Highly efficient silicon photomultipliers with bulk integrated quenching resistor
-
concept and characterization

Young Scientist Workshop, Ringberg 2010

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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
- summary & outlook

Motivation

many future experiments will need >> 100 000 photon detectors

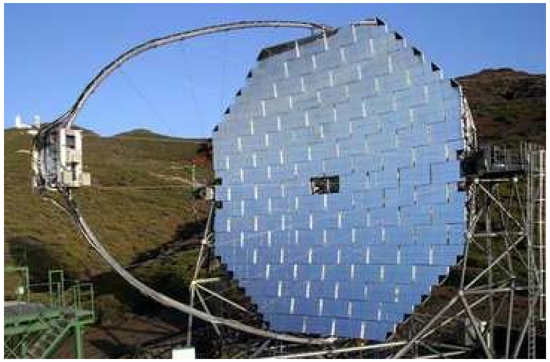
Cherenkov Telescope Array (CTA)

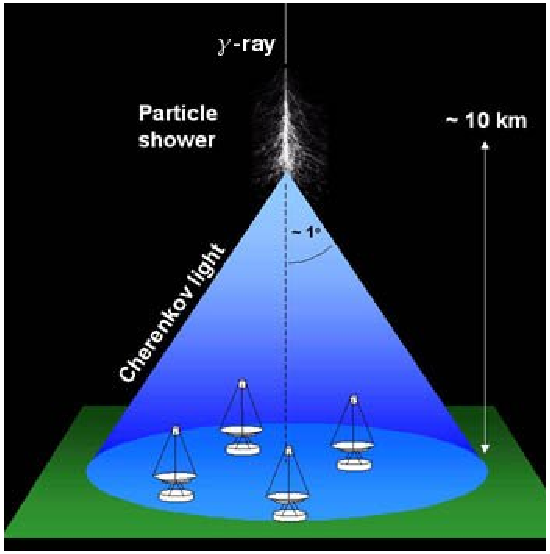
ground-based gamma ray astronomy

Cherenkov light by gamma generated particle shower

large arrays → higher sensitivity

increased number of photon detectors



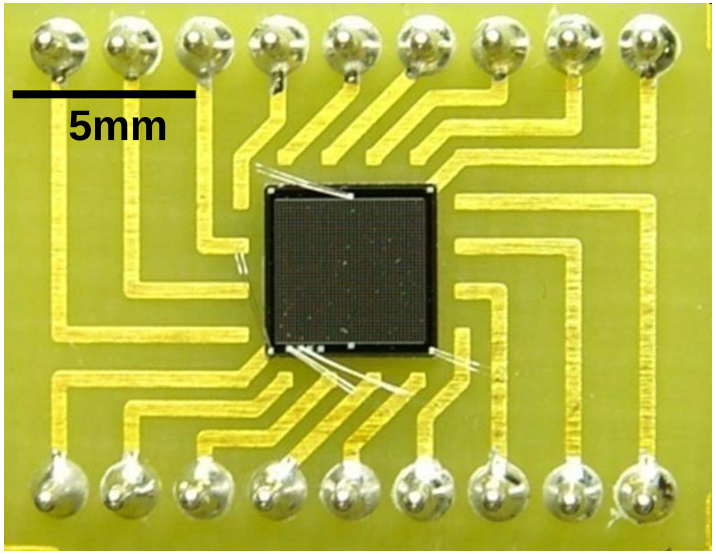


Why silicon photomultipliers (SiPM)?

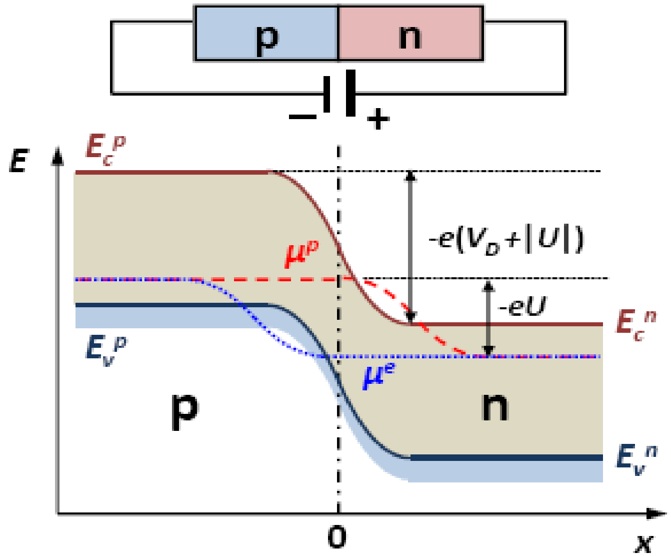
requirements for photon detectors:

- 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



Silicon 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

Silicon photodetectors

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

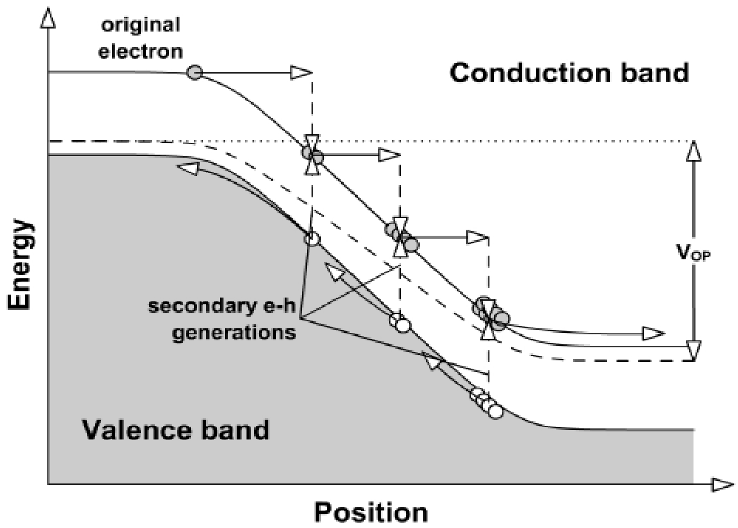
also holes contribute to avalanche generation → single photon detection

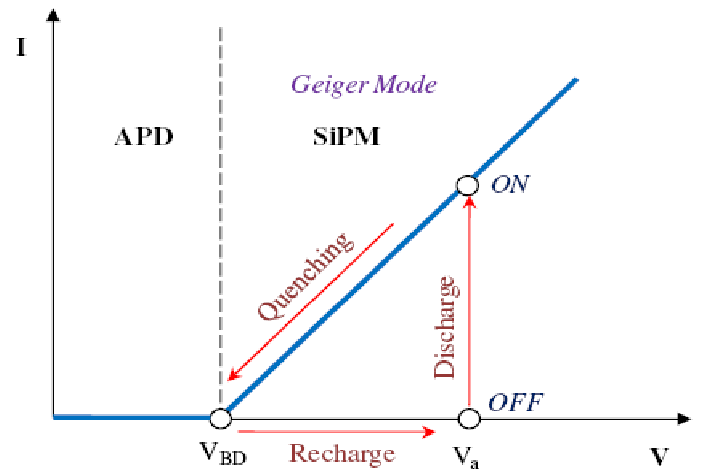
gain ~ $10^5 – 10^6$

quenching resistor stops discharge

BUT: binary device → no information about incident photons

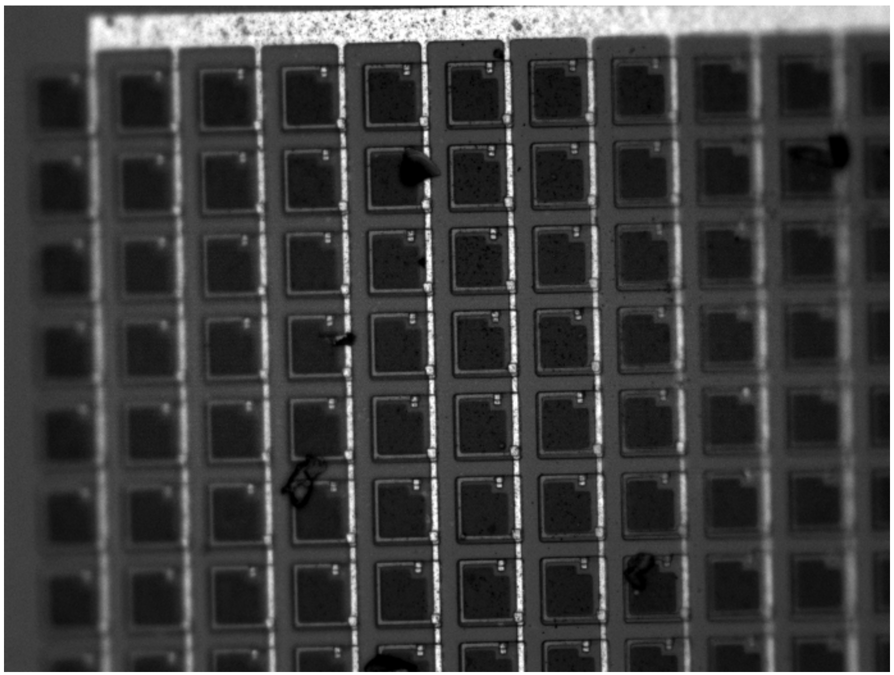
→ Silicon photomultipliers

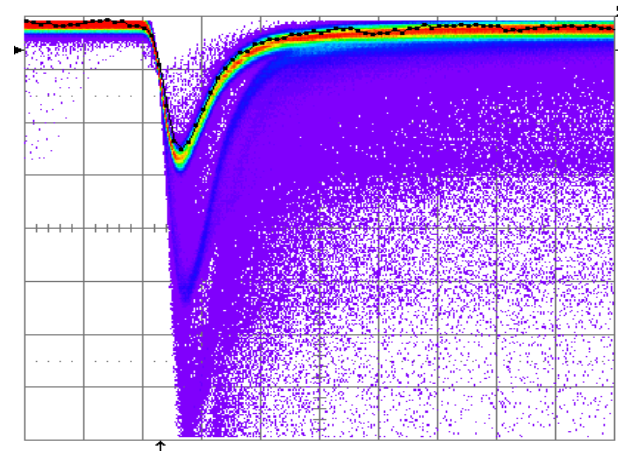


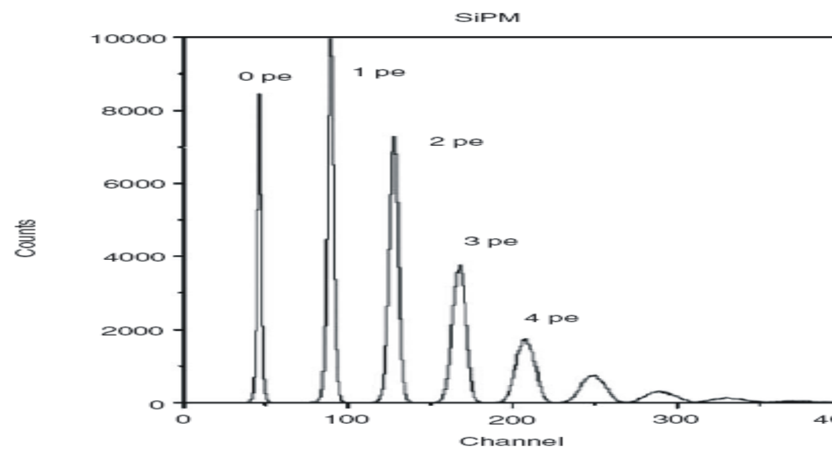


Conventional silicon photomultiplier

- 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





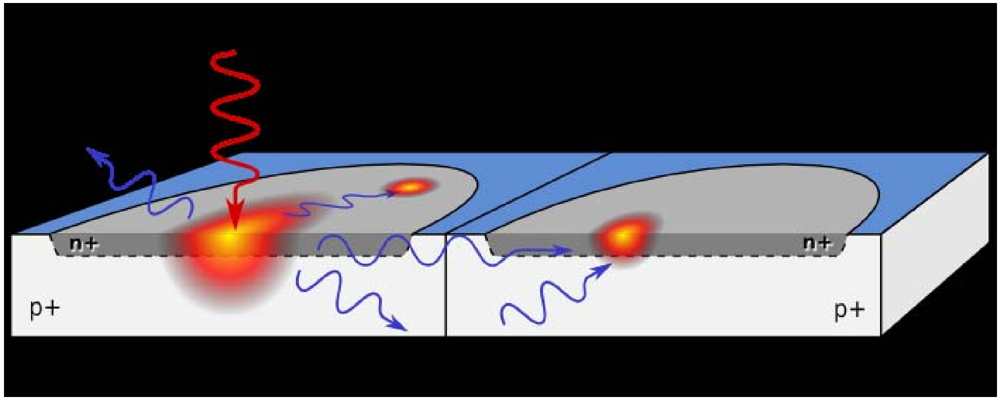


Optical crosstalk

hot-carrier luminescence:

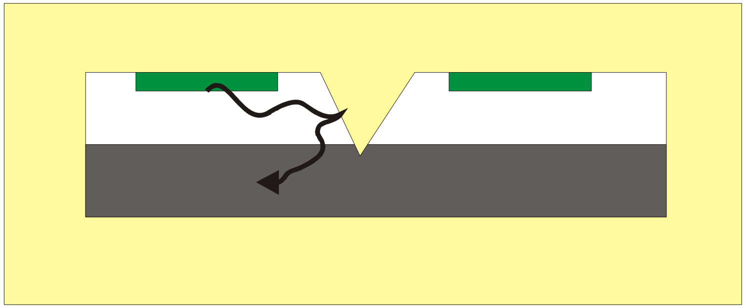
in an avalanche breakdown
10^5 carriers emit in average
1 photon with E > 1.14 eV

A. Lacaita et al, IEEE TED (1993)



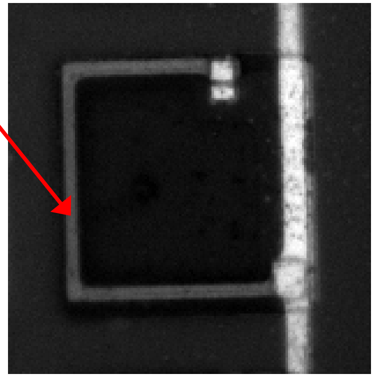
solution:

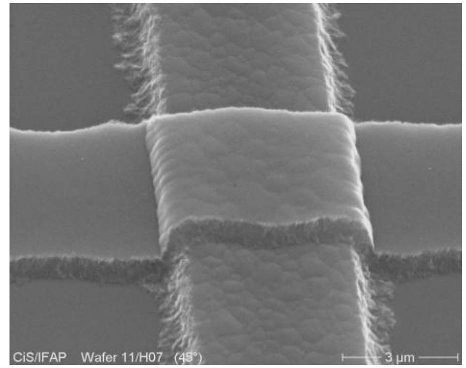
- optical isolation between pixels
- lower gain (lower detection efficiency)



Polysilicon quench resistors

polysilicon





complex fabrication step

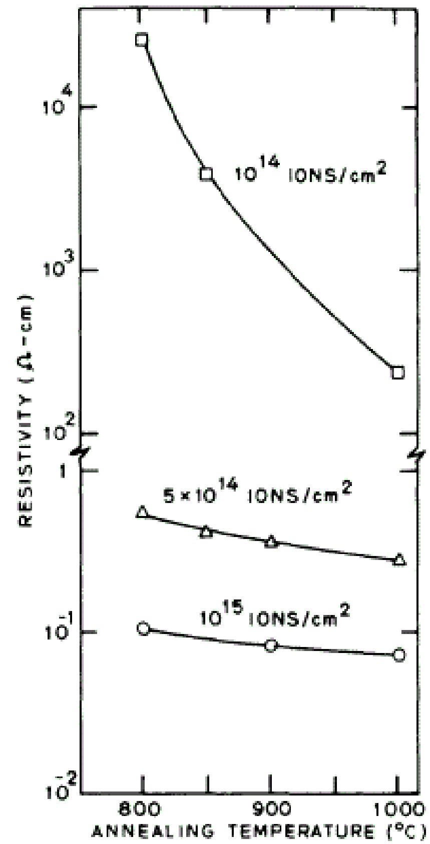
critical resistance range

influenced by: grain size, dopant segregation, carrier trapping, barrier height,…

→ rather unreliable process step

obstacle for incident light

→ limitation to fill factor

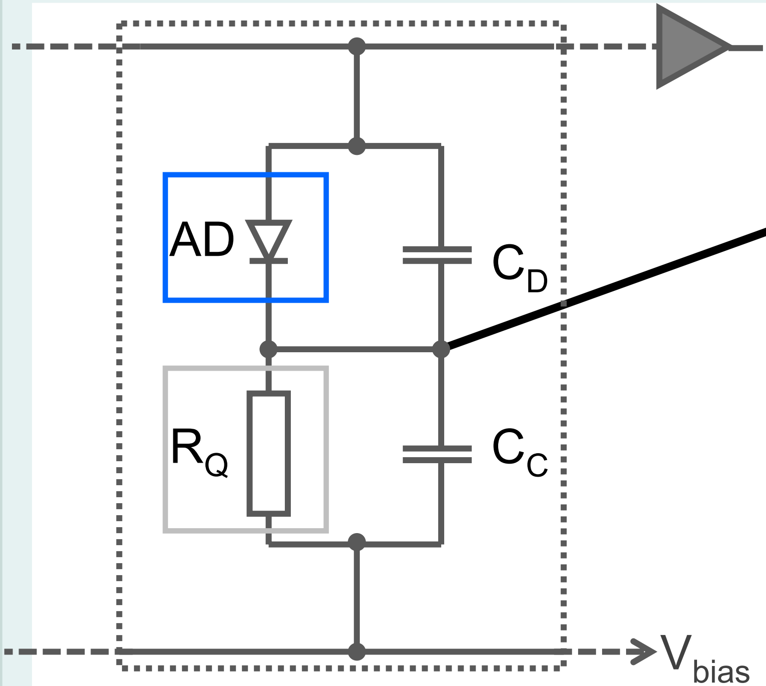


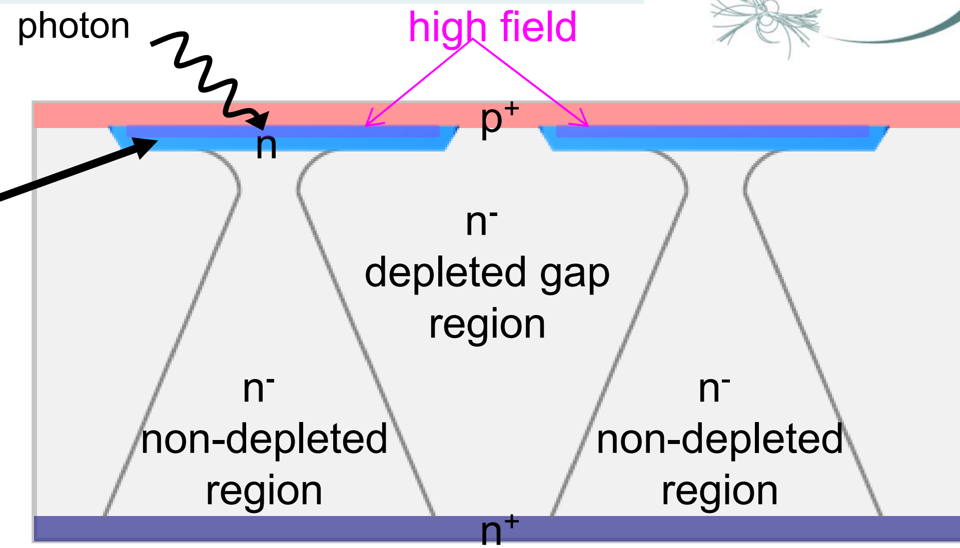
M. Mohammad et al.

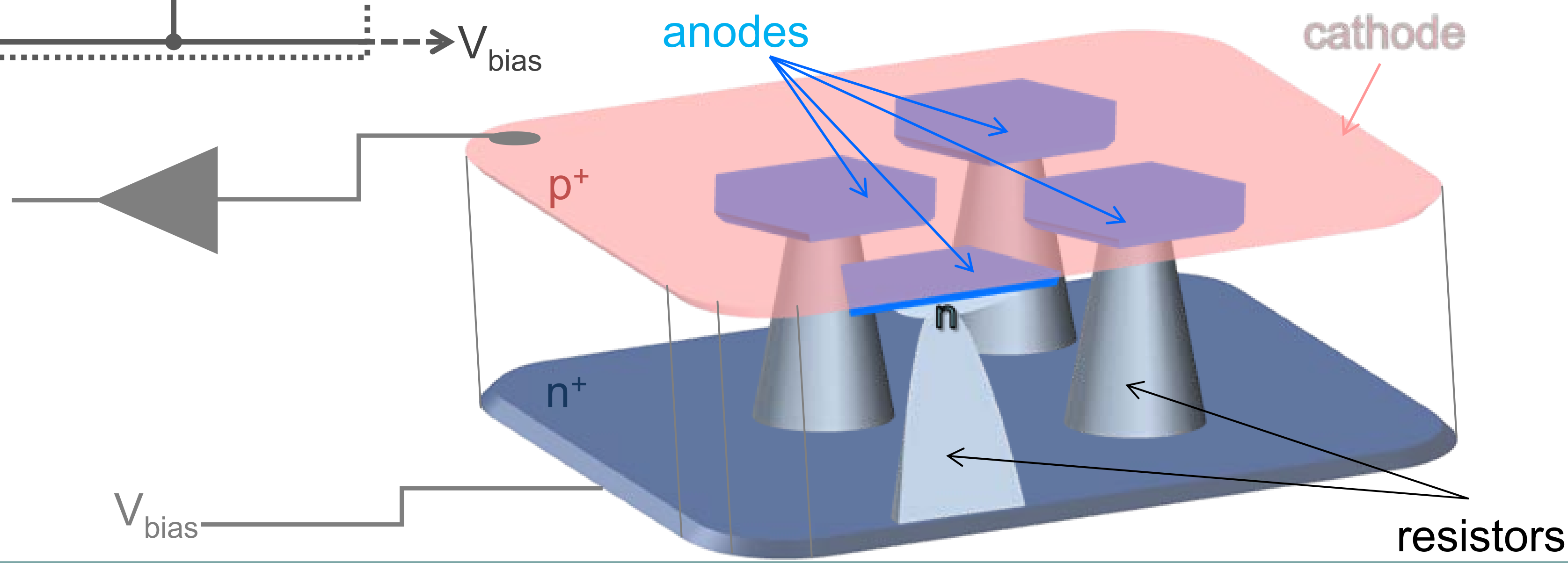
'Dopant segragation in polycrystalline silicon',

J. Appl. Physics, Nov.,1980

SiPM cell components → SiMPI approach



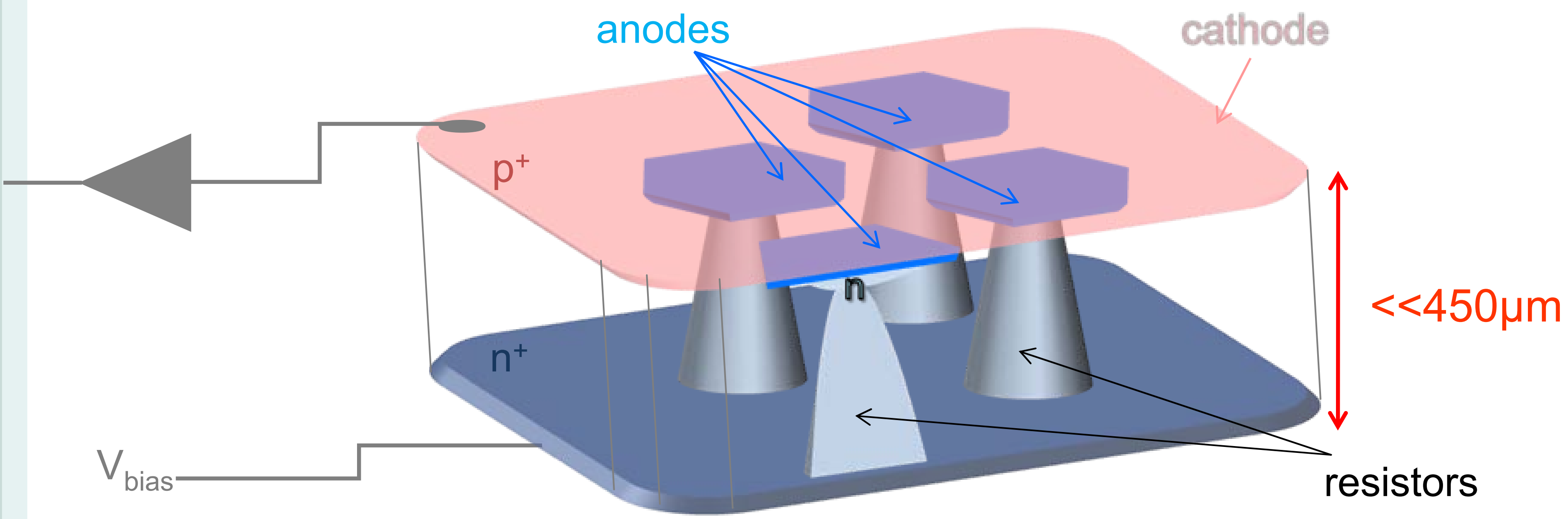




SiPM cell components → SiMPI approach

Resistor matching requires thin wafers !

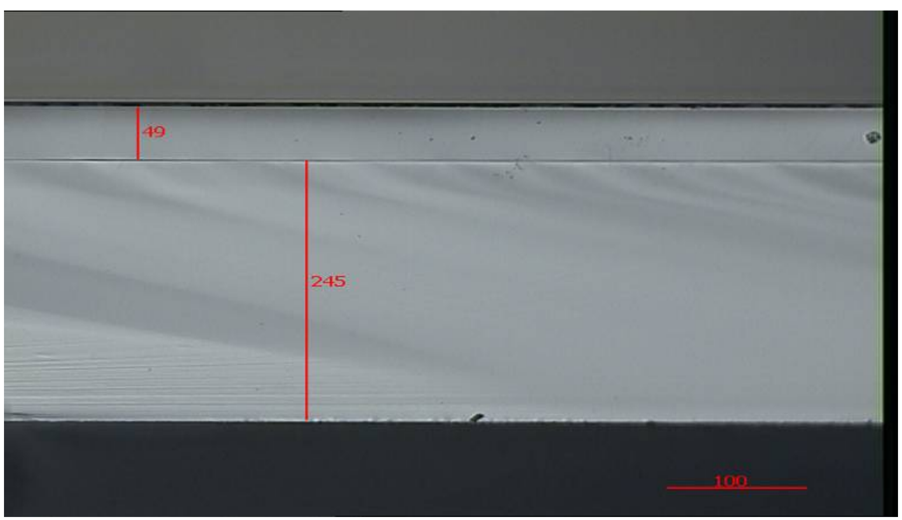
→ wafer bonding

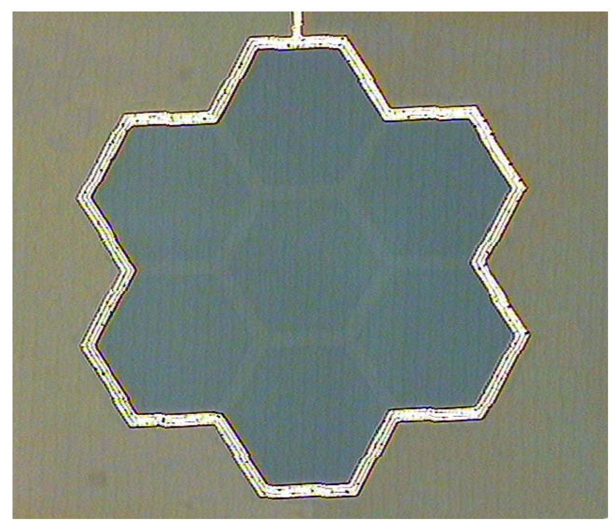


SOI wafers

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

Industrial partners → MPI HLL





Advantages and Disadvantages

Advantages:

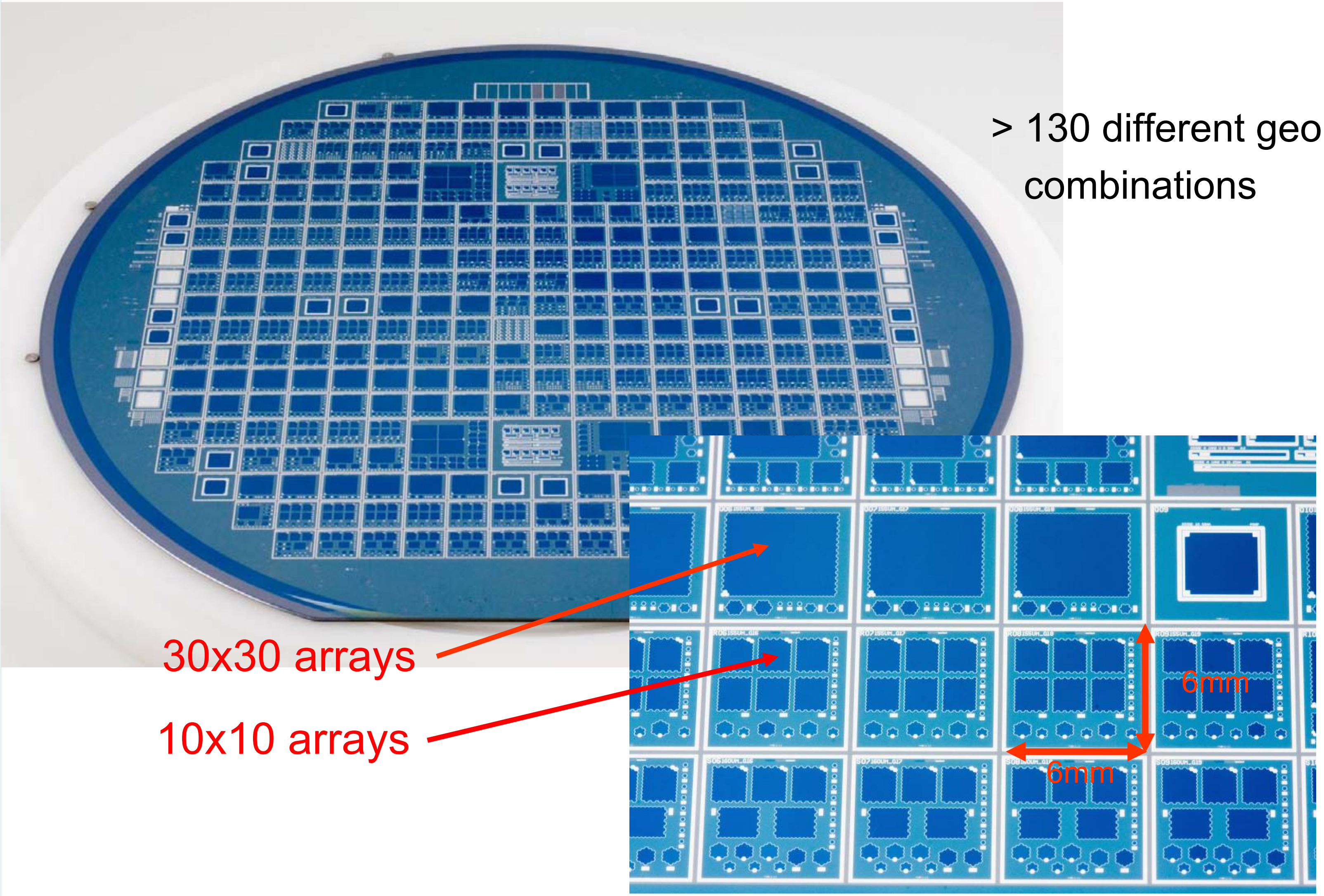
- no need of polysilicon
- free entrance window for light, no passive elements within array
- less demanding lithographic level
- inherent diffusion barrier against minorities in the bulk → less optical cross talk
- hopefully better radiation hardness

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

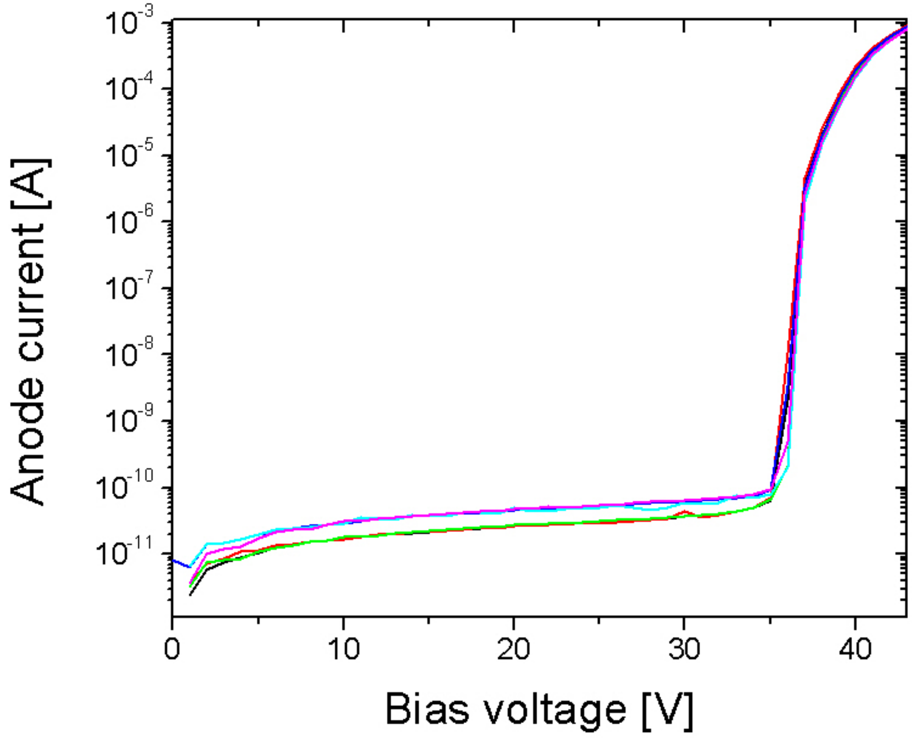
Prototype production

SOI material



> 130 different geometrical combinations

Static measurements



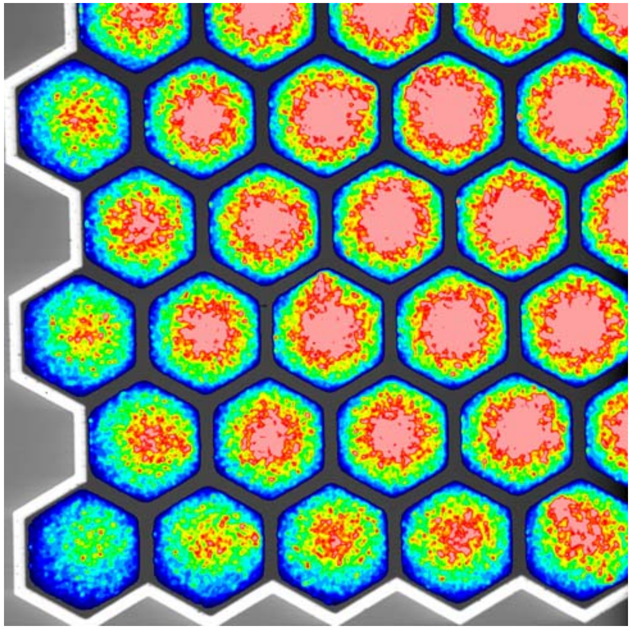
information about:

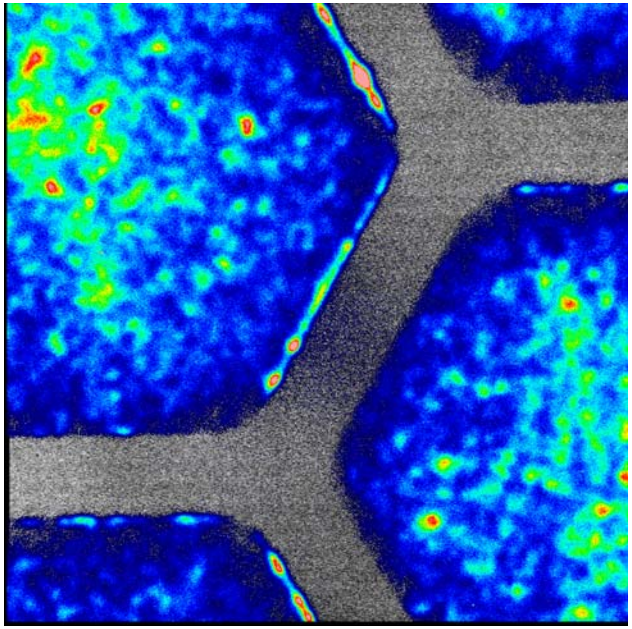
- operating device
- breakdown voltage
- edge breakdown
- leakage current

homogeneous breakdown voltage

6 (10x10) arrays placed over 6mm distance

Photoemission microscopy



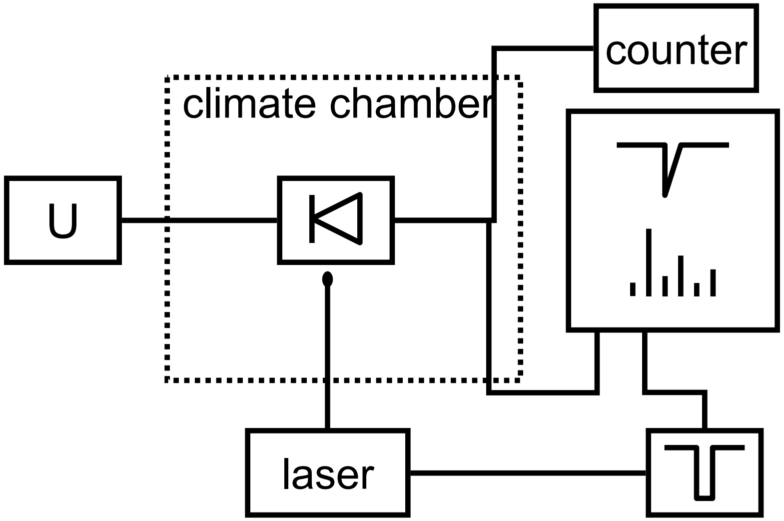


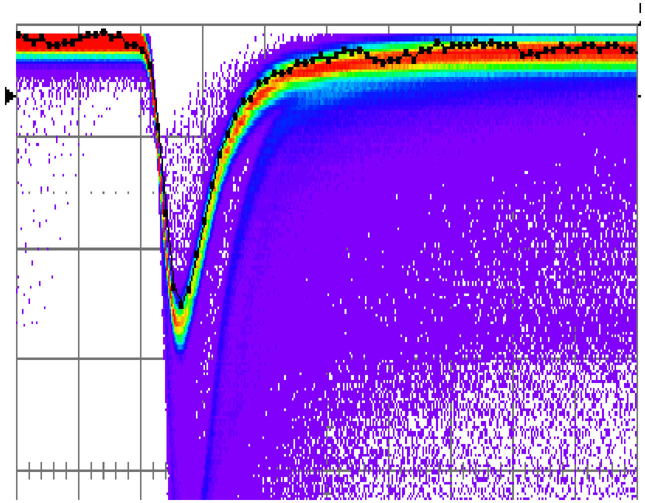
hot carrier luminescence of avalanche

→ localization of high field region

determination of fill factor and edge breakdown

Dynamic measurements





- recovery time (time from 90% - 10% of amplitude)
- dark counts (counts/s without illumination)
- pulse distribution (histogram of signal amp.)

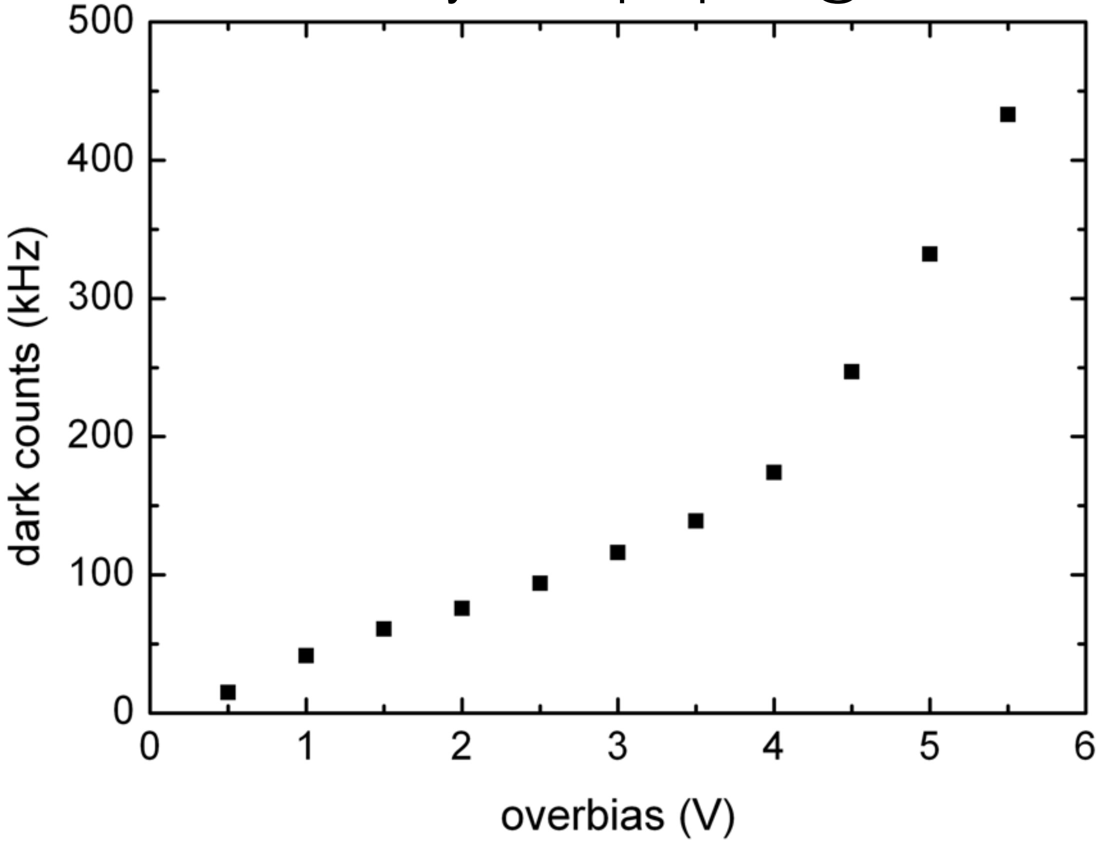
Dark counts

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

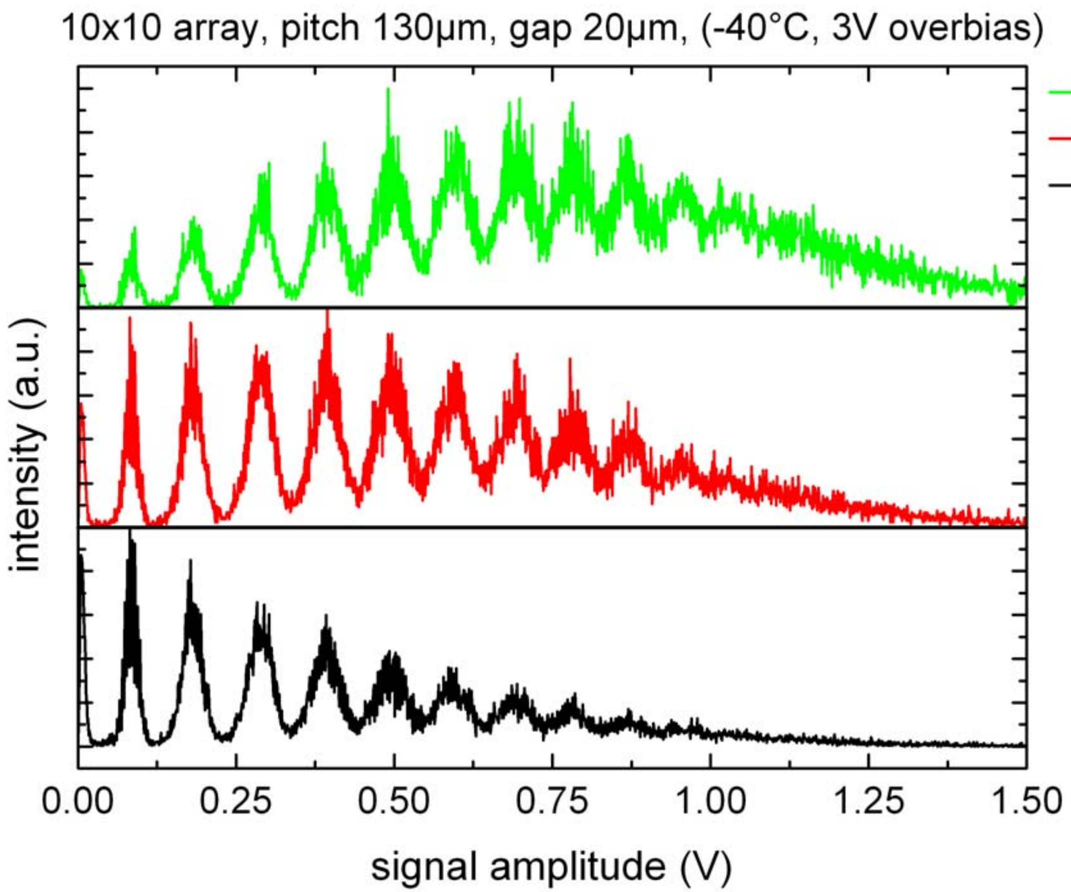
normal operation up to
4V overbias @233K

overbias > 4V
→ non quench condition

10x10 array of 130µm pitch @ 233K



Pulse distribution

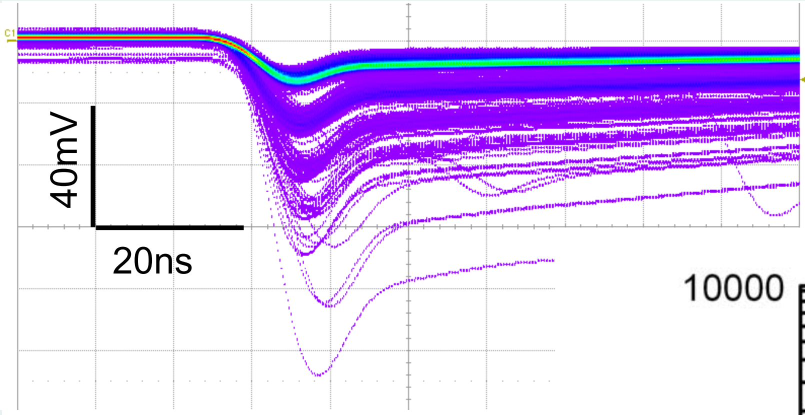


laser @ 800nm
50kHz, 3ns

information about:

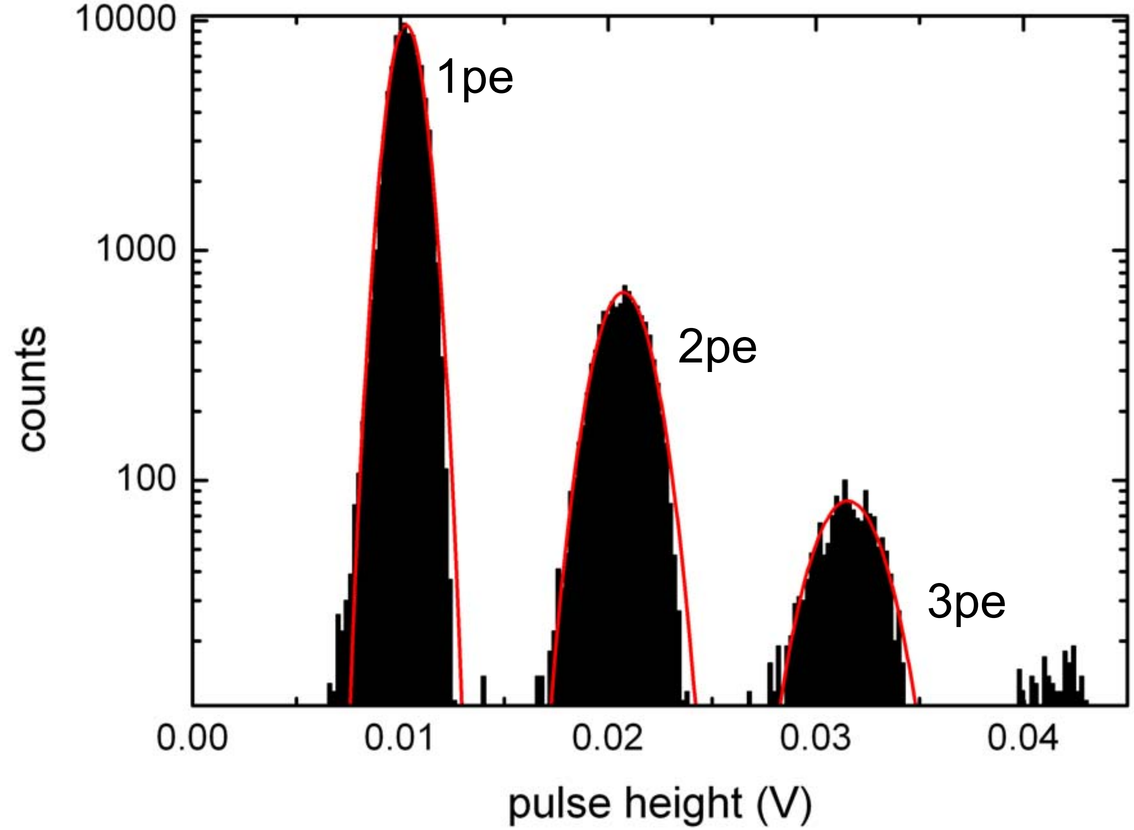
- gain
- photon resolution
- crosstalk

Pulse distribution of dark counts



p.e.	mV
1	10.3
2	20.7
3	31.5

10x10 array of 135µm pitch @ 253K



Gain linearity

pulse height ∝ Q

↓

Q = e·G = C·ΔU

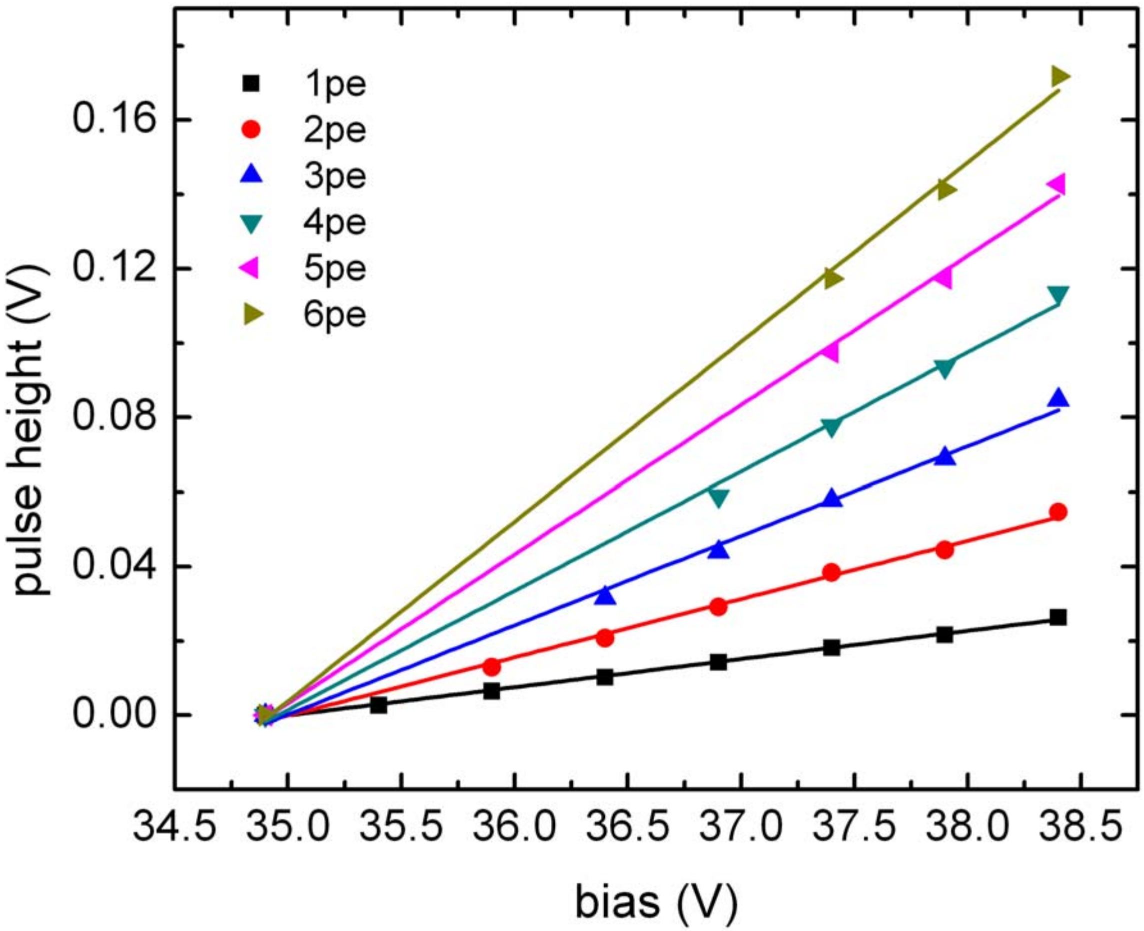
↓

linear behaviour

↓

normal operation

10x10 array of 135μm pitch @ 253K



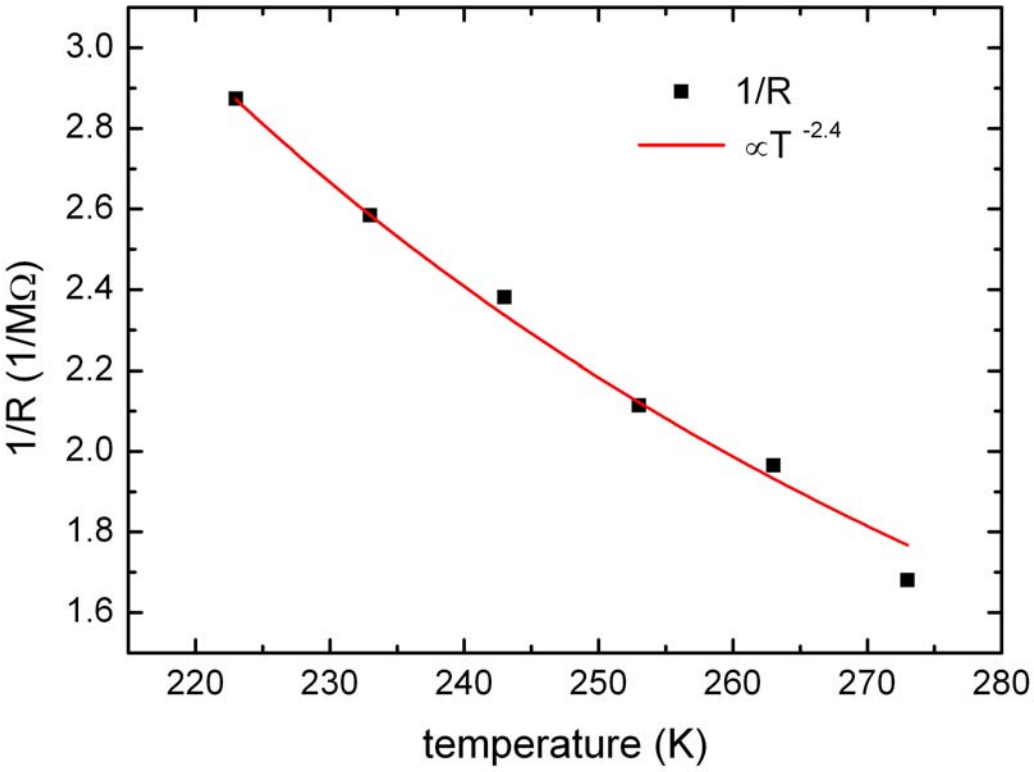
Temperature dependence of quench resistor

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

$t_{rec} = R \cdot C$

mobility:

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



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, relaxed lithography requirements
  → cost reduction in mass production

Prototype production

- quenching works
- first results very promising

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

Thanks

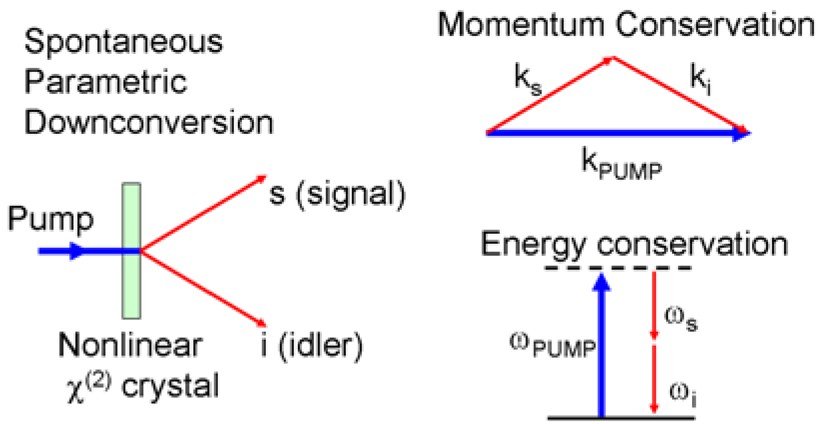
Photon detection efficiency

PDE = quantum efficiency x fill factor x 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)

Parametric down conversion



phase-matching condition

only simultaneous generation of signal & idler photon