The SiMPl detector
-
silicon photomultipliers with bulk-integrated quench resistor

Young Scientist Workshop, Wildbad Kreuth 2011

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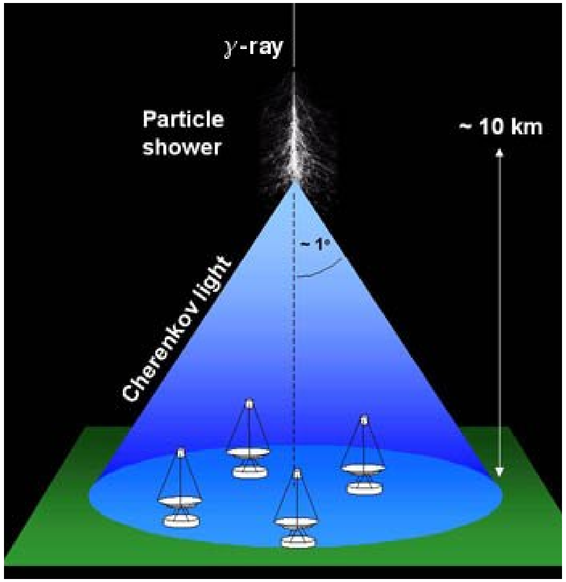
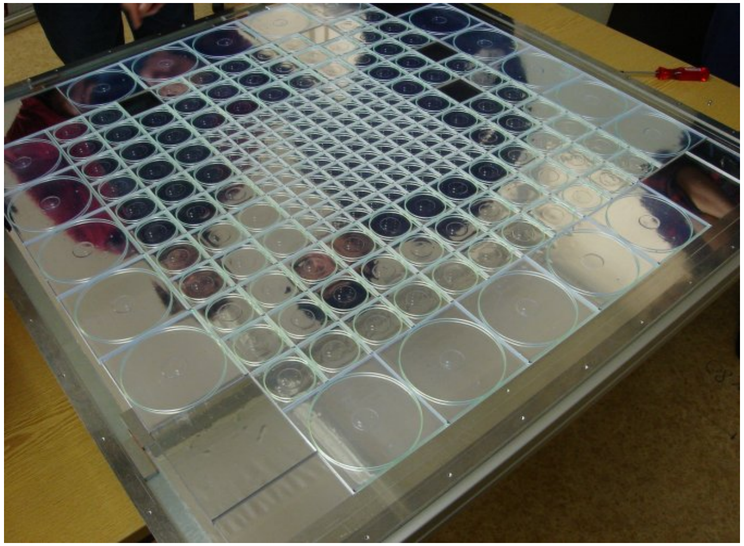
Outline

- motivation
- introduction to silicon photomultiplier
- SiMPl concept: **S**ilicon **M**ulti**P**ixel **l**ight detector
- first results on SiMPl
- method for determination of non-quenching in SiPMs
- summary & outlook

Motivation for novel photon detectors





Low light level camera in ground-based gamma-ray astronomy

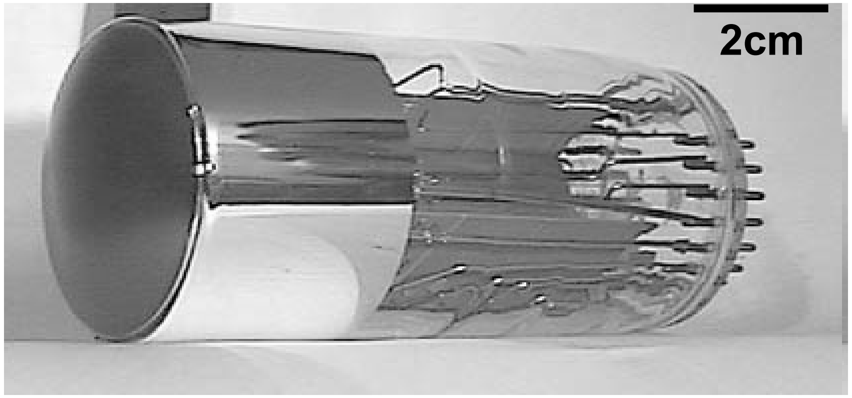
Single tile readout for high granularity in calorimetry

large number of photon detectors for future experiments and applications

Why silicon photomultipliers (SiPM)?

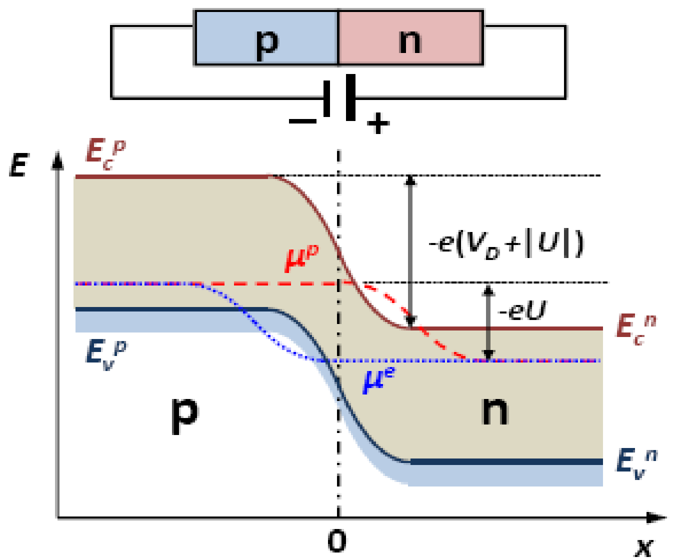
requirements for photon detectors:

- robust and stable
- easy to calibrate
- compact
- low costs
- low power consumption
- insensitive to magnetic fields
- highest possible detection efficiency
- …



SiPM is promising candidate to achieve all requirements

Semiconductor photodetectors



- pn-*junction in reverse bias*

incident photon creates e-h-pair

photocurrent $\propto$ 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 ($U_{bias} > U_{breakdown}$)

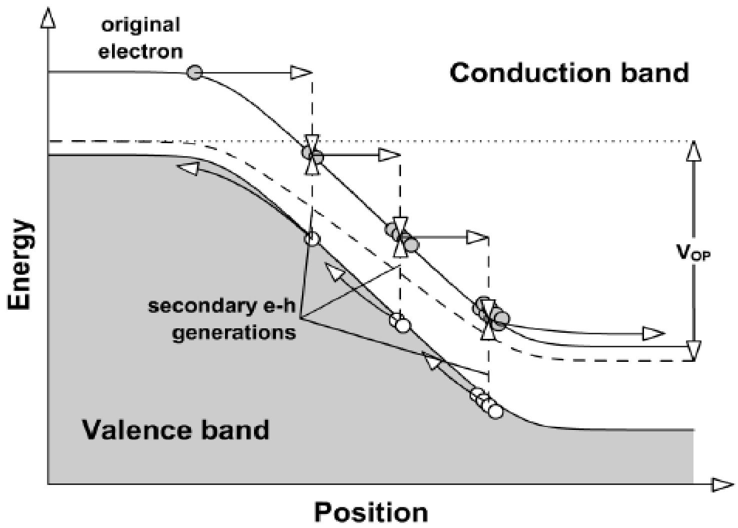
also holes contribute to avalanche generation → single photon detection

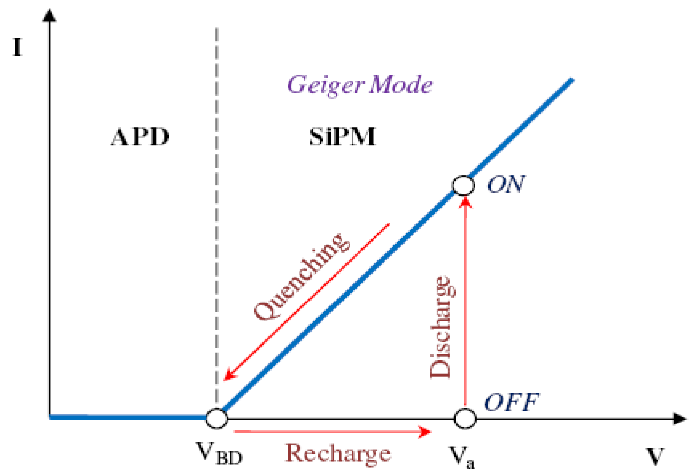
gain ~ $10^5 – 10^6$

quenching resistor stops discharge

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

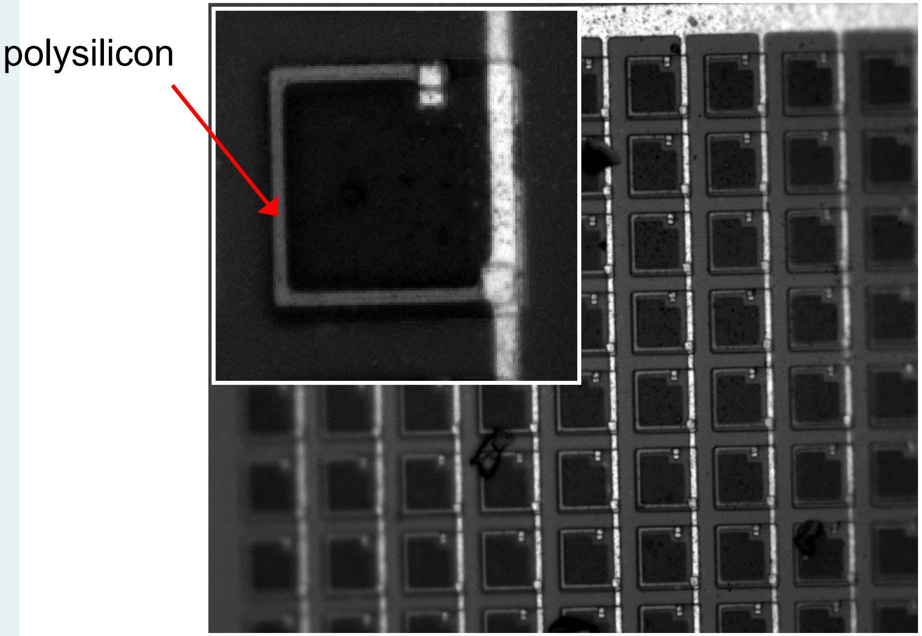
→ Silicon photomultipliers





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



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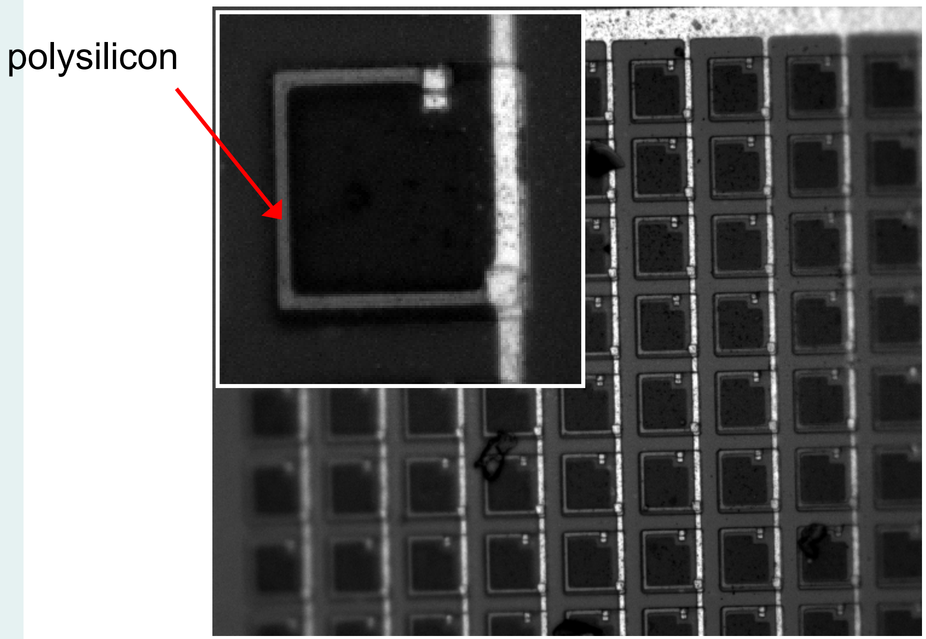
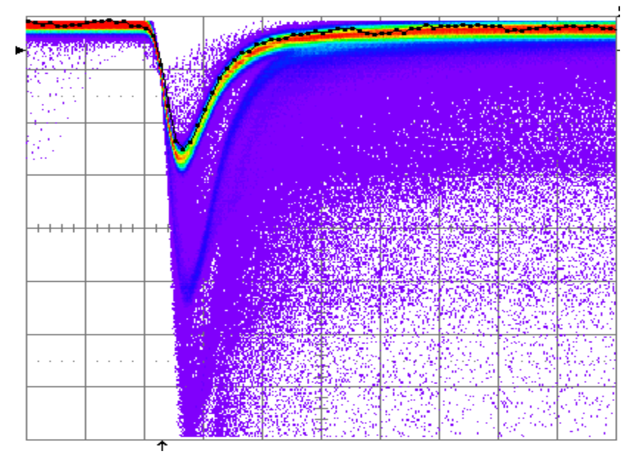
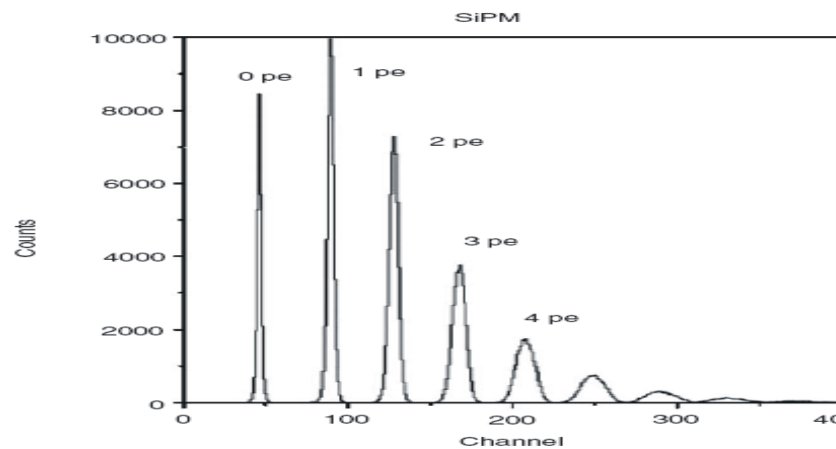






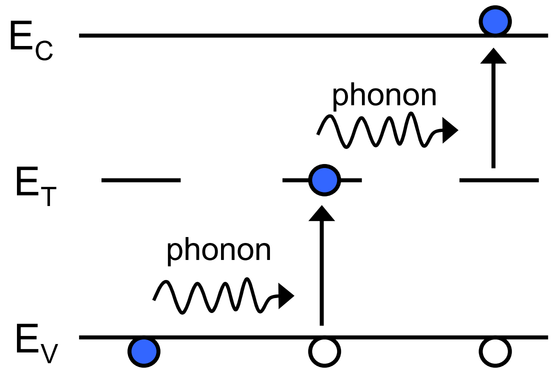
Drawbacks – dark counts

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)



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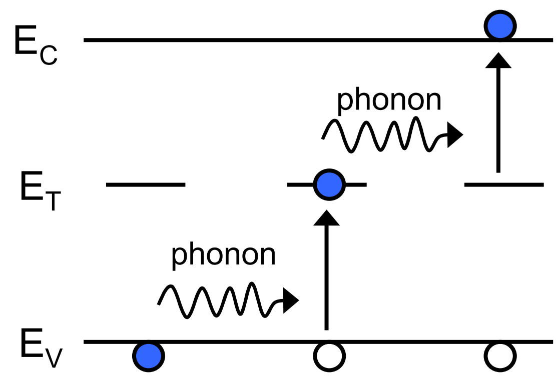
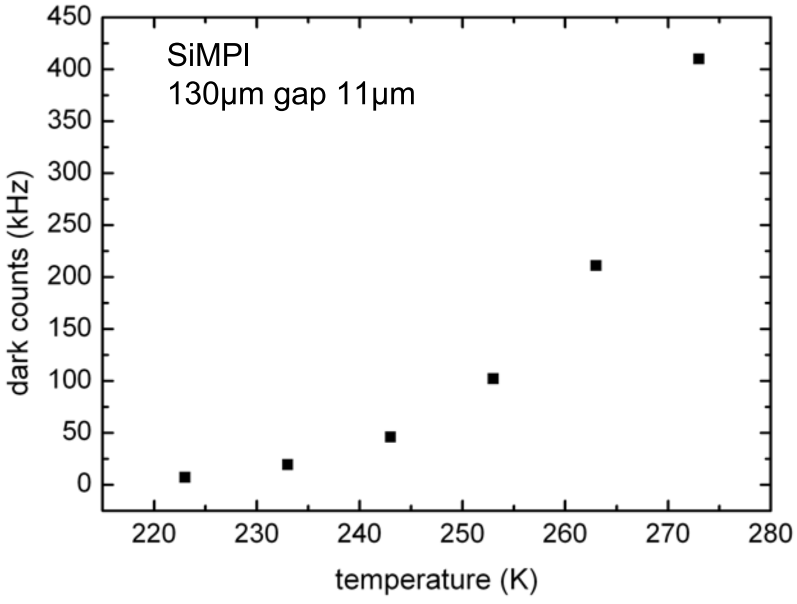


cooling of the device → decrease of dark counts by a factor of 2 every 8K



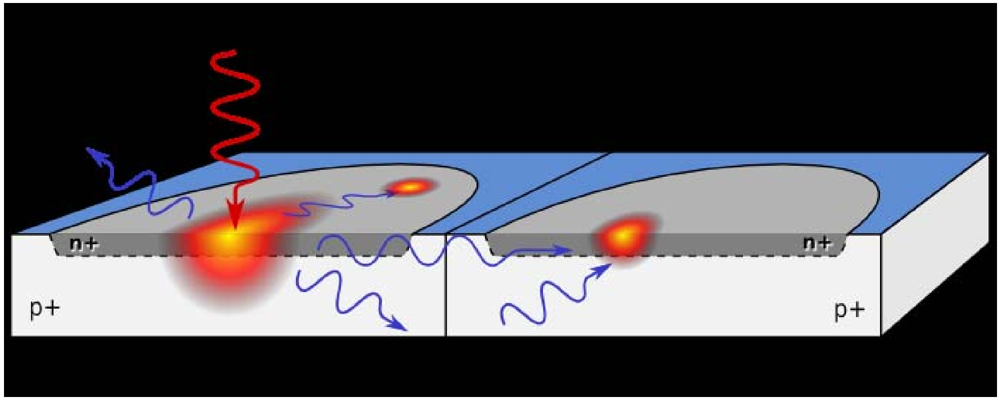
in future:
improvement of technology to reduce defects

Drawbacks – optical cross talk

hot-carrier luminescence:

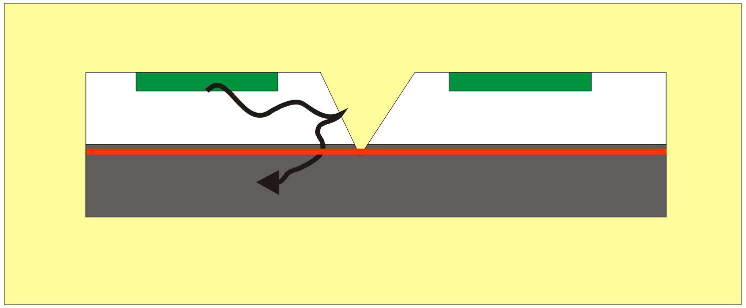
in an avalanche breakdown
10^5 carriers emit in average
1 photon with E > 1.14 eV

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

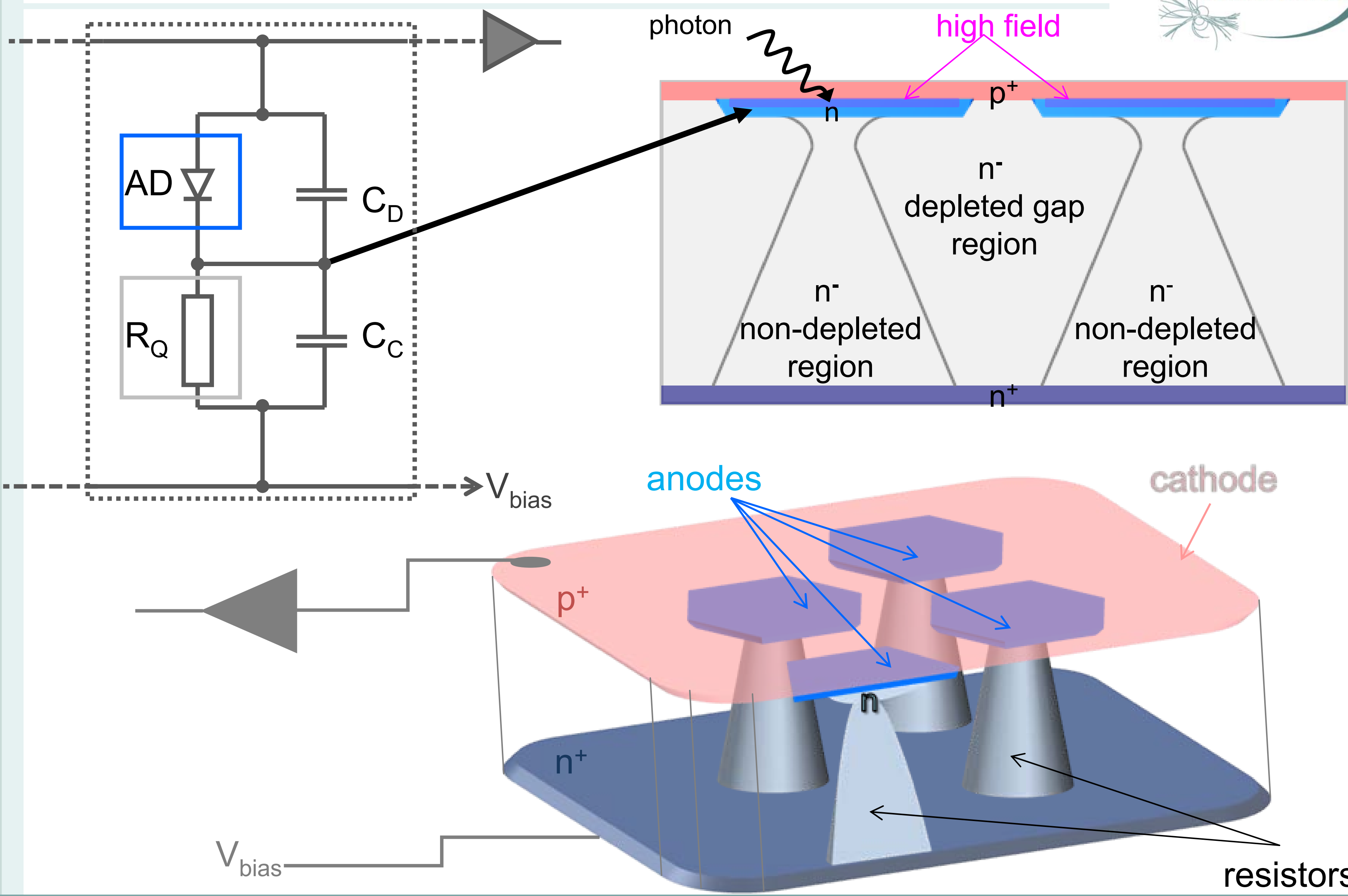


solution:

- optical isolation between pixels (trench)
- 2nd *pn*-junction as barrier for contribution of bulk



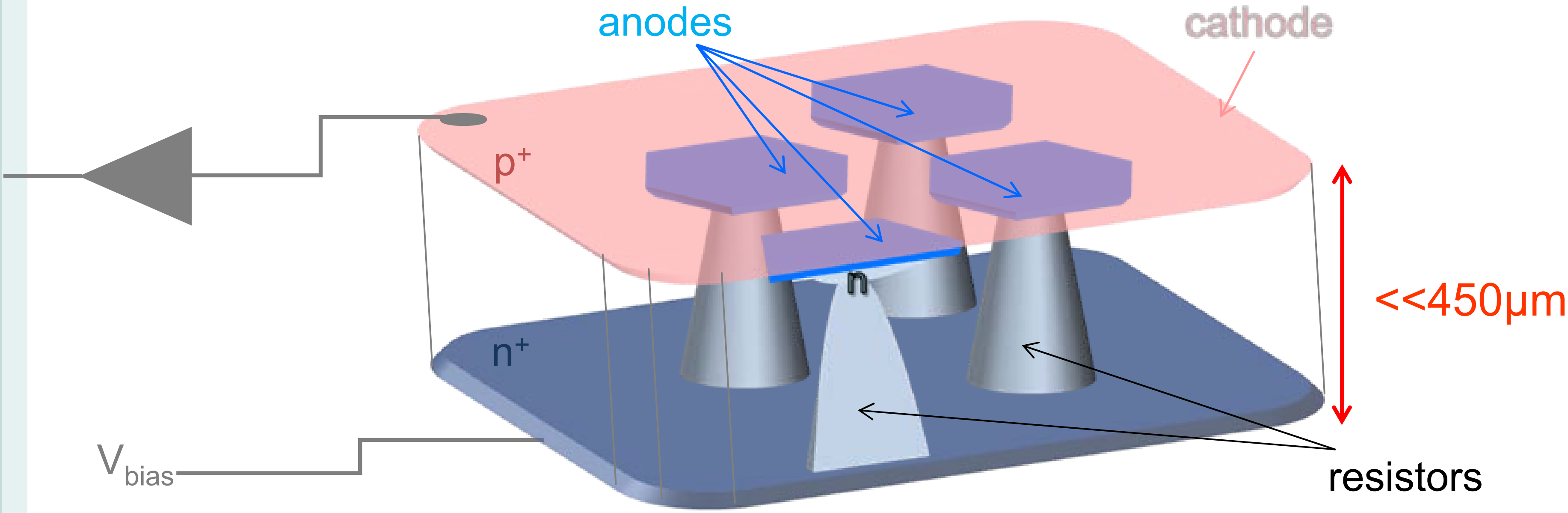
SiPM cell components → SiMPI approach



SiPM cell components → SiMPI approach

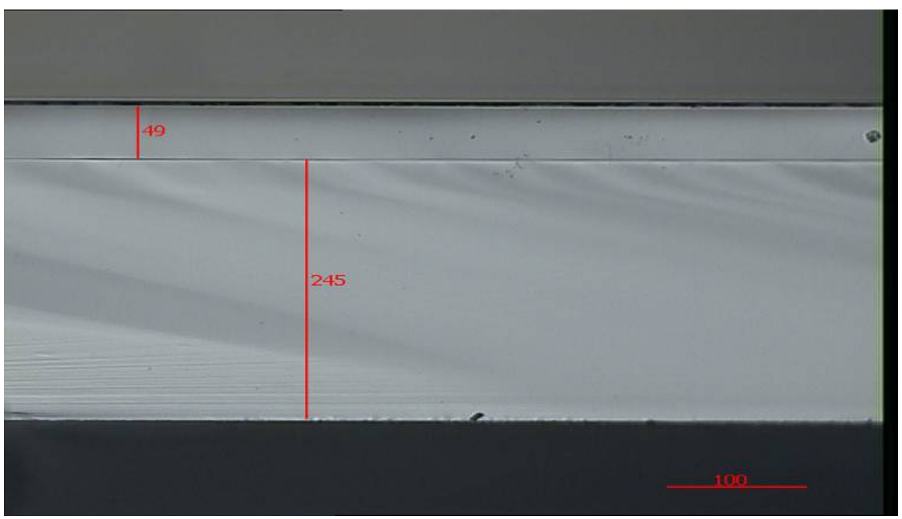
Resistor matching requires thin wafers !

→ wafer bonding



SOI 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



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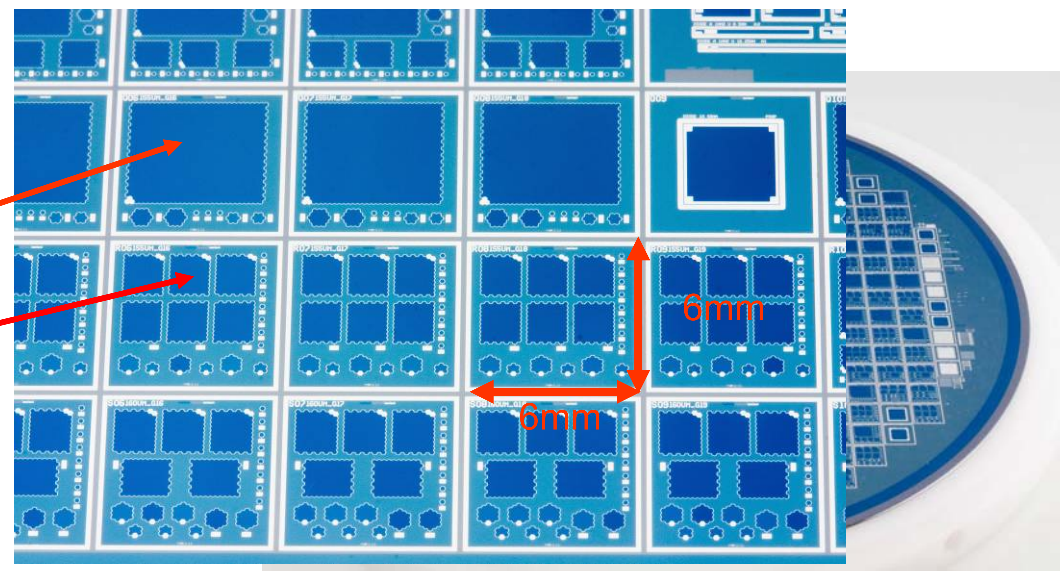
Industrial partners → MPI HLL

30x30 arrays

10x10 arrays



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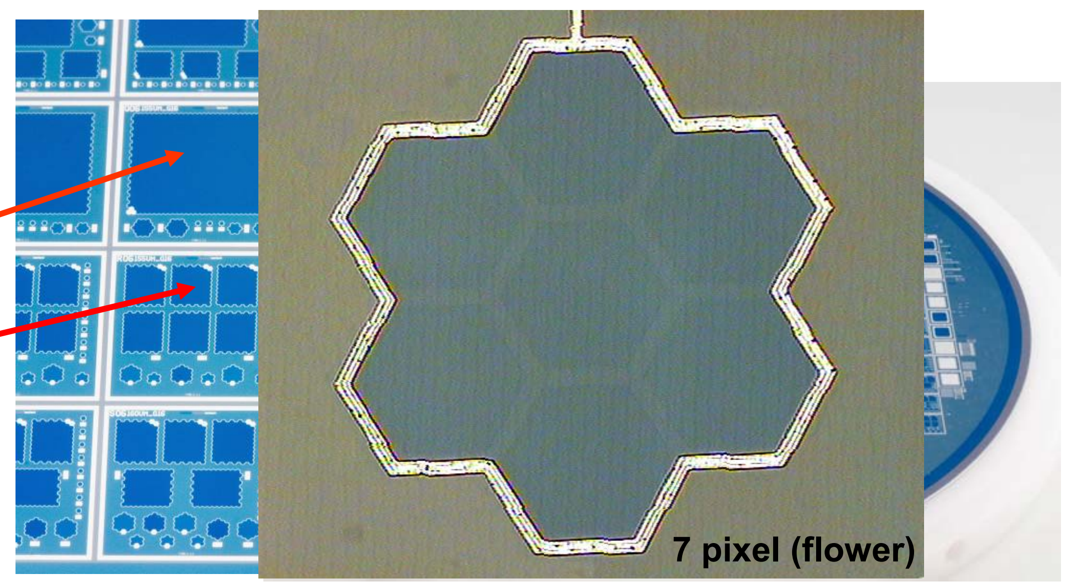
10x10 arrays



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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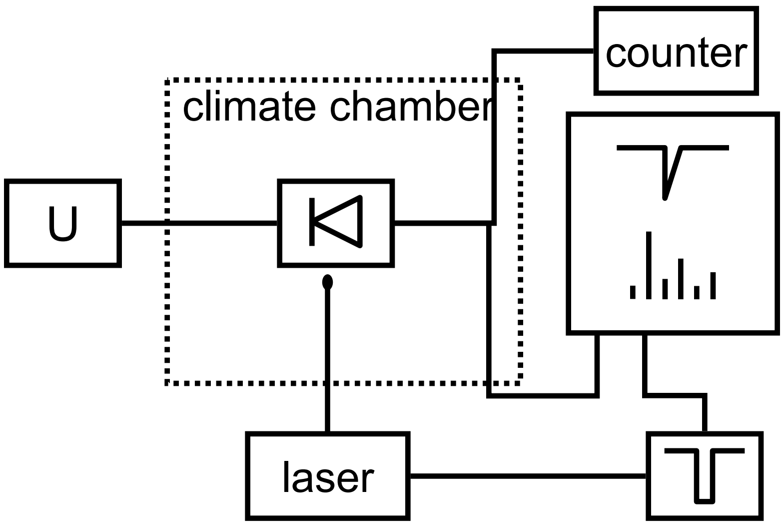
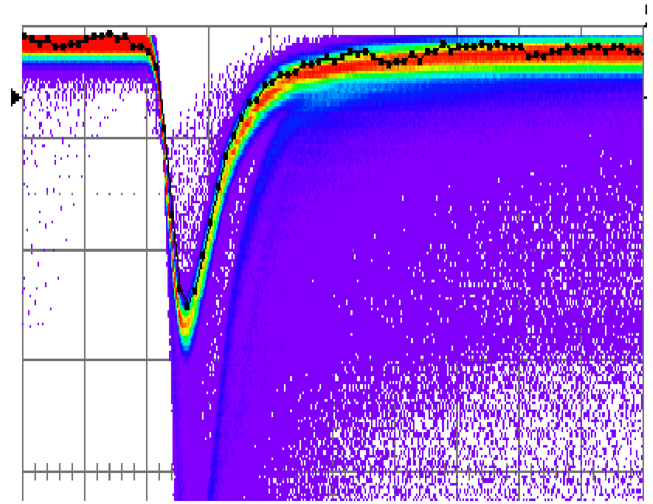
Drawbacks:

- 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 → parabolic IV → longer recovery times

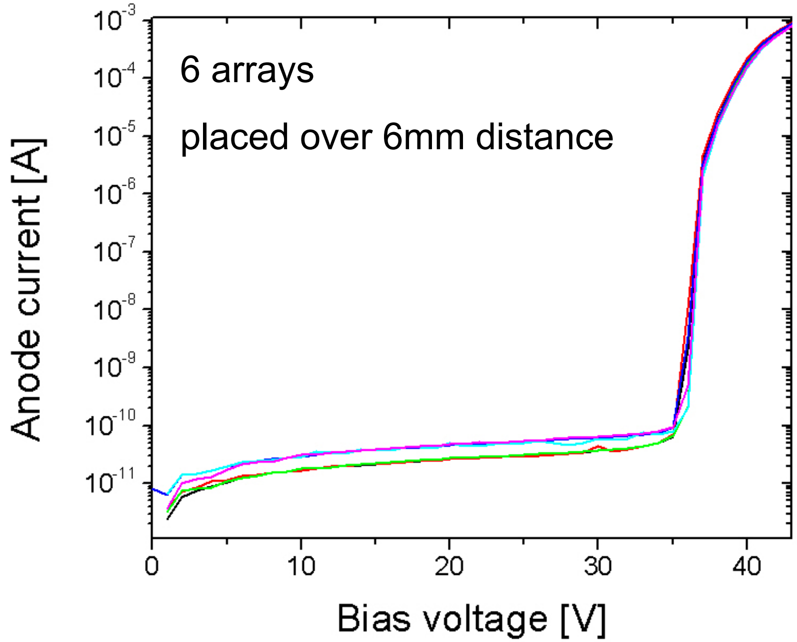
Measurement setup



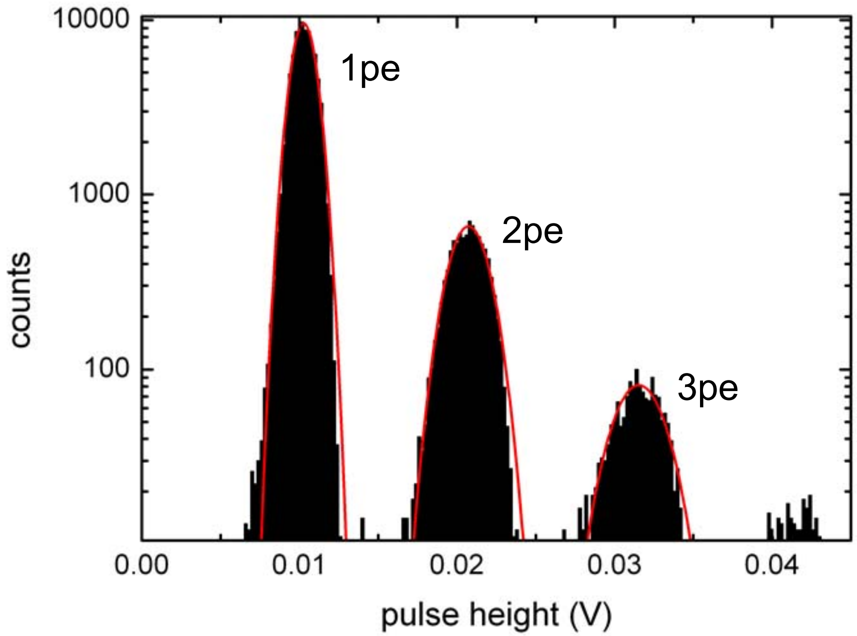


- IV-measurement in reverse bias → breakdown voltage
- dark counts
- amplitude spectra
- recovery time (time from 90% - 10% of amplitude) → $\tau = RC$

IV-measurement & amplitude spectrum



homogeneous breakdown voltage

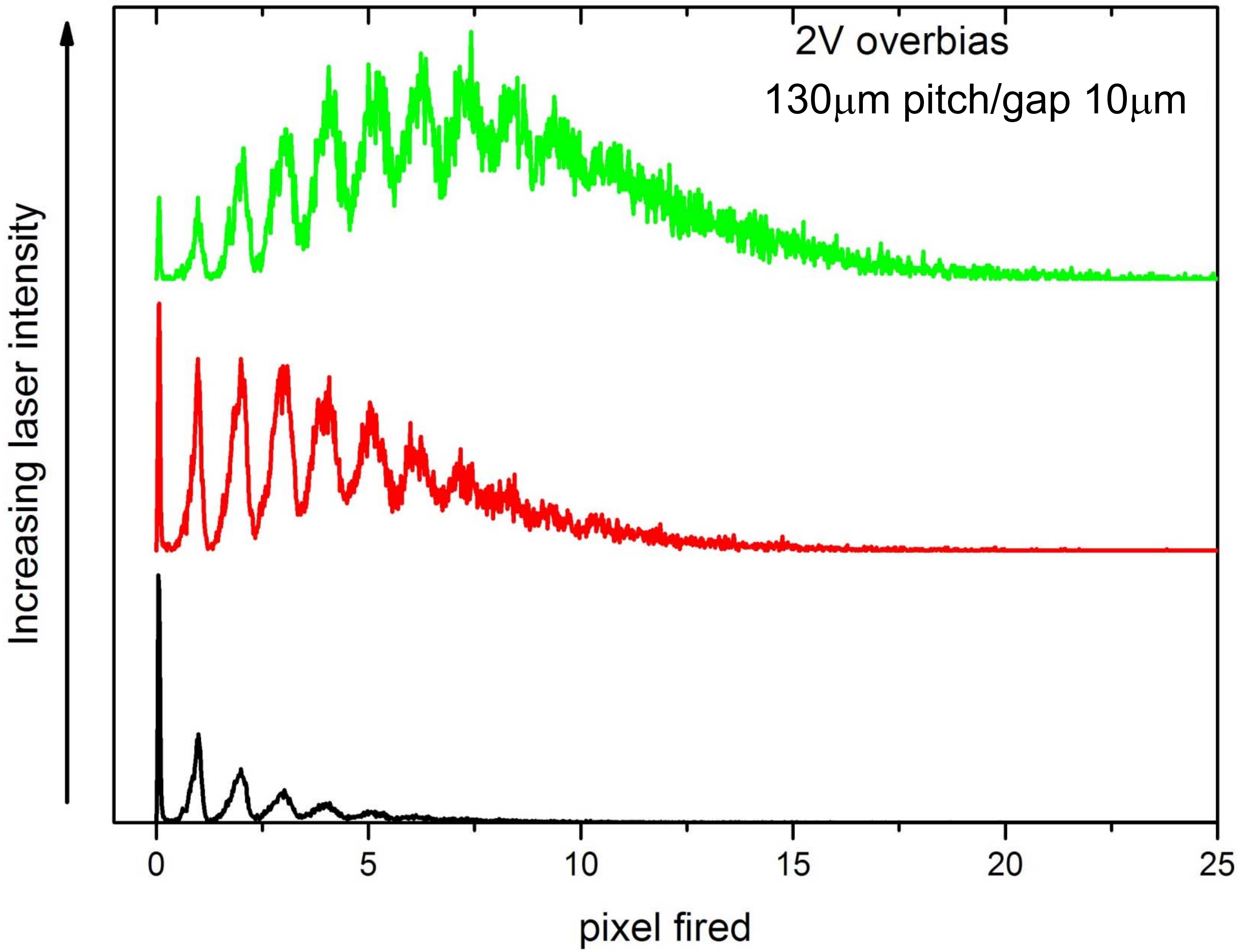


10x10 array of 135µm pitch @ 253K

@1V overbias

Gain = $6.95 \cdot 10^{6}$

Laser light response



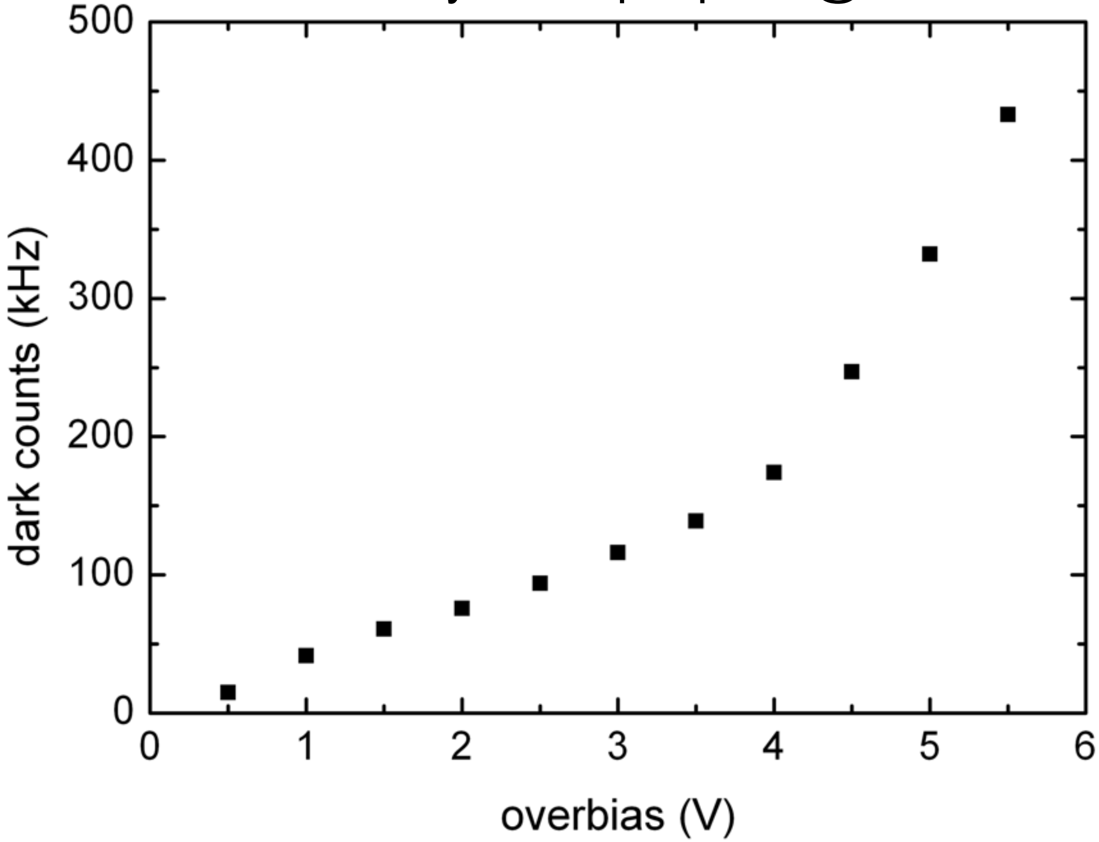
Dark counts

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

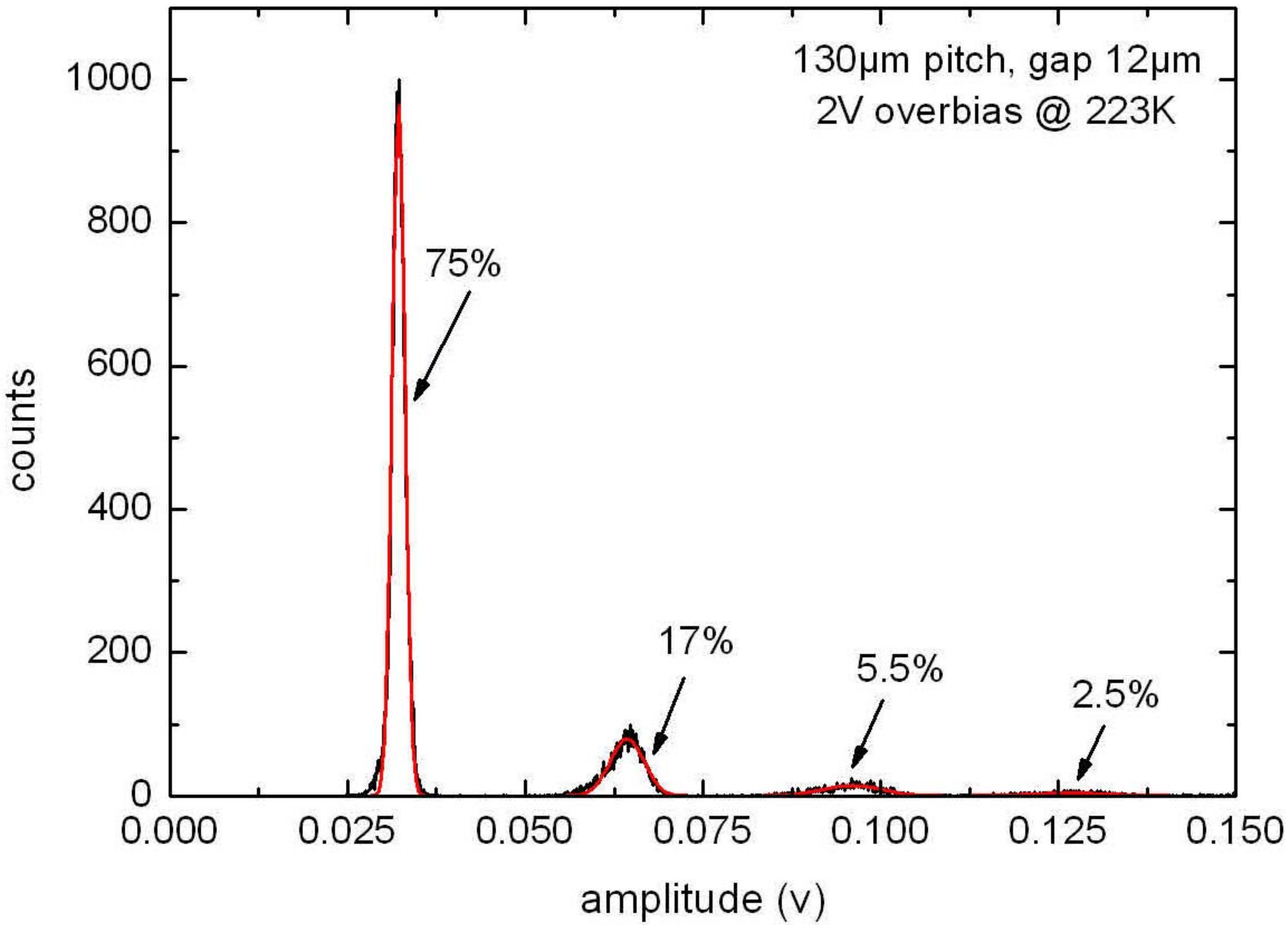
normal operation up to
4V overbias @233K

overbias > 4V
→ non quench condition

10x10 array of 130µm pitch @ 233K



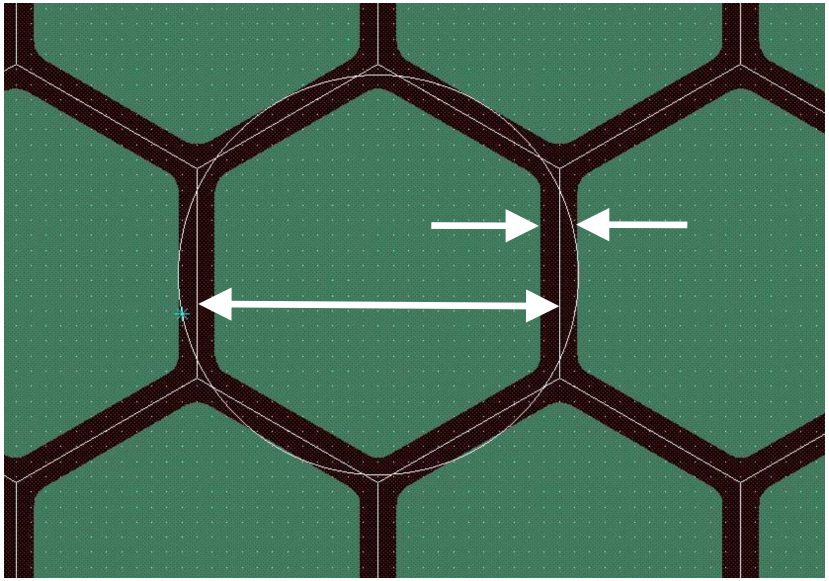
Cross Talk

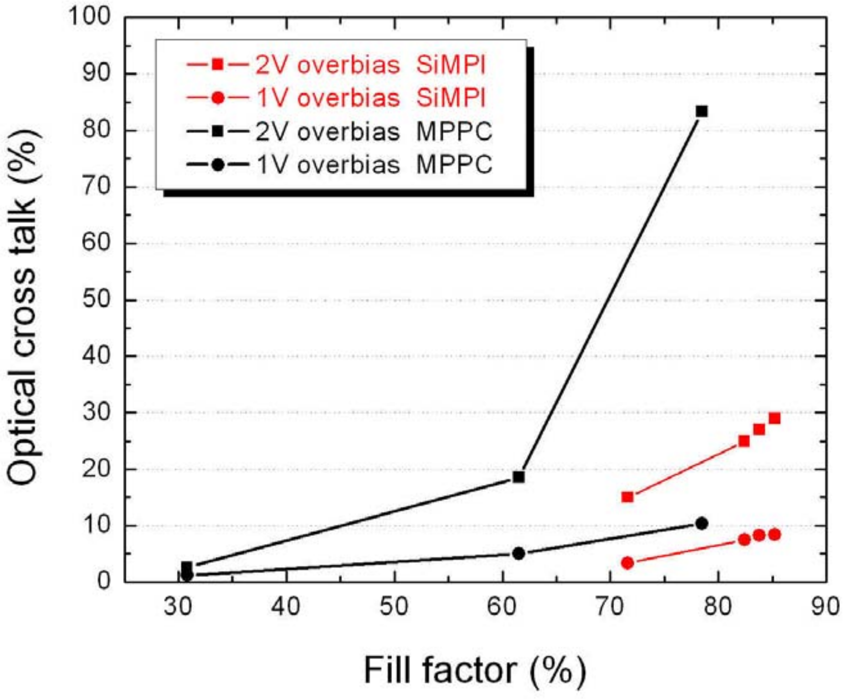


NOTE: no optical barriers for cross talk suppression implemented

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%





Cross Talk & PDE

Pitch / Gap	Fill factor	Cross talk (2V V_{ob})
130µm / 10µm	85.2%	29%
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Photon Detection Efficiency estimation:

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

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

Cross Talk & PDE

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

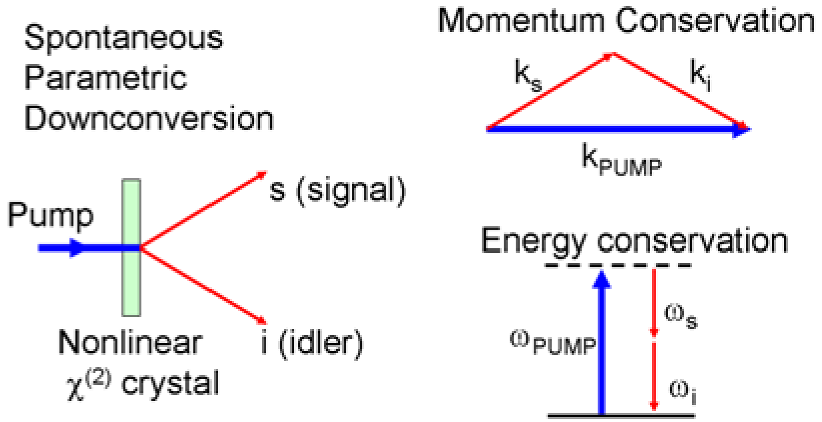
Photon Detection Efficiency estimation:

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

Pitch / Gap	Fill factor	PDE	
130µm / 10µm	85.2%	39%	69%
130µm / 11µm	83.8%	38%	68%
130µm / 12µm	82.4%	37%	67%
130µm / 20µm	71.6%	32%	58%

PDE measurement

absolute measurement by spontaneous parametric downconversion (SPDC)

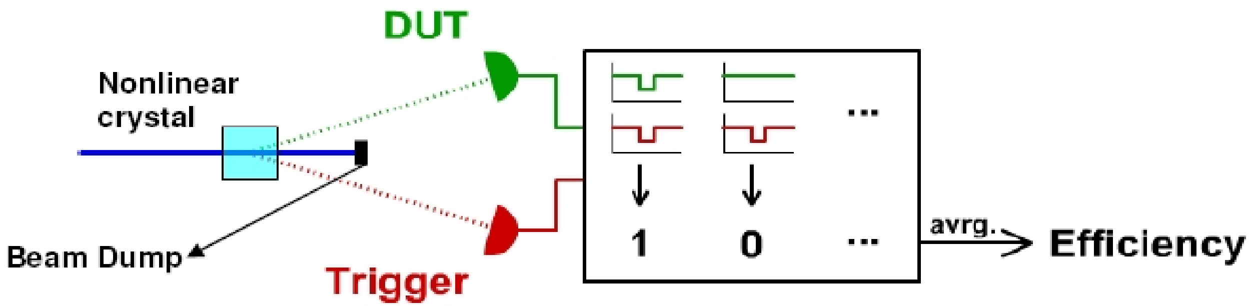


phase-matching condition

only simultaneous generation of signal & idler photon

PDE measurement

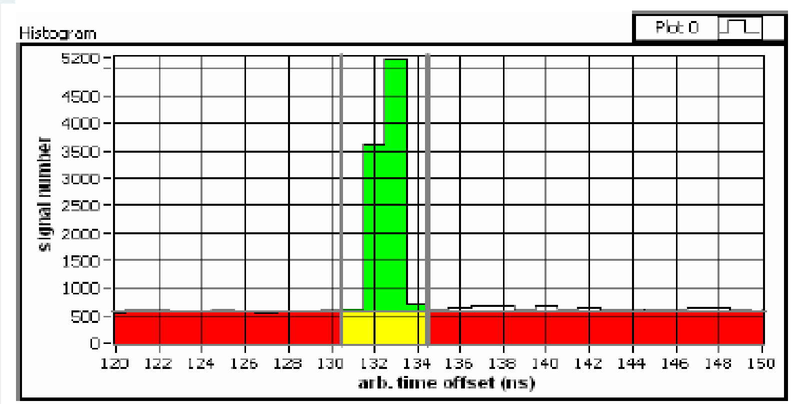
absolute measurement by spontaneous parametric downconversion (SPDC)

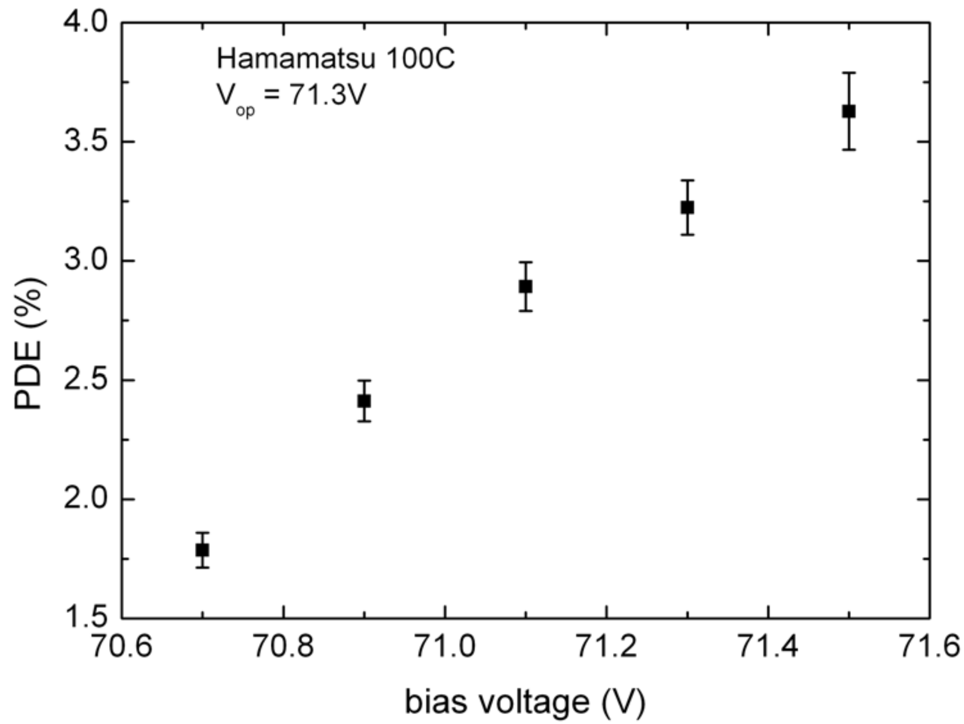


two setups available @ HLL: 810nm + 569nm

BUT: no sufficient cooling possible at the moment

Results with PDC setup (810nm)





$$PDE = \frac{\text{real coincident DUT pulses}}{\text{real trigger pulses}}$$

$$= \frac{N_{win} - (t_{win}/t_{oow})\, N_{oow}}{N_T - (n_{T,dark}/n_T)\, N_T}$$

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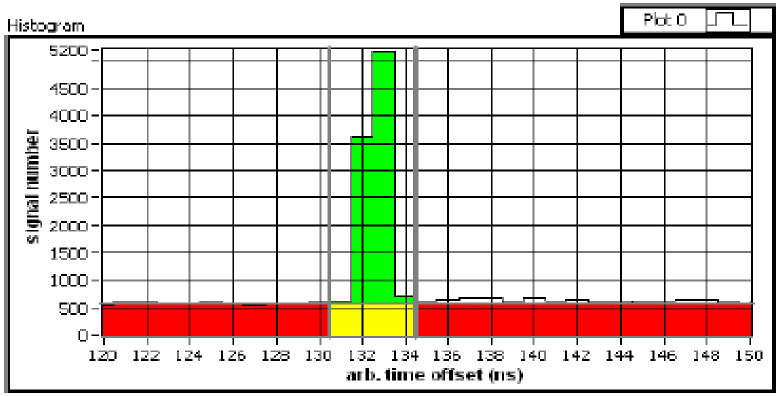

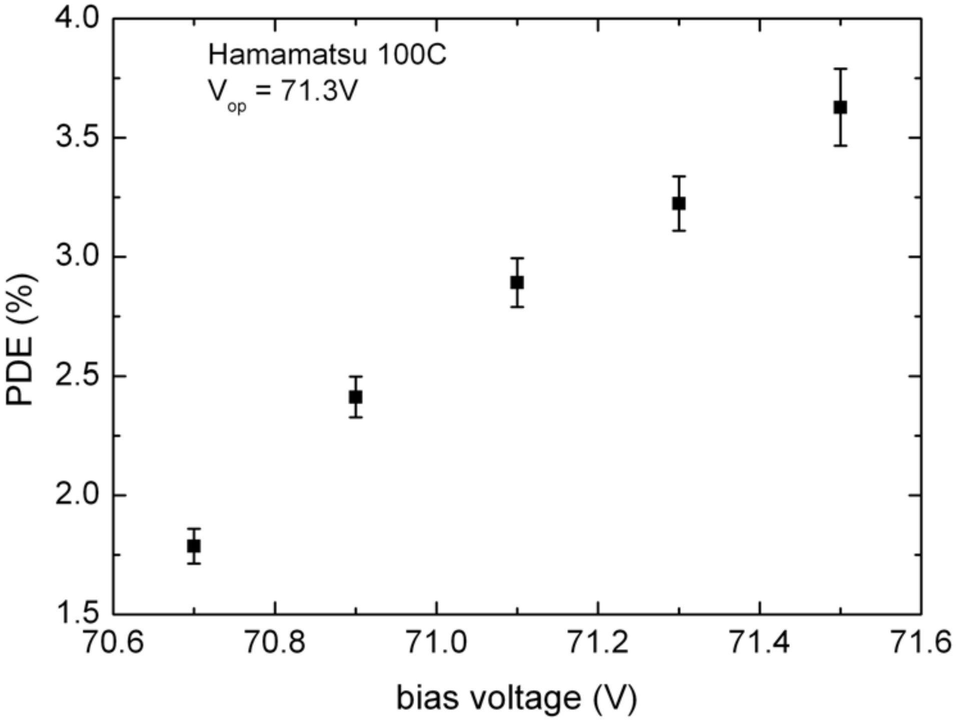

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planned:
combine with relative efficiency measurements (subpixel resolution)

→ more details next talk

Temperature dependence of quench resistor

Resistors designed for room temperature operation

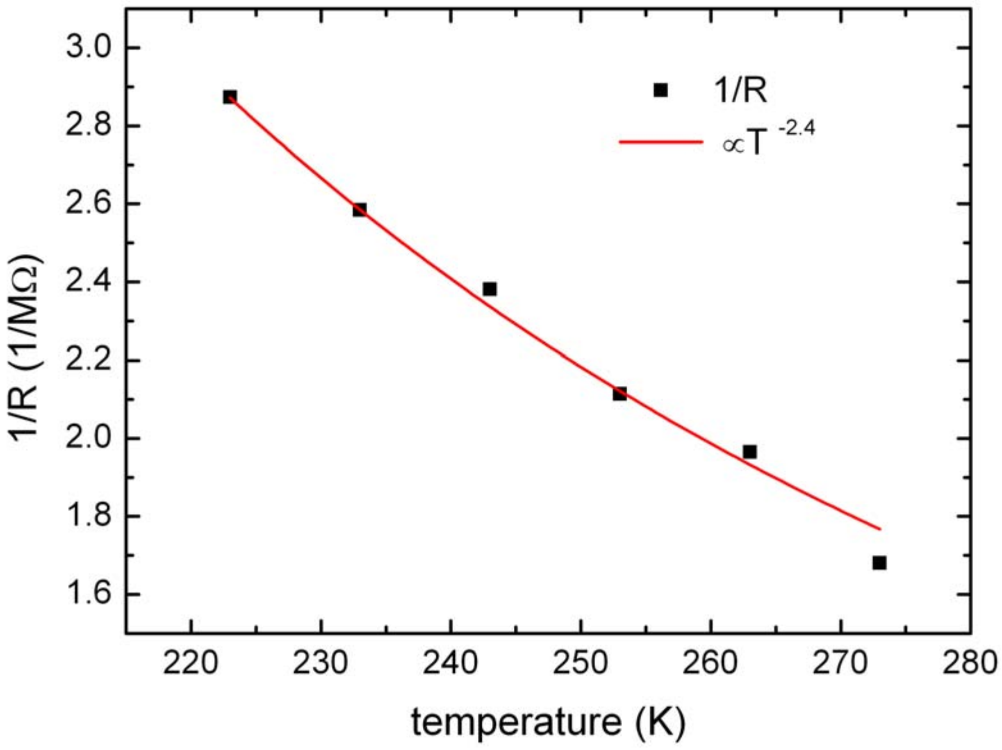
→ limitation of operation voltage (non-quenching)

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

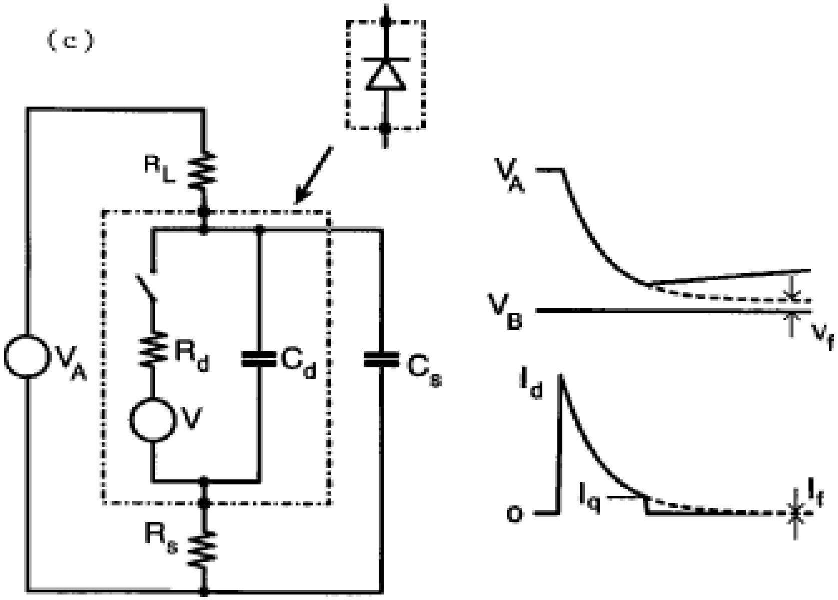
$\tau = R \cdot C$

mobility:

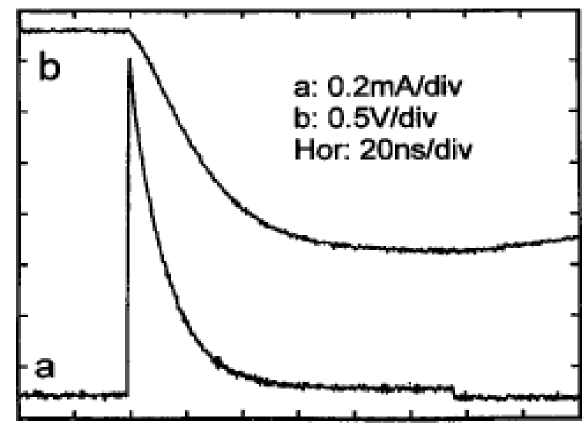
$\mu_n(Si) \propto T^{-2.4}$



New method for determination of non-quenching of SiPMs



Cova et al., Appl. Opt., *vol. 35, no. 12, 1996*



Increasing overbias → maximization of efficiency but avalanche quenching problematic

Asymptotic steady-state value of diode current

$$I_f = \Delta V / R_L$$

Cova rule of thumb : quenching condition: $I_f < 20\mu A$

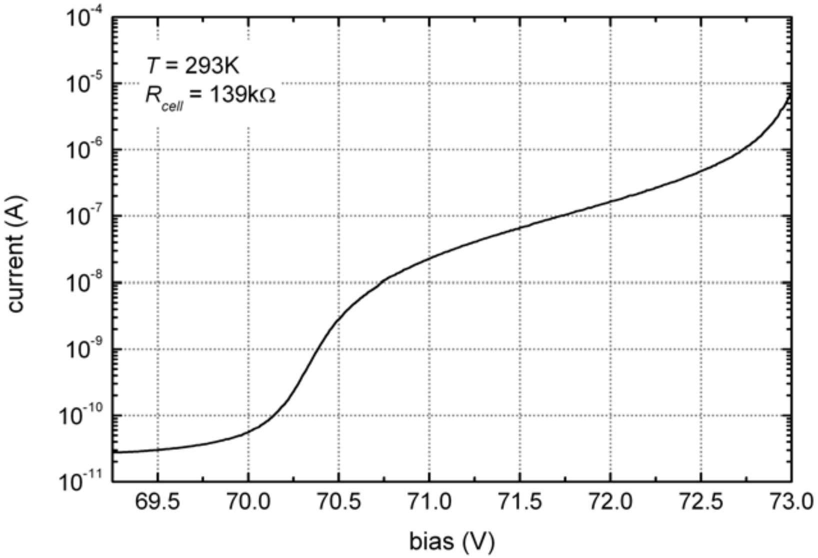
→ Is there a way to measure?

New method for determination of non-quenching of SiPMs

Our approach:
compare measured with calculated dark current

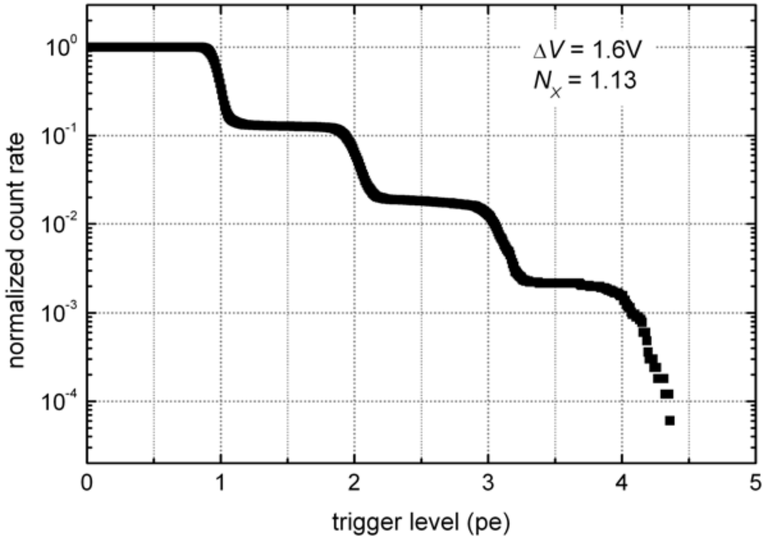
$$I_{calc} = DC \cdot N_X \cdot G \cdot e$$

Ratio $R = I_{meas}/I_{calc} >> 1$ indicates non-quenching



Procedure:

- *IV*-measurement of dark current
- measurements of dark counts *DC* vs. overbias
- measurement of optical crosstalk contribution N_X vs. overbias (integral of normalized count rate)
- measurement of internal gain *G* vs. overbias



First results with polysilicon and bulk-integrated resistors

polysilicon resistor:

temperature coefficient *dR/dT*: negative

low overbias: ratio = 1
→ good agreement I_{calc} : I_{meas}

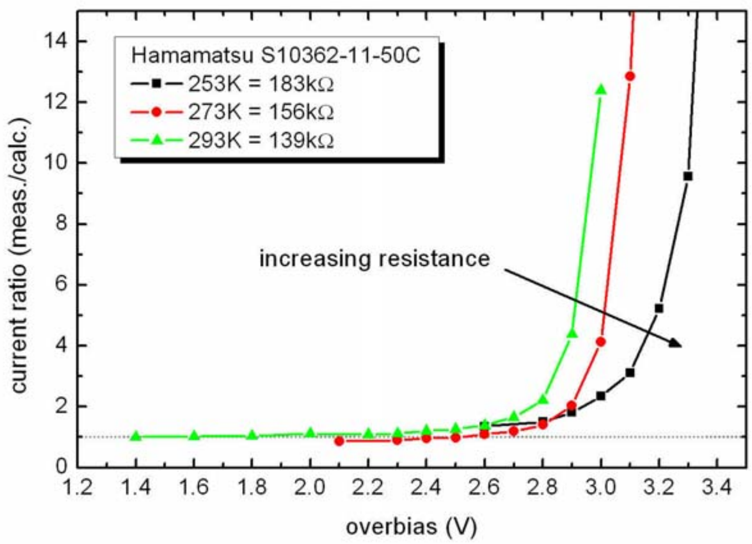
high overbias: disproportional increase of ratio
→ initiation dependent on resistance values

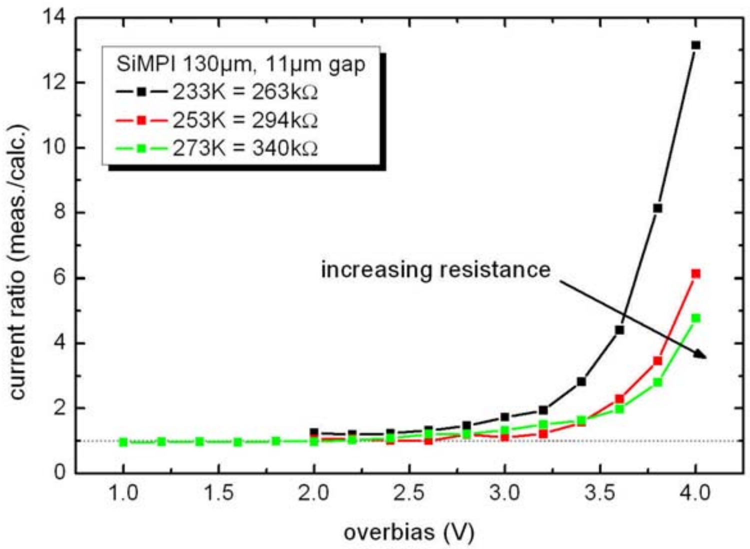
bulk-integrated resistor:

temperature coefficient *dR/dT*: positive

low overbias: ratio = 1
→ good agreement I_{calc} : I_{meas}

high overbias: disproportional increase of ratio
→ initiation dependent on resistance values





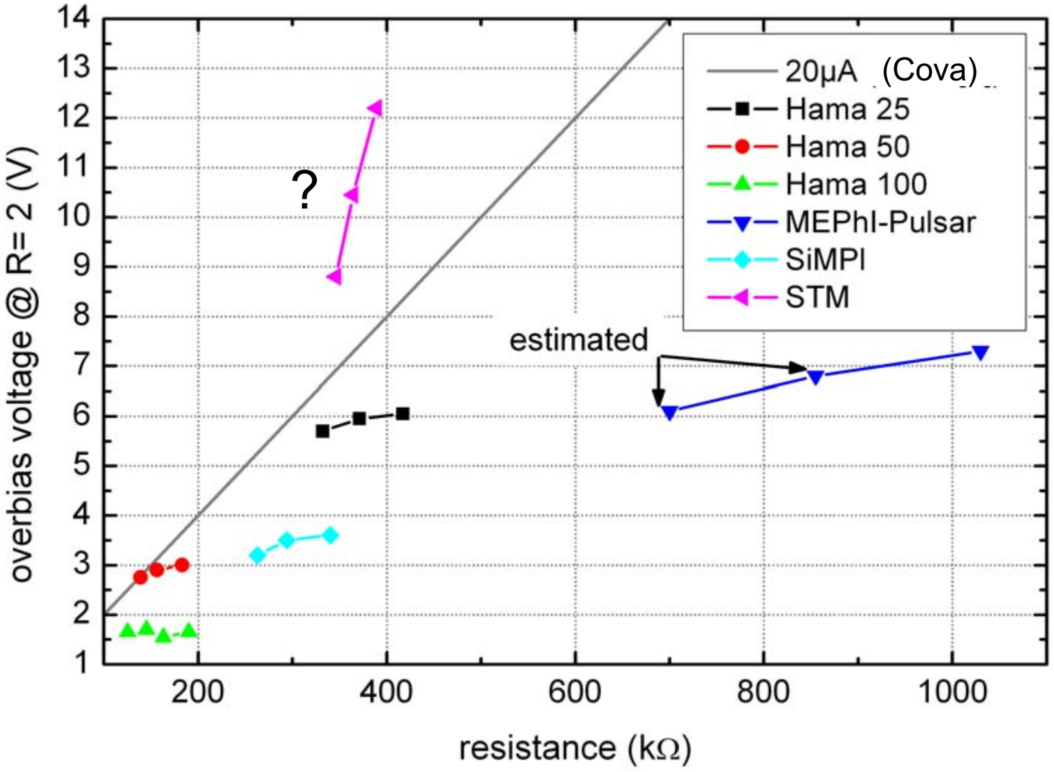
Comparision of different SiPMs

Note:
Not corrected for afterpulsing

But:
20µA rule of thumb seems not to be sufficient

more precise determination of non-quenching

No fit for all devices → influenced by other parameters?



Further studies and improvements necessary

Summary

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

Further studies of the produced sensors (geometry dependence of the sensor performance, PDE, …) are ongoing

New production to reduce dark counts and implement small pixels (end of 2011?)

Further improve new method for determination of non-quenching of SiPMs

Thanks

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)*

absolute measurement by spontaneous parametric down conversion (SPDC)

two setups with wavelengths 810nm + 569nm

Gain linearity

pulse height ∝ Q

↓

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

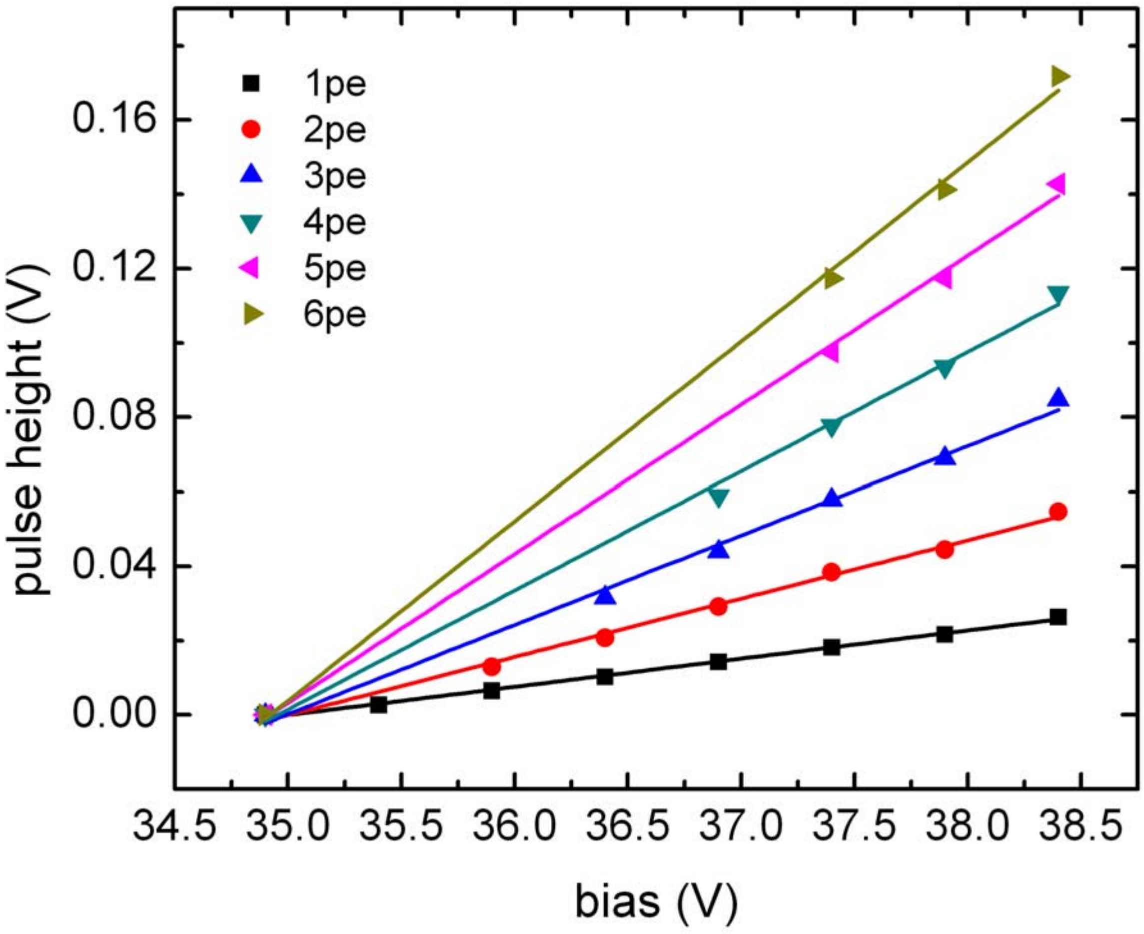
↓

linear

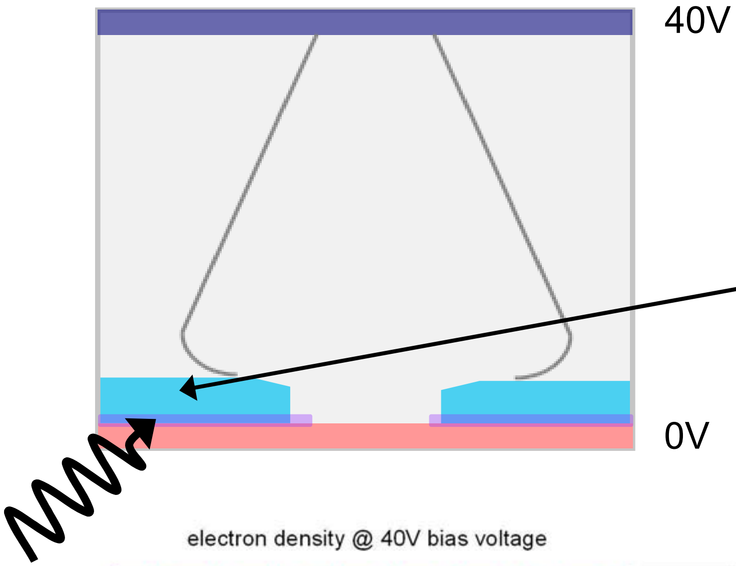
↓

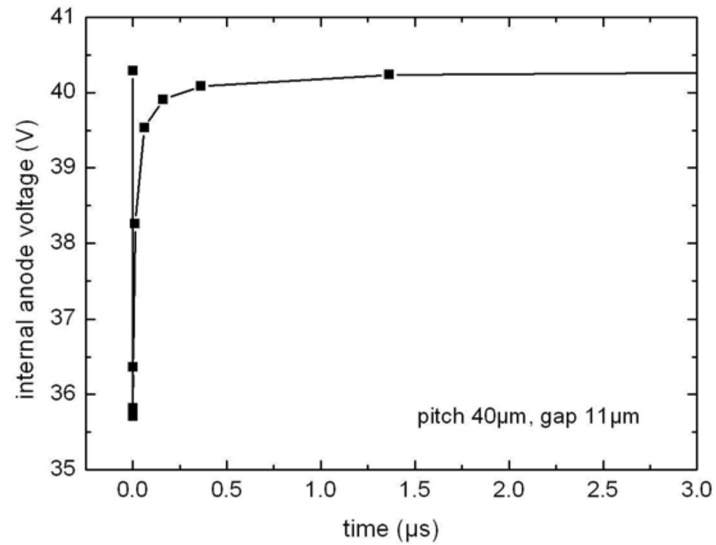
normal operation

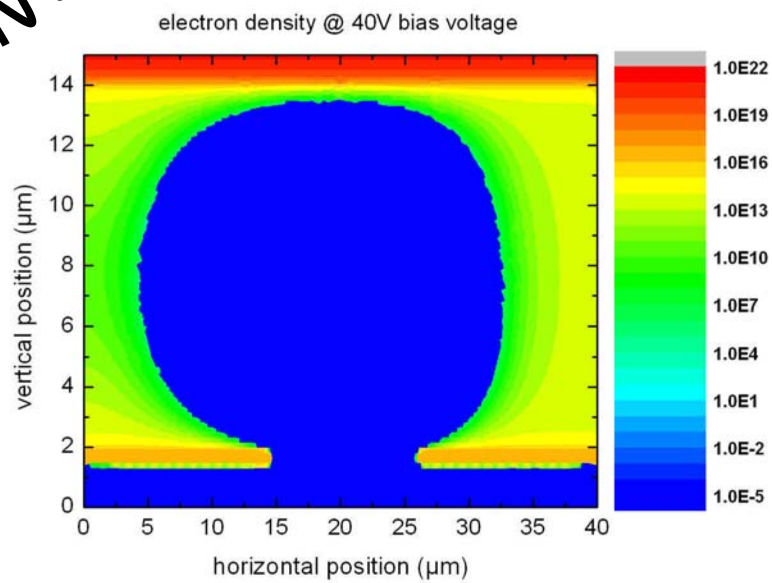
10x10 array of 135µm pitch @ 253K



Simulations for small pixels







- small pixel for high dynamic range
- simulation for resistor value estimation
- fill factor of 60% achievable (40µm pitch)
- recovery time of about 0.7 µs

Measured devices

Device	Pitch (µm)	V_{break} (V)	R_{Cell} (kΩ)
Hamamatsu 25	25	69.4 (293K)	332
		68.4 (273K)	371
		67.5 (253K)	417
Hamamatsu 50	50	70.1 (293K)	139
		68.9 (273K)	156
		67.6 (253K)	183
Hamamatsu 100	100	70.2 (300K)	125
		68.7 (273K)	145
		67.6 (253K)	163
		66.5 (233K)	190
MEPhI-Pulsar	35	77.5 (293K)	700
		76.2 (273K)	855
		74.9 (253K)	1030
STMicroelectronics	60	28.7 (293K)	346
		28.3 (273K)	364
		27.8 (253K)	389
SiMPl	130 gap 11	35.2 (273K)	340
		34.5 (253K)	294
		33.9 (233K)	263

Polysilicon quench resistors

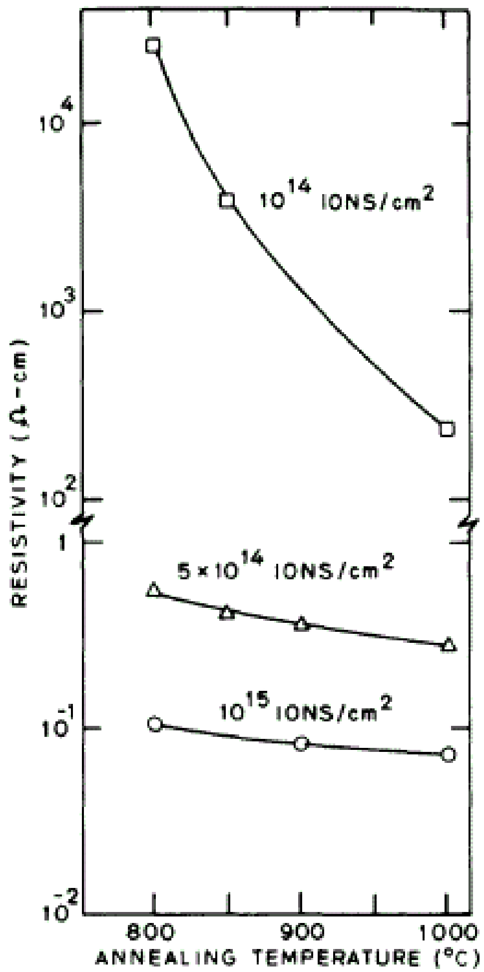
critical resistance range

→ rather unreliable process step

obstacle for incident light

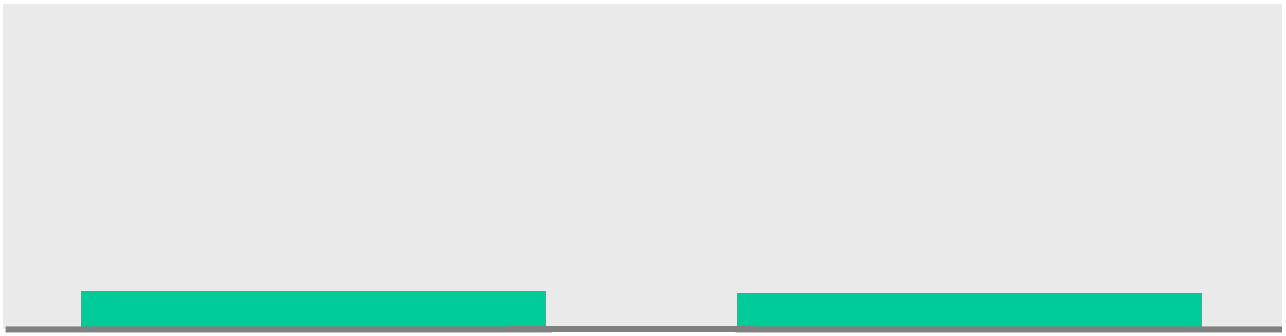
→ fill factor decreased
→ limitation of detection efficiency

Is there different way to do it?
Can we use the silicon bulk material?

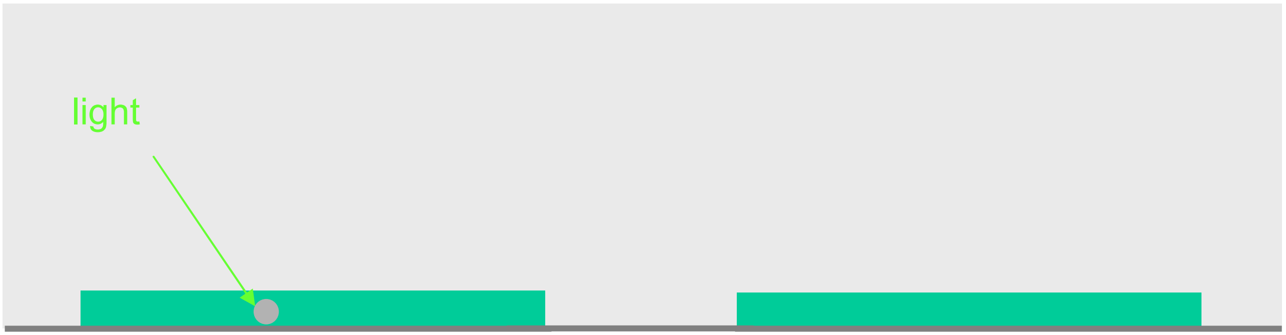


M. Mohammad et al.
'Dopant segragation in polycrystalline silicon',
J. Appl. Physics, Nov.,1980

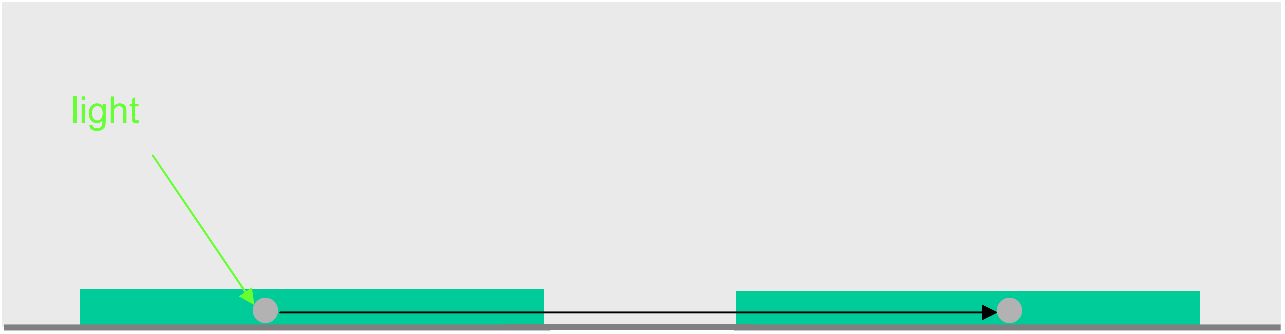
Optical cross talk suppression



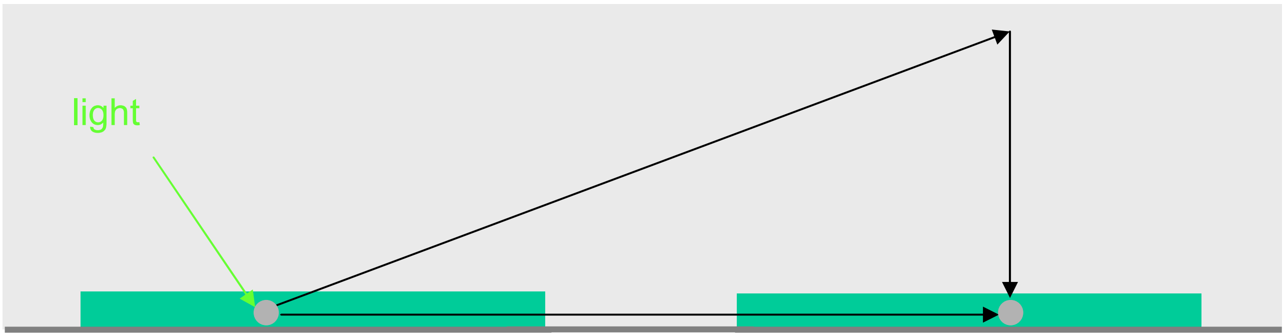
Optical cross talk suppression



Optical cross talk suppression



Optical cross talk suppression



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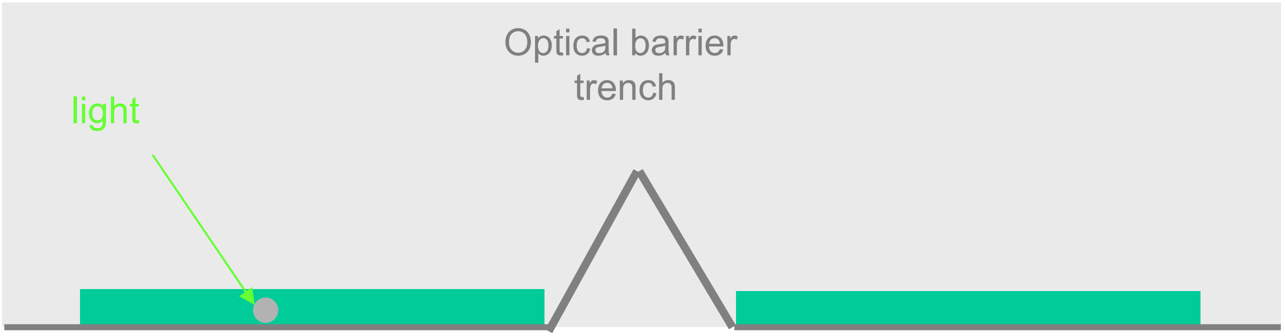

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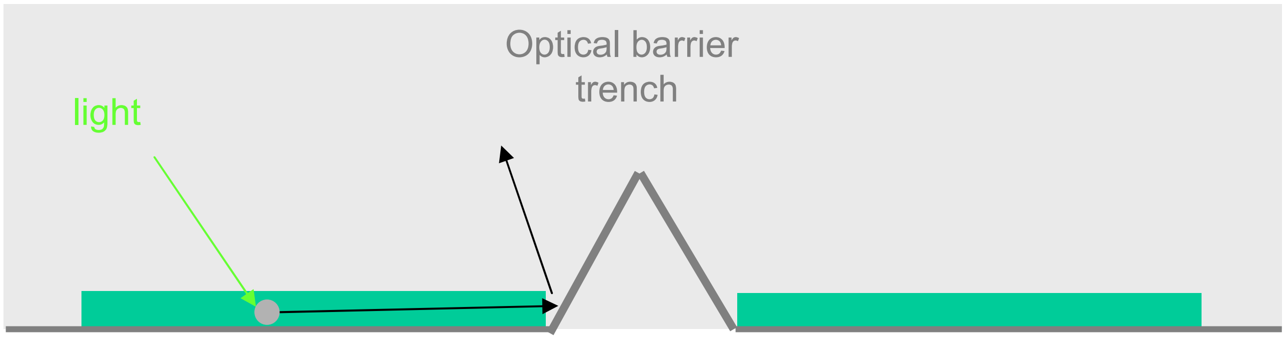

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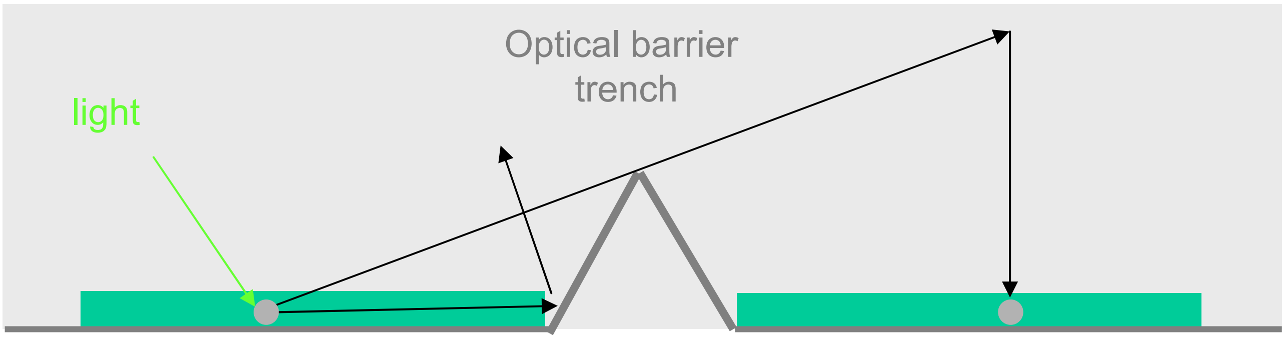
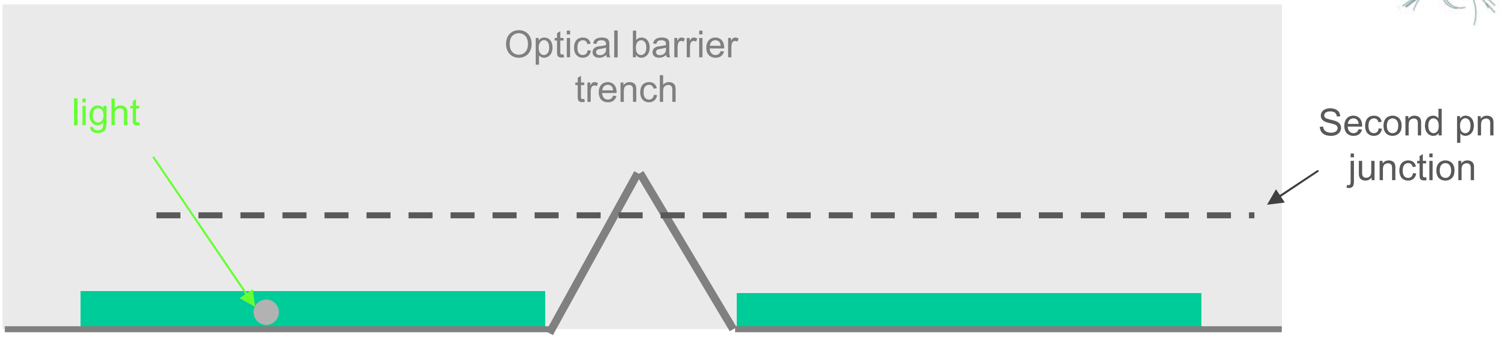


Optical cross talk suppression



Optical cross talk suppression