Precision measurement of photon detection efficiency of silicon photomultipliers

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MAX-PLANCK-GESELLSCHAFT

$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$

mpi halbleiterlabor

Outline

Usage in high energy physics

- future collider experiments demand high jet energy resolution

⇒ this can be met by highly granular calorimeters

- such a device cannot use PMTs for light detection (too large)
- one alternative is to “read out” the light from scintillators with SiPM
- application in calorimeter CALICE for future linear collider experiments
- other possible applications in astroparticle physics (e.g. MAGIC), medicine, etc.

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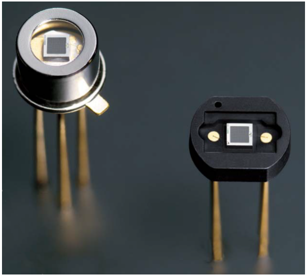

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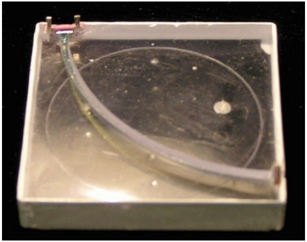
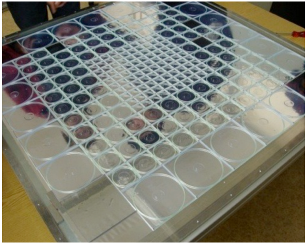




Silicon PM properties overview

Advantages

- small dimensions (usually $\sim 1\times1$ mm^2)
- insensitivity to magnetic field
- low supply voltage (tens of volts)
- single photon counting capability
- high gain

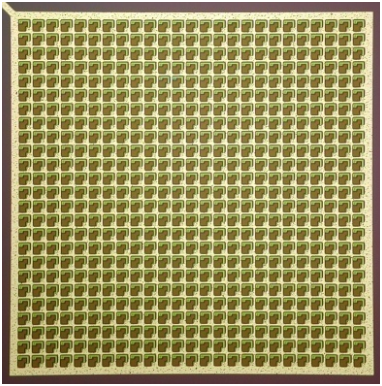
Drawbacks

- low radiation tolerance
- high thermal noise rate (dark count) ★
- optical crosstalk ★
- afterpulsing ★

★ will be explained further

Silicon Photomultipliers (SiPM, MPPC, ...)

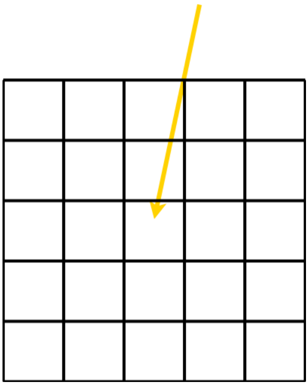
- silicon photon detectors made of an array of avalanche photodiodes (APD)
- APDs are operated in Geiger mode (slightly above breakdown voltage)
- incident photon induces an avalanche
- the avalanche is quenched by a decrease of bias voltage over a quenching resistor



Basic parameters

Optical crosstalk

- incident photon fires an avalanche (Geiger breakdown)



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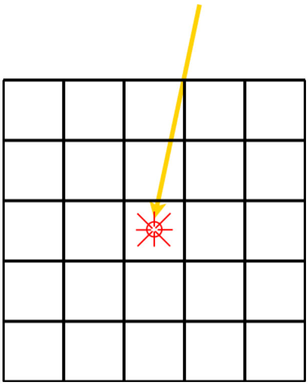

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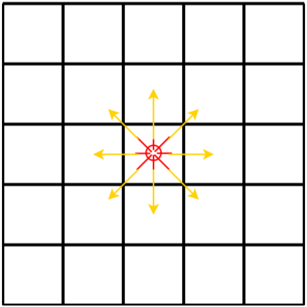

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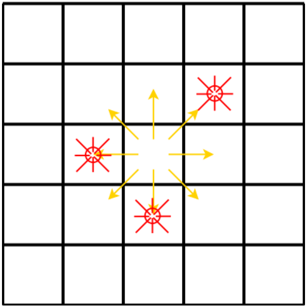

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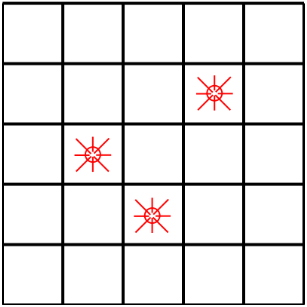

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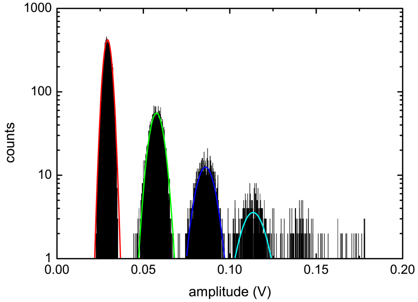

Afterpulsing

- some charge carriers can be trapped on impurities or vacancies in silicon and released later
- carriers released after/during the avalanche quenching can trigger another delayed breakdown
- this effect is more significant at lower temperatures

Dark count

- thermally excited charge carriers in the material can induce an avalanche
- when the sensor is operated in a dark box some output signal is still present
- dark count grows with temperature

- PDE is a probability that a photon hitting any point on the device will trigger a Geiger breakdown
- can be written as a product:

$$PDE = <quantum\ eff.> \times <breakdown\ eff.> \times <geometrical\ fill\text{–}factor>$$

- quantum eff. - probability that a photon creates an electron-hole pair
- breakdown eff. - probability of inducing an avalanche by an electron-hole pair
- geometrical fill-factor - fraction of whole area of the sensor which is sensitive

Basic parameters

Photon detection efficiency (PDE)

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- geometrical fill-factor - fraction of whole area of the sensor which is sensitive

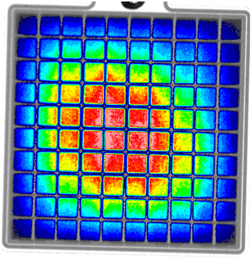
☆ relative PDE is that what my work is about!

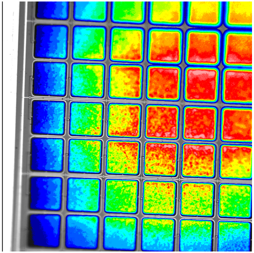
Goal of our study

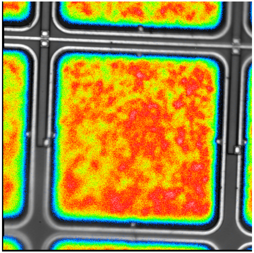
Ultimate goal

discovering of sensitivity distribution of a SiPM over its area

- separating real response from dark count and leakage current
- test SiPMs even within a single microcell
- use this very detailed information to calculate spread of PDE over whole array

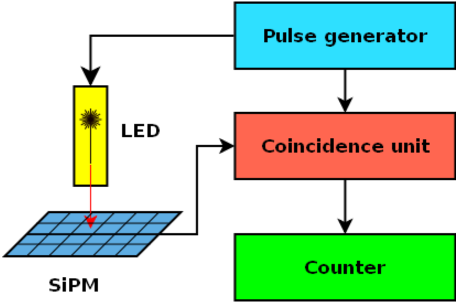






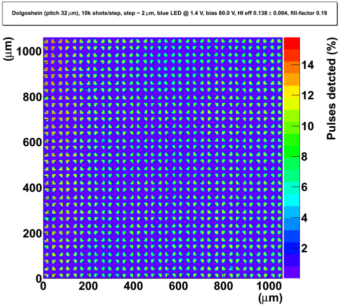
Photoemission images

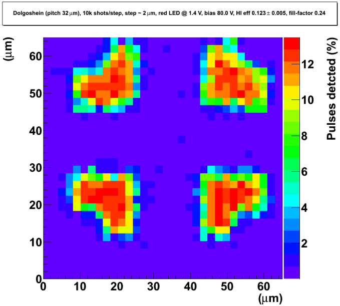
Basic idea of the measurement



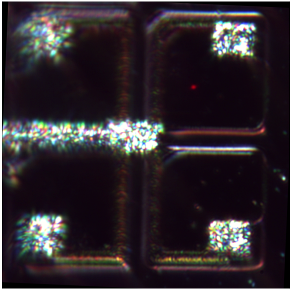
- light from an LED is focused to a small point
- the LED is pulsed
- SiPM response is measured in coincidence with LED pulses
- the light beam is driven through pixel matrix in discrete steps
- a sensitivity scan of a 1×1 mm^2 device with 1 μm step size can be completed in $\sim$ 40 hours

Results: MEPhi (Dolgoshein) (32 μm pitch)

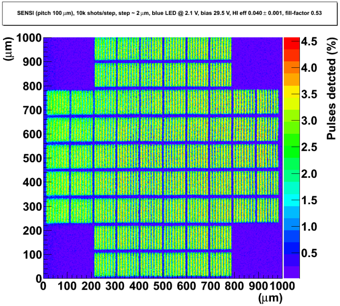


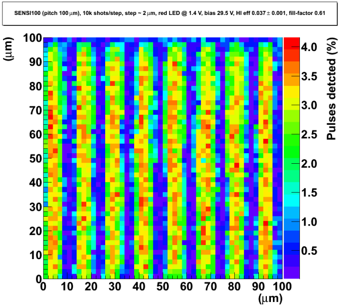


different quenching resistor shape can be observed on the sensitivity map



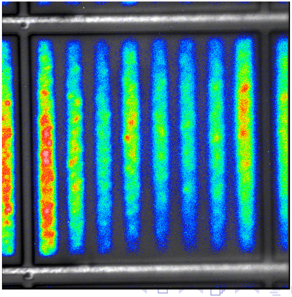
Scan image: SENSI (100 μm pitch)



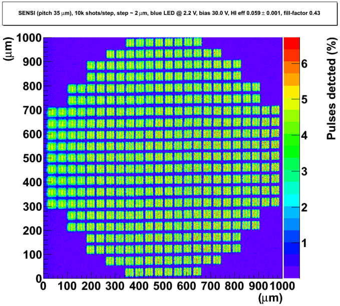


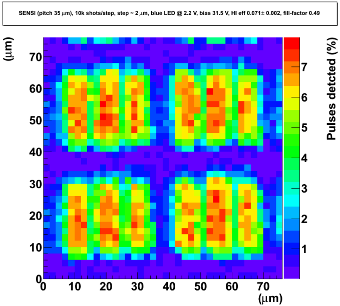
different quenching resistor shape can be observed on the sensitivity map

Photo + photoemission image



Scan image: SENSI (35 μm pitch)





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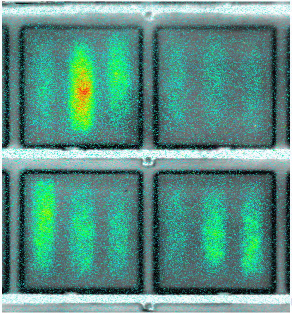
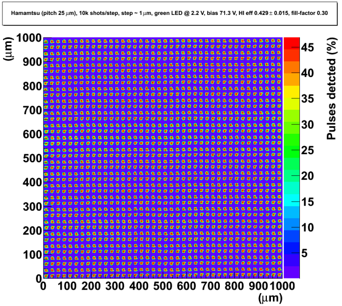
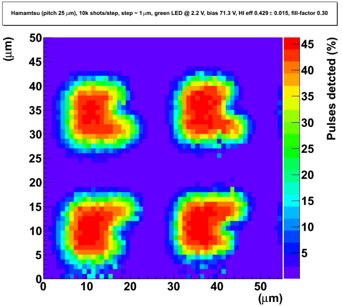
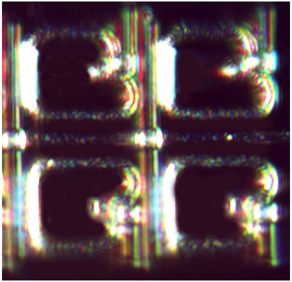


Scan image: Hamamatsu (MPPC) (25 μm pitch)

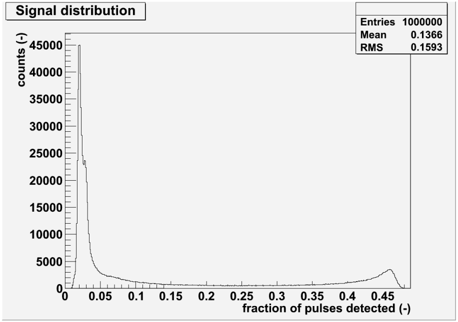




sensitive area is obviously significantly reduced by the quenching resistor placed on surface of the device



Single pixel analysis procedure: noise cut-off



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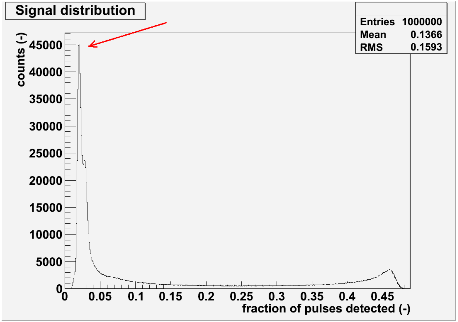

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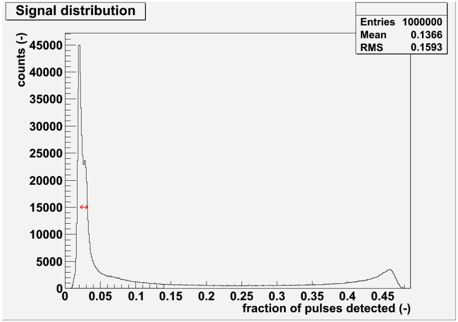

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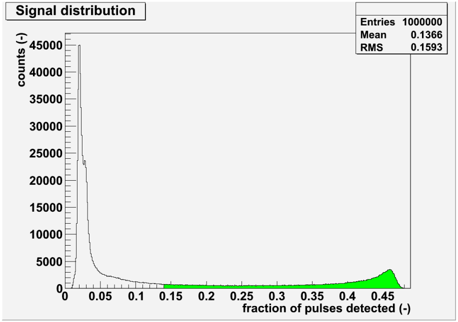

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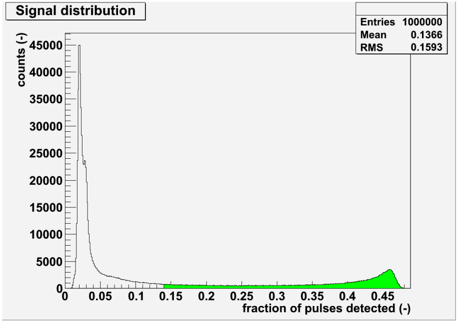

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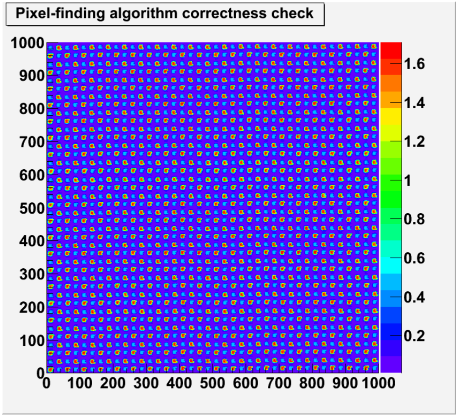

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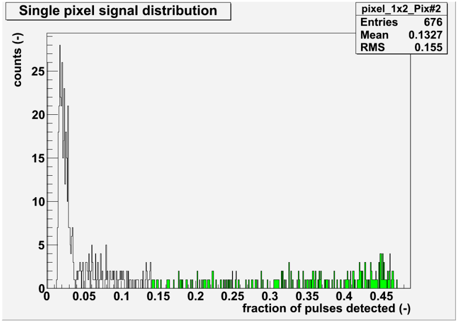

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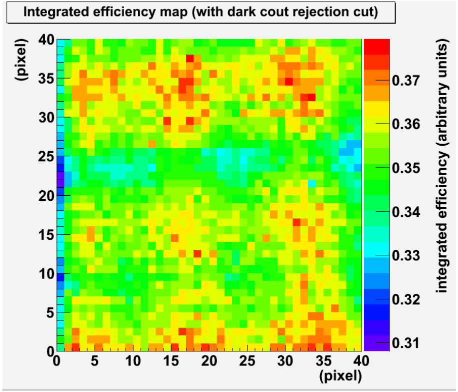
⇒ resulting values are again plot in 2D



Other quantities of interest

Quantities obtainable from our measurement

- noise
- fill factor (even separately for a single microcell)
- uniformity of efficiency over the device
- photon detection efficiency ★

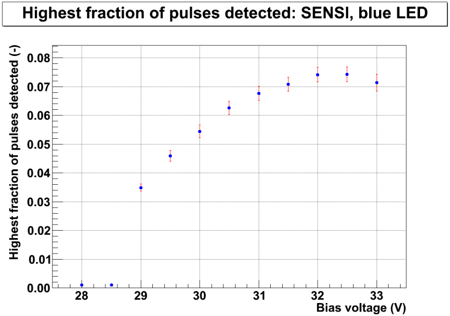
★ normalisation with other absolute measurement needed

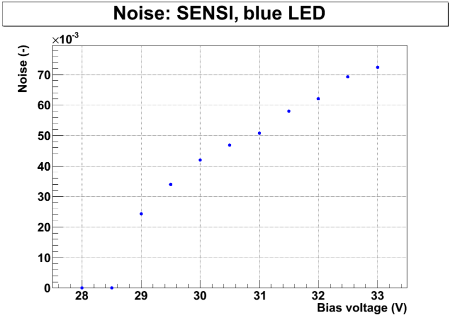
~ wavelength dependencies (not yet possible)

+ bias voltage dependencies

Bias voltage dependencies

- can be used as a cross check of stage calibration (LED focus), correct settings of thresholds etc.
- shows when quenching ceases
- possible later comparison of different wavelengths (further improvements needed)





Summary

- SiPMs are novel devices for single photon counting
- due to their small dimension etc. are promising replacement of PMTs
- there are still properties to be studied/improved/suppressed
- development of new technologies is ongoing

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Conclusions

Accomplished

- new stage calibration developed
- new scanning procedure applied
- higher level of automation reached
- data storage and analysis framework developed

⇒ scanning speed improved by three orders of magnitude

⇒ capability of scanning arbitrarily aligned SiPM surfaces

⇒ first successful uniformity analysis done (still to be improved)

Future plans

- scans of further devices (including SIMPL)
- try to normalise with an absolute measurement
- estimate light output of used LEDs
- implement cooling of measured samples