



# Performance studies of Silicon Photomultipliers with quench resistors integrated to silicon bulk

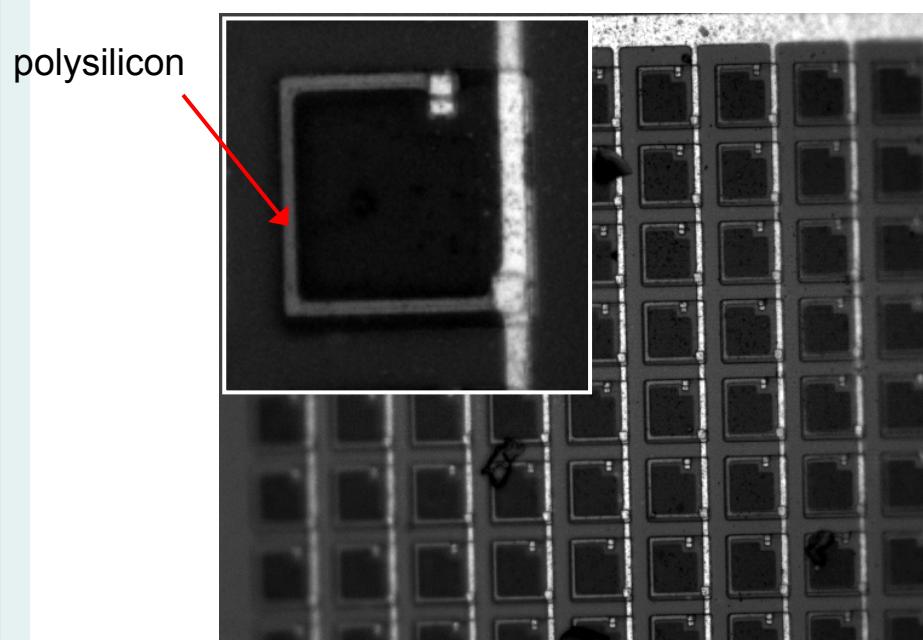
International Workshop on New Photon-detectors  
LAL Orsay, France 2012

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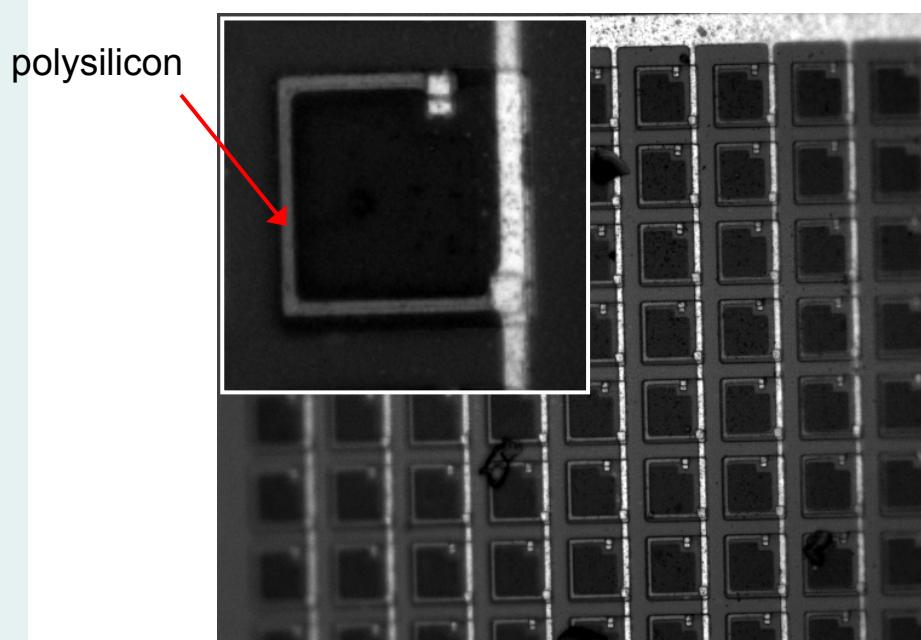
## ● Conventional Silicon Photomultiplier – SiPM

- 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



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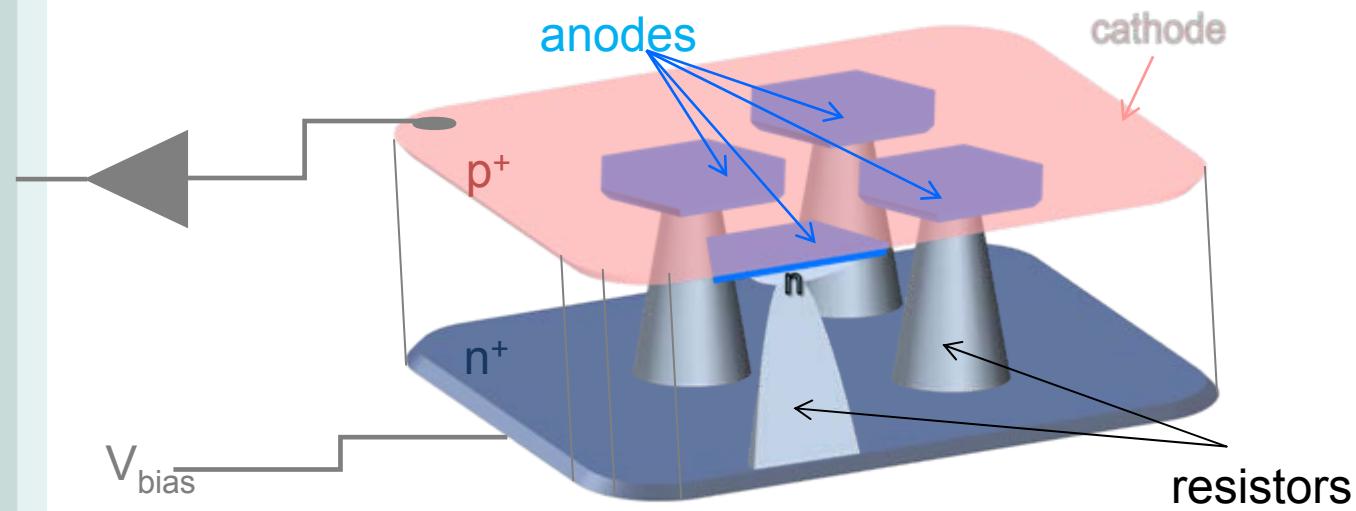
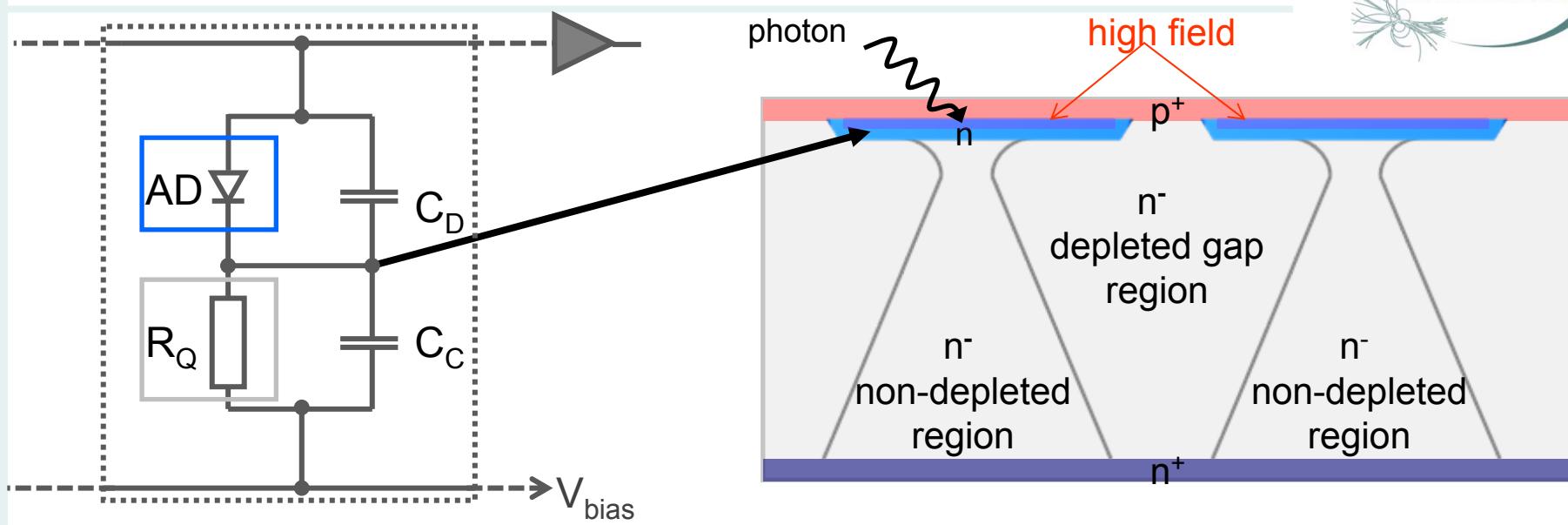


polysilicon resistor:

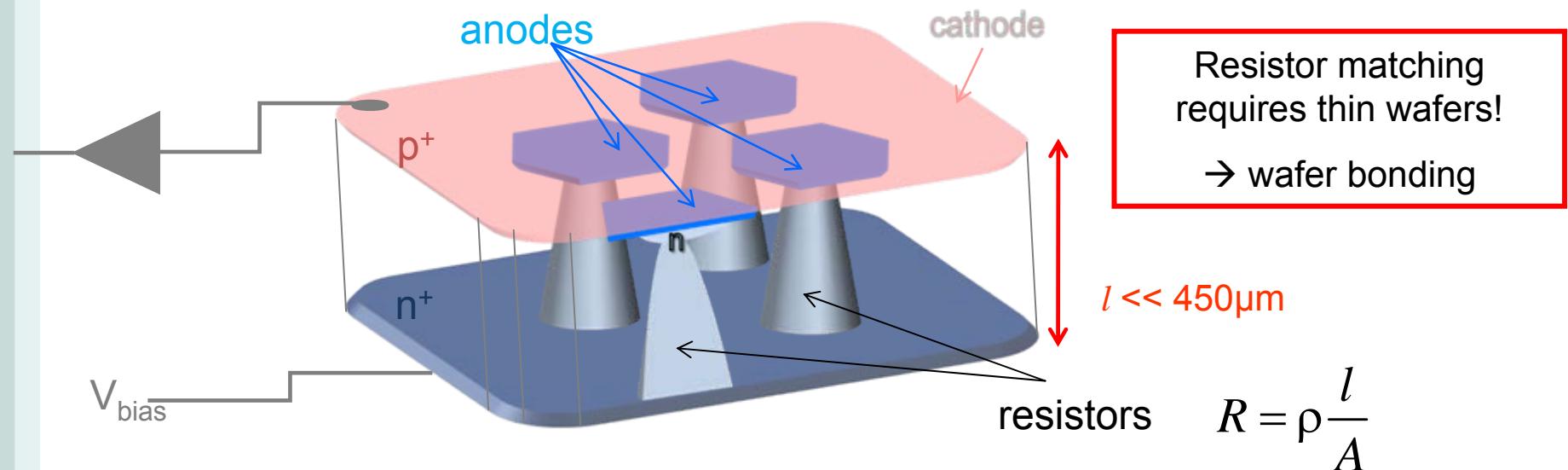
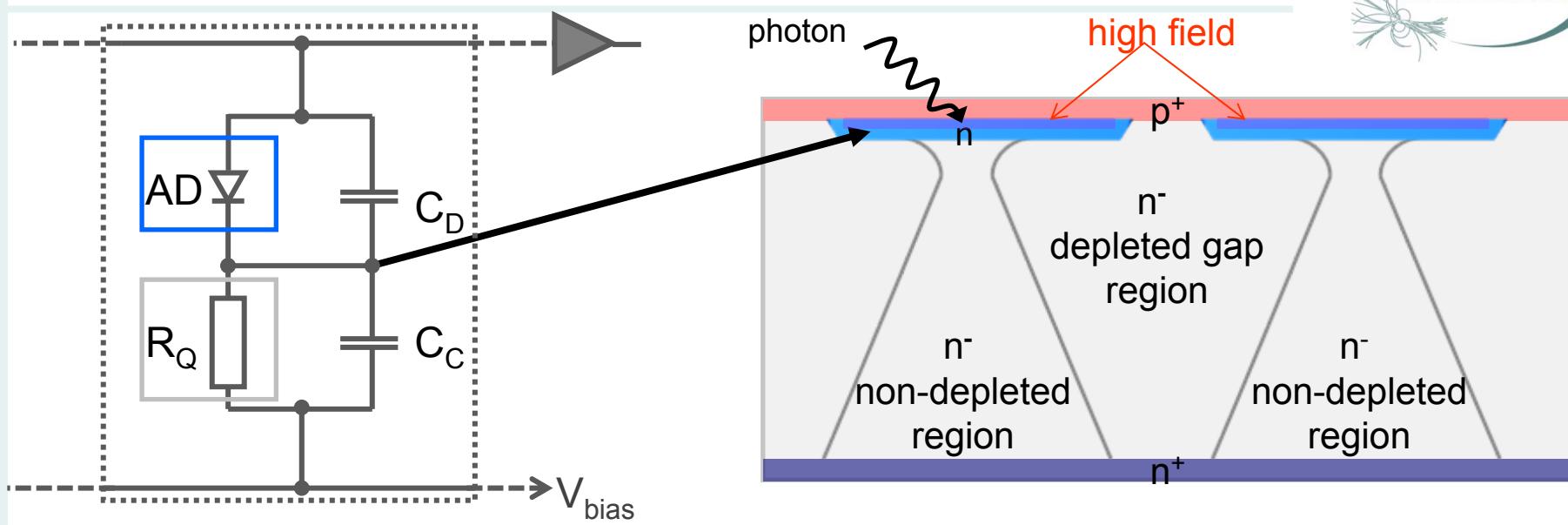
→ obstacle for light

→ limitation of PDE

## SiPM cell components → SiMPI approach

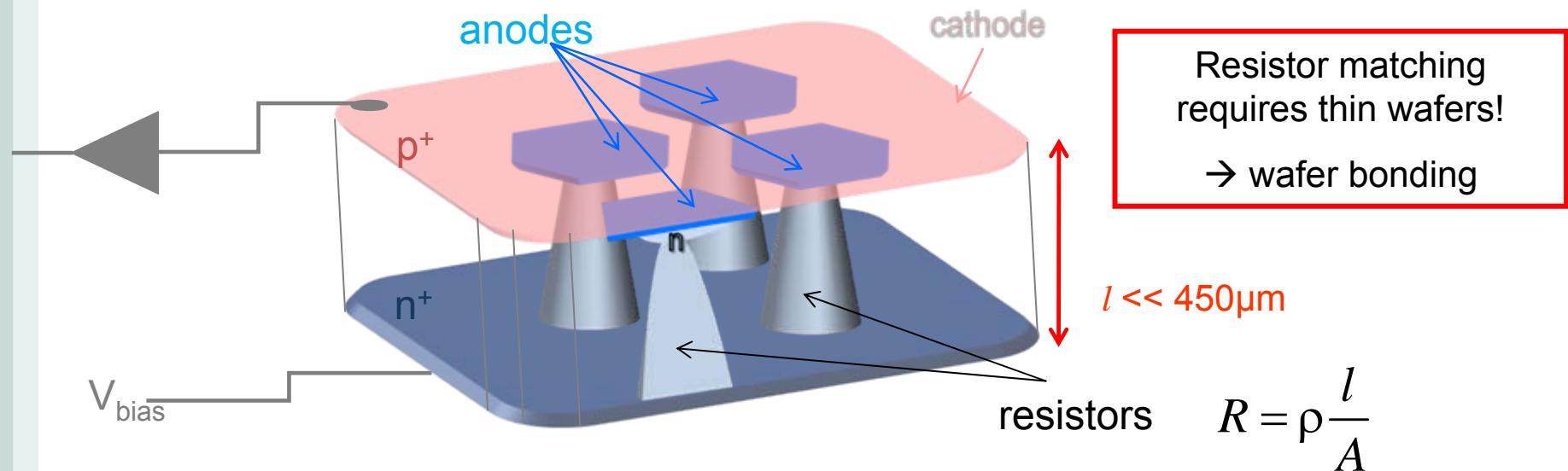
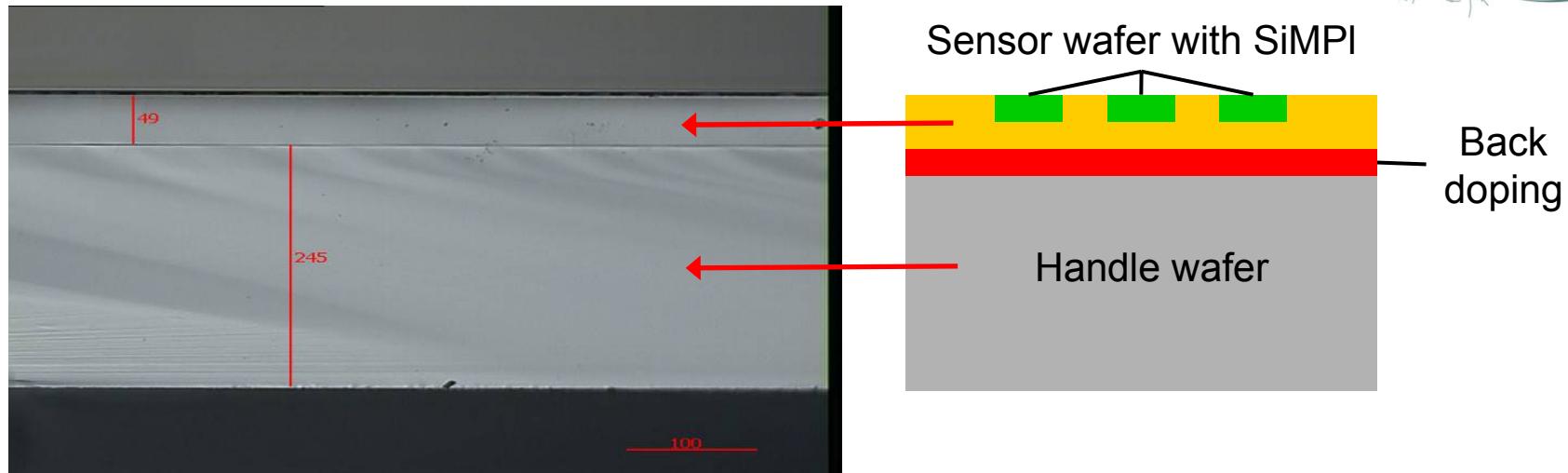


## SiPM cell components → SiMPI approach



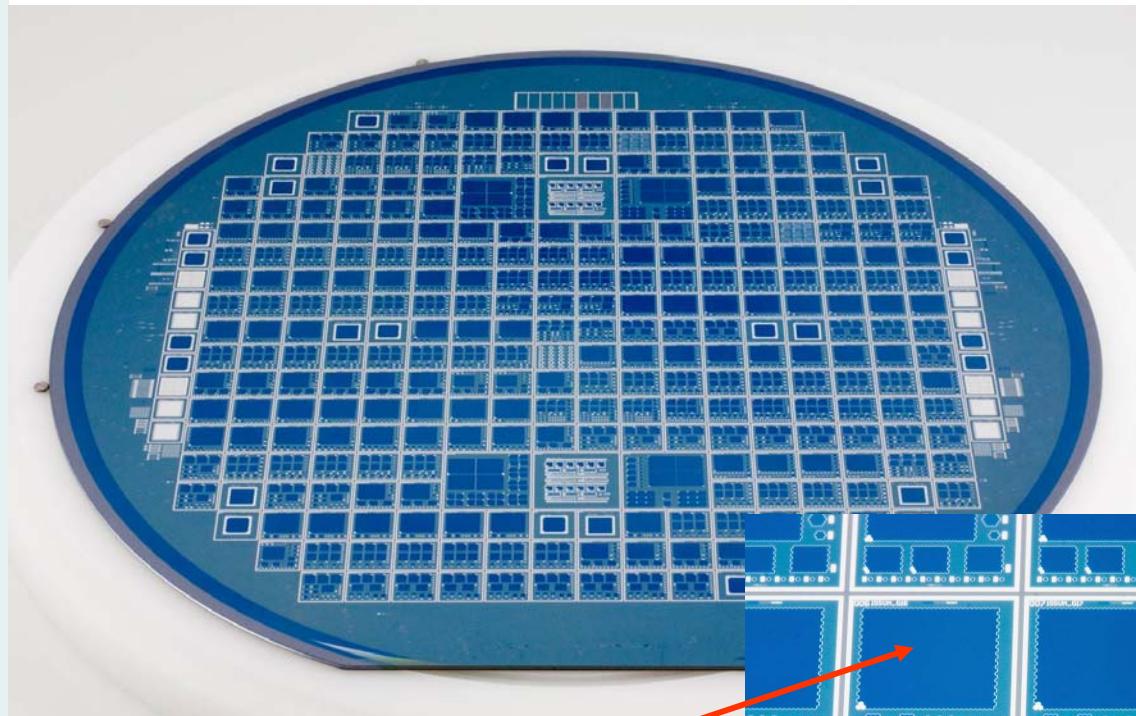
$$R = \rho \frac{l}{A}$$

## ● SiPM cell components → SiMPI approach



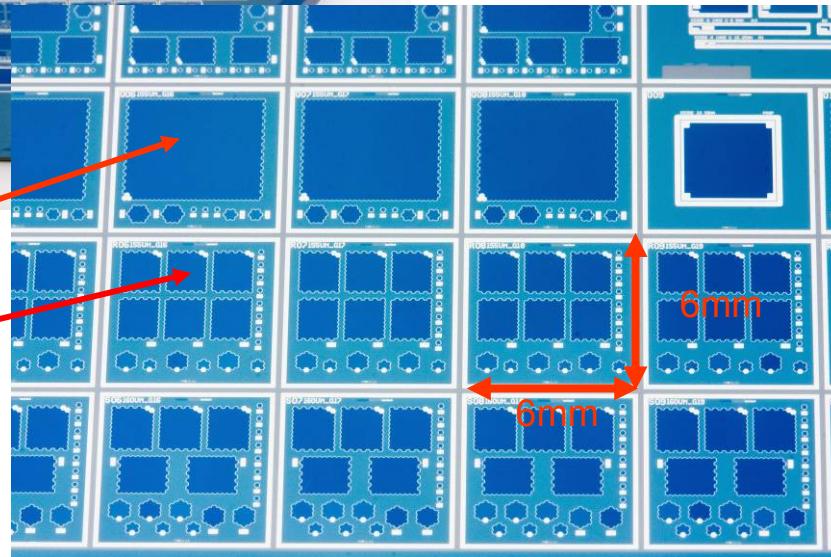
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## ● SiMPI prototype



30x30 arrays

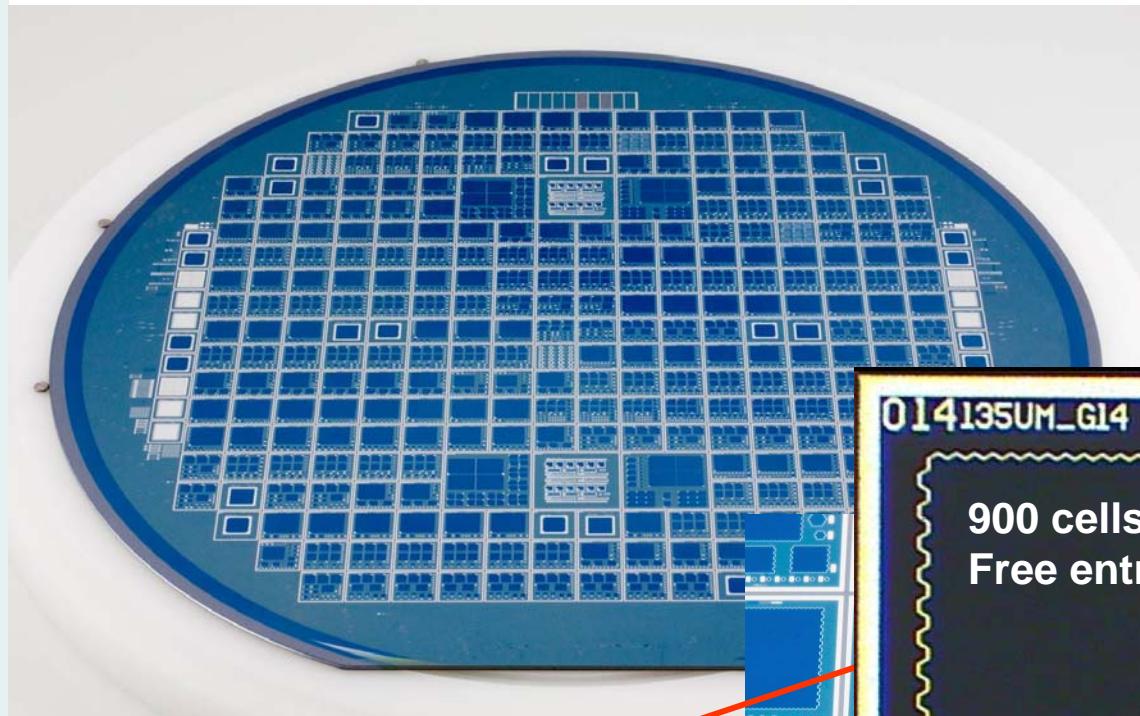
10x10 arrays



Wide range of  
geometrical variations

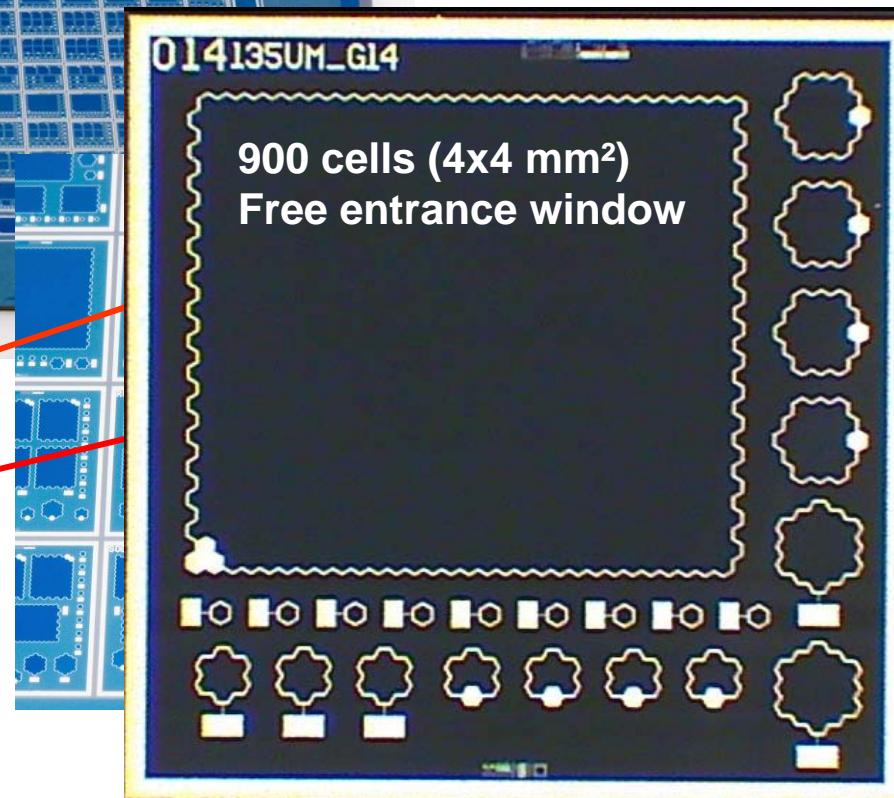
pitch: 90 -160 µm  
different gap size

## ● SiMPI prototype

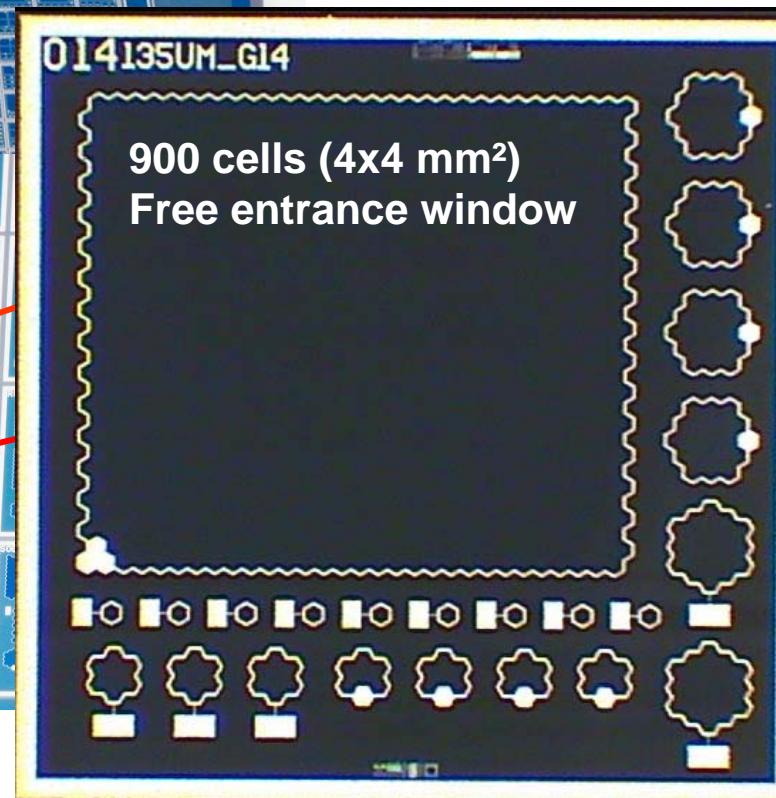
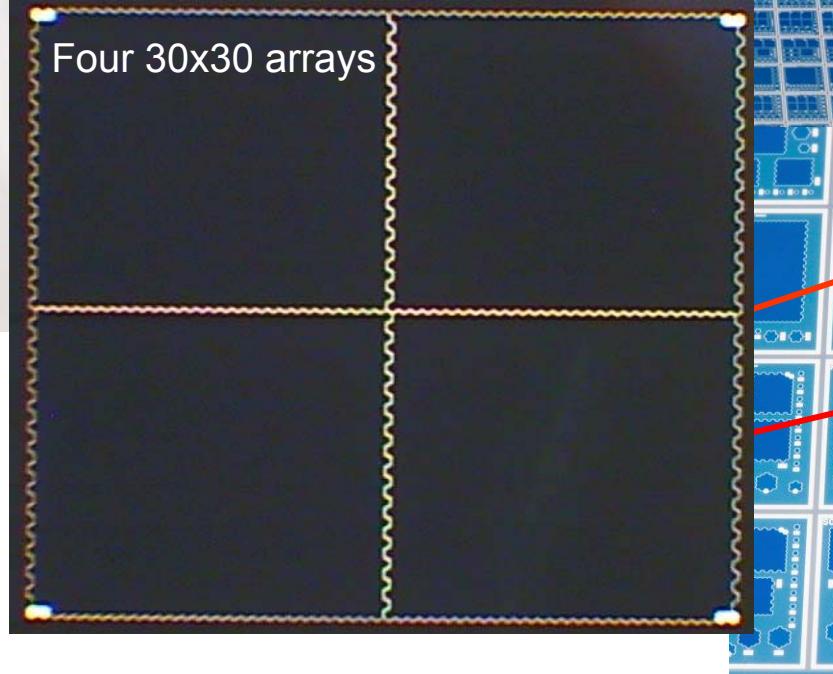


30x30 arrays

10x10 arrays



## ● SiMPI prototype



## ● Advantages and Disadvantages

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### 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

## ● Advantages and Disadvantages

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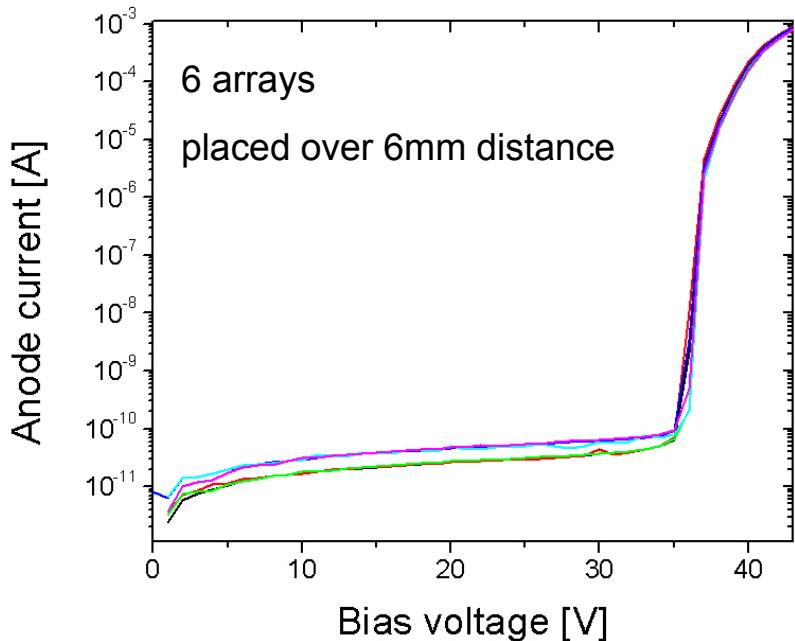
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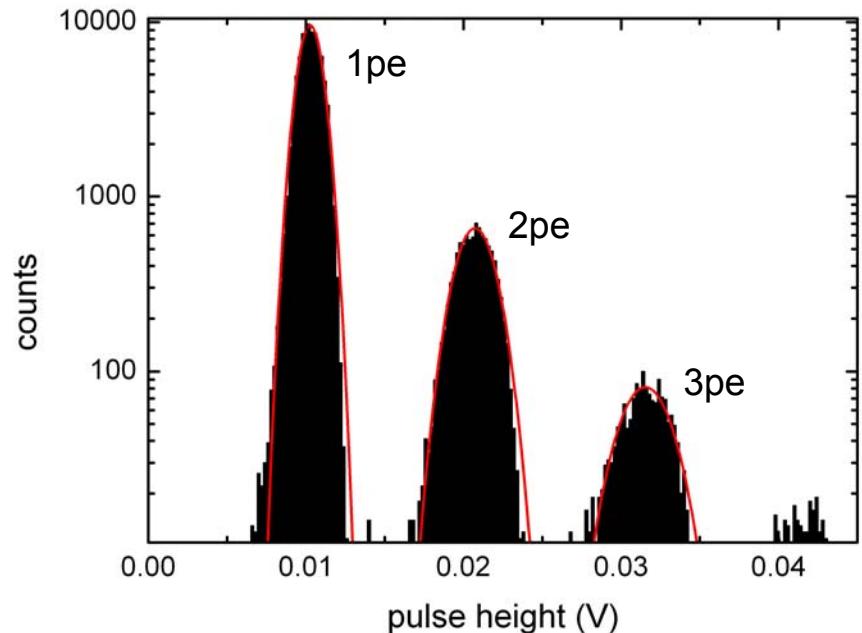
### Drawbacks:

- 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  $135\mu\text{m}$  pitch @ 253K  
(only dark count spectrum)

## ● Dark counts

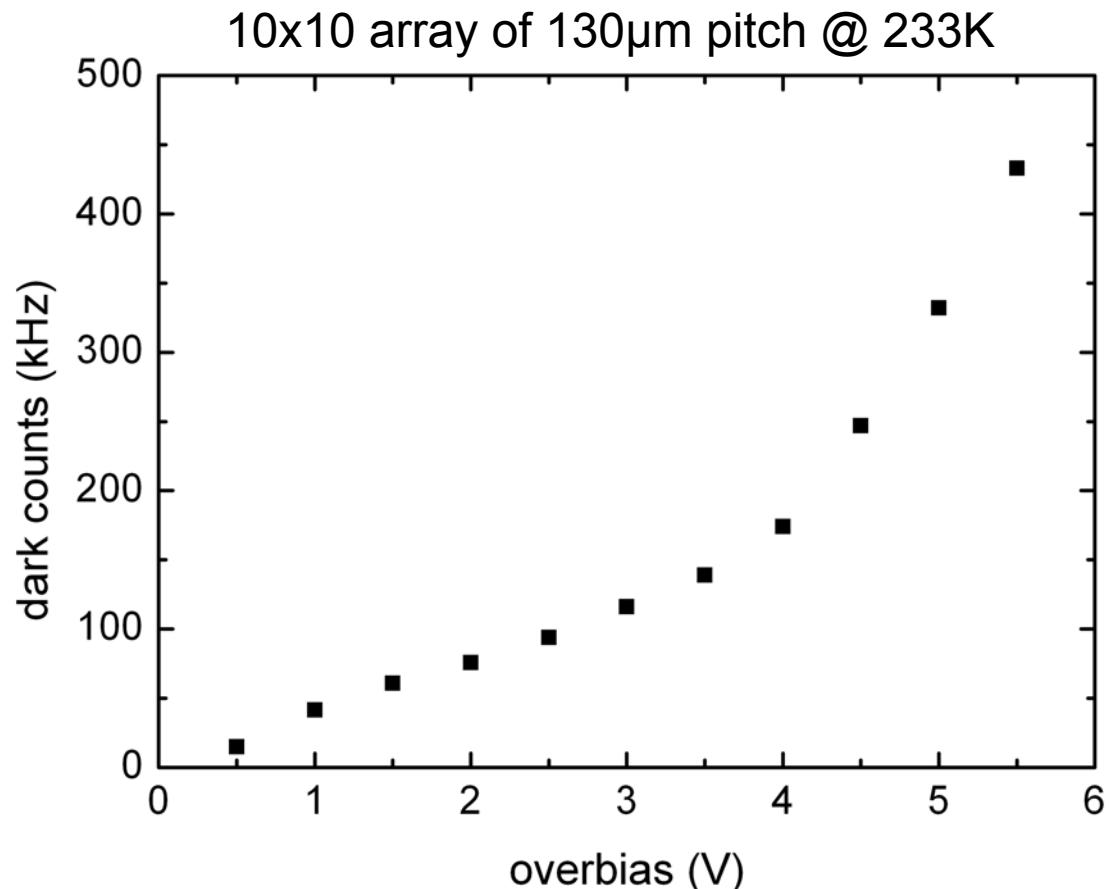
due to non-optimized process sequence  
~10MHz/mm<sup>2</sup> @300K for 4V overbias

Thermal generation

→ cooling helps

normal operation up to  
4V overbias @233K

overbias > 4V  
→ non-quench condition



## ● Temperature dependence of quench resistor

Resistors designed for room temperature operation

→ limitation of operation voltage (non-quenching)

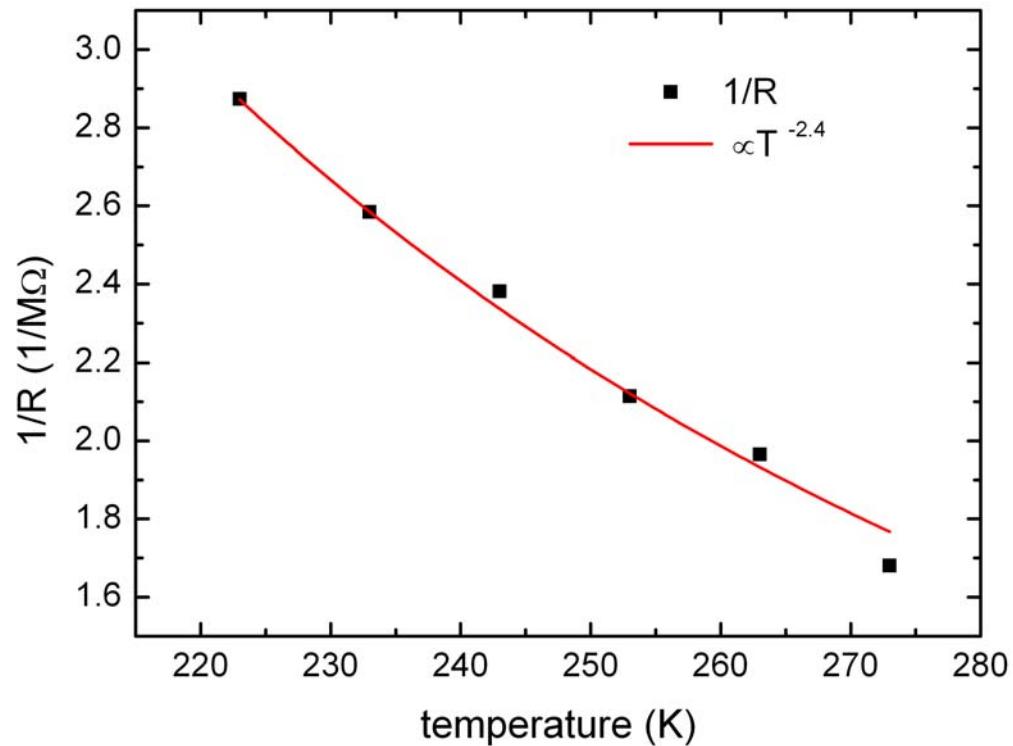
S. Cova et al., Appl. Opt. 35 (1996)

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

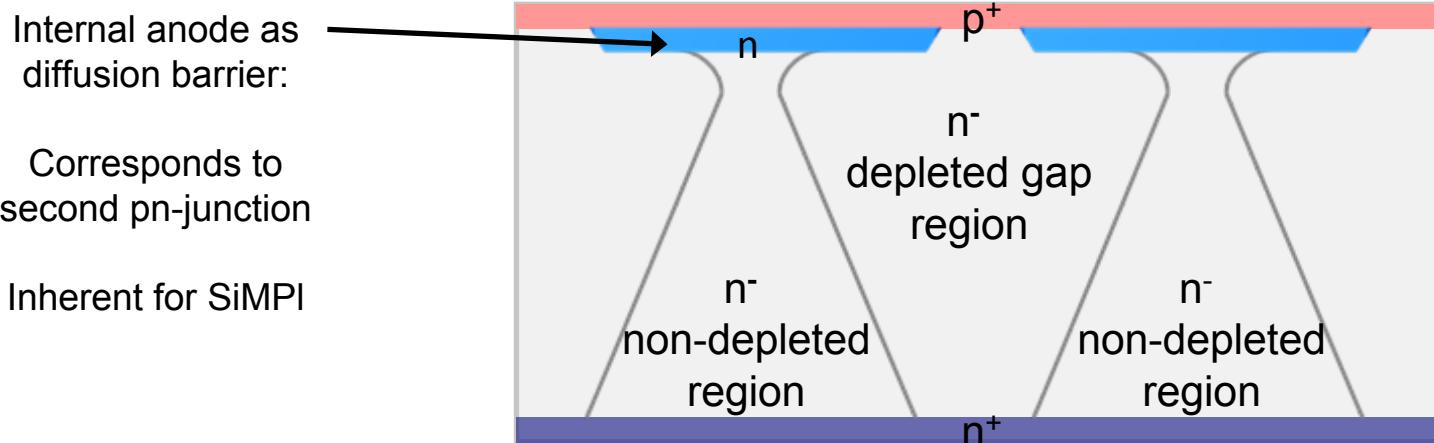
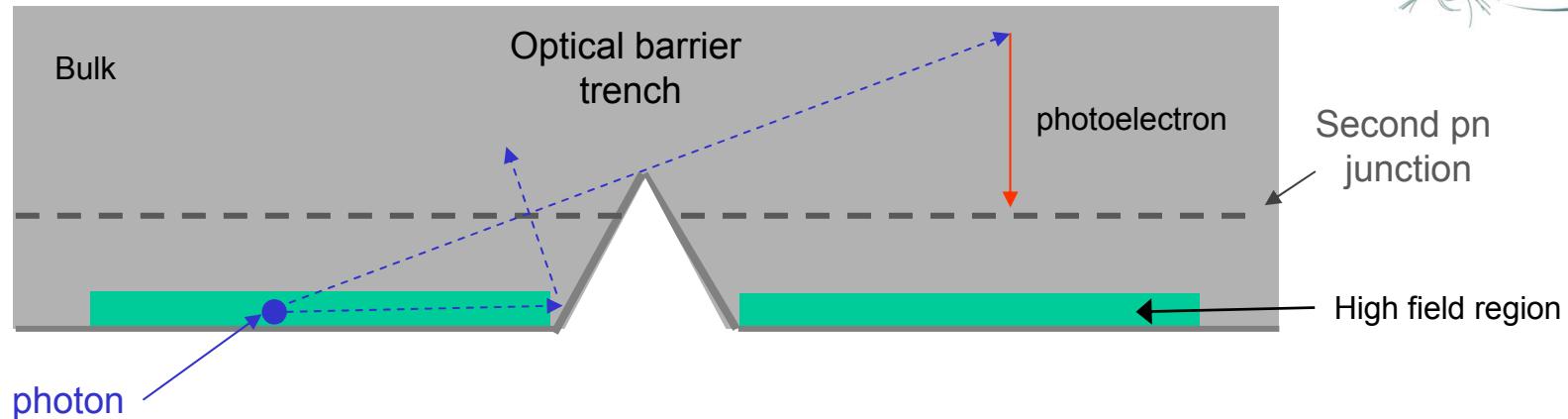
$$\tau = R_Q \cdot C_D$$

mobility:

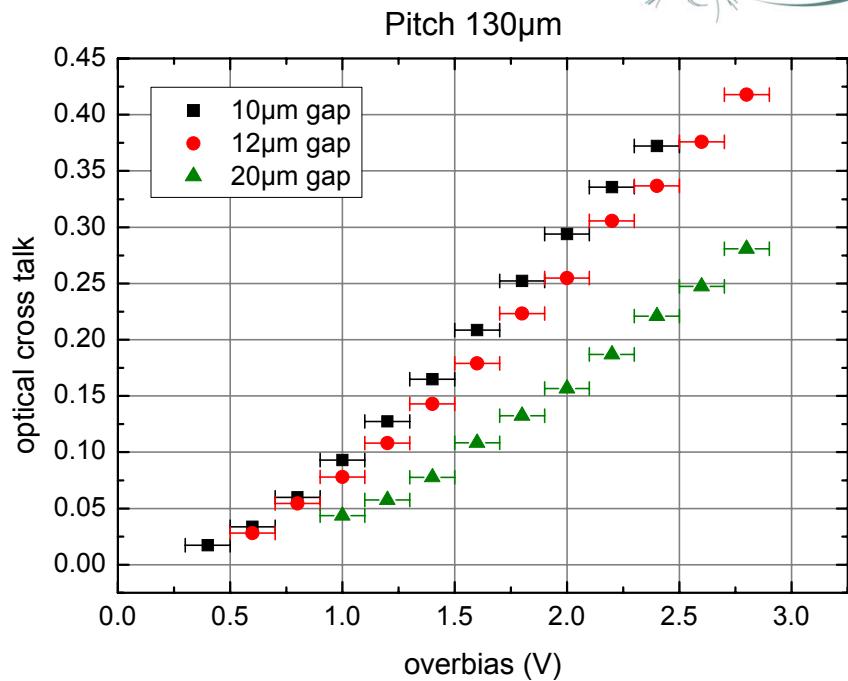
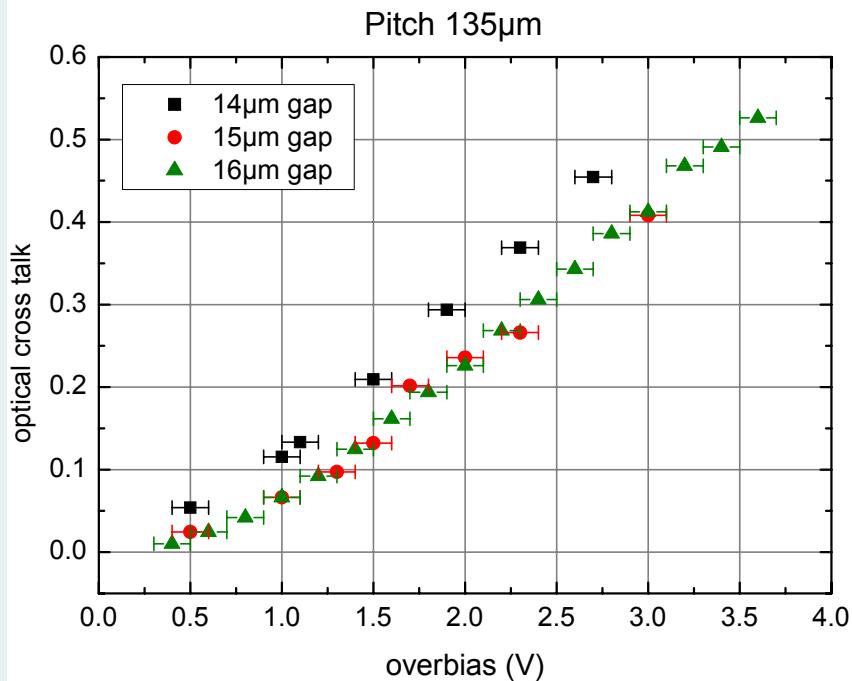
$$\mu_n(\text{Si}) \propto T^{-2.4}$$



## Optical cross talk



# Optical cross talk

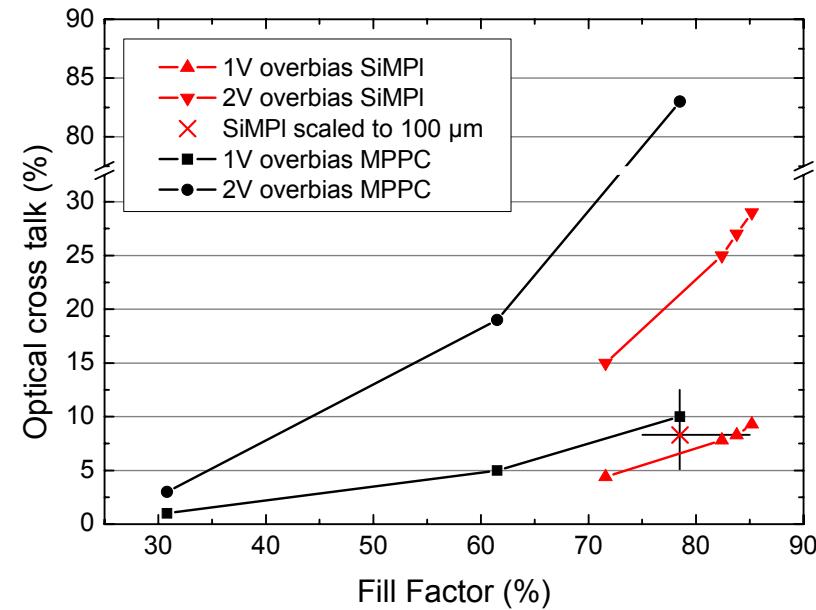
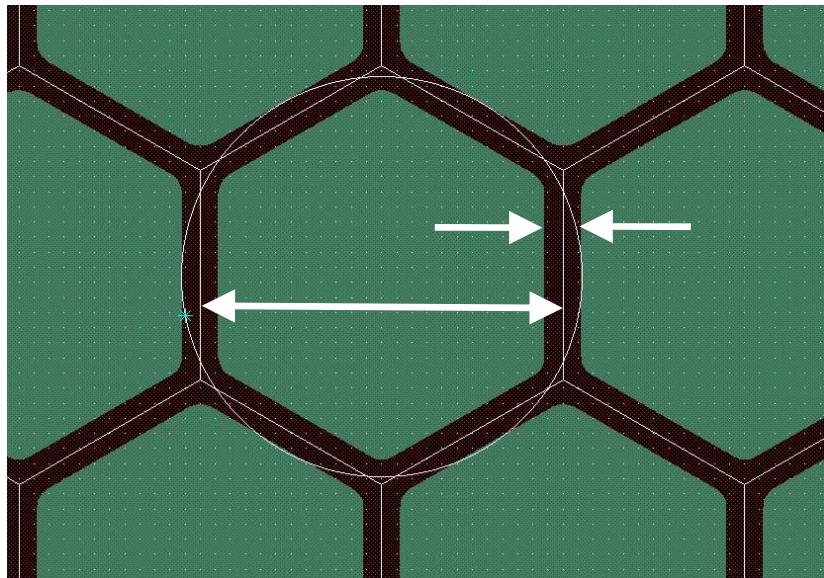


Increasing overbias  
~ increasing gain  
~ increasing trigger efficiency

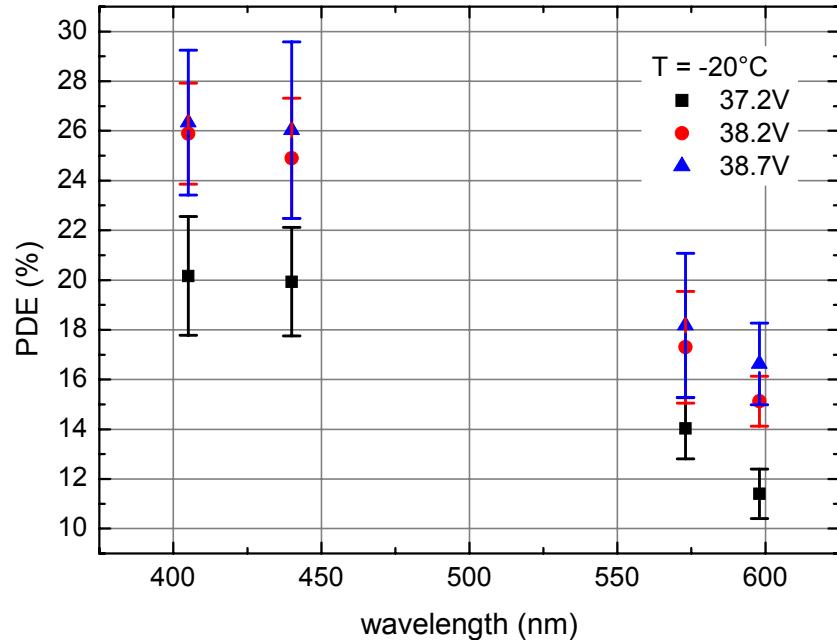
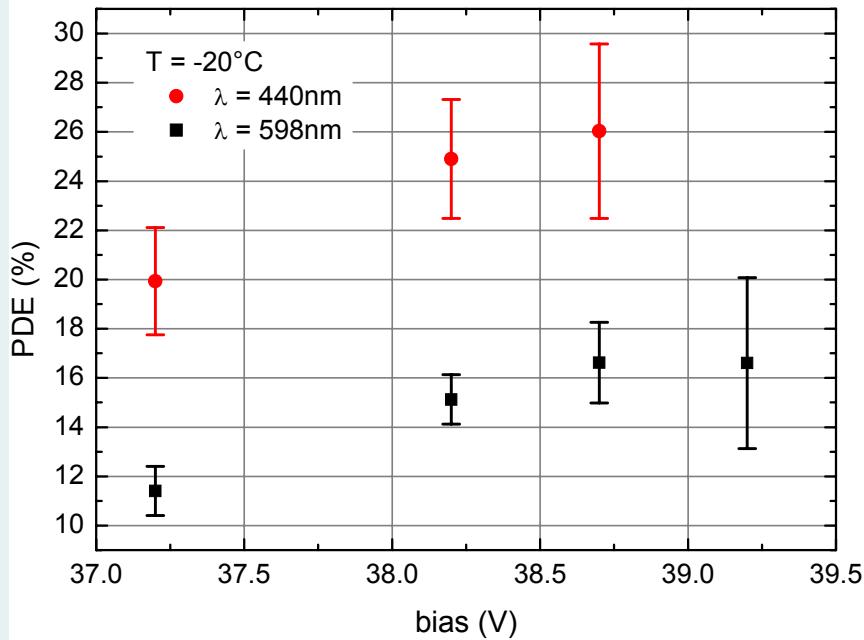
Non-linear dependency on overbias

## 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: 130 $\mu$ m pitch, 20 $\mu$ m gap



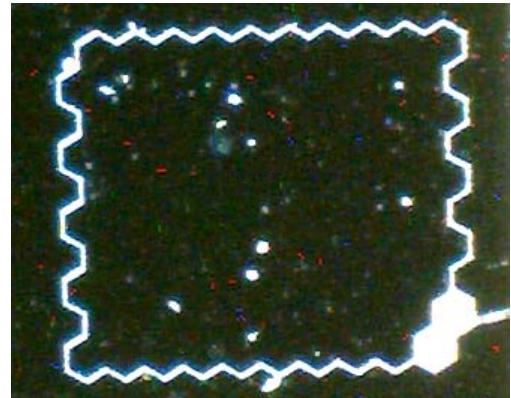
Breakdown voltage: 35.2V

Fill factor: 0.716

Laser repetition rate: 0.5MHz

→ Max. recovery time 2 $\mu$ s

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%

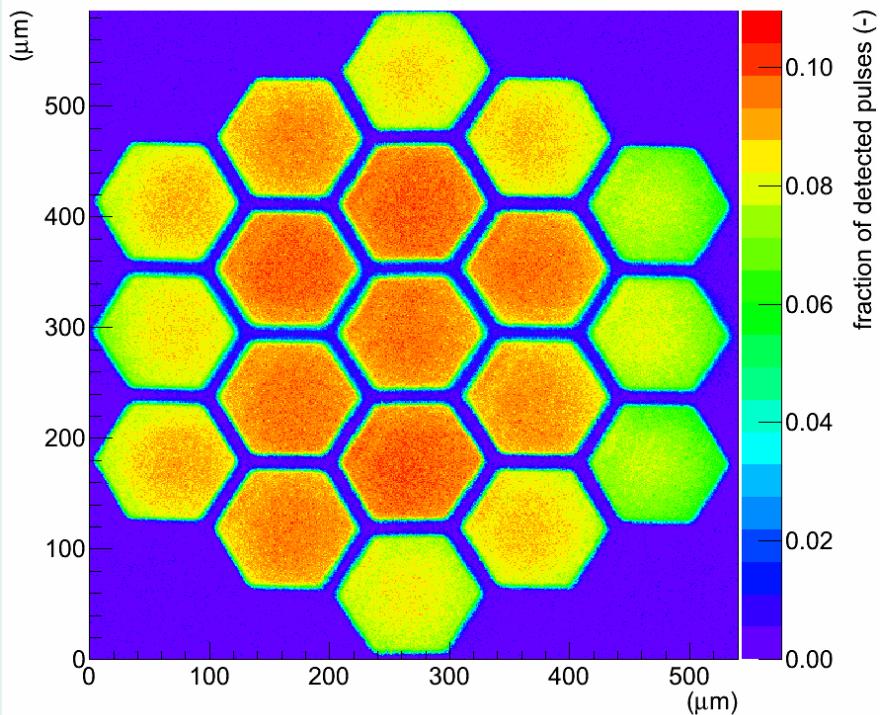
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**With optimization (85% GE & 90% transmission) PDE of 65% easily achievable**

## ● Detection efficiency homogeneity scan

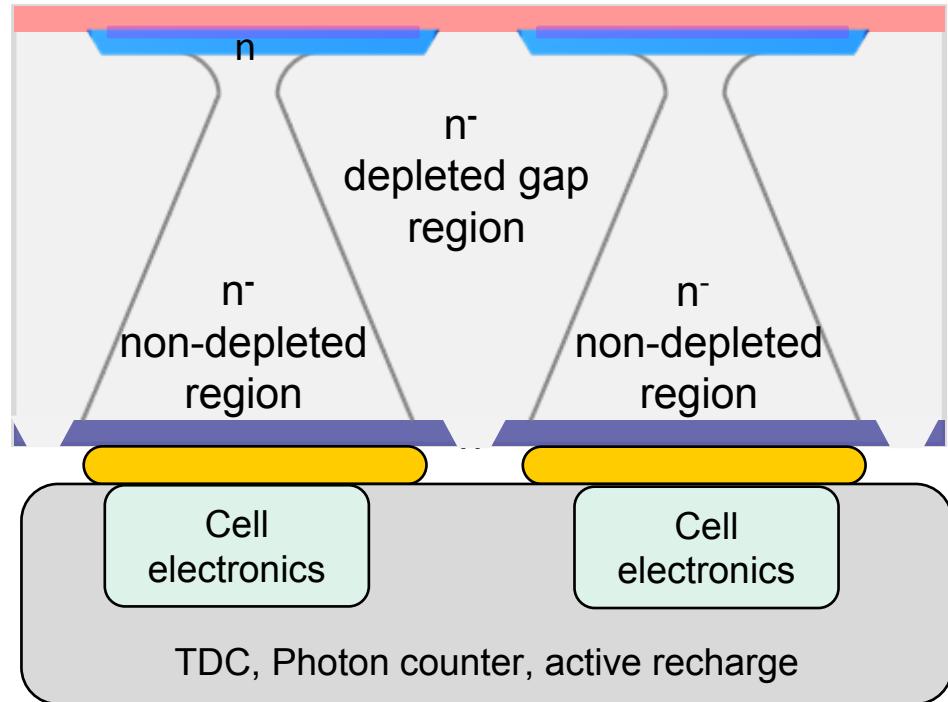


Scan of SiPM response with pulsed light source (ca.  $1\mu\text{m}$  spot size)

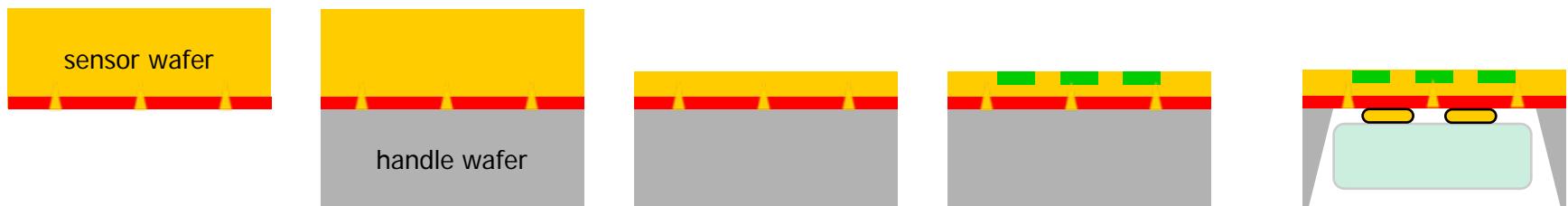
- relative PDE map
- overall geometrical fill factor
- ...

For details → Poster by M. Tesař (Session B)

## ● Next SiMPI generation – photon detection



Topologically flat & free surface  
High fill factor  
Sensitive to light

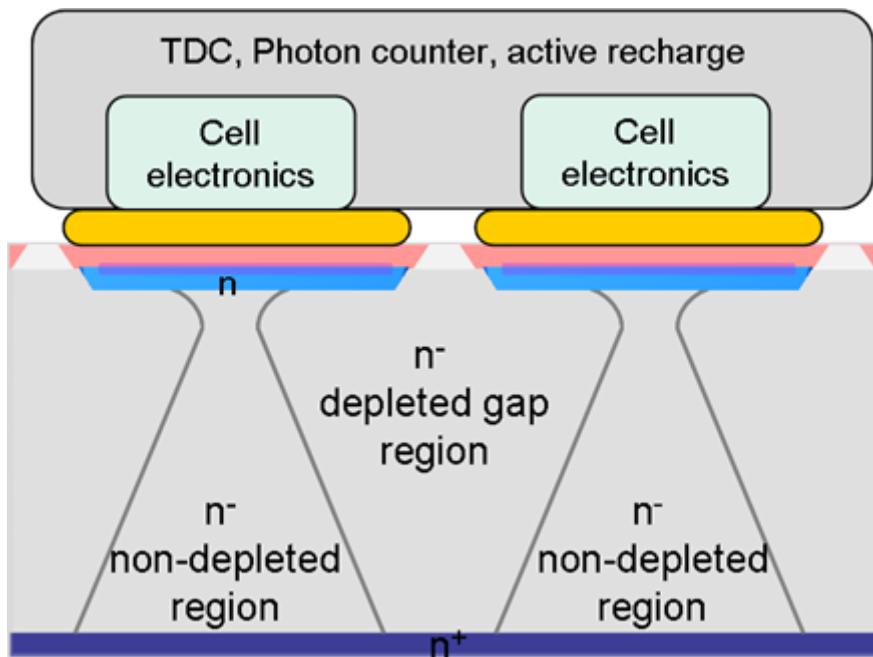


## ● Next SiMPI generation – particle detection

### Detection of particles:

- Excellent time stamping due to avalanche (sub-ns)
- Minimum ionizing particles generate about 80 e-h-pairs/ $\mu\text{m}$
- 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

## ● Summary & Outlook

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### 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, ...) are ongoing

New production to reduce dark counts and implement small pixels

Next SiMPI generation → first concepts for single cell readout

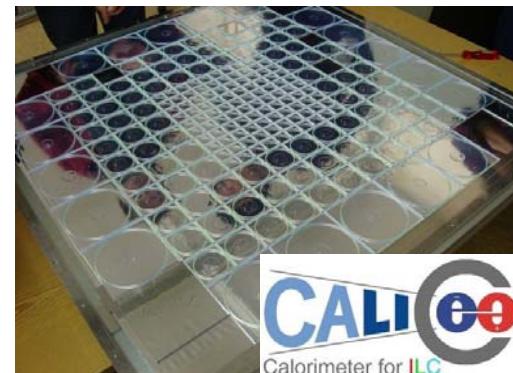
# Thanks

## 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

Silicon Photomultiplier promising candidate

## ● Polysilicon quench resistors

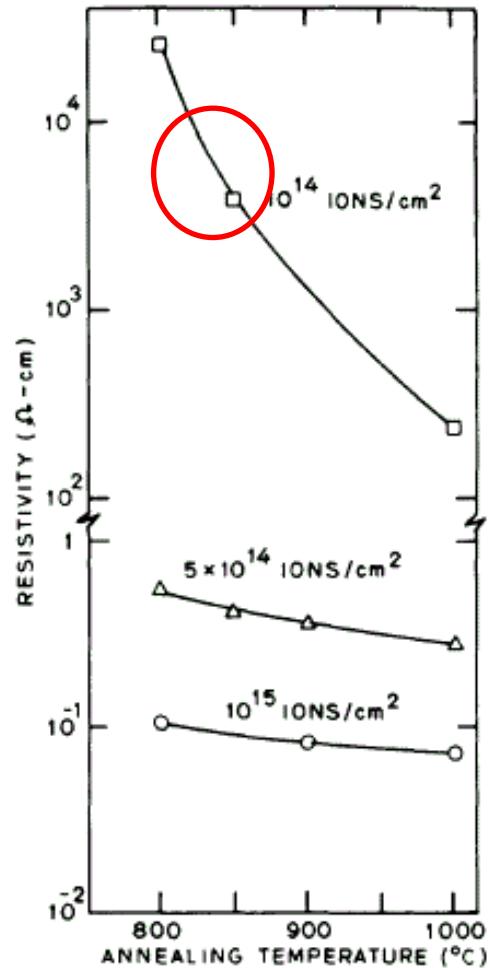
critical resistance range

→ rather unreliable process step

obstacle for incident light

→ fill factor decreased

→ limitation of detection efficiency

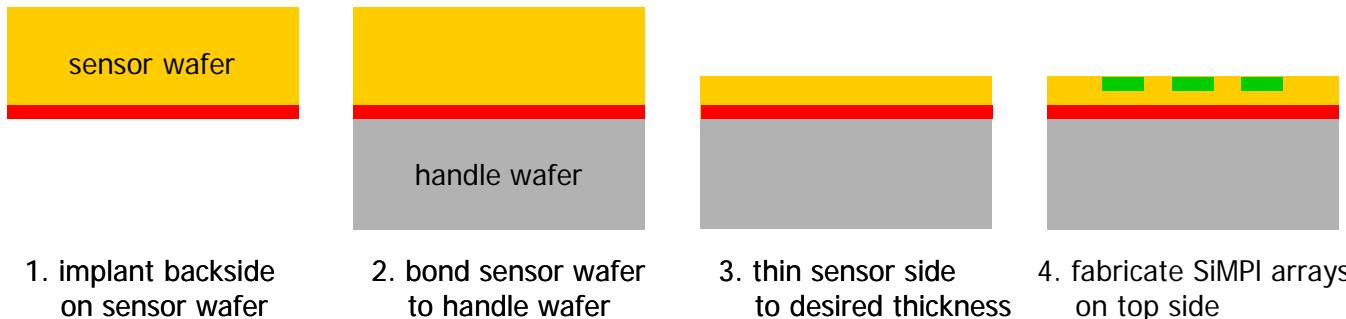


M. Mohammad et al.

'Dopant segregation in polycrystalline silicon',

J. Appl. Physics, Nov., 1980

## Wafer bonding – Silicon On Insulator wafers



Industrial partners

MPI HLL

## Gain linearity

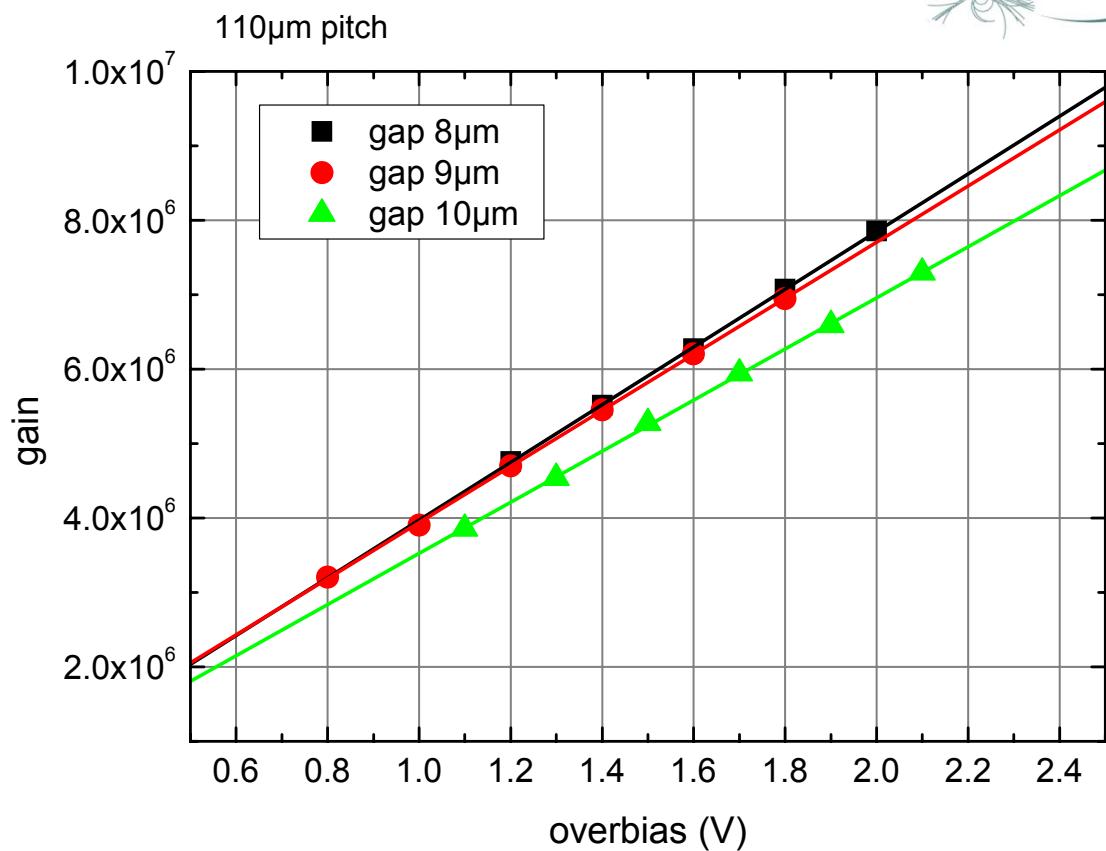
Expected:  
linear with overbias voltage

Gain at 1V overbias

$$08 \mu\text{m}: 3.88 * 10^6$$

$$09 \mu\text{m}: 3.77 * 10^6$$

$$10 \mu\text{m}: 3.43 * 10^6$$



## Gain linearity

pulse height  $\propto Q$



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

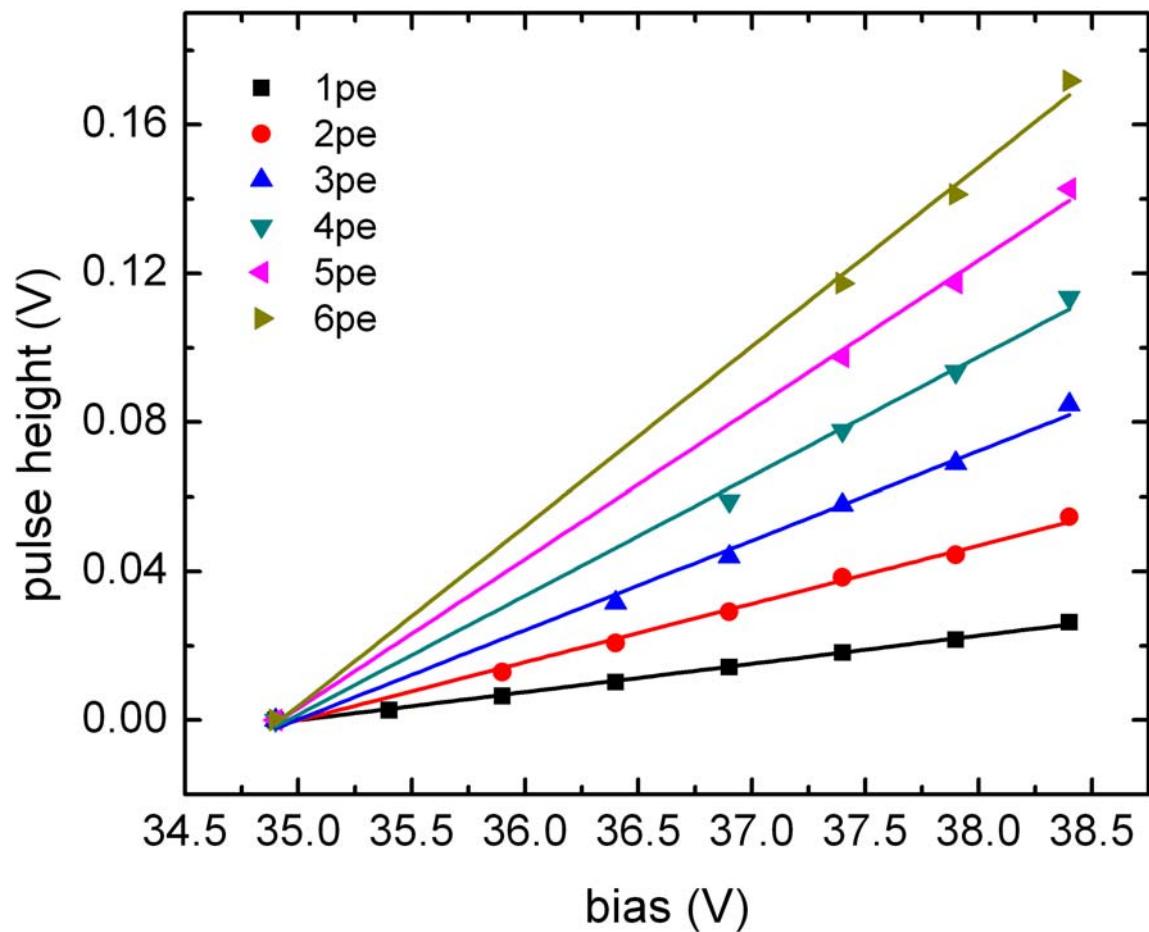


linear



normal operation

10x10 array of 135 $\mu$ m pitch @ 253K



## Photon Detection Efficiency



$$PDE = \text{quantum efficiency} \cdot \text{fill factor} \cdot \text{Geiger efficiency}$$

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

## Optical cross talk & PDE

Pitch / Gap	Fill factor	Cross talk (2V V <sub>ob</sub> )
130µm / 10µm	85.2%	29%
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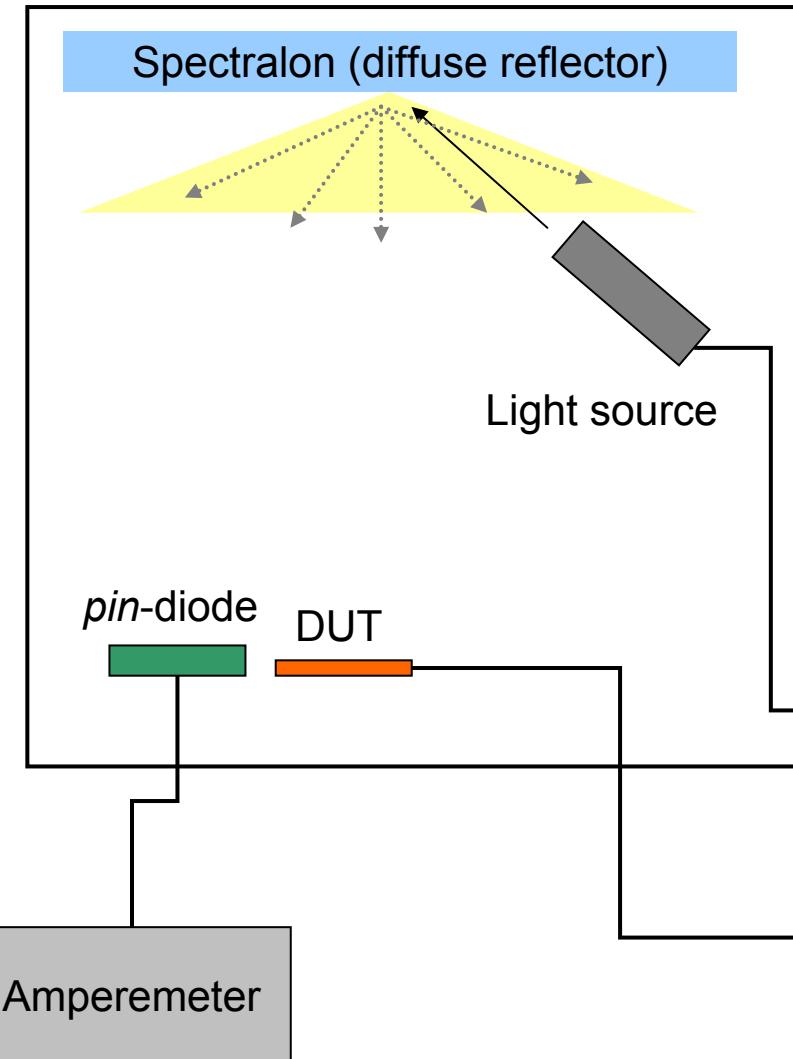
Photon Detection Efficiency estimation:

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

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

## PDE measurements - setup

Light-tight climate chamber



### Method:

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

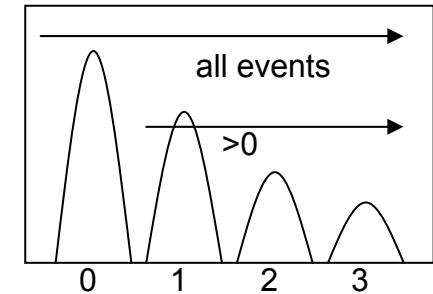
No distortion by optical cross talk or after-pulsing

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

Pulse generator

Scope

Histogram



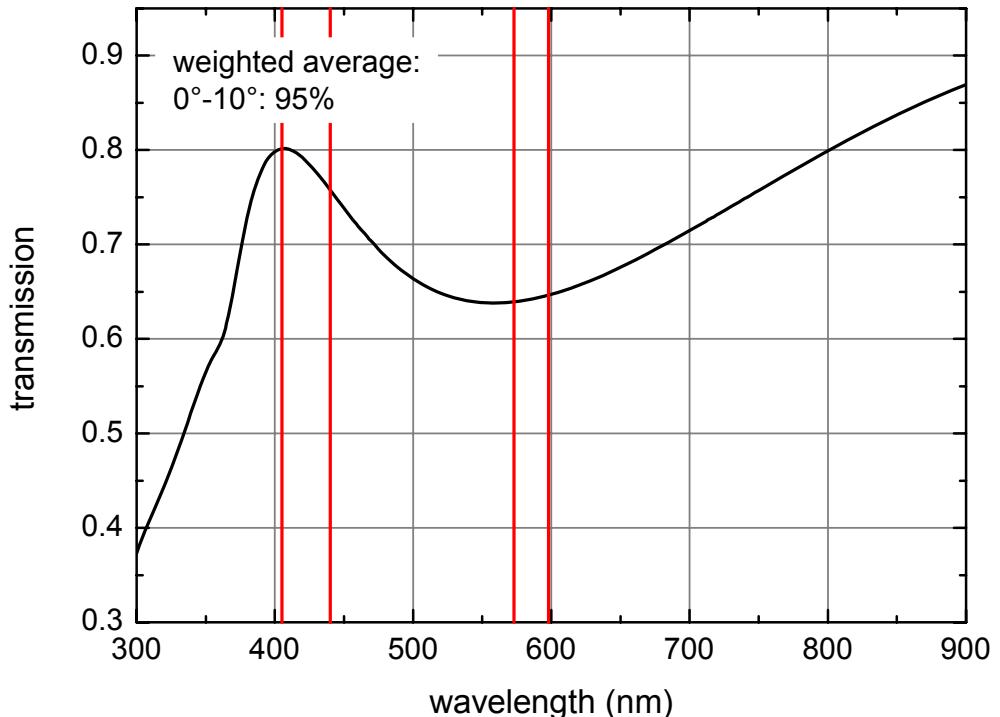
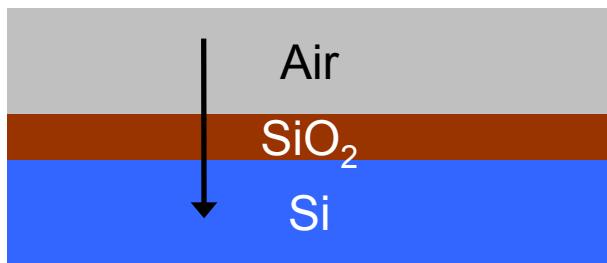
## ● Transmission to silicon

200nm  $\text{SiO}_2$

Prototype: no optimized entrance window

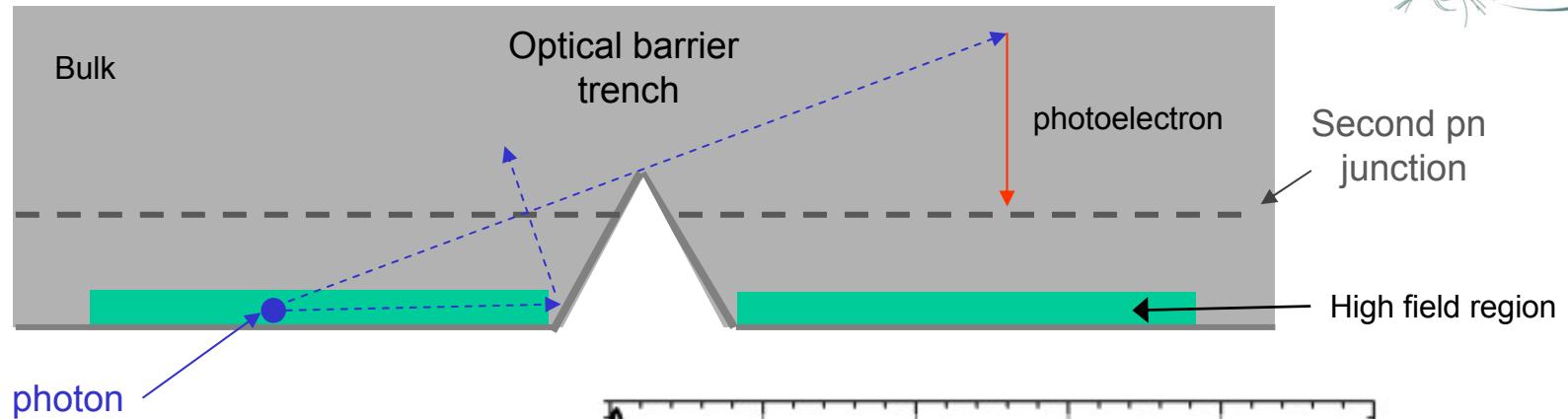
Simulations with OpenFilters\* for transmission into silicon

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



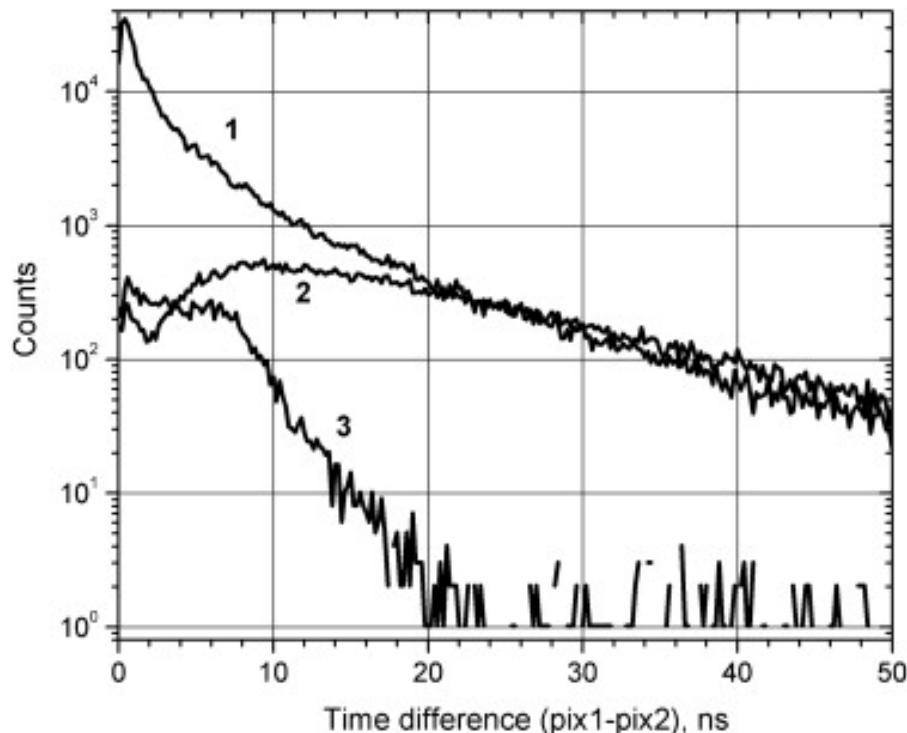
PDE measurements @ 405nm, 440nm, 573nm, 598nm

## Optical cross talk



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

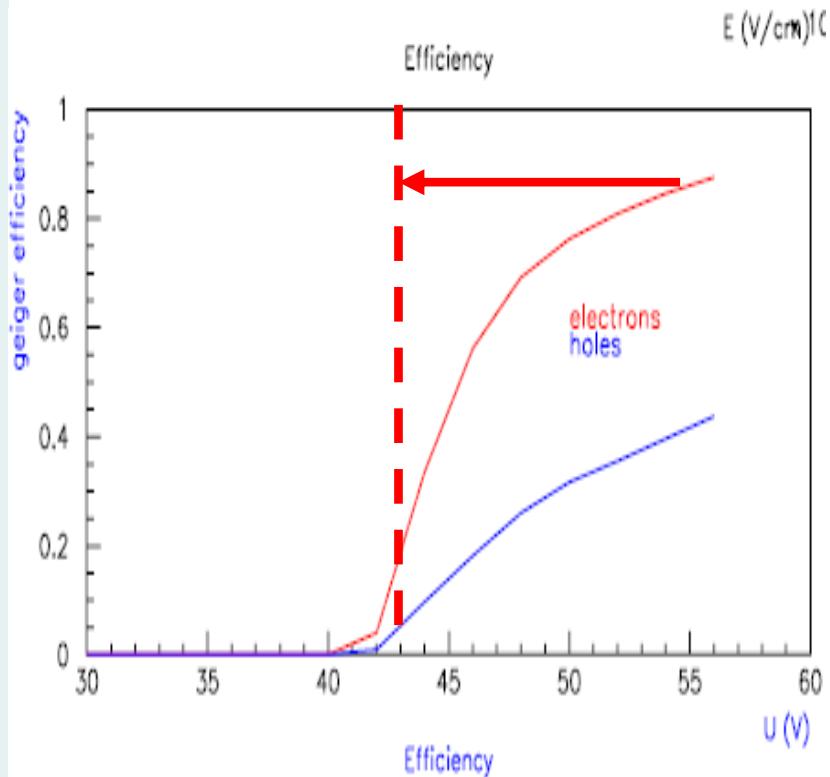


P. Buzhan et al., NIM A 610 (2009)

## ● Next SiMPI 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

