The measurement of the SiPM photon detection efficiency at ITC-irst

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Fermi National Accelerator Laboratory, October 2006

Outline

- Photon Detection Efficiency (PDE) of the SiPM
- Experimental methods used for the PDE measurement
- PDE of the first SiPM prototypes developed at ITC-irst
- Summary and outlook

Photon detection efficiency of the SiPM

- **Traditional PDE:**

$$\eta = \frac{nr.of\ output\ pulses\ recorded}{nr.of\ photons\ emited\ by\ light\ source}$$

- **PDE of the SiPM:**

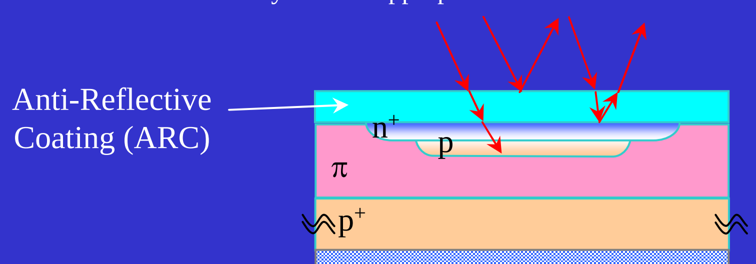
$$\eta_{SiPM} = QE \times P_{triggering} \times \varepsilon_{geom}$$

1. QE – the quantum efficiency

- probability that a photon generate an e/h pair in the active region of the device (e.g. n^+/p junction of a pixel) - wavelength dependent

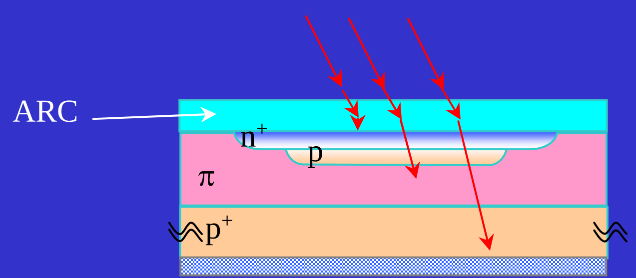
a) transmission efficiency through ARC

(ARC = stack of dielectric layers with appropriate thickness and refraction index)



SiPM pixel

b) internal quantum efficiency



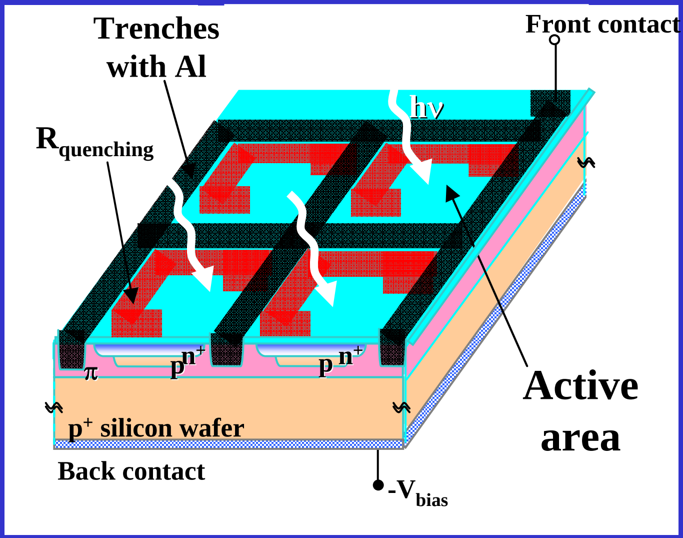
SiPM pixel

Photon detection efficiency of the SiPM (cont)

2. $P_{triggering}$ – the triggering probability ($P_t = P_e + P_h - P_e{*}P_h$)
   - probability that a carrier (e or h) traversing the high field region triggers an avalanche
   - P_e & P_h are linked to the impact ionization rates of the electrons and holes
     - electrons have higher ionization rates than holes
     - both electrons and holes ionization rates increase with the electric field (e.g. overvoltage)

3. ε_{geom} – the geometrical efficiency (active area / total area)

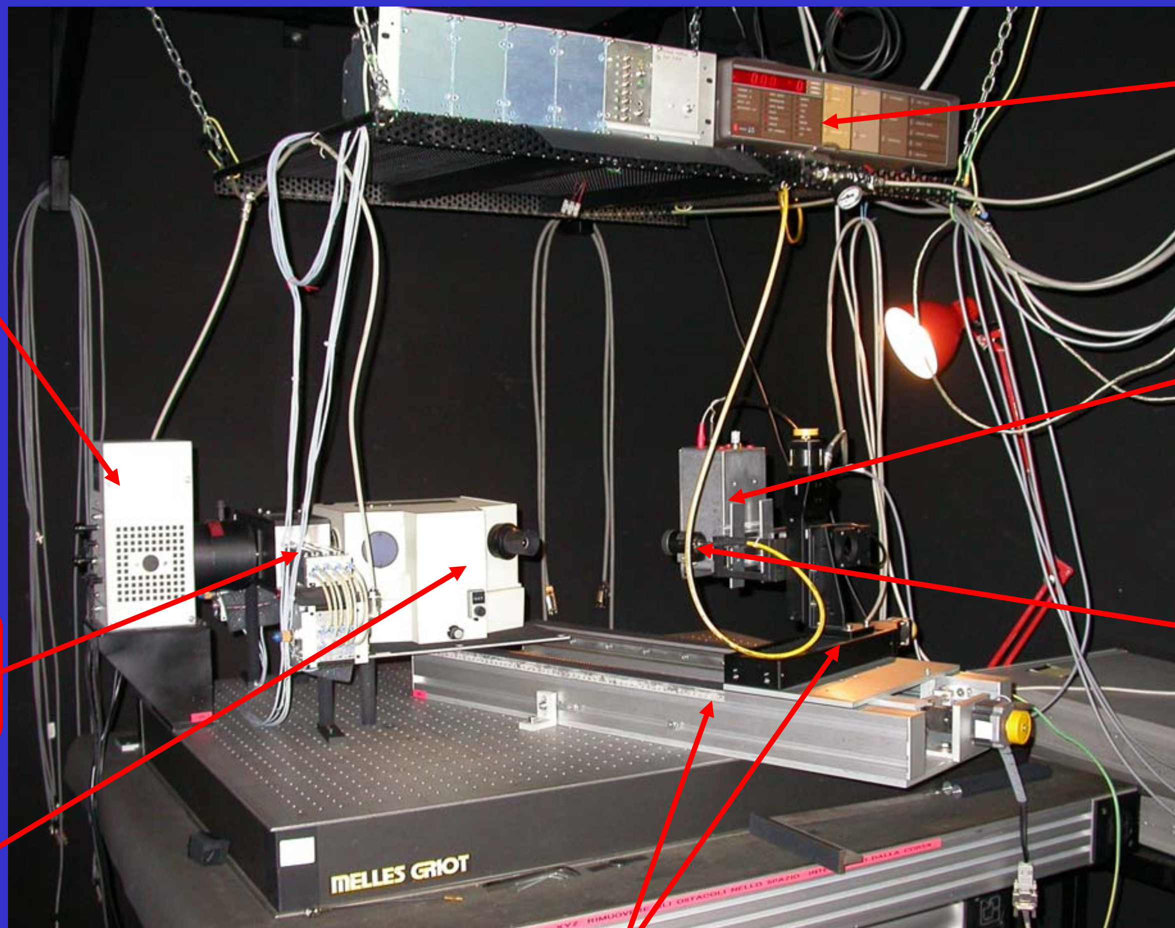
SiPM



(design not in scale)

- <u>Total area includes dead regions given by:</u>
  - quenching resistors
  - trenches
  - metal layers
- <u>Active area:</u>
  - ~ 15- 30% of total area depending of the layout design

The experimental set-up



Optometer

Halogen white lamp (OSRAM)

SiPM + preamplifier

Neutral filters (filter transmittance 10%)

Photodiode (UDT 221)

Monocromator (Jobin Yvon HR250)

Stage with 3D micrometric movement (50µm precision)

The methods for the PDE measurement

$$\eta_{SiPM} = \frac{N_{photons\ recorded\ by\ the\ SiPM}}{N_{incident\ photons\ on\ the\ SiPM\ surface}}$$

$$N_{incident\ photons\ on\ the\ SiPM\ surface}$$

reference calibrated detector
(photodiode)

$$N_{inc.\,ph./s/mm^2} = \Phi_{(W/mm^2)} \cdot \frac{\lambda}{hc}$$

$$N_{photons\ recorded\ by\ the\ SiPM}$$

1 DC method

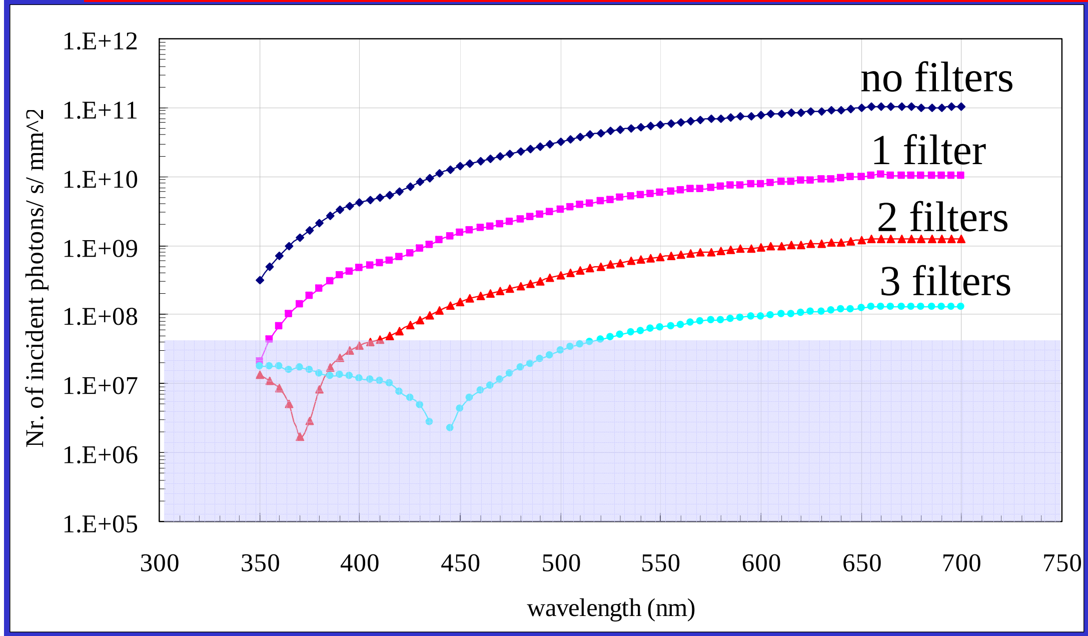
$$N_{rec.\,ph./s/mm^2} = \frac{I_{light} - I_{dark}}{G_{SiPM} \cdot q}$$

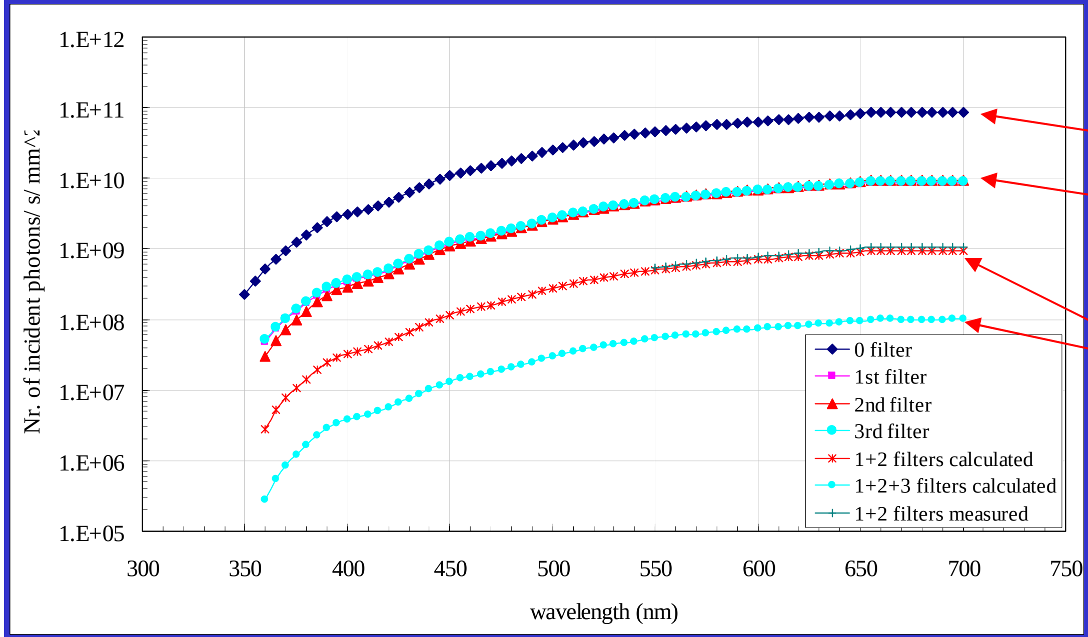
2 Pulses counting method

$$N_{rec.\,ph./s/mm^2} = (light\ counts/s) - (dark\ counts/s)$$

(for low optical power densities)

Set-up calibration





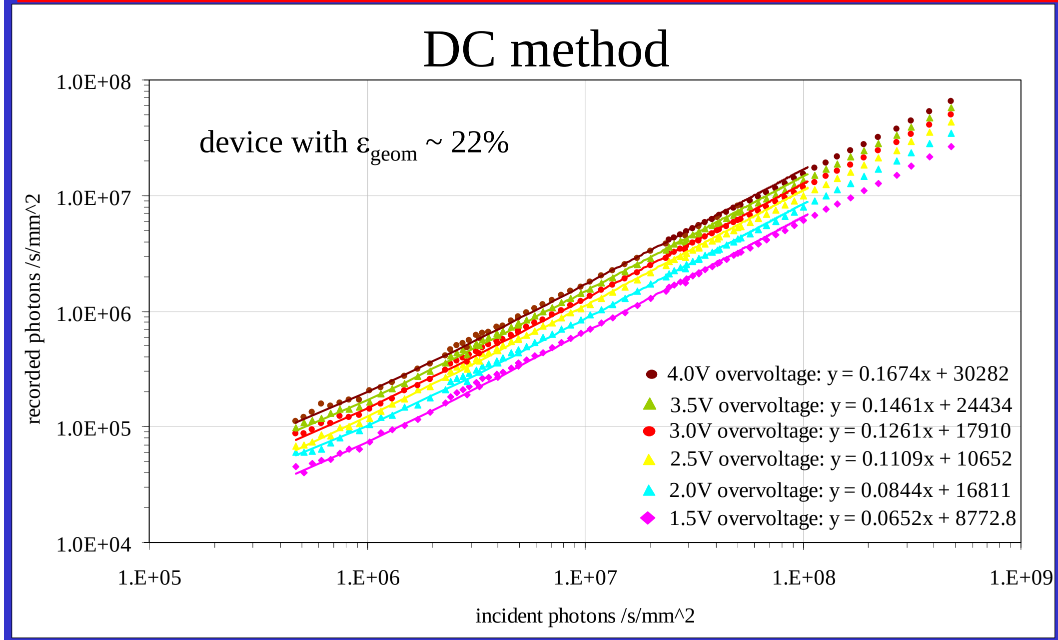
$$N_{inc.ph./s/mm^2} = \Phi_{(W/mm^2)} \cdot \frac{\lambda}{hc}$$

$$\Phi_{(W/mm^2)} = \frac{1}{A_{phot}(mm^2)} \cdot \frac{I_{phot}(A)}{R_{phot}(A/W)}$$

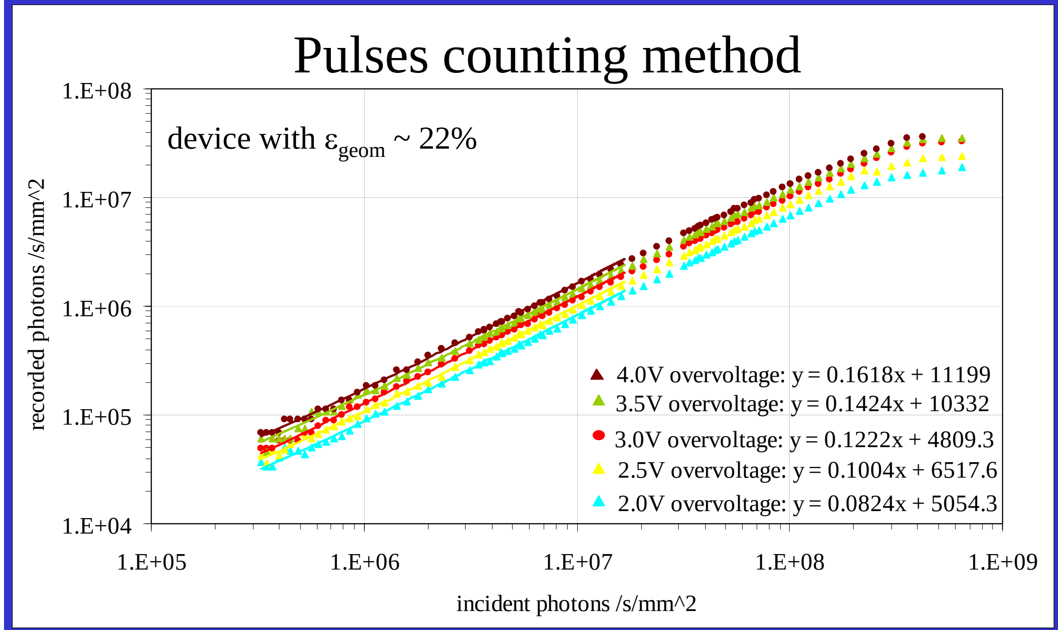
- Photodiode sensibility:
  - ~ 4 x 10^7 photons/s/mm^2

- Calibration method:
  - light beam without any filter
  - each filter separately
  - each filter factor is calculated at all wavelengths
  - if 2 or 3 filters are inserted simultaneously, the optical power density is calculated based on each filter factor determined previously

PDE @ 550nm – DC & pulses counting methods (1)

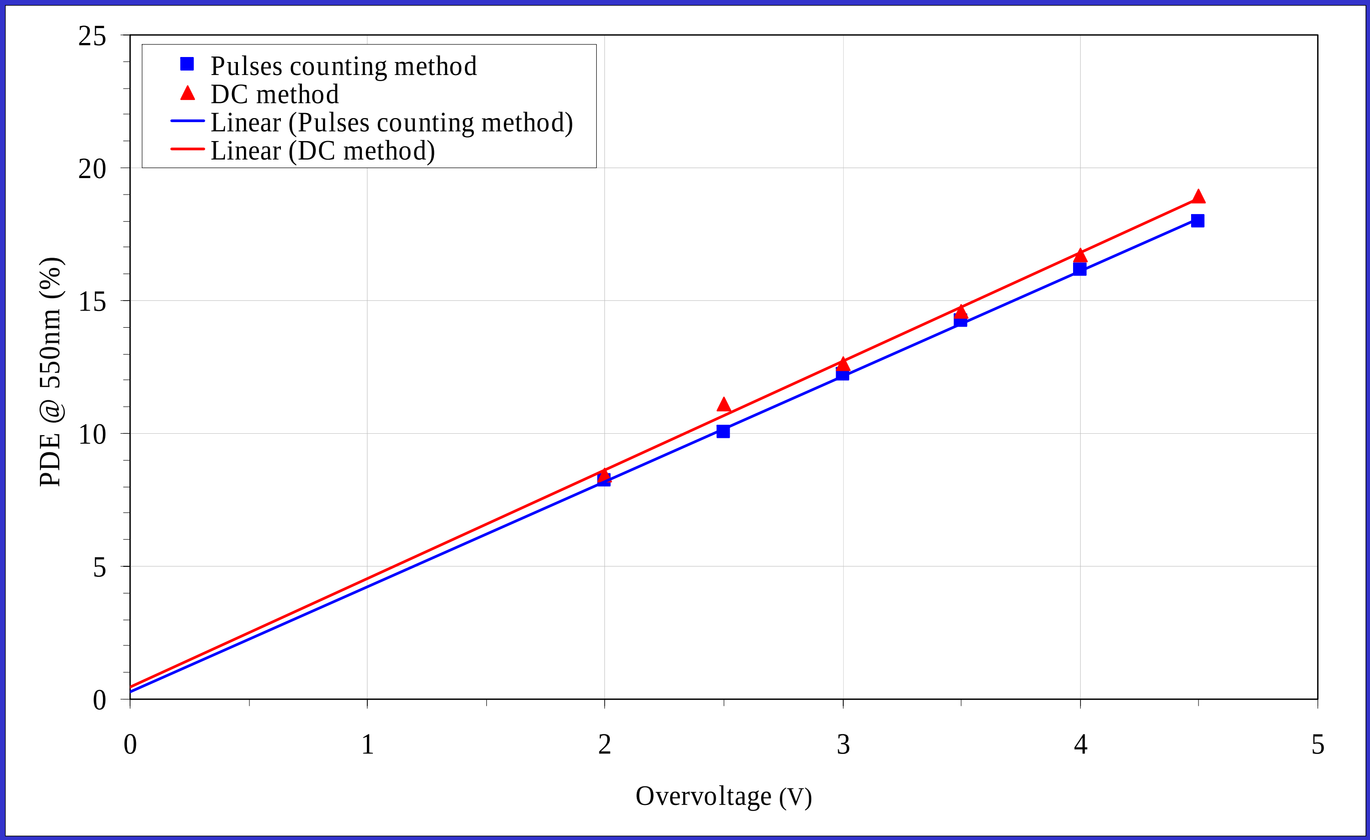


$$N_{rec.\,ph./s/mm^2} = \frac{I_{light} - I_{dark}}{G_{SiPM} \cdot q}$$



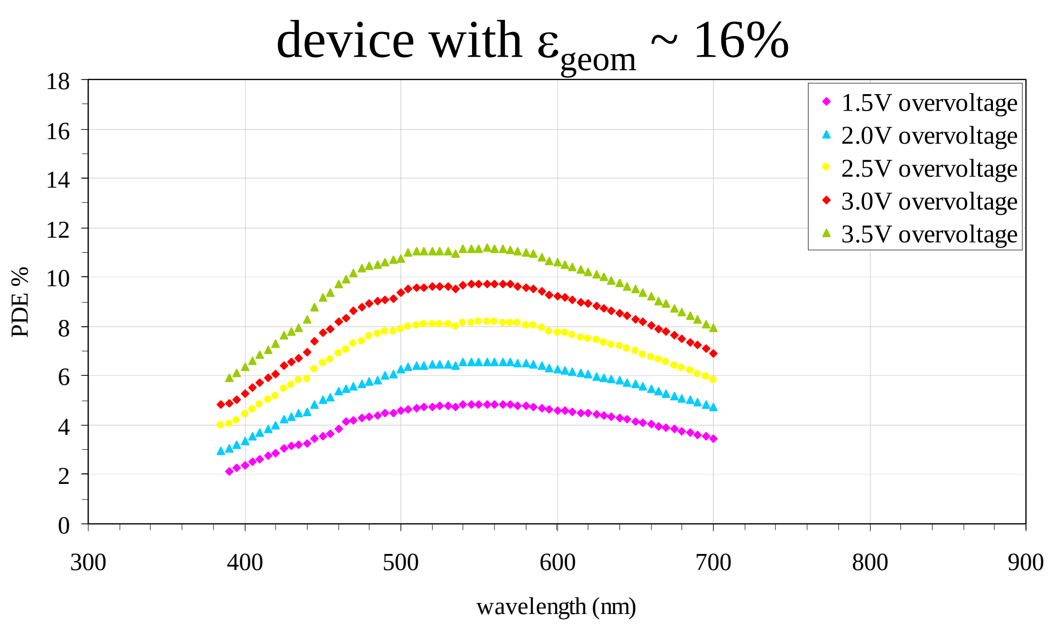
$$N_{rec.\,ph./s/mm^2} = (\text{light counts/s}) - (\text{dark counts/s})$$

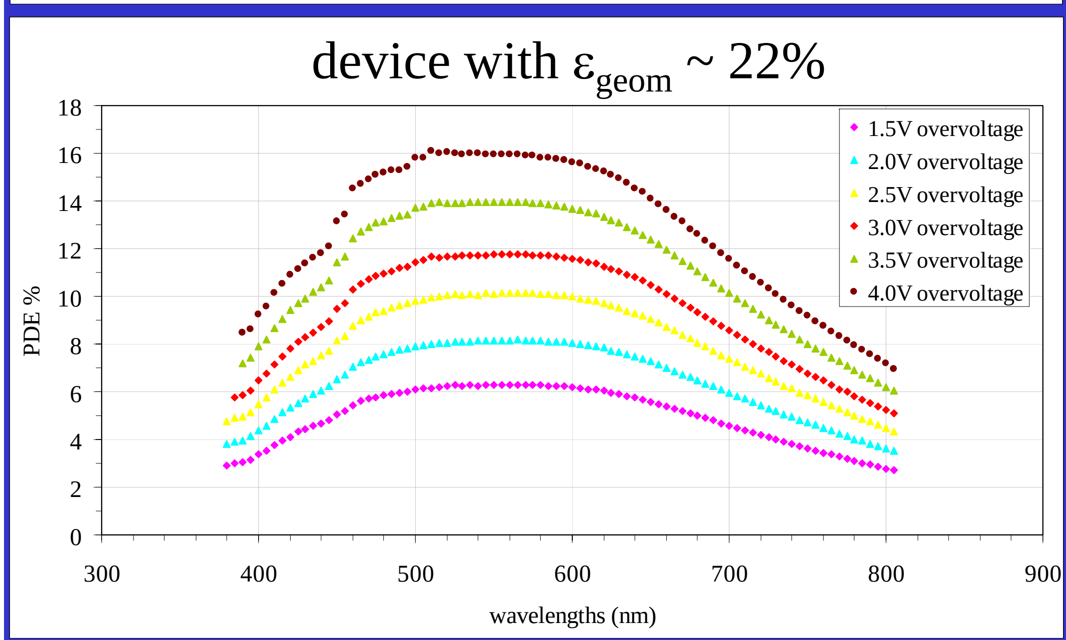
PDE @ 550nm – DC & pulses counting methods (2)



- Very good agreement in between the DC and counting pulses methods
- PDE increases linearly with the overvoltage at least up to 5V overvoltage

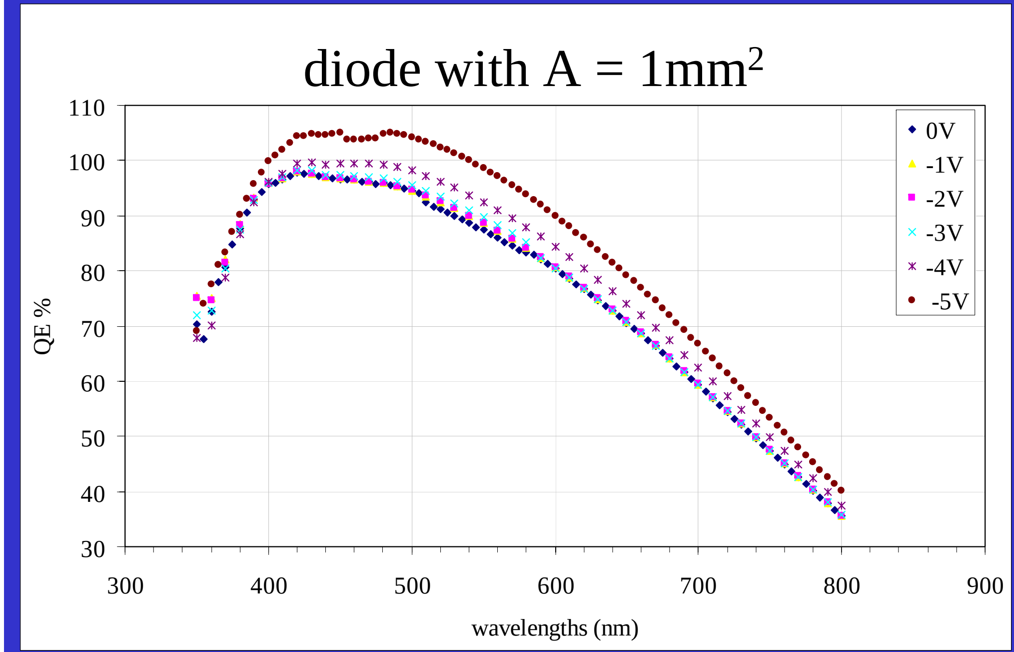
Photon detection efficiency – DC method

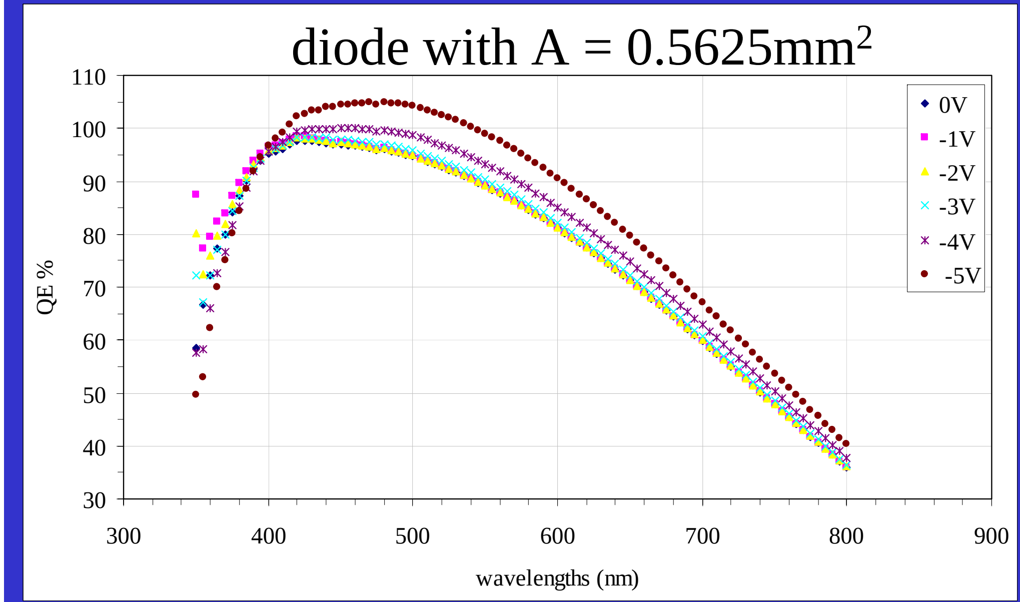




- <u>Maximum PDE in the range 500 ÷ 600 nm</u>
  - ~ 16% @ 4V overvoltage for a SiPM of ε_{geom} ~ 22%
- <u>For low λ</u>
  - the PDE is reduced by the $P_{triggering}$ (only holes trigger the avalanche)
- <u>For high λ</u>
  - the PDE is reduced by the QE (QE was optimized for low λ)

Quantum efficiency



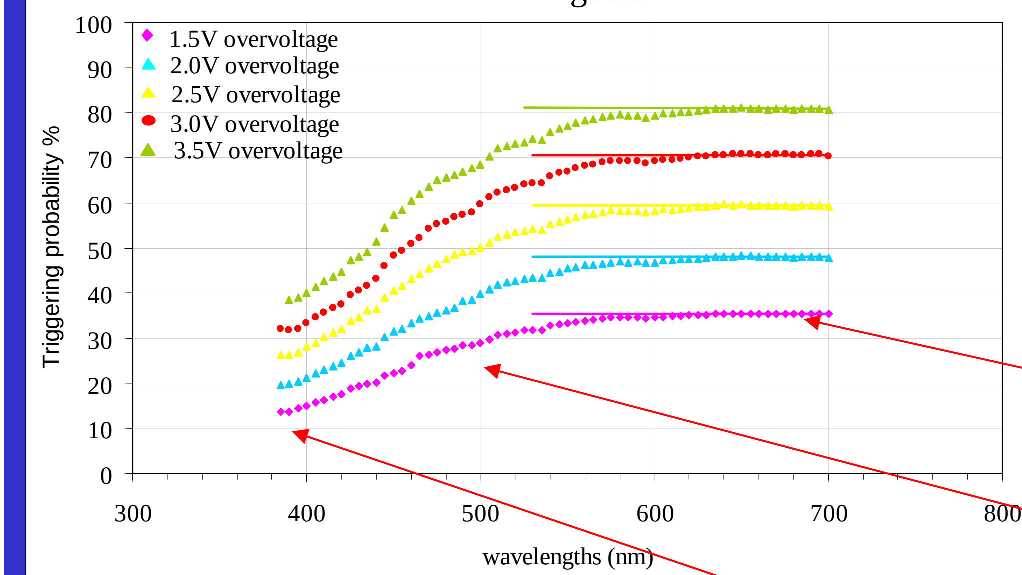


- Diode:
  - Test structure with the same (n^+/p junction + ARC) as each SiPM pixel
  - Works as a photodiode at low reversed bias (0V, 1V or 2V)
  - Allows the measurement of the QE (transmission through ARC & internal quantum efficiency)
- The impact ionization effect already visible at 3-4V

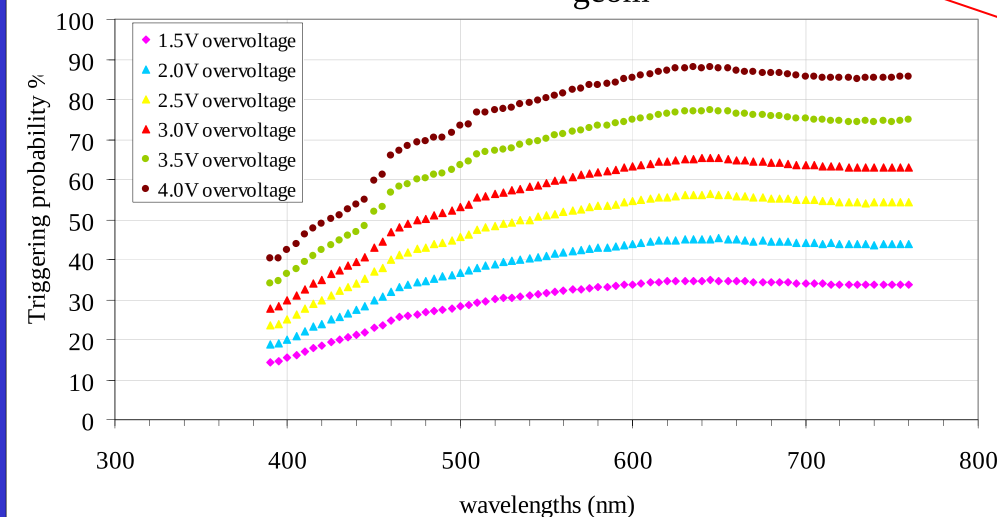
- QE > 95% in the blue region (optimized for $\lambda \sim 420$nm)

Triggering probability

device with ε_{geom} ~ 16%



device with ε_{geom} ~ 22%



- Calculated from:

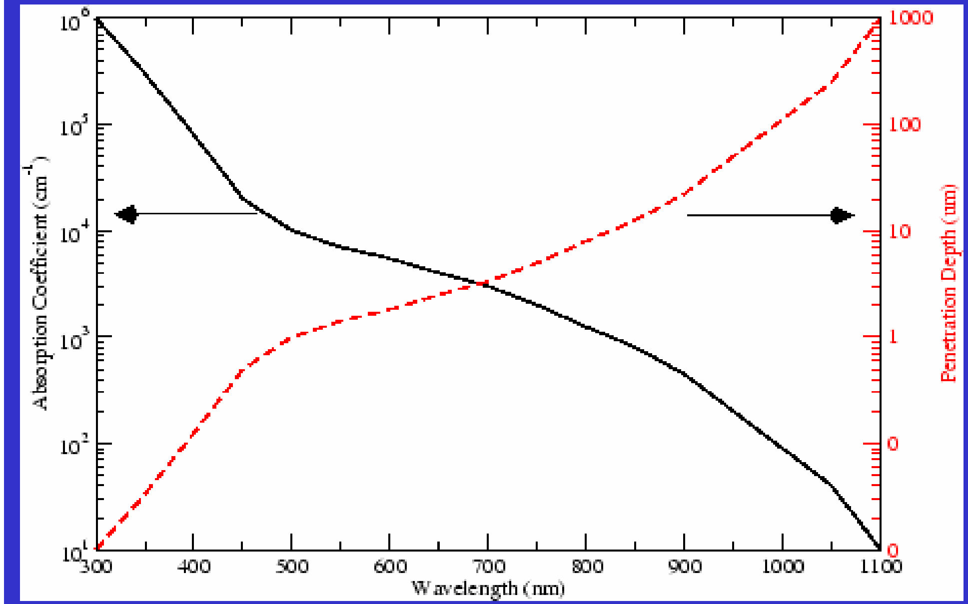
$$\eta_{SiPM} = QE \times P_{triggering} \times \varepsilon_{geom}$$

Only electrons trigger the avalanche

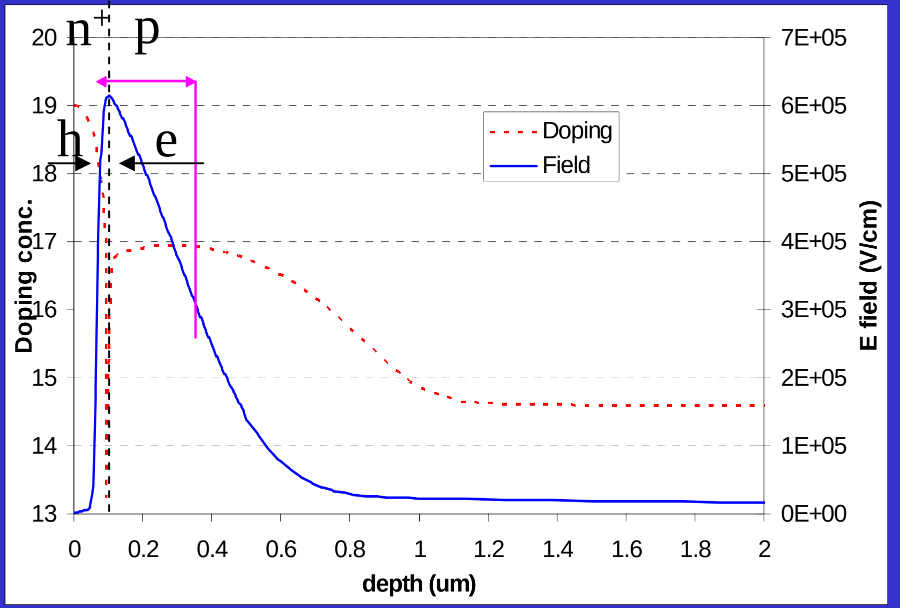
Both holes and electrons trigger the avalanche

Only holes trigger the avalanche

Light absorption



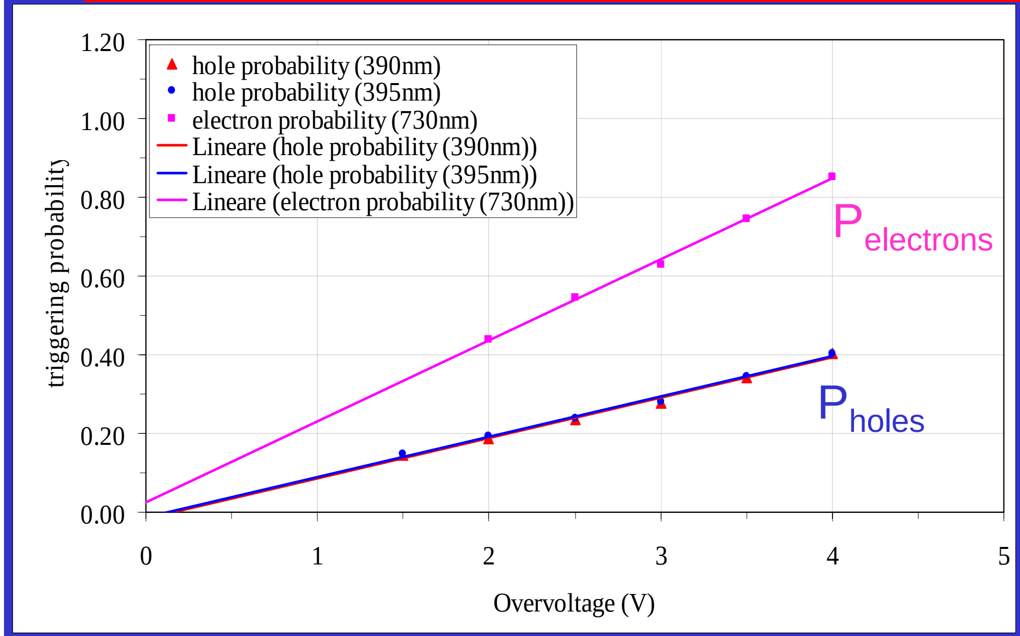
Attenuation of the light intensity in silicon (Beer-Lambert law)



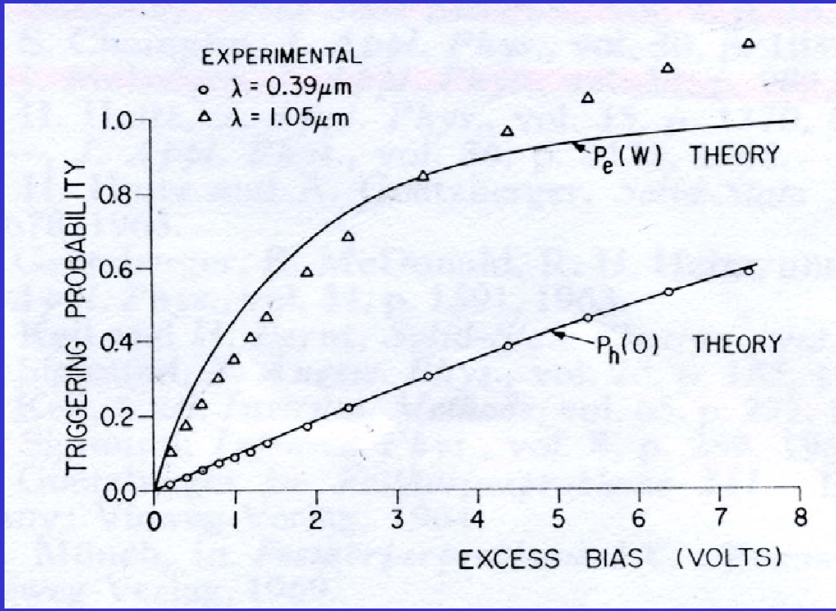
Simulated doping profile and electric field of the SiPM

- At low wavelengths only the holes cross the high field region & trigger the avalanche
  - ⇒ triggering probability @ low λ (e.g. 385, 390, 395nm) = hole triggering probability
- At high wavelengths only the electrons cross the high field region & trigger the avalanche
  - ⇒ triggering probability @ high λ (e.g. 700nm) = electron triggering probability

Electron & hole triggering probability



- P_e & P_h increase linearly with the overvoltage up to 4V
- The slight difference of 0V point could arises from the unavoidable statistical variation of the $V_{breakdown}$ across the structure



- *Ref. data: W. Oldham & all,*
- *"Triggering phenomena in avalanche diodes", IEEE Trans. on Electron Devices Vol. ED-19, No.9, Sept. 1972*

Summary

- Photon detection efficiency of the SiPM devices developed at ITC-irst

- Two experimental methods:
    - DC & pulses counting
    - very good agreement in between the two methods (λ=550nm)

- Photon detection efficiency:
    - Depends of three factors:
        - geometrical efficiency: ~15-30% (e.g. function of the layout design)
        - quantum efficiency: > 95% in the blue region (optimized for 420nm)
        - triggering probability: $P_e > P_h$
    - Maximum in the range 500-600 nm :
        - ~ 16% @ 4V overvoltage for a device of ε_{geom}= 22%
        - for low λ it is reduced by the $P_{triggering}$ (only holes trigger the avalanche)
        - for high λ it is reduced by the QE (optimized for blue region)
    - Increases linearly with the overvoltage (at least up to 4V overvoltage)