

# Study of the Breakdown Voltage of SiPMs

or

What the SiPM user does not want to know about SiPM breakdown

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# Introduction

## SiPMs

Relevant parameters for the user:

- Gain
- Photon det. efficiency (PDE)
- Breakdown voltage  $V_{bd}$
- Dark-count rate (DCR)
- Cross talk (XT)
- After pulsing (AP)

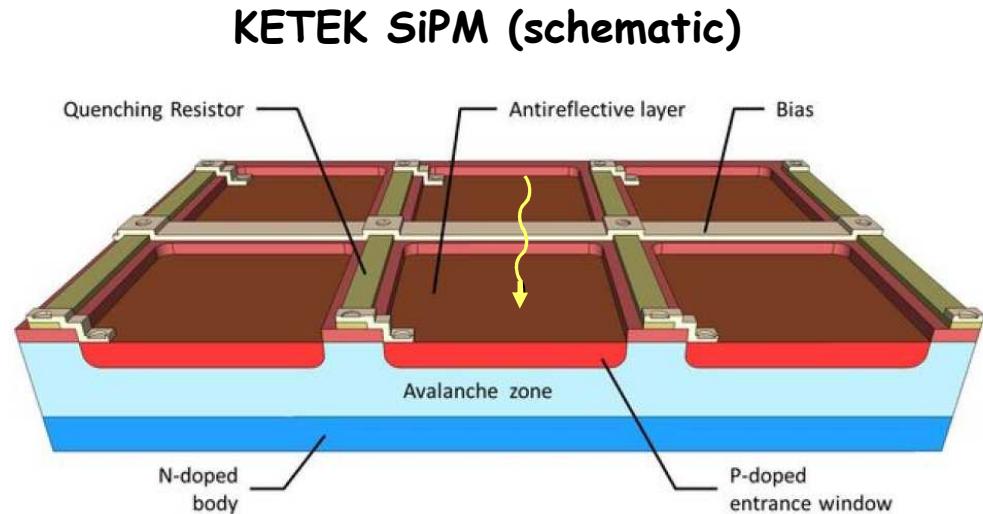


Figure 1: Cross section of micro cells processed in Standard Technology.

Aim of the work:

Better understanding + modeling of Geiger breakdown

- Simplify measurement of the breakdown voltage for large no. of samples
- Improve SiPM performance, in particular with respect to radiation tolerance

# Geiger discharge of a single pixel

e-h pair generated by  $\gamma$  or thermal excitation/diffusion

→ e/h → into amplification region

Avalanche multiplication

→ discharge „plasma“ channel

→  $V_{pix}$  decreases

→ discharge stops, when charge multiplication can not maintain plasma channel →  $V_{turn\ off}$

Recharging:  $V_{pix}$ :  $V_{turn\ off} \rightarrow V_{bias}$

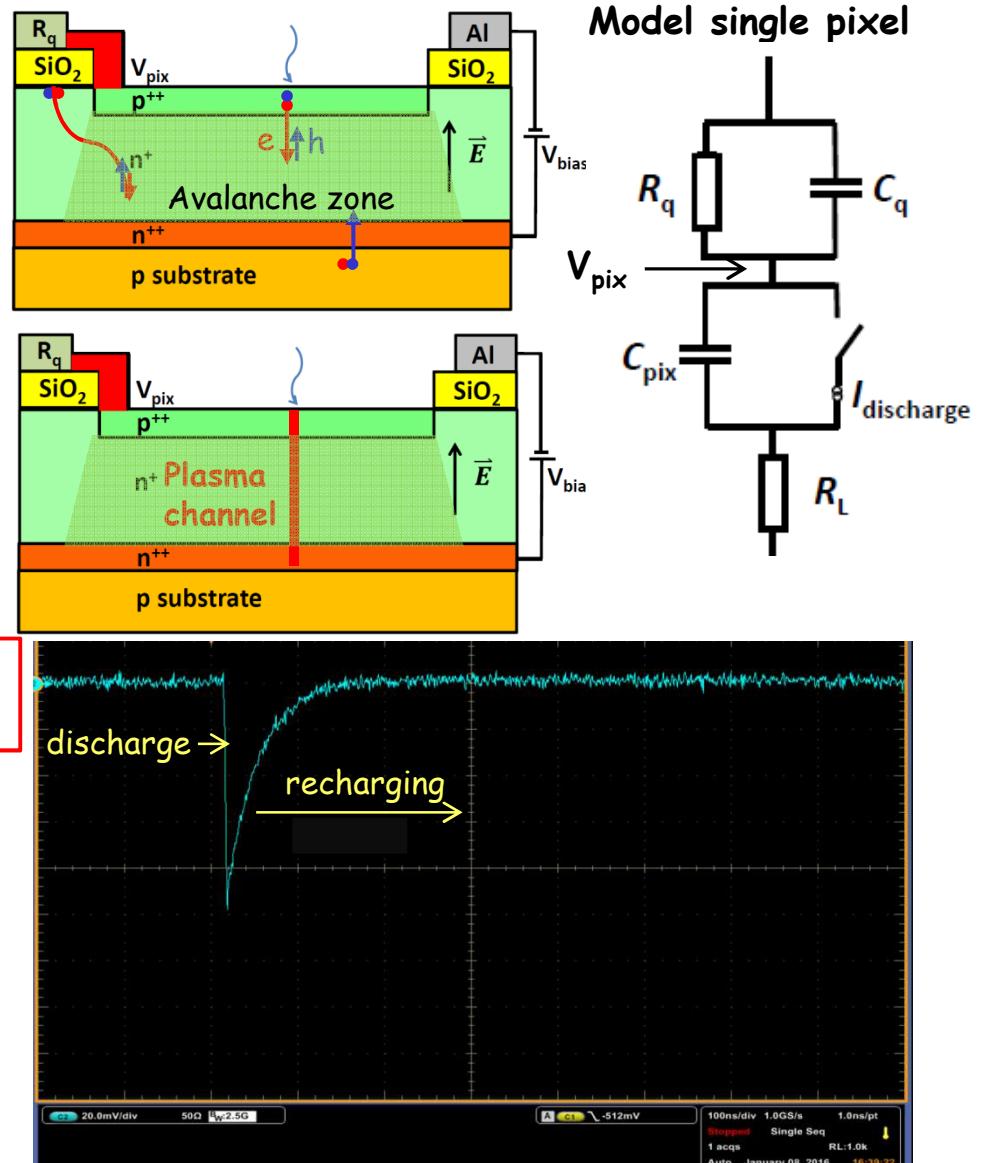
Folklore

$$Gain \approx C_{pix} \cdot \frac{V_{bias} - V_{bd}}{q_0}; V_{bd} \equiv V_{turn\ off}$$

This work: determine v.s. pixel size:

- $V_{Gain}$ :  $Gain \propto (V_{bias} - V_{Gain})$
- $V_I$ : Voltage, at which the reverse current shows „breakdown“
- $V_{PDE}$ : Voltage, at which  $PDE > 0$

→ Learn about  $V_{bd}$  and  $V_{turn\ off}$

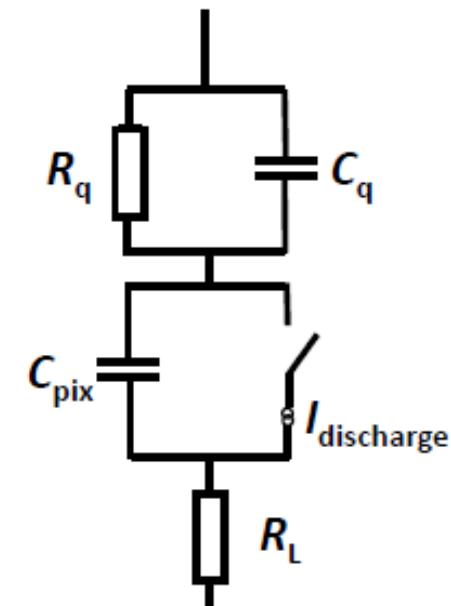
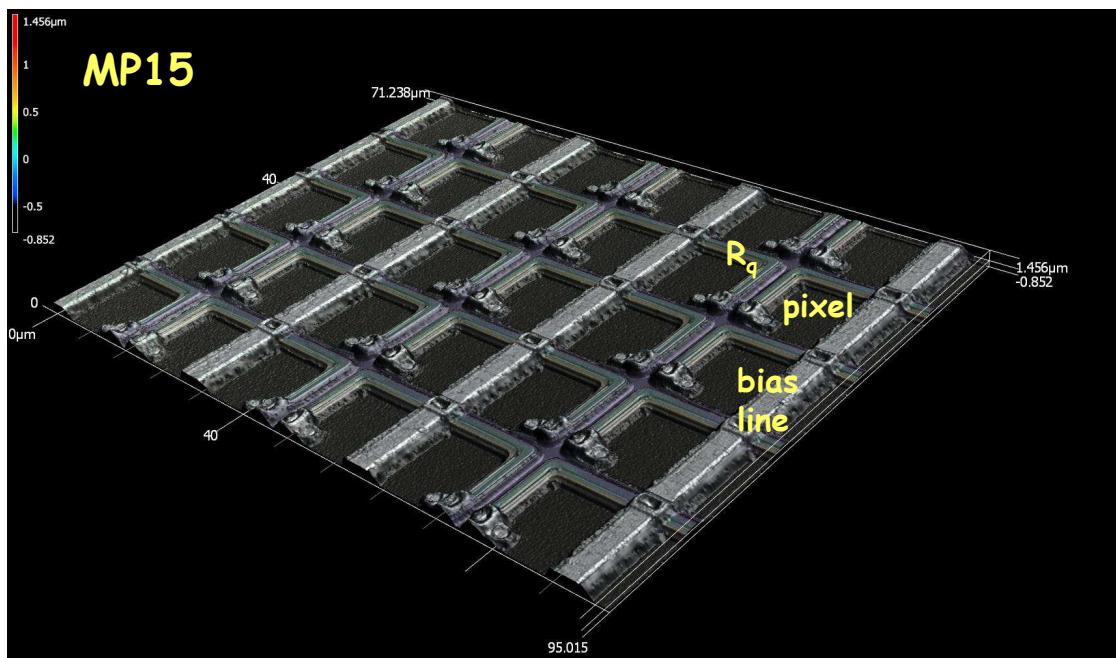
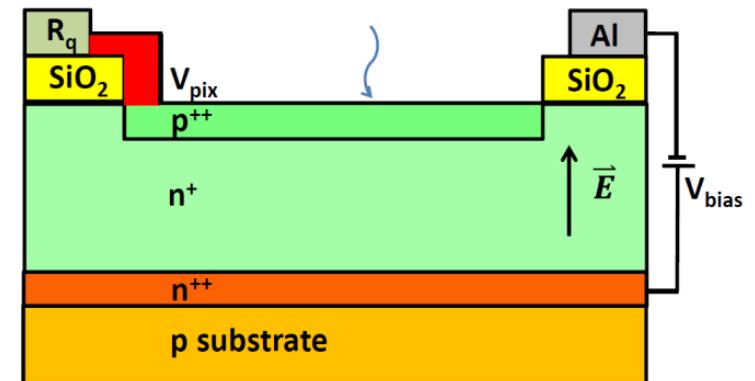


# Sensors studied

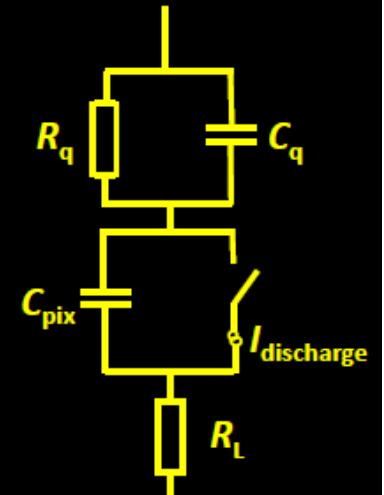
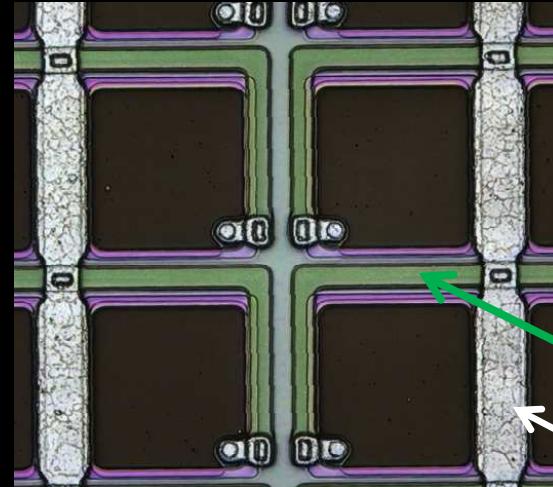
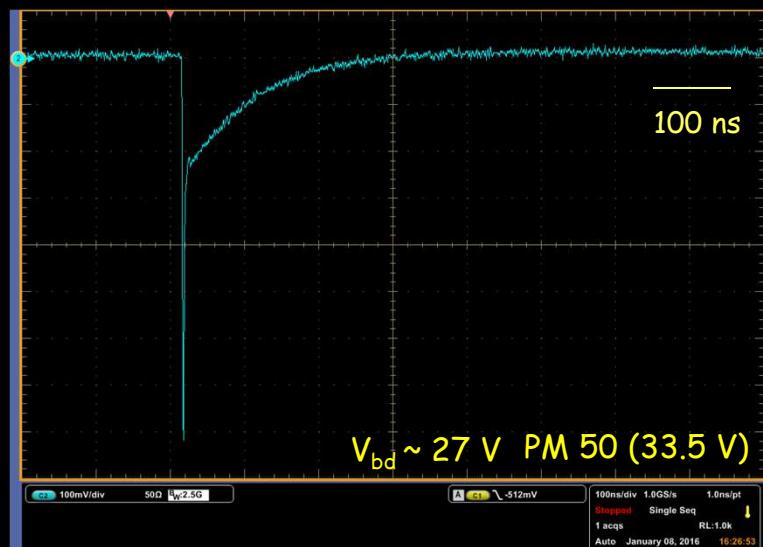
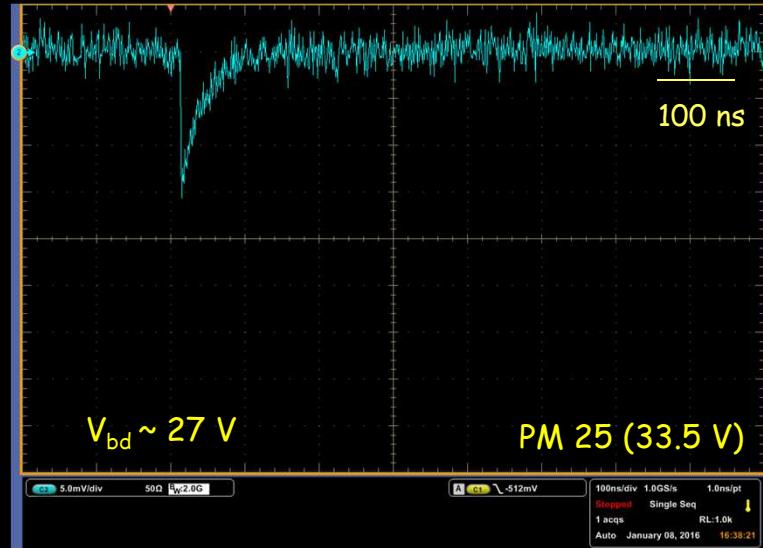
Producer: KETEK

|                  | MP15             | PM25             | PM50             | PM100             | PNCV |
|------------------|------------------|------------------|------------------|-------------------|------|
| N <sub>pix</sub> | 4382             | 1600             | 400              | 100               | 1    |
| pitch            | 15 $\mu\text{m}$ | 25 $\mu\text{m}$ | 50 $\mu\text{m}$ | 100 $\mu\text{m}$ | 1 mm |

(MP15) - (PM25,PM50,PM100 and PNCV) diff. productions



# Pulse shapes for single PE (LED) - Layout

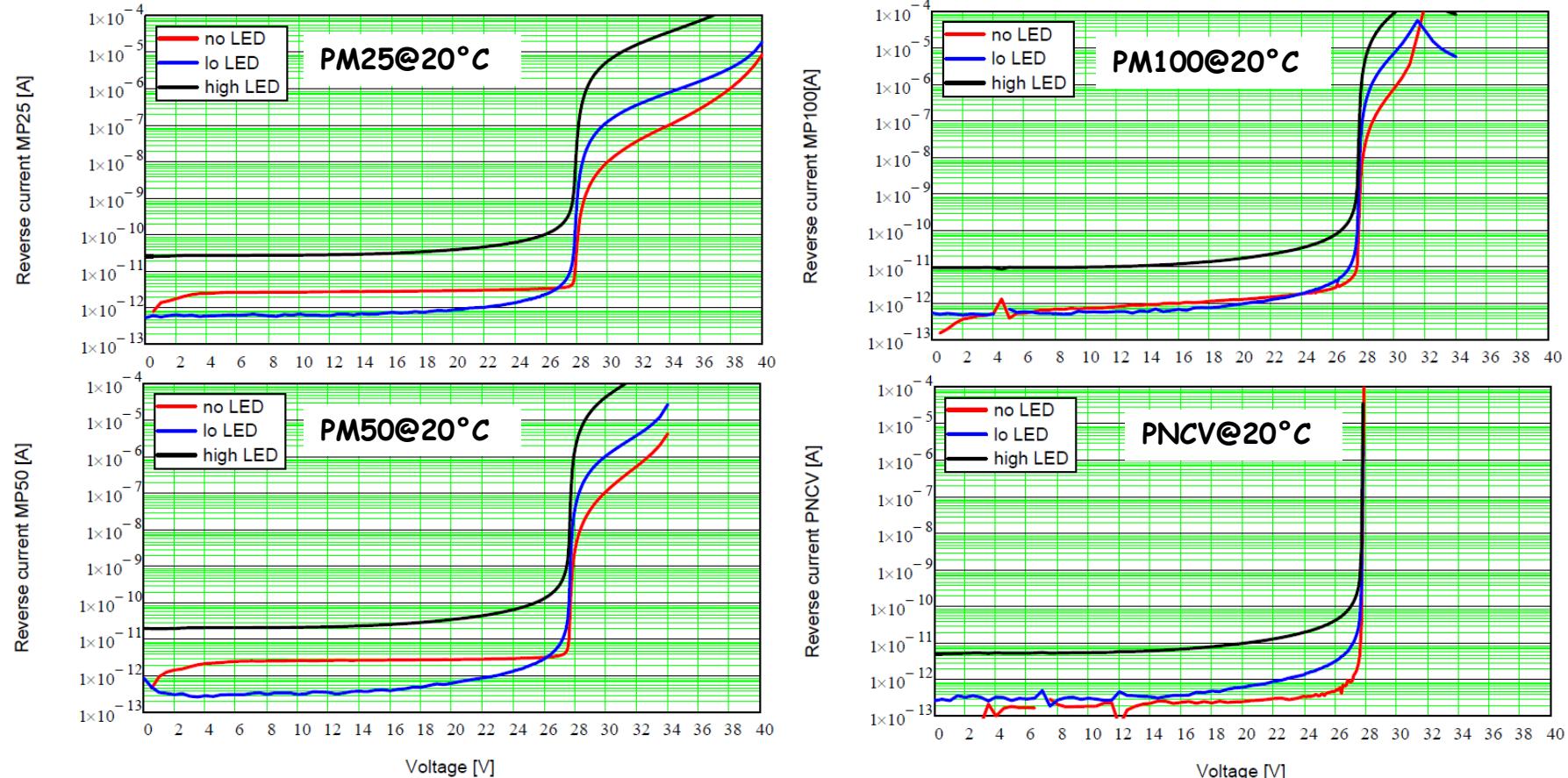


$R_q$   
Bias lines

$C_q$   
responsible for fast component

# $V_I$ - "reverse current breakdown (bd)"

Measure:  $I_{rev}(V)$  for noLED, lowLED, high LED ( $\lambda=470$  nm) @ -20, 0, +20°C



Below bd: LED → avalanche multiplication

noLED = „dark“ → no mult. for 15, 25, 50  $\mu\text{m}$  → generated e/h miss avalanche region

Above bd: PNCV „run-away“ breakdown, quenched for SiPMs by  $R_q$

2<sup>nd</sup> breakdown at a voltage, which decreases for SiPMs with larger pixels

# $V_I$ - "reverse current breakdown (bd)"

## Determination of $V_I$ : Method of Inverse Logarithmic Derivative (ILD)

$$ILD = \left( \frac{d\ln[I(V)]}{dV} \right)^{-1} \equiv \left[ \frac{1}{I} \cdot \frac{dI(V)}{dV} \right]^{-1}$$

ILD allows to characterize  $I(V)$  curves, in particular the „bd“ behaviour

- $I(V) = A \cdot e^{\alpha V} \Rightarrow ILD = 1/\alpha \rightarrow I_{\text{form}}$
- $I(V) = A \cdot (V - V_0)^n \Rightarrow ILD = (V - V_0)/n$ 
  - below bd:**  $n < 0$
  - above bd:**  $I(V) \propto (V - V_{bd}) \cdot PDE \cdot (1 + XT)$

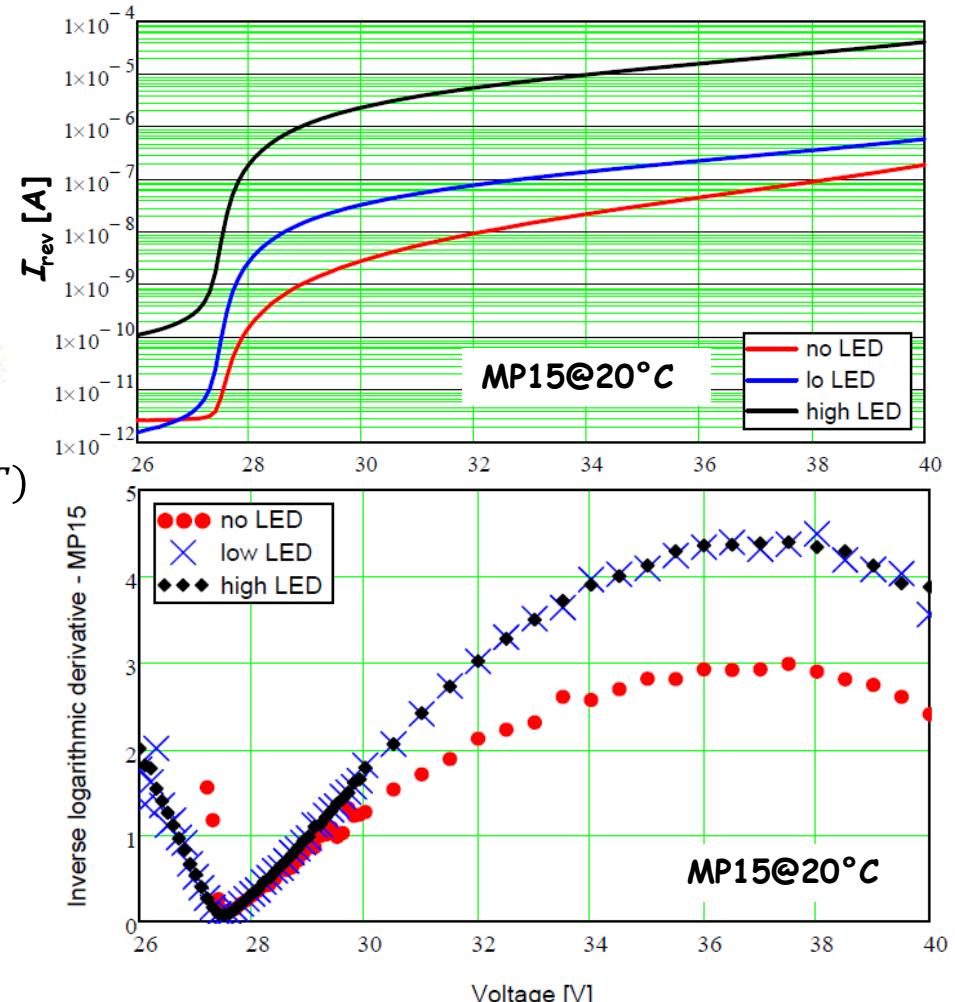
ILD  $\rightarrow$   $I(V)$  parametrization using

$$I(V) = A \cdot e^{\int_{V_{bd}}^V \frac{dx}{ILD(x)}}.$$

ILD calculated using 3<sup>rd</sup> order splines

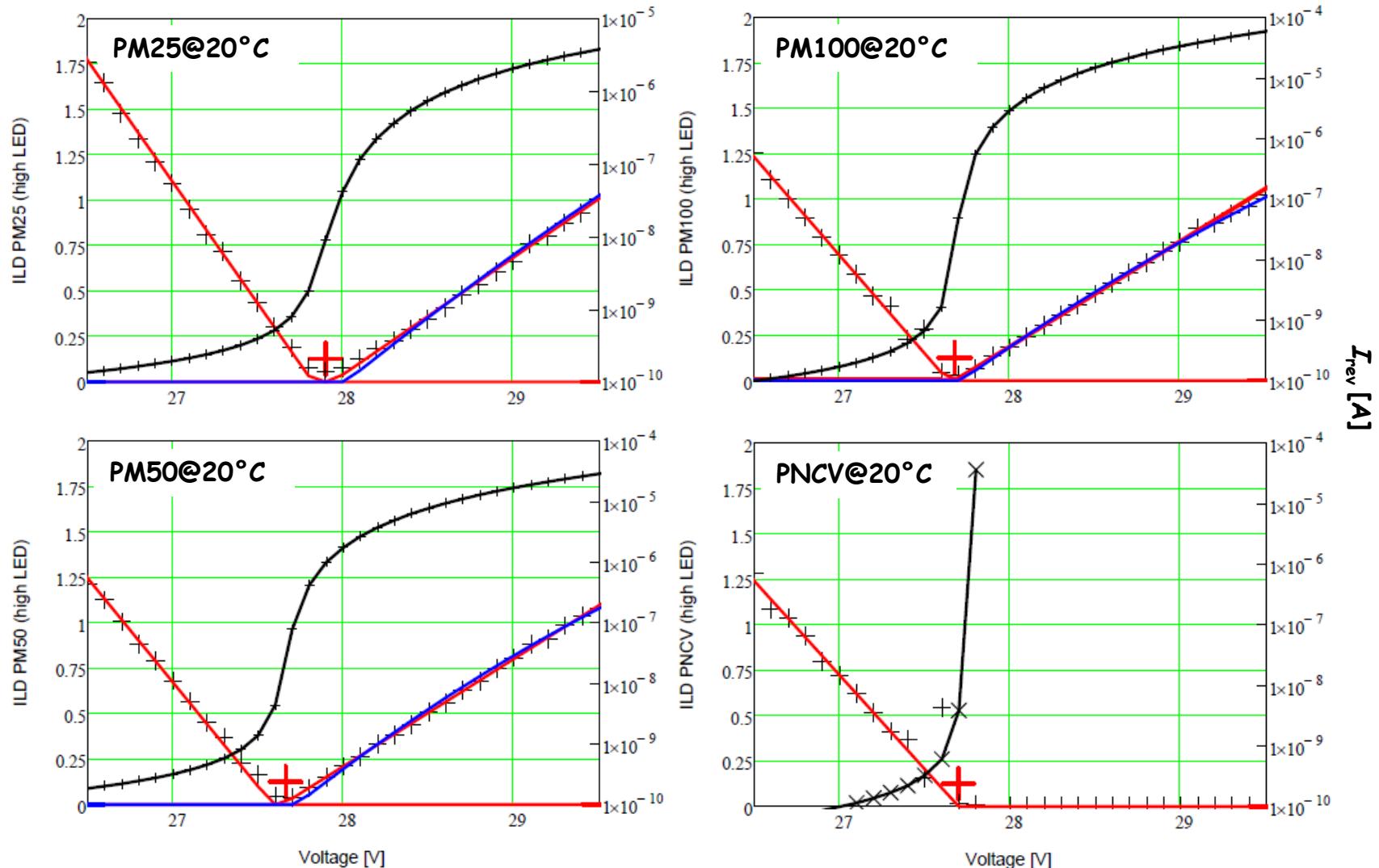
Methods for  $V_I$  determination:

- Minimum ILD
- Lin. fit to ILD below bd
- Lin. and quad. fit to ILD above bd



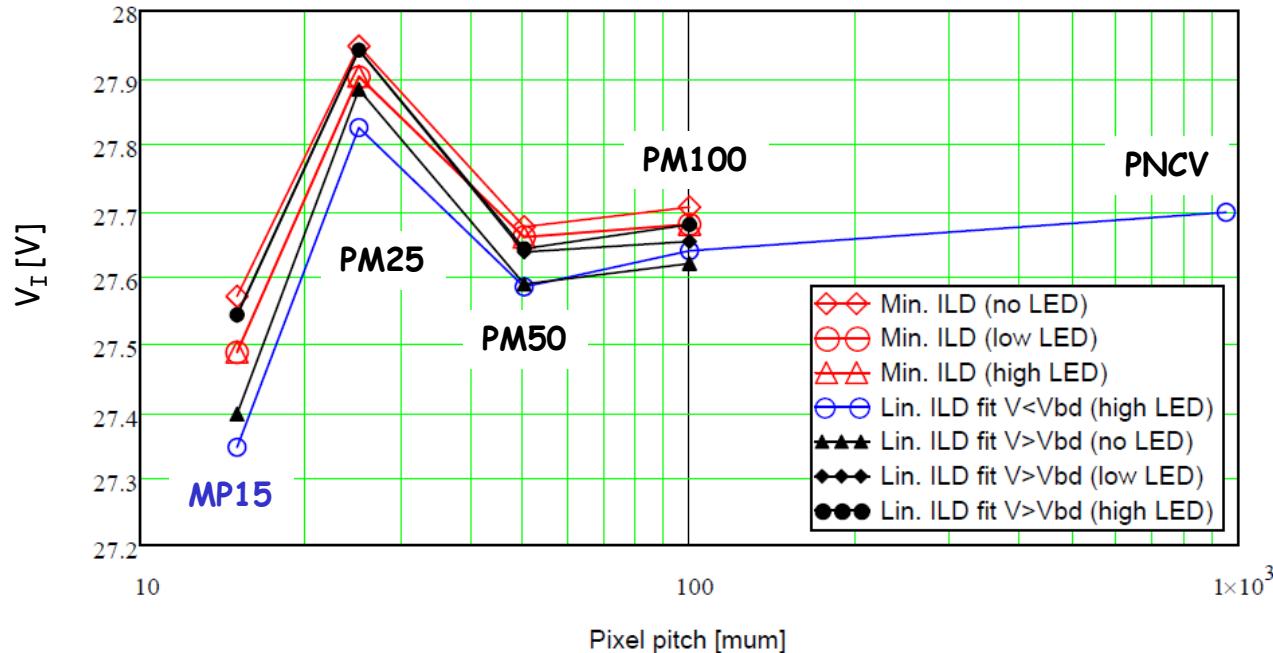
# $V_I$ - "reverse current breakdown (bd)"

$V_I$  determination: Minimum (ILD) (+), intercept lin. and quad. fits to ILD



# $V_I$ - "reverse current breakdown (bd)"

$V_I$  determination: Minimum (ILD) (+), intercept lin. and quad. fits to ILD



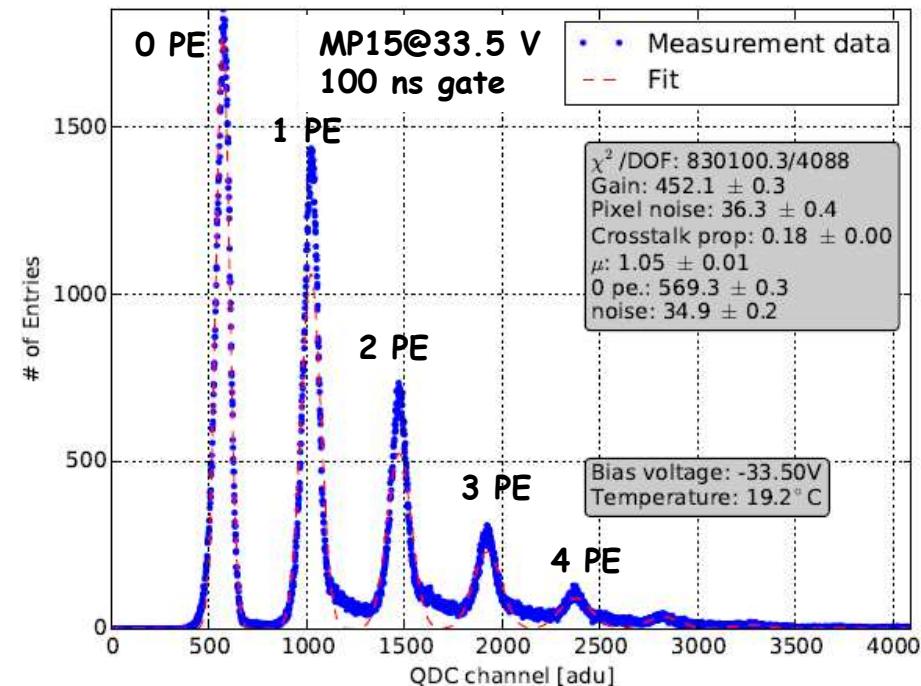
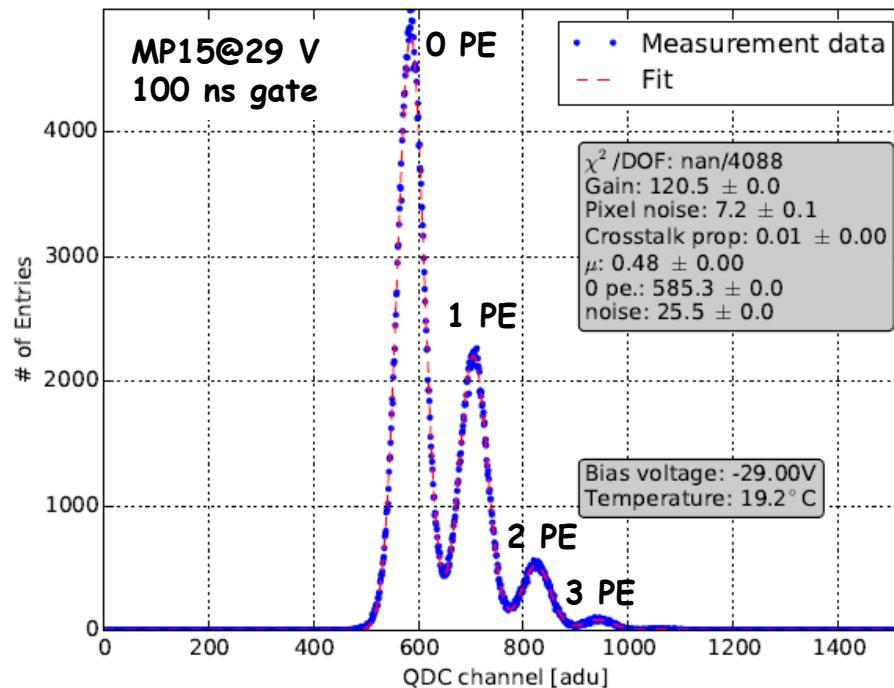
MP15 diff.  
production

- Differences:  $\pm 100$  mV for MP15, for PMs  $\pm 50$  mV (fit errors 5  $\rightarrow$  20 mV)
  - Results „no LED“ =  $I_{dark} \sim 50$  mV higher than „LED“ (method?)
  - Results for  $V < V_{bd}$   $\sim 50-100$  mV lower than for  $V > V_{bd}$
  - Pixel size dependence: reason not (yet?) clear
- Minimum of ILD for "high LED"  $\rightarrow$  simple and reliable method for  $V_I$  determination

## $V_{Gain}$ - "Gain breakdown"

**Gain:** Pulse-area spectrum with QDC vs.  $V_{bias}$  @ 20°C with/without LED

- "no LED" → DCR (dark count rate), XT (prompt cross talk), (AP after pulsing)
- "low LED" → Gain + relative PDE (photon detection efficiency)

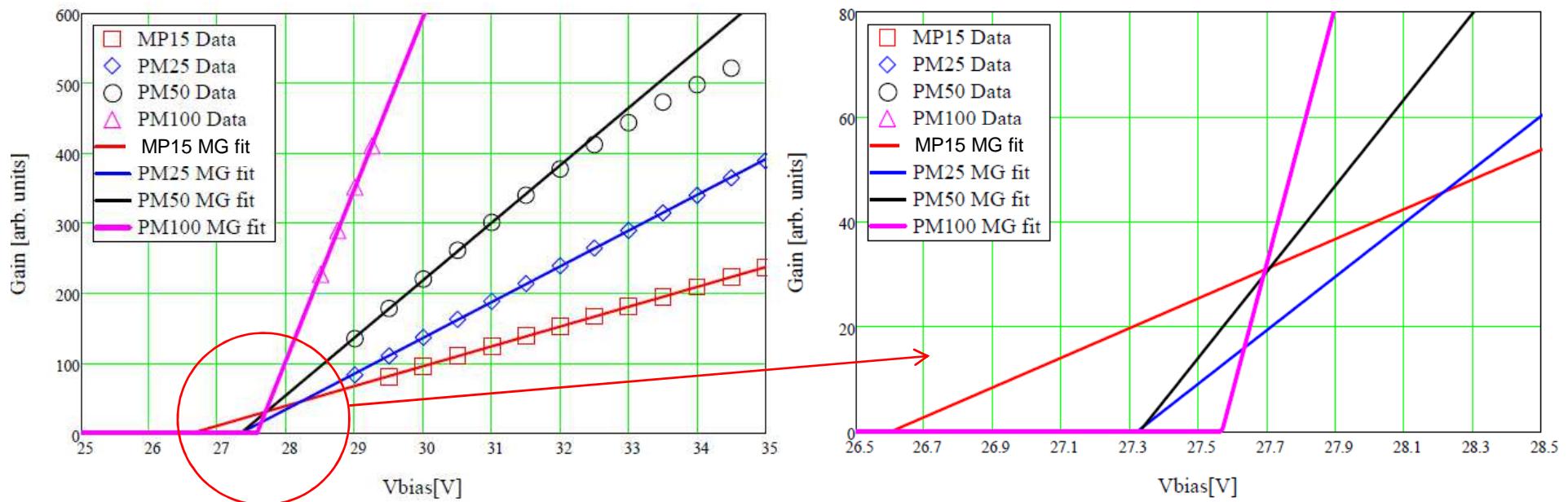


**Gain** = Distance between peaks 0, 1, 2, ... „PEs (photo electrons)“

Different methods: multi-Gauss fit, multi-Gauss + dark pulses, FFT  
 → similar results (for nPE < ~4)

## $V_{Gain}$ - "Gain breakdown"

$V_{Gain}$  = Intercept of straight-line fit of Gain(V) with V-axis



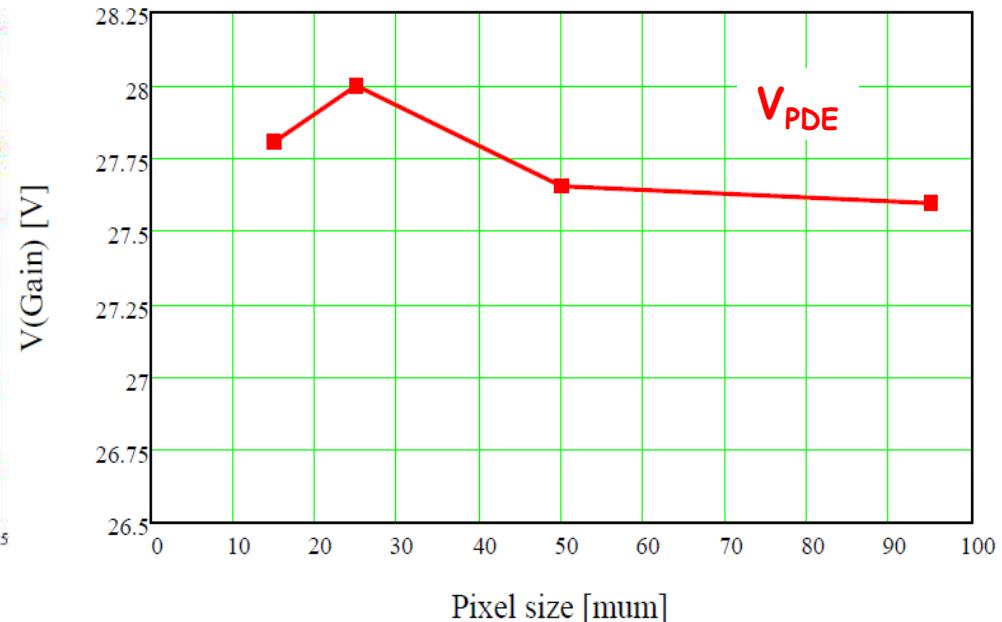
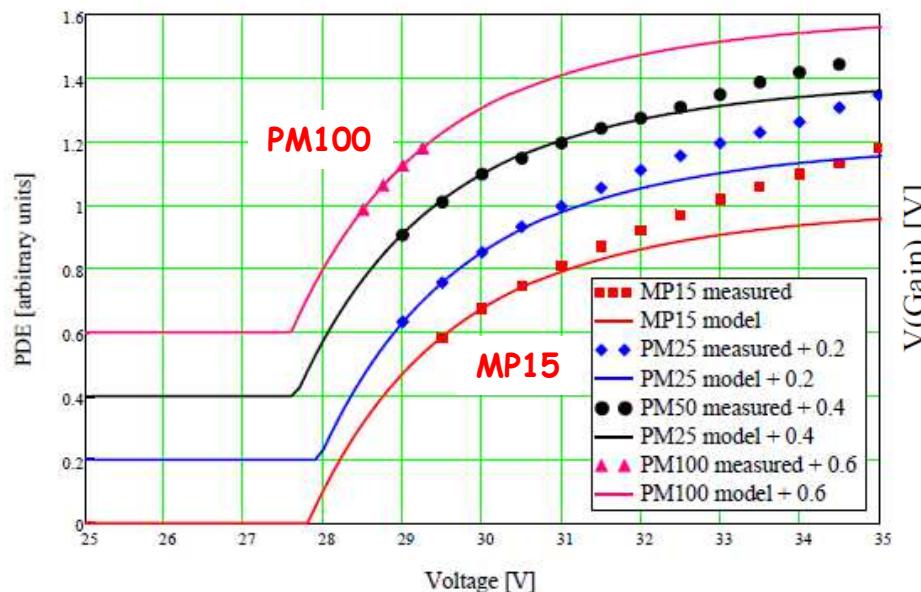
|                      | MP15               | PM25               | PM50               | PM100              |
|----------------------|--------------------|--------------------|--------------------|--------------------|
| $V_{Gain}$ (MG) [V]  | $26.599 \pm 0.008$ | $27.319 \pm 0.008$ | $27.327 \pm 0.012$ | $27.568 \pm 0.018$ |
| $V_{Gain}$ (FFT) [V] | $26.659 \pm 0.012$ | $27.300 \pm 0.012$ | $27.223 \pm 0.012$ | $27.526 \pm 0.025$ |

$V_{Gain}$  determined with statistical accuracy of 10-20 mV  
 → systematic uncertainties  $\sim \pm 50$  mV dominate

## $V_{PDE}$ - PDE > 0 voltage

Same measurements as for  $V_{Gain}$ : Pulse area vs.  $V_{bias}$  for low LED

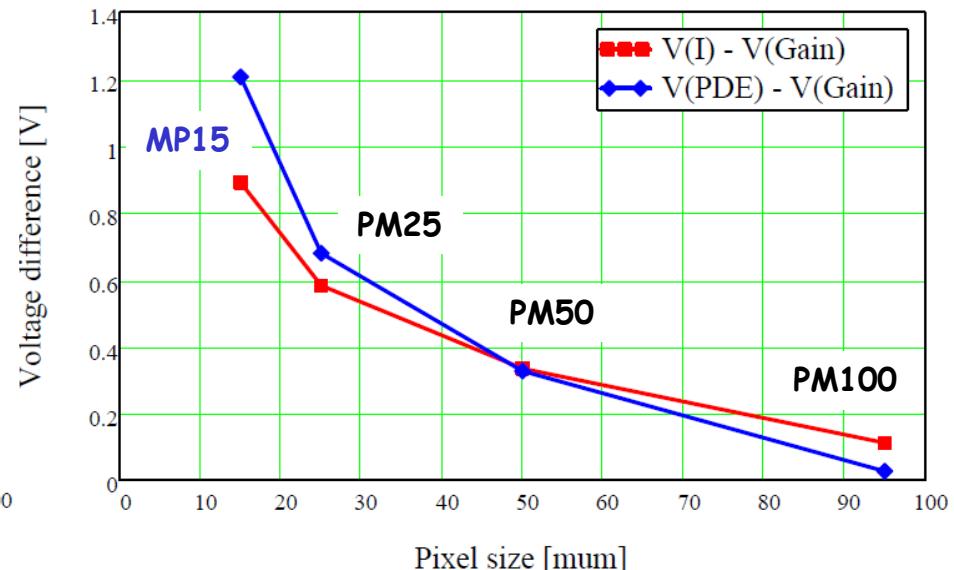
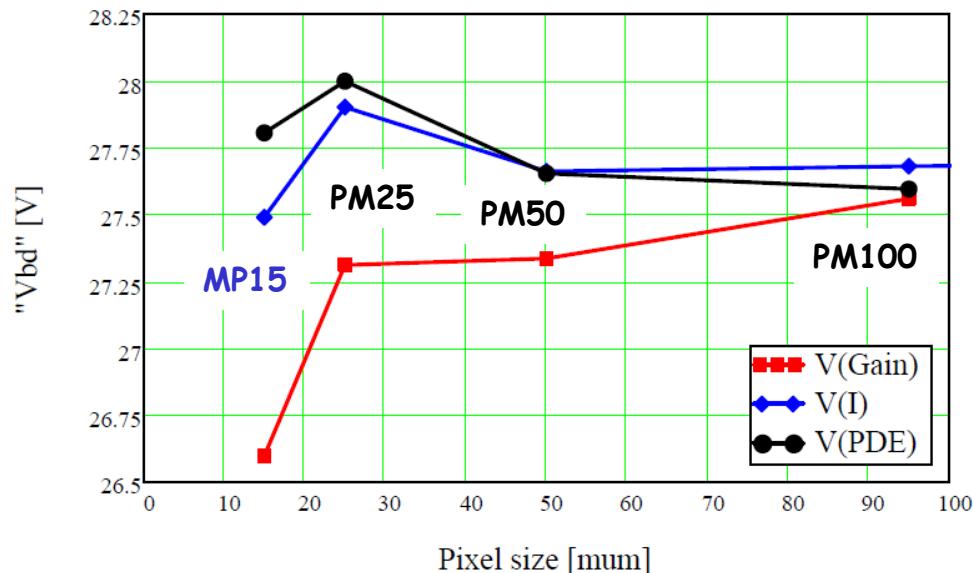
-  $f_0$  = fraction of events with 0 pe  $\rightarrow$   $PDE(V) \propto -\ln(f_0(V))$



$PDE(V)$  parametrization:

- Assume constant electric field in avalanche region of width  $w$
- PDE = probability  $e$  produces avalanche (R.J. McIntyre, IEEE-ED20(1973)637-641)
- Vary  $w$  until PDE-data  $\approx$  described  $\rightarrow V_{PDE}$  = Voltage at which  $PDE \geq 0$
- Description of data improves with pixel size  $\rightarrow$  for small pixels "effective pixel area" increases with voltage  $\rightarrow$  systematic uncertainties of  $V_{PDE}$  determination ???

## Comparison $V_I$ , $V_{Gain}$ and $V_{PDE}$



- There is a significant difference between  $\Delta V = V_I - V_{Gain}$
- $\Delta V$  decreases with increasing pixel size → to be understood !
- $V_I \approx V_{PDE} = \text{Geiger breakdown voltage } V_{bd}$   
(cross check: no signal seen on scope for  $V < V_I$  for many photons from LED)
- $V_{Gain}$  is the voltage relevant for the user →  $\text{Gain} \sim (V_{bias} - V_{Gain})$
- Model calculations underway to understand relation  $V_{turn-off}$  vs  $V_{Gain}$  vs  $V_{bd}$

# Simple model for $I_{LED}$ and comparison to data

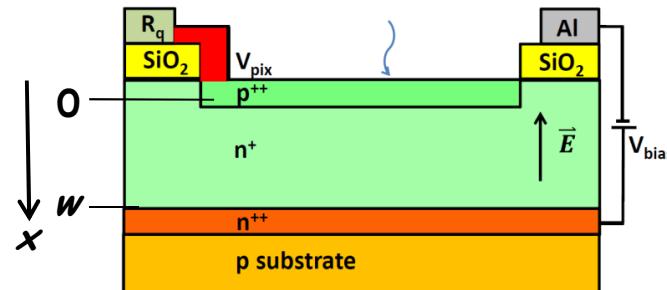
**Below breakdown:**

[R.J. McIntyre IEEE-ED13(1966)164]

$M(x)$  multiplication for  $\times$  where e/h created

$$M(x) = \frac{\exp[-\int_x^w (\alpha - \beta) dx']}{1 - \int_0^w \alpha \cdot \exp[-\int_{x'}^w (\alpha - \beta) dx''] dx'}$$

Breakdown:  $M \rightarrow \infty$  and  $I_{Led} \propto M(0)$



**Above breakdown:**

[R.J. McIntyre IEEE-ED20(1973)637]

Avalanche probability  $P_i(x)$

(Probability charge carrier at  $x \rightarrow$  avalanche)

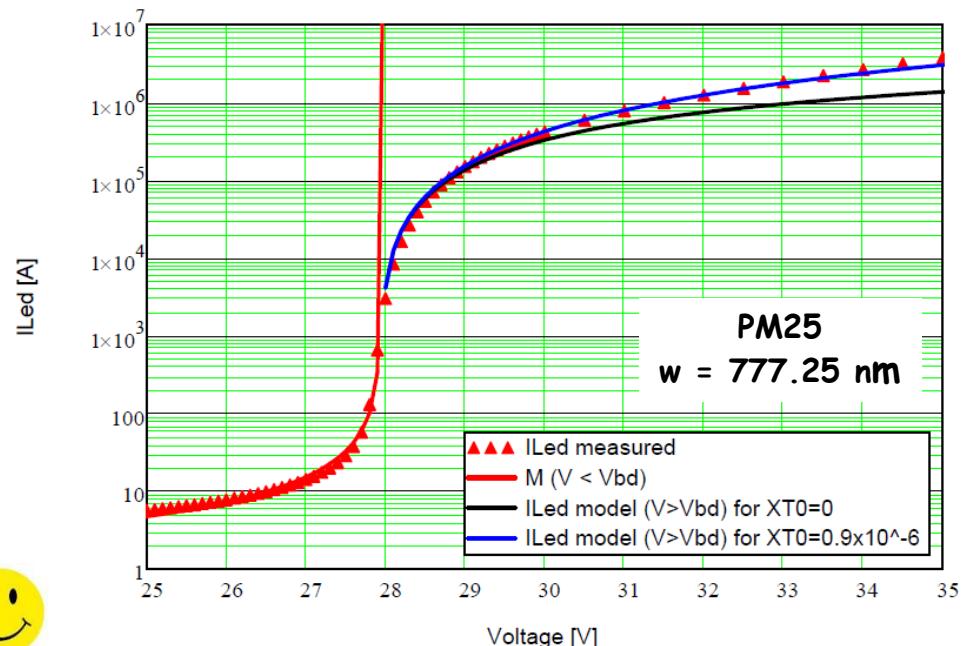
$$I_{LED} \propto P_e(0) \times Gain \times (1 + XT)$$

$$Gain \approx (C_{pix} + C_q) \times (V - V_G)/q_0$$

$$XT = XT_0 \times Gain \times \langle P_i \rangle$$

**Model:** assume  $E = V_{bias}/w$  for  $0 < x < w$

Model provides a reasonable description of the data



## Summary

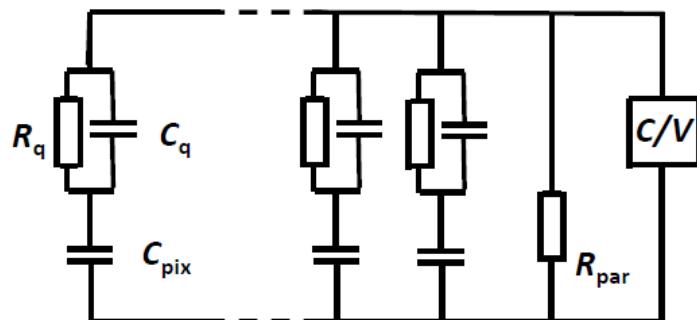
The breakdown characteristics of KETEK SiPMs with different pixel sizes has been investigated

- There are several "breakdown voltages"
  - Gain breakdown voltage  $V_{Gain}$
  - Current breakdown voltage  $V_I$
  - PDE start voltage  $V_{PDE}$
  - Pixel breakdown voltage  $V_{bd}$
  - Geiger discharge turn-off voltage  $V_{turn-off}$
- We observe:
  - $V_I \approx V_{PDE} \neq V_{Gain}$  [ $V_{bd} = V_I = V_{PDE}$ ]
  - $(V_I - V_{Gain}) > 0$ , and decreasing with pixel pitch [ $V_{turn-off} \neq V_{Gain}$  ?]
- Message for the SiPM user:
  - $V_{Gain}$  is the relevant parameter  $Q \sim (V_{bias} - V_{Gain})$  with  $V_{Gain} \neq V_{bd}$
  - $I(V)$  measurement does not give  $V_{Gain}$

A model for  $I(V)$  and pulse shape of SiPMs, which relates the experimental with the model parameters, is under development

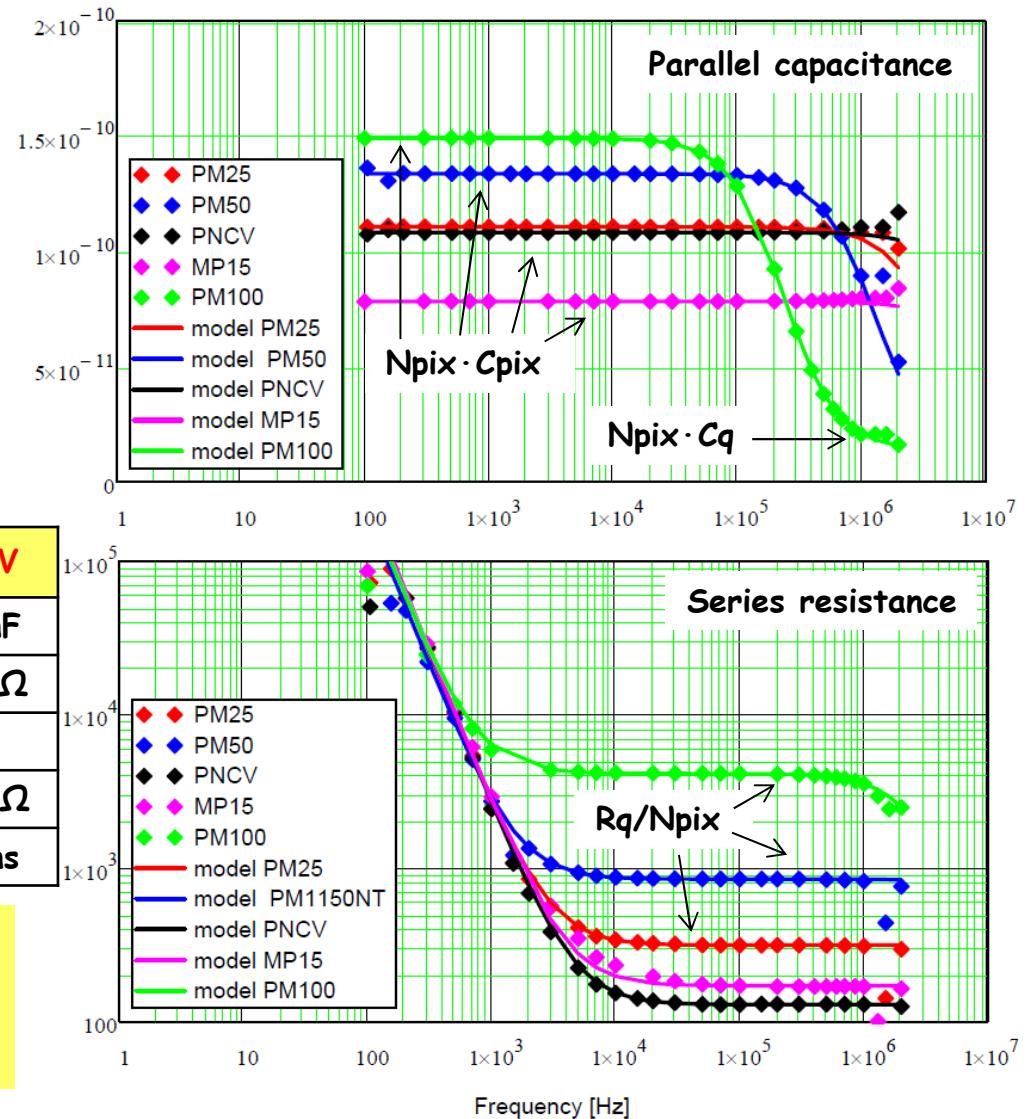
# Determination of DC electrical parameters

C/G-frequency measurement just below breakdown  
→ determine el. parameters



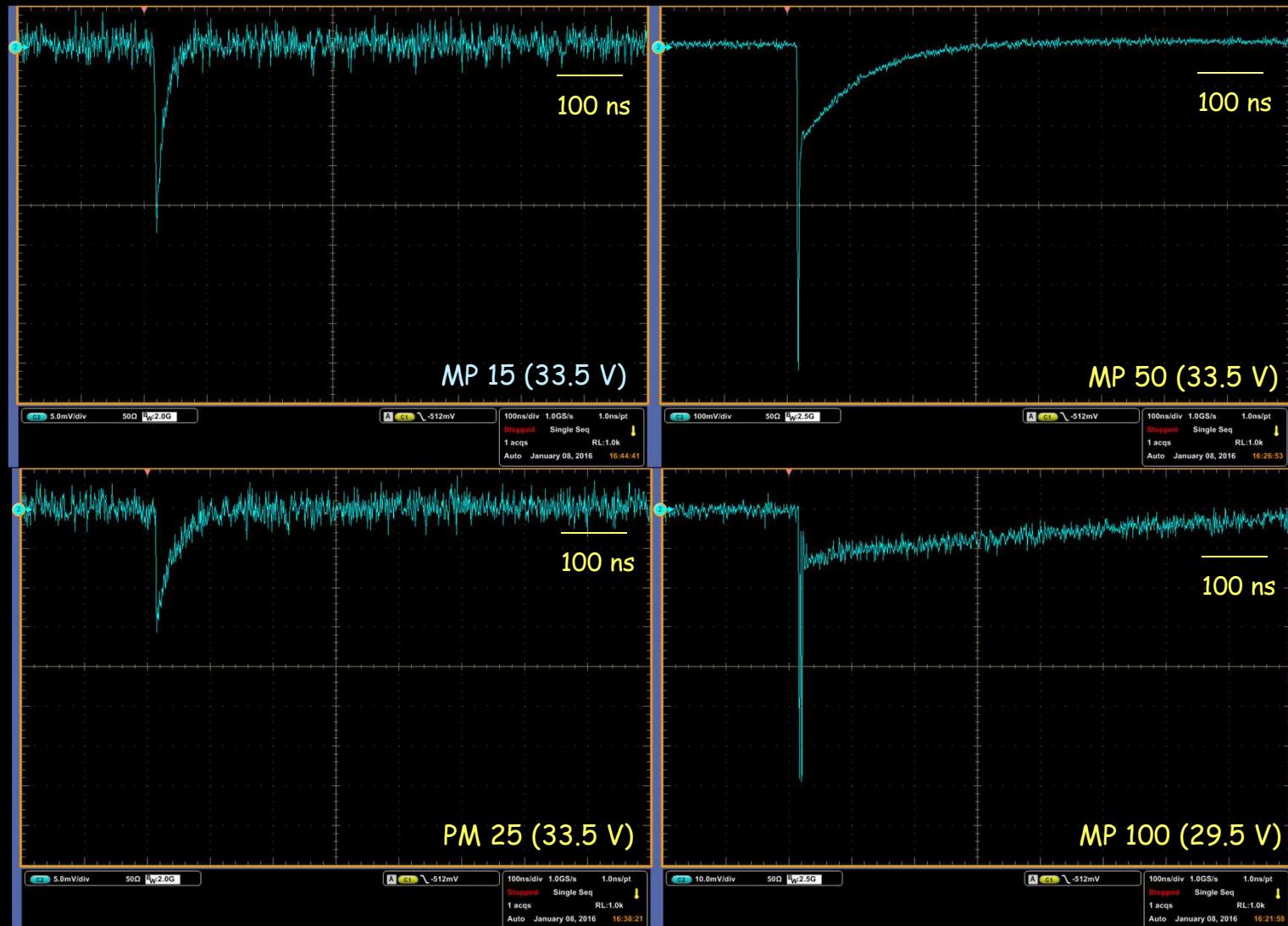
|           | MP 15  | PM 25  | PM 50  | PM 100 | PNCV  |
|-----------|--------|--------|--------|--------|-------|
| $C_{pix}$ | 18 fF  | 69 fF  | 330 fF | 1.5 pF | 11 nF |
| $R_q$     | 750 kΩ | 500 kΩ | 340 kΩ | 410 kΩ | 130 Ω |
| $C_q$     | <5 fF  | <10 fF | 25 fF  | 155 fF | -     |
| $R_{par}$ | 85 GΩ  | 80 GΩ  | 70 GΩ  | 50 GΩ  | 85 GΩ |
| $\tau$    | 14 ns  | 35 ns  | 110 ns | 620 ns | 14 ns |

- Parameters with few % accuracy
- $\tau = R_q \cdot C_{pix}$  agrees with pulse shape
- $C_q$  responsible for fast component



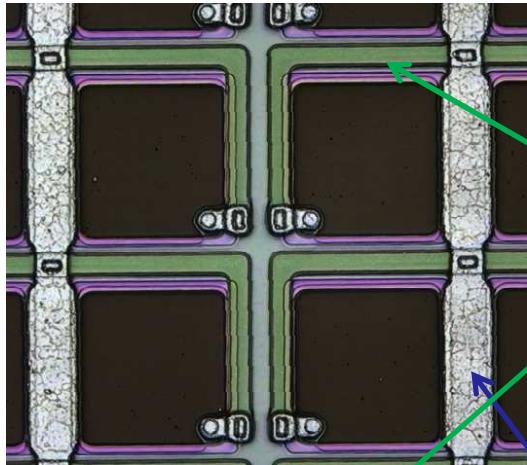
# Pulse shapes - single PE (LED)

$V_{bd} \sim 27$  V

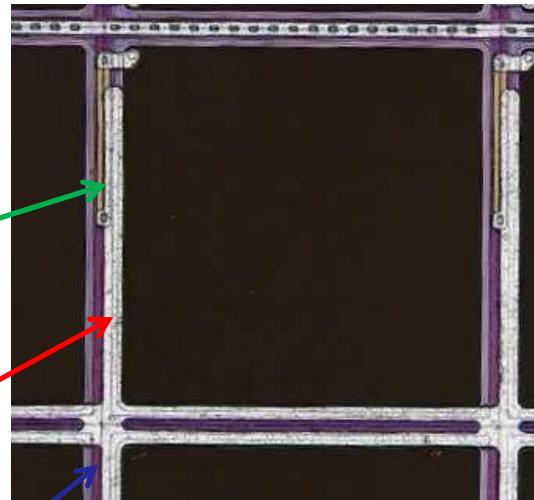


# Details of SiPM layouts

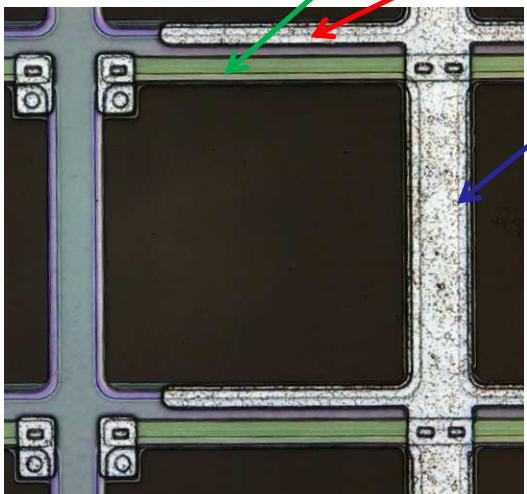
PM 25



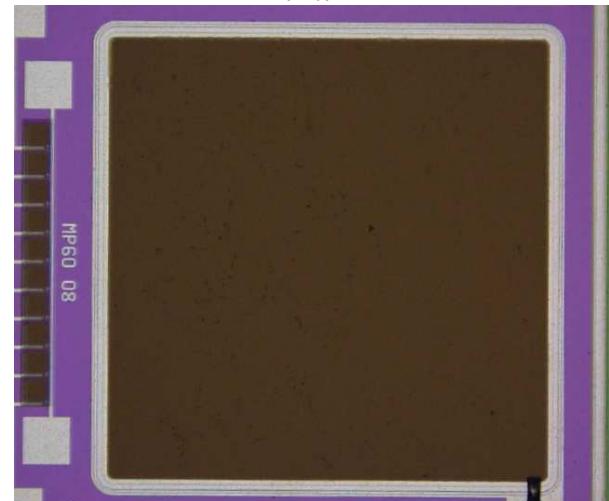
PM100



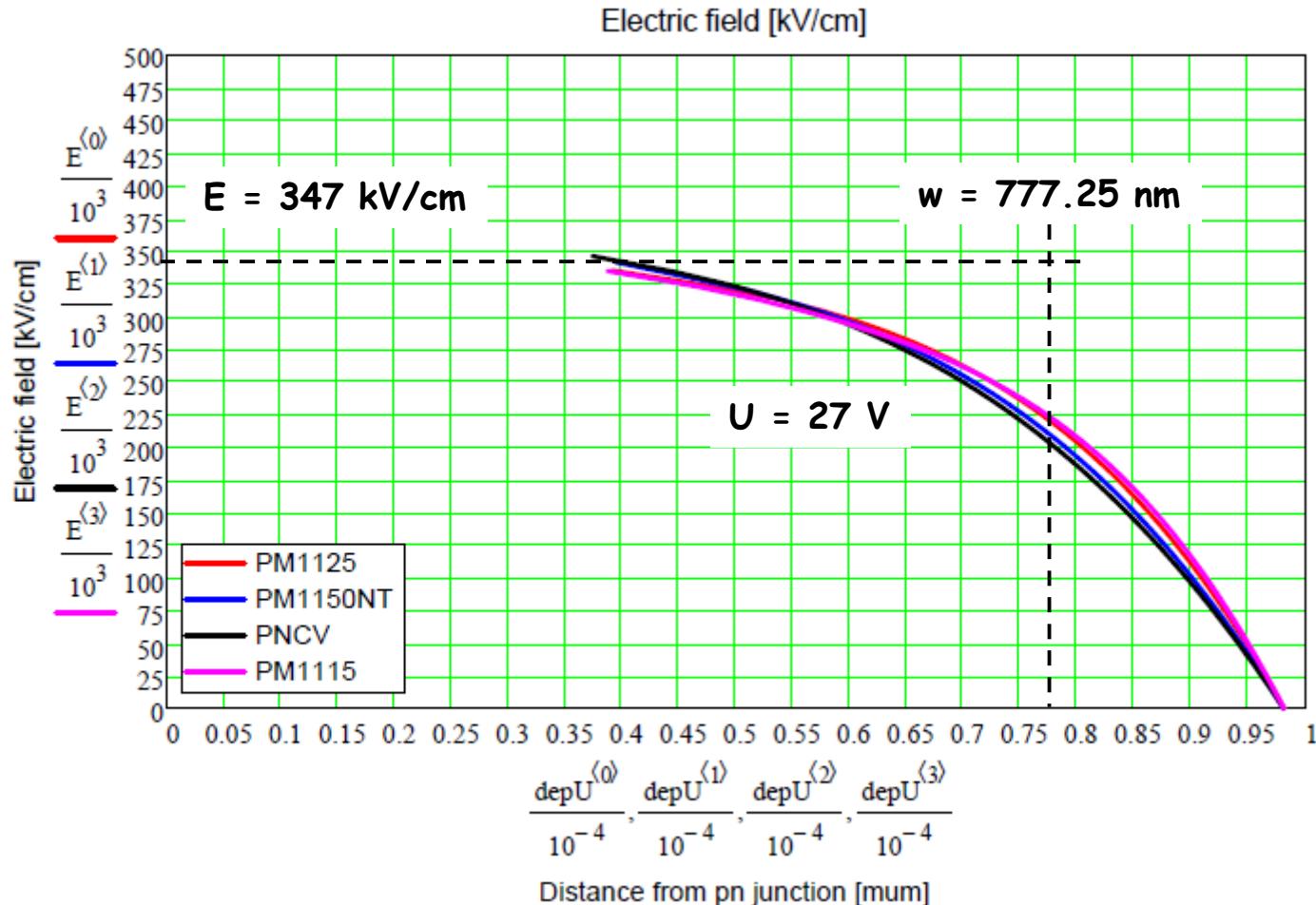
PM 50



PMNCSV



# E-field from C/V measurement



# Finis

More bla-bla