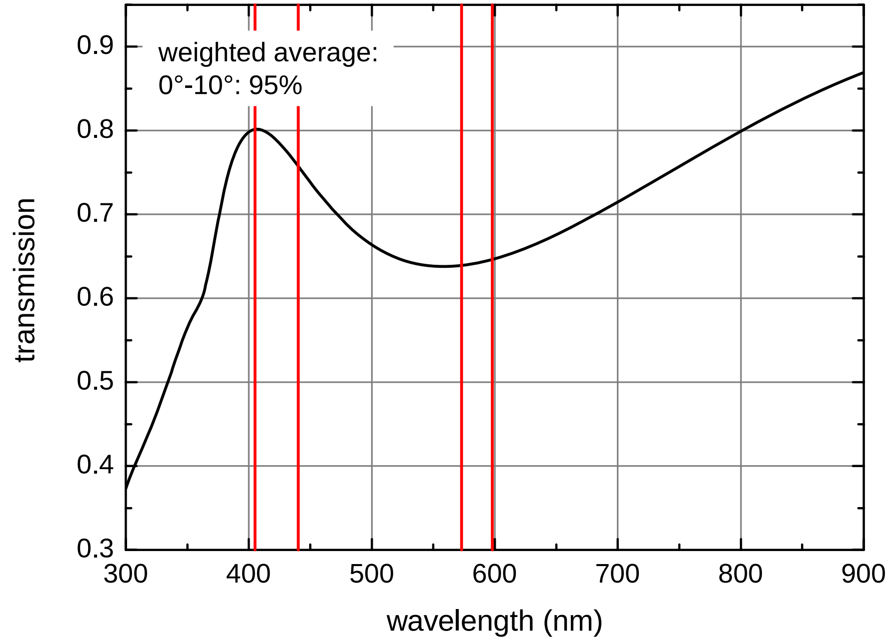
200nm SiO_2
Prototype: no optimized entrance window

Simulations with OpenFilters* for transmission into silicon

S. Larouche, L. Martinu, Appl. Opt. 47 (2008)

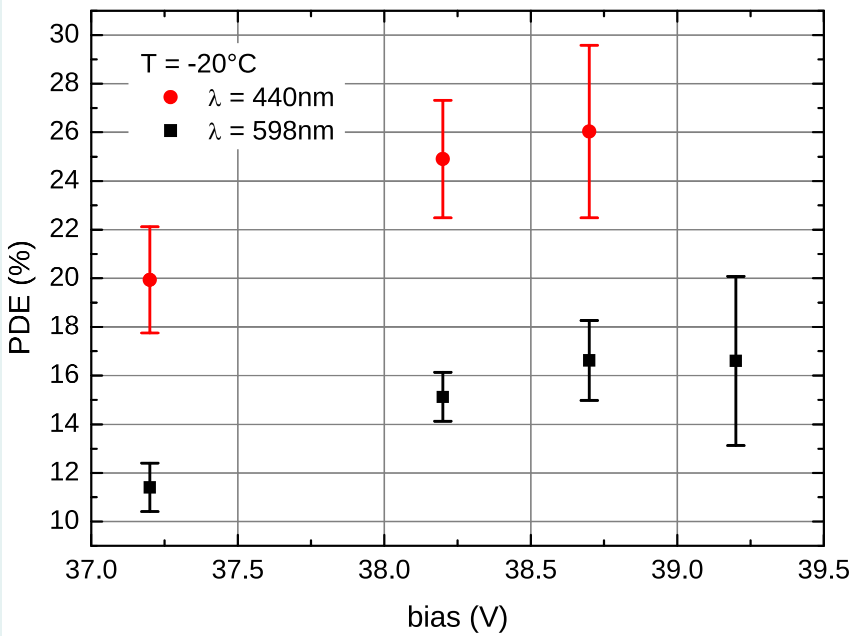


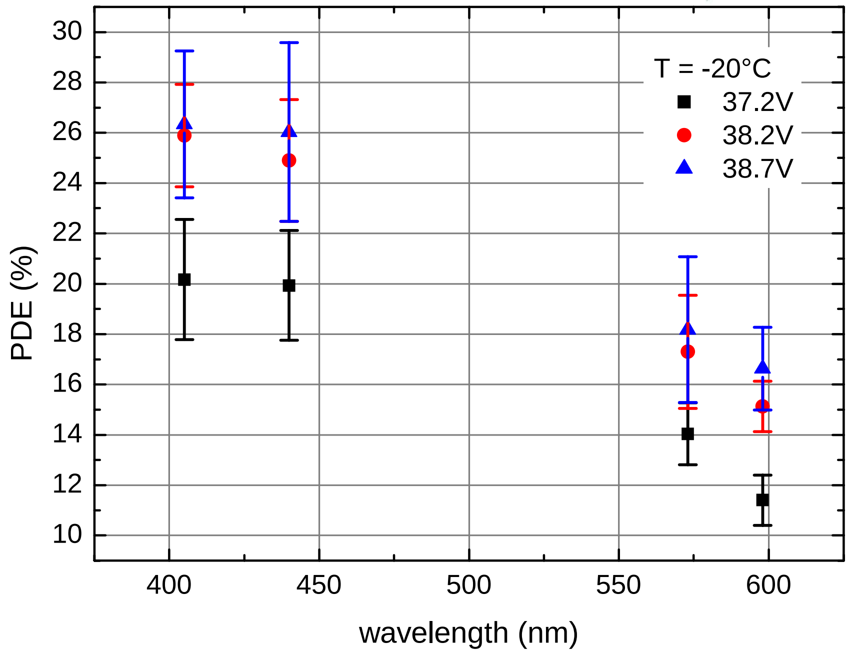




PDE measurements @ 405nm, 440nm, 573nm, 598nm

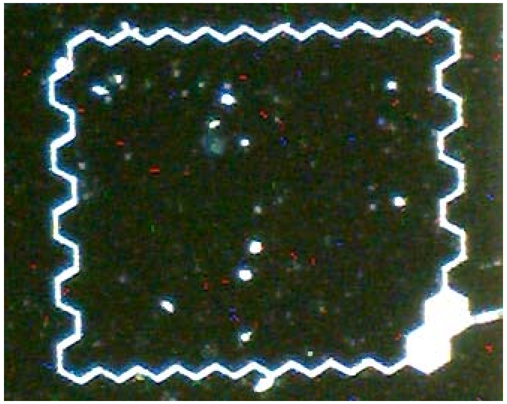
PDE: 130µm pitch, 20µm gap





Breakdown voltage: 35.2V
Fill factor: 0.716
Laser repetition rate: 0.5MHz
→ Max. recovery 2µs

Quenching limit → PDE not in saturation



Summary PDE measurement

Geiger-Efficiency (GE) @ 2V overbias: ca. 50%

Wavelength	405nm	440nm	573nm	598nm
Transmission (sim.)	0.80	0.76	0.64	0.65

Pitch/gap	Fill Factor	405nm	440nm	573nm	598nm
130/10	0.852	**26%**	**24%**	**14%**	**12%**
130/11	0.838	**29%**	**28%**	**14%**	**13%**
130/12	0.824	**25%**	**23%**	**14%**	**13%**
130/20	0.716	**20%**	**20%**	**14%**	**11%**

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With optimization (85% GE & 90% transmission) PDE of 65% easily achievable

Summary & 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

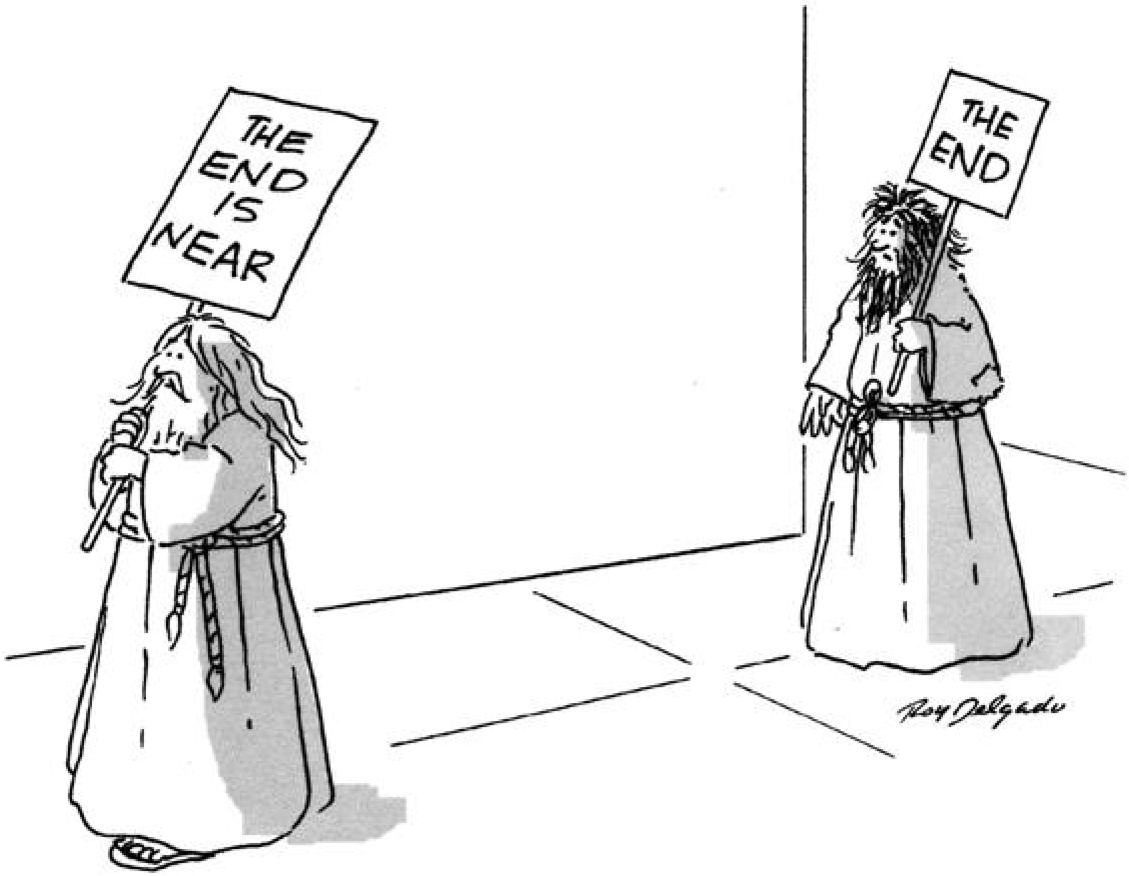
Prototype production

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

Further studies of the produced sensors (geometry dependence of the sensor performance, after pulsing, quench resistor…) are ongoing

New production to reduce dark counts and implement small pixels

Thanks



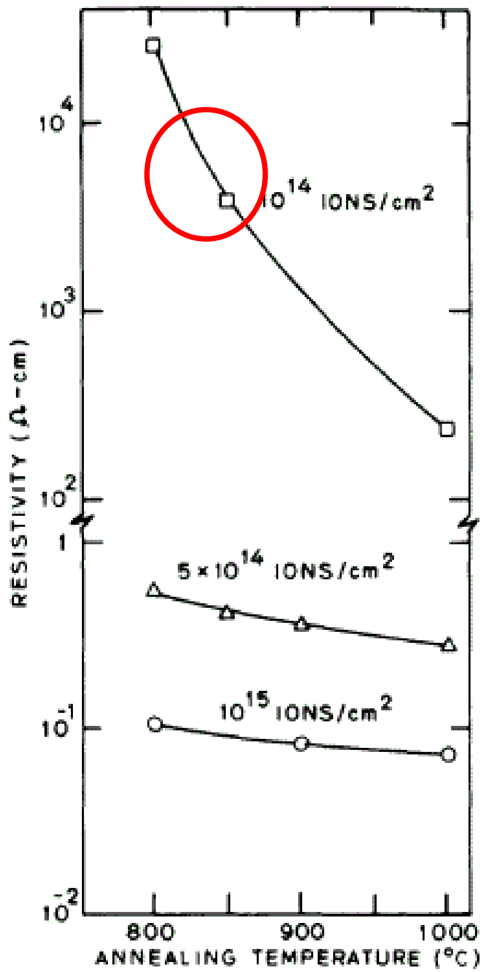
Polysilicon quench resistors

critical resistance range

→ rather unreliable process step

obstacle for incident light

→ fill factor decreased
→ limitation of detection efficiency



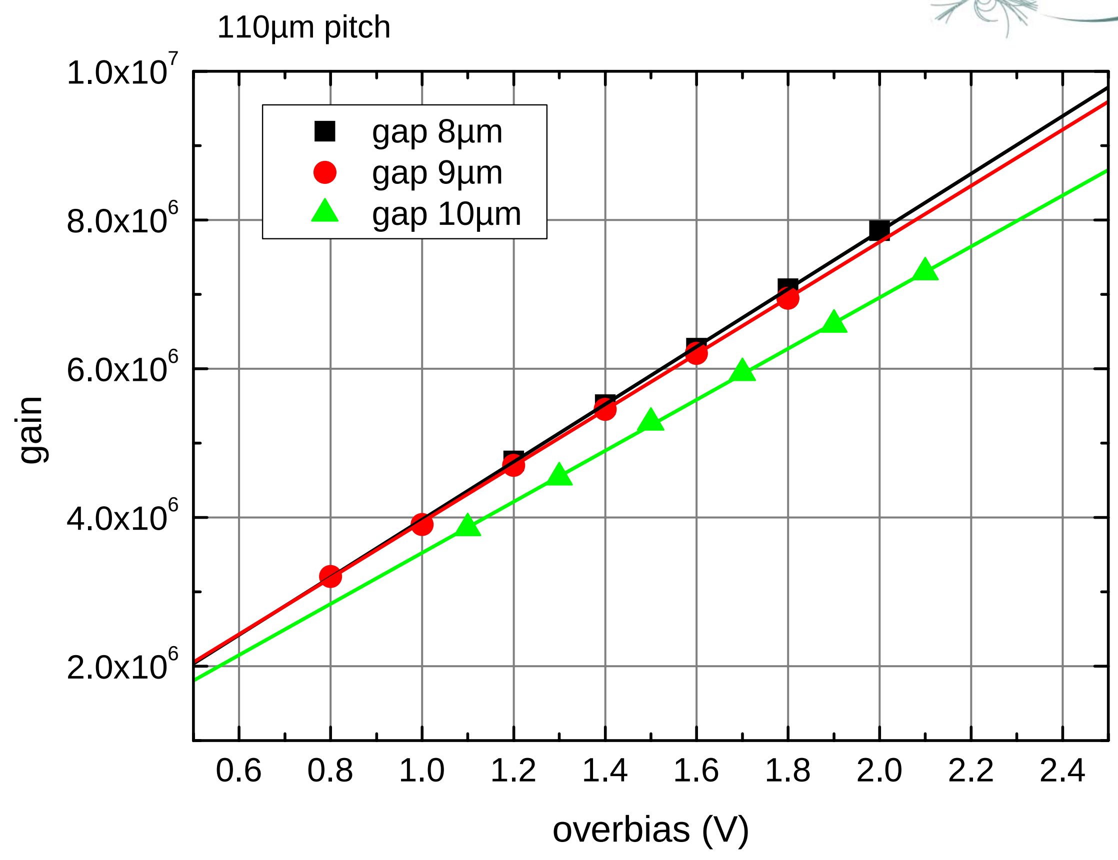
M. Mohammad et al.
'Dopant segragation in polycrystalline silicon',
J. Appl. Physics, Nov.,1980

Gain linearity

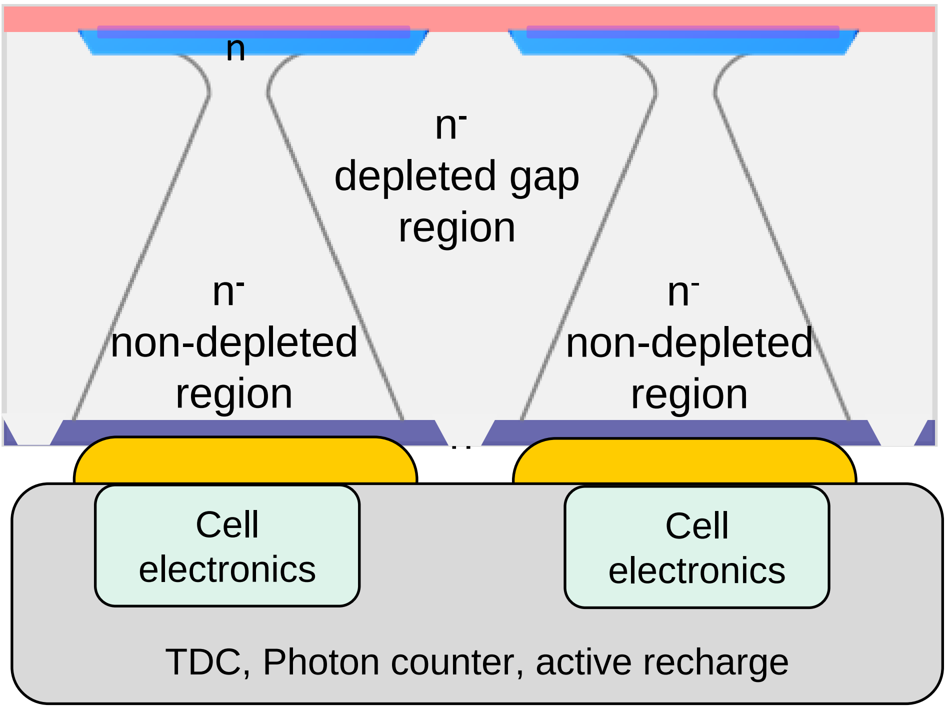
Expected:
linear with overbias voltage

Gain at 1V overbias

08 µm: 3.88 * 10^6
09 µm: 3.77 * 10^6
10 µm: 3.43 * 10^6



Next SiMPl generation – photon detection



Topologically flat & free surface

High fill factor

Sensitive to light

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

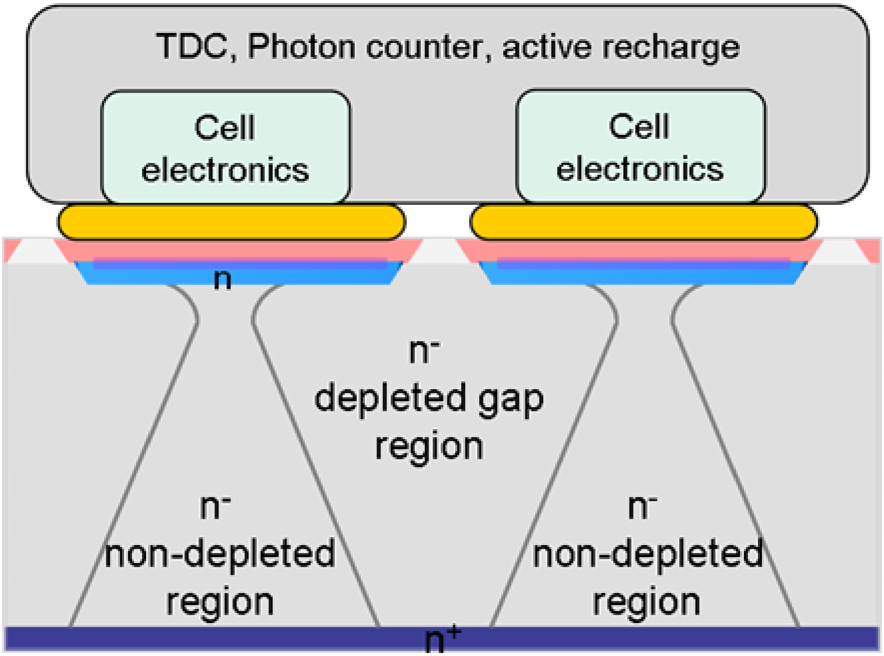
Next SiMPl generation – particle detection

<u>*Detection of particles:*</u>

- Excellent time stamping due to avalanche (sub-ns)
- Minimum ionizing particles generate about 80 e-h-pairs/µm
- No need for high trigger efficiency

→ Allows operation at low overbias voltage

→ Decrease of dark count rate & optical cross talk



Topologically flat surface

High fill factor

Adjustable resistor value

Pitch limited by bump bonding

Photon Detection Efficiency

PDE = quantum efficiency · fill factor · Geiger efficiency

- quantum efficiency: e-h pair generated in depletion layer, *QE(λ)*
- fill factor: fraction of active to total area of device
- Geiger efficiency: avalanche triggered by generated carrier, *GE(E)*

Comparison: theoretical estimation - measurement

Estimation shows reasonable agreement with measurement results

Not taken into account here:
- Dirt on surface
- Wavelength dependency (depth of absorption → efficiency drops)

With optimization (85% GE & 90% entrance window) PDE of 65% easily achievable

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		theo	meas	theo	meas	theo	meas	theo	meas
130/10	0.852	34%	26%	32%	24%	27%	14%	28%	12%
130/11	0.838	34%	29%	32%	28%	27%	14%	27%	13%
130/12	0.824	33%	25%	31%	23%	26%	14%	27%	13%
130/20	0.716	29%	20%	27%	20%	23%	14%	23%	11%

Optical cross talk & PDE

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%

Photon Detection Efficiency estimation:

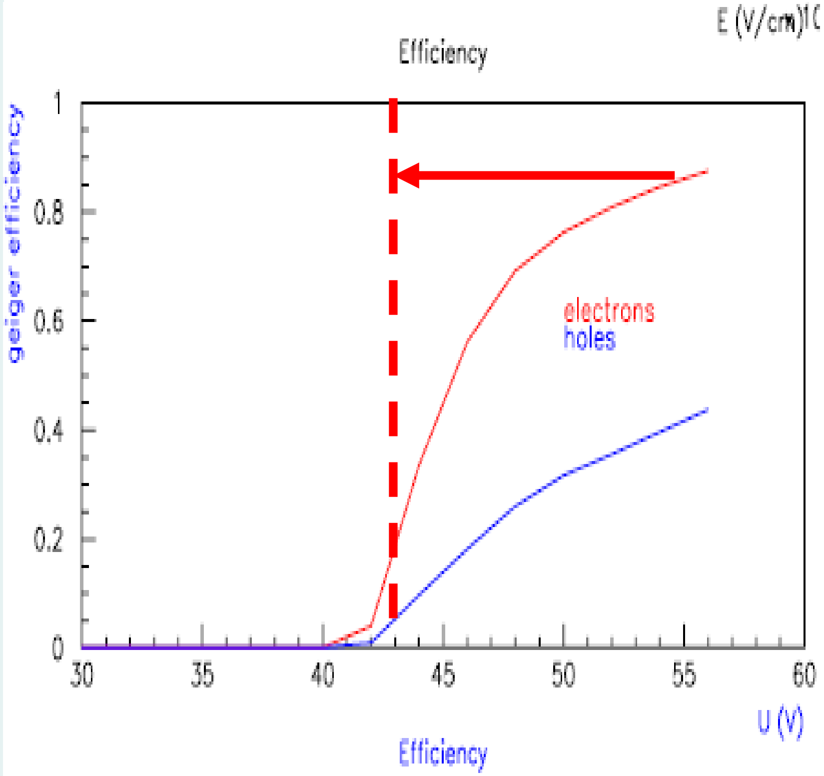
- Optical entrance window: 90% @400nm
- Geiger efficiency : 50% @ 2V overbias 85% @ 6V overbias

Pitch / Gap	Fill factor	PDE	
130µm / 10µm	85.2%	39%	65%
130µm / 11µm	83.8%	38%	64%
130µm / 12µm	82.4%	37%	63%
130µm / 20µm	71.6%	32%	55%

Next SiMPl generation – particle detection

Decrease of dark count rate and optical cross talk

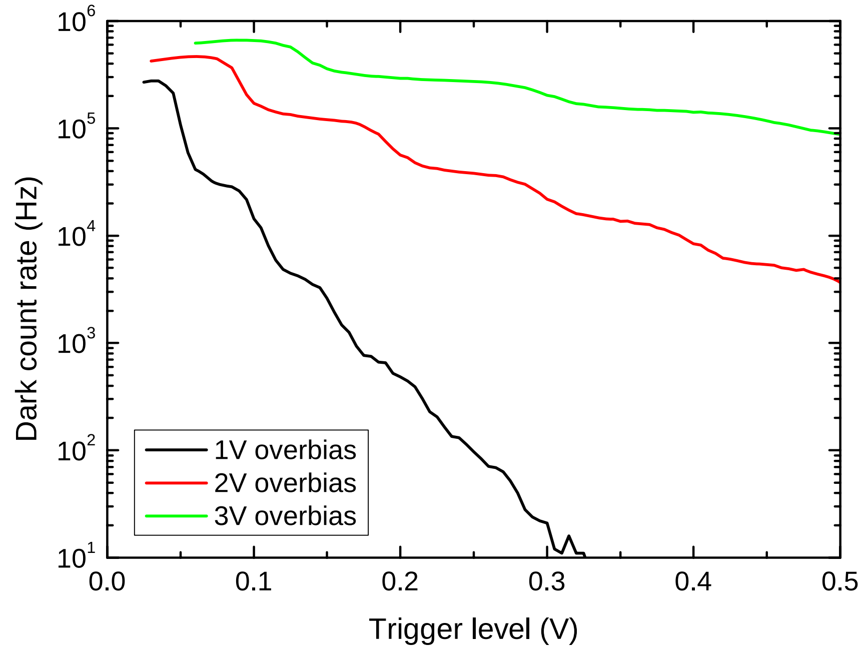
Geiger efficiency vs. bias voltage



10% GE still gives >98% MIP detection

Staircase of dark counts at different overbias

110µm



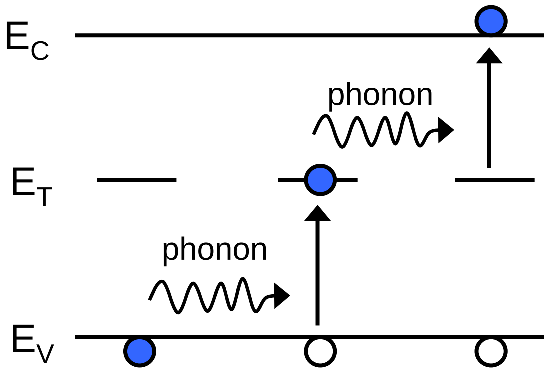
Drawbacks – dark counts

avalanche triggered by thermally generated charge carriers → high dark count rate

two processes:

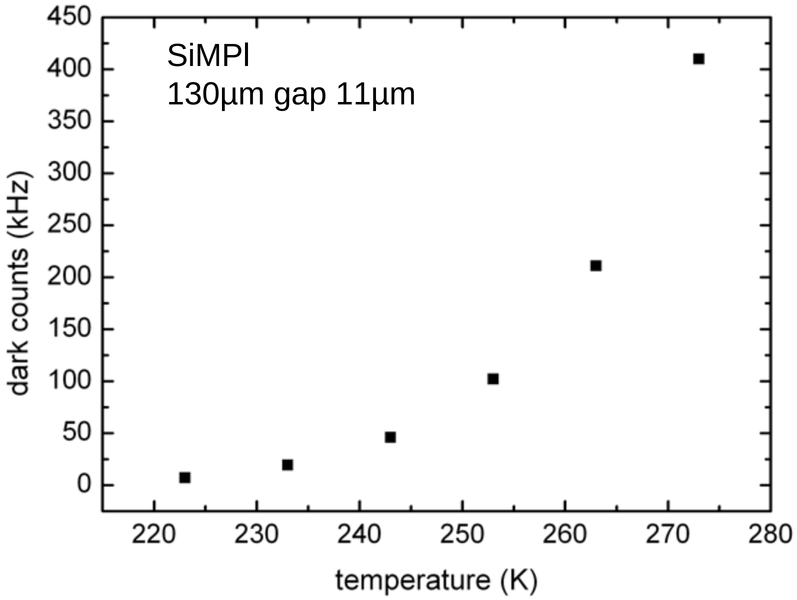
- diffusion of minority carriers into high field region

- Schockley-Read-Hall generation due to traps within bandgap (lattice defects)

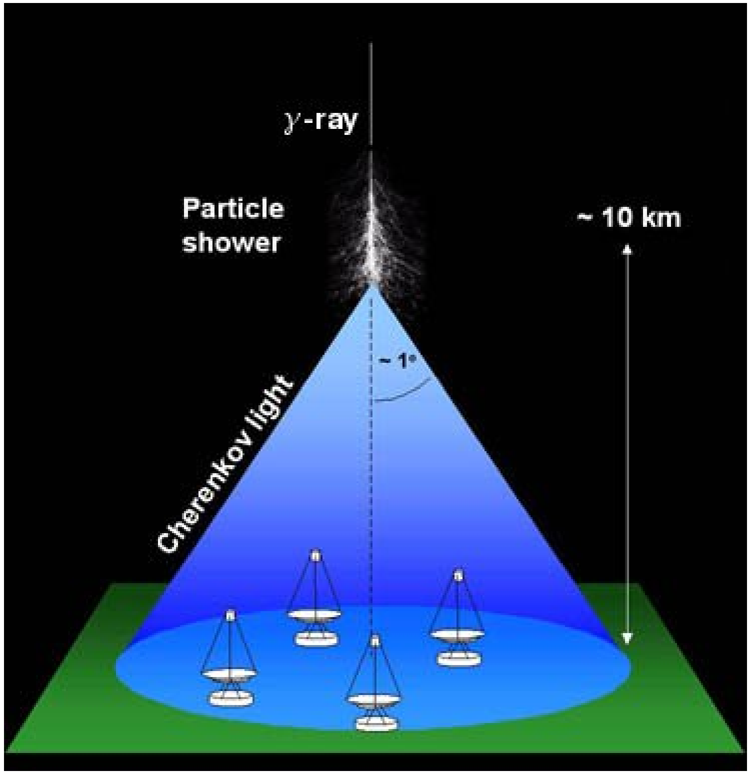


cooling of the device → decrease of dark counts by a factor of 2 every 8K

in future:
improvement of technology to reduce defects



Cherenkov Telescope Array



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