

PIXEL 2000 International Workshop on Semiconductor Pixel Detectors for Particles and X-rays
Magazzini del Cotone al. Porto Antico, Genova, Italy, 5-8 June 2000

Simulation and Measurements of Charge Collection in Monolithic Active Pixel Sensors

Grzegorz DEPTUCH

IReS Strasbourg / UMM Cracow



J.D.Berst, G.Claus, C.Colledani, W.Dulinski, Y.Hu,
D.Husson, J.P.Le Normand, J.L.Riester, R.Turchetta¹



G.Deptuch², U.Goerlach, G.Orazi, M.Winter

¹ at present with Rutherford Appleton Laboratory, Didcot, UK

² visitor from University of Mining and Metallurgy, Cracow, PL



Contents:

- ▶ **CMOS - Monolithic Active Pixel Sensors for particle tracking**
 - ▶ **Charge Collection Simulation**
 - device simulation with ISE-TCAD package
 - ▶ **Charge Collection Measurements**
 - 660nm laser diode
 - 1060nm laser diode
- ▶ **Conclusion and future development prospects**

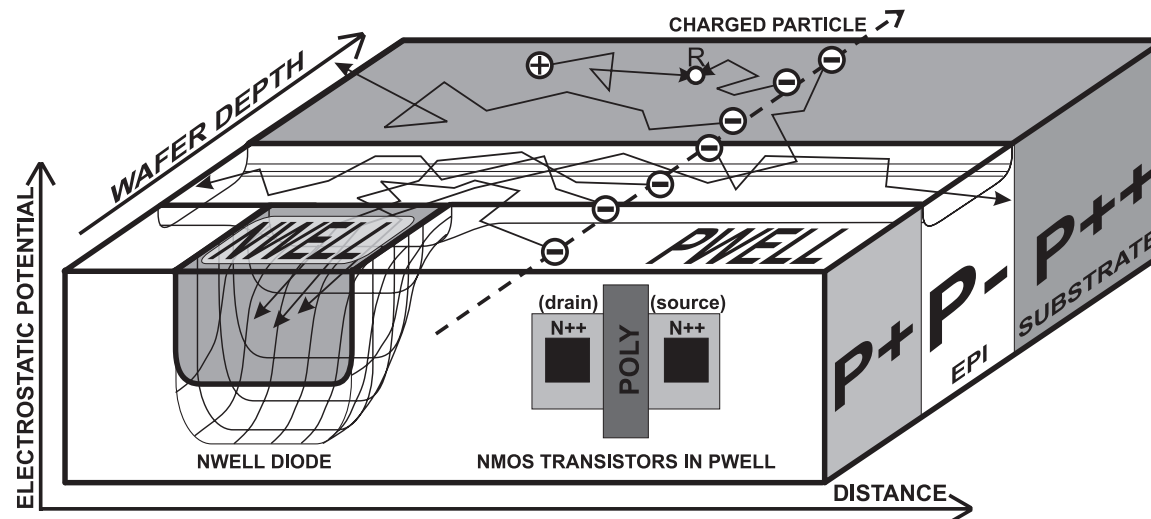
Monolithic pixel detectors - advantages:

- ▶ 1 unique substrate for the detector and electronics - reduced detector thickness (*reduced multiple scattering effect*)
- ▶ No detector - electronics connection (*neither complicated and expensive bump- nor fragile wire- bonding*)
 - ▶ High spatial resolution (*CMOS APS ~ 1 μ m*)
- ▶ Radiation hardness (*submicron VLSI processes*) !!!
- ▶ System on chip - integration of different functionalities (ADC, data filtering ...) on the detector
- ▶ low price - **if standard CMOS process is used !!!**

Monolithic pixel detectors: present approach

◉ epitaxial layer - CMOS camera

100% fill factor



- standard VLSI process on a low-resistivity substrate
- only NMOS transistors allowed within the pixel

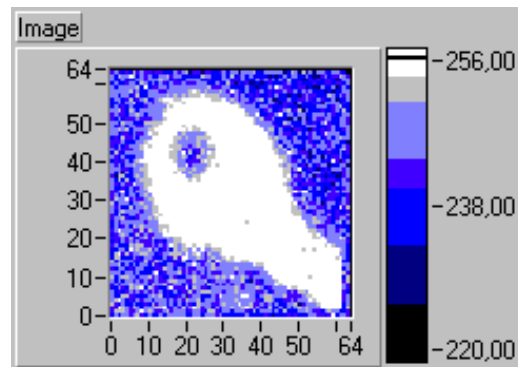
The detector is inseparable from the readout electronics, since both of them are integrated onto the same, standard for a CMOS process, low resistivity silicon wafer. The undepleted thin epitaxial layer is used as a sensitive detector volume. The charge is collected by an n-well/p-epi diode. Charge collection is dominated by carriers thermal diffusion.

Pixel size - $20 \times 20 \mu\text{m}^2$ or even less.

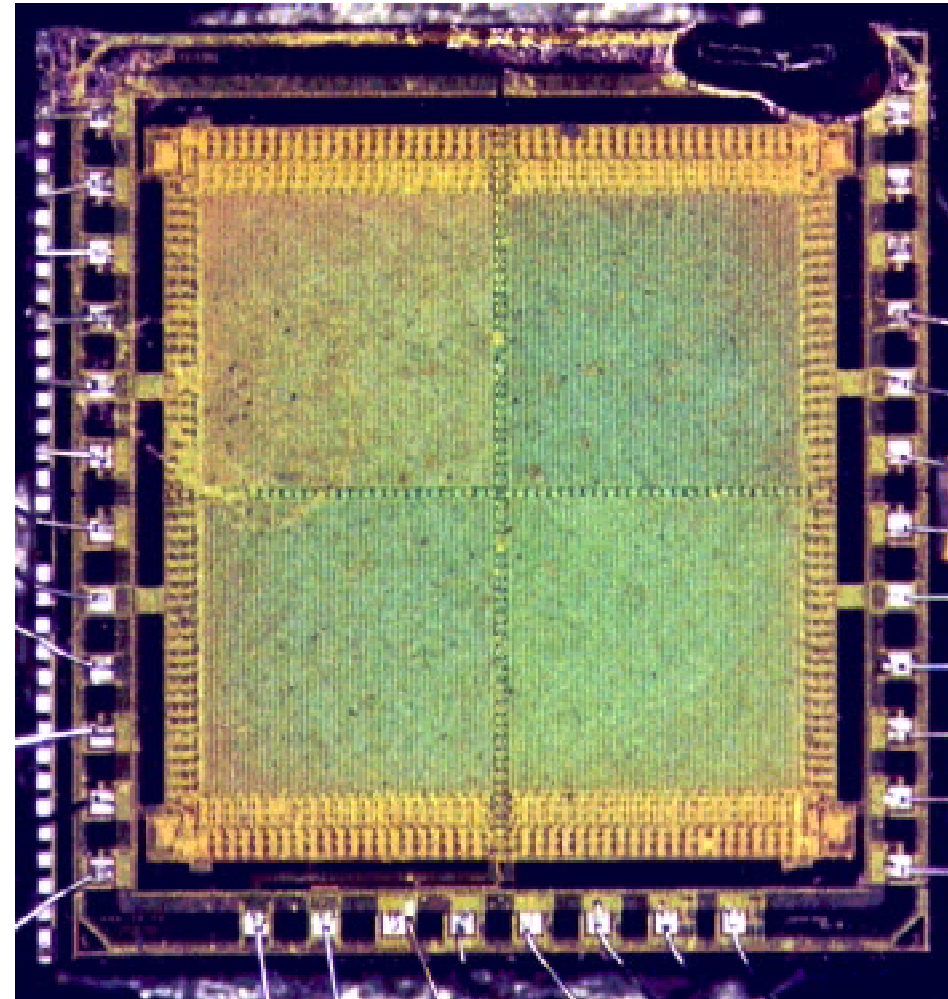
MIMOSA I (Minimum Ionising particle MOS Active pixel detector)

Goal of fabrication:

- ▶ feasibility study
- ▶ understanding/tests
 - standard $0.6\mu\text{m}$ CMOS ($t_{ox}=12.7\text{nm}$)
 - $14\mu\text{m}$ thick EPI layer (10^{14}cm^{-3})
 - 4 arrays 64×64 pixels
 - pixel pitch $20\times 20\mu\text{m}$
 - diode (*nwell/pepi*) size $3\times 3\mu\text{m}$ - 3.1fF
 - readout clock $f < 10\text{MHz}$
 - readout - serial analog
 - die size $3.6\times 4.2\text{mm}^2$

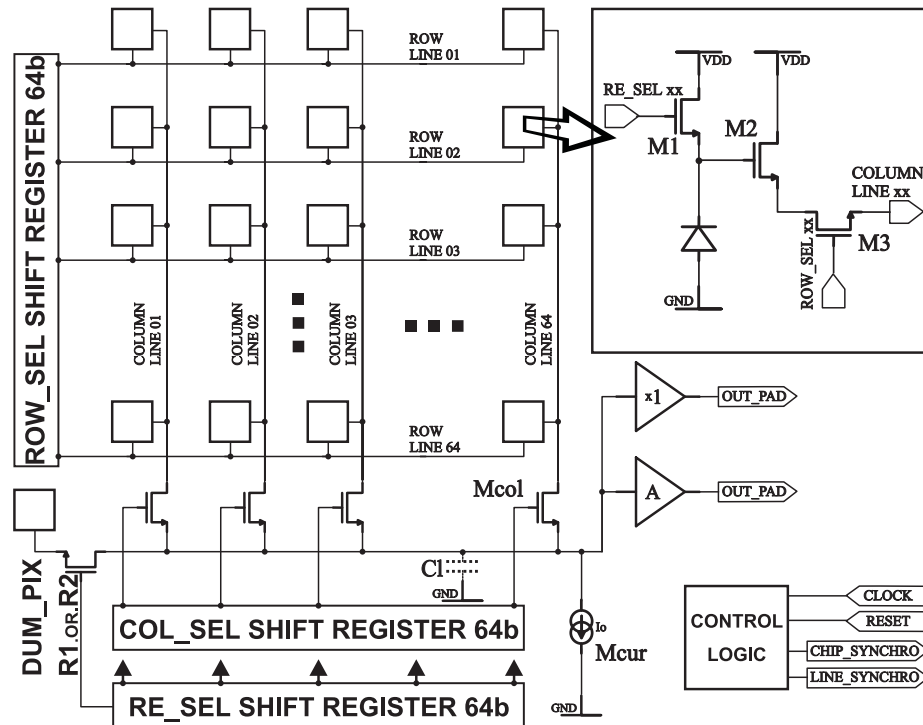


“visible light photography with
MIMOSA”



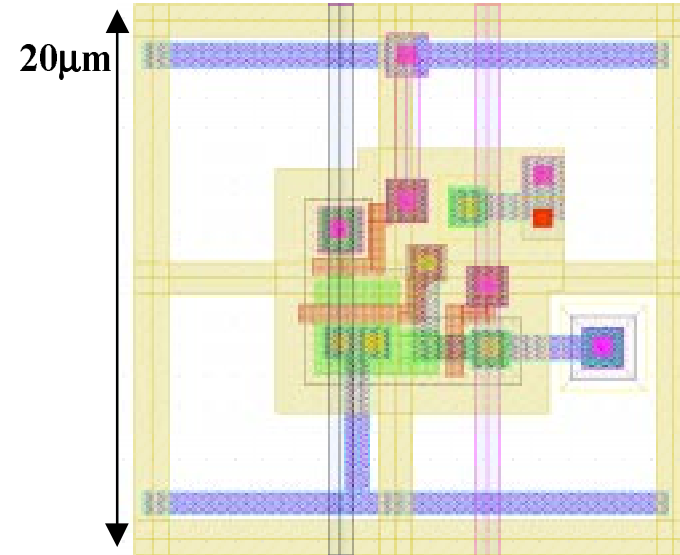
MIMOSA I

Single cell electronics and readout:

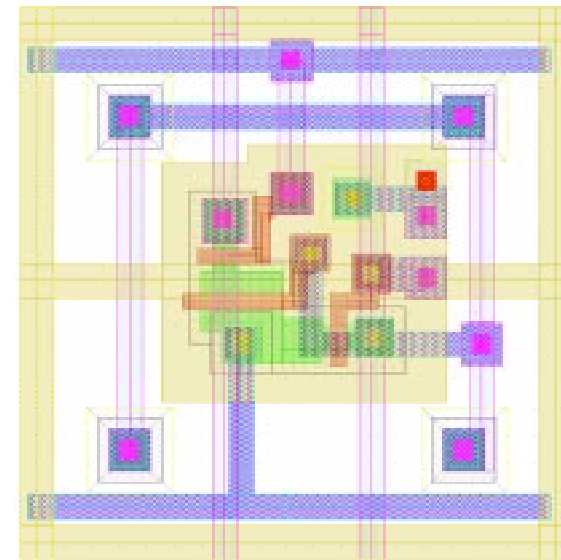


- work regime:
... RESET ... READOUT ... RESET...

- technology 3M+2P
- power supply 4÷5V



1P



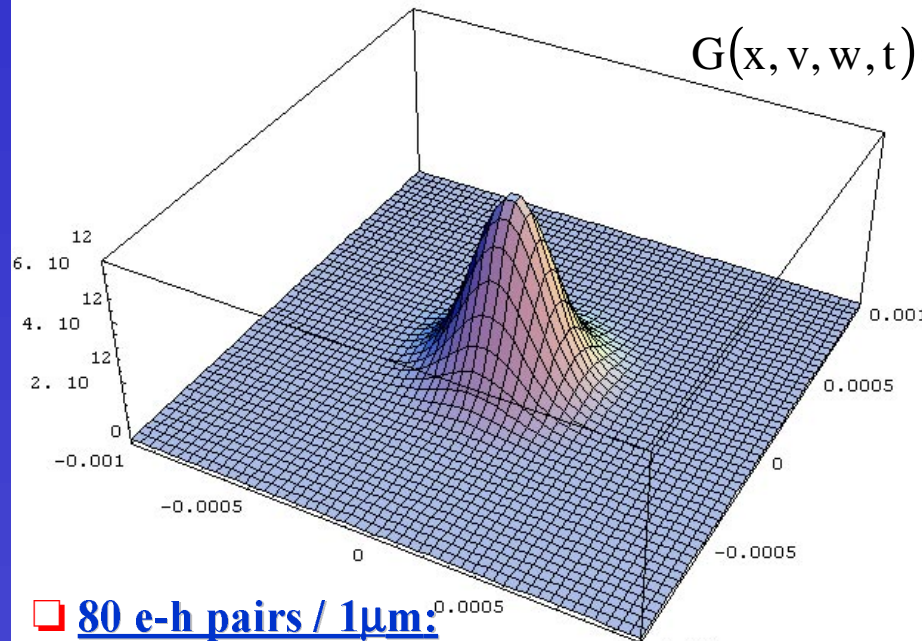
4P

MIMOSA I

Simulation with ISE-TCAD package

Charge Collection Simulation

MIP simulation - model of ionisation density:



$$G(x, v, w, t) = \frac{a}{\sqrt{2\pi} \cdot s} \cdot e^{-\frac{1}{2} \left(\frac{t-t_m}{s} \right)^2} \cdot e^{-\frac{1}{2} \left(\frac{v^2+w^2}{w_t^2} \right)} \cdot \left[c_1 e^{\alpha x} + c_2 e^{-\frac{1}{2} \left(\frac{x-\alpha_1}{\alpha_2} \right)^2} \right]$$

if $x < \alpha_1 + \alpha_3$

and $G(x, v, w, t) = 0$

if $x \geq \alpha_1 + \alpha_3$

where:

$\alpha_1 = a_0 + a_1 \cdot E_n + a_2 \cdot E_n^2$ and

$c_1 = e^{\alpha_1 [10 \text{ MeV}] - \alpha_1 [E_n]}$

factor a found after normalization:

$$\int_0^\infty \int_{-\infty}^\infty \int_{-\infty}^\infty \int_{-\infty}^\infty G(x, v, w, t) dt dw dv dx = \frac{E_n}{E_p}$$

80 e-h pairs / 1 μm :

$w_t = 1.5 \text{E}(-4) \text{ cm}$, $c_2 = 0$, $\alpha = 1 \text{E}(-20) \text{ cm}^{-1}$,

$a_0 = 1 \text{ cm}$, $a_1 = 0 \text{ cm/eV}$, $a_2 = 0 \text{ cm/eV}^2$,

α_2, α_3 – arbitrary, $E_p = 3.6 \text{ eV}$, $E_n = 2.88 \text{ MeV}$

$s = 2 \text{E}(-12) \text{ s}$

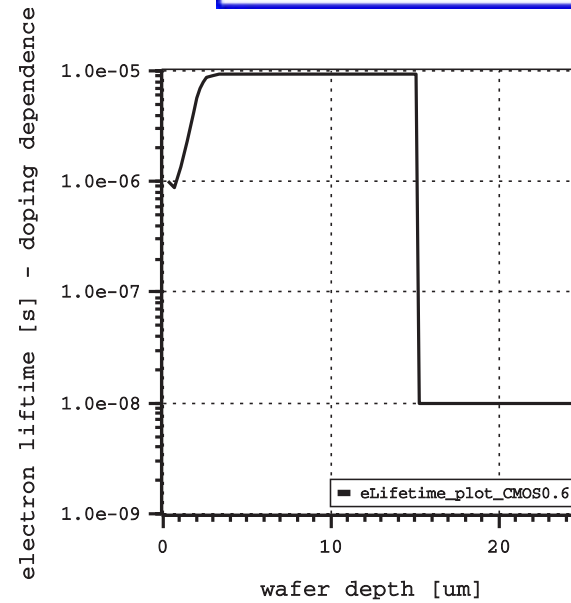
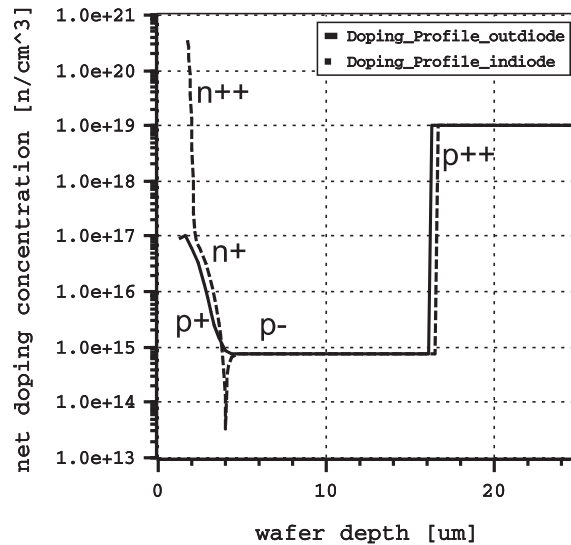
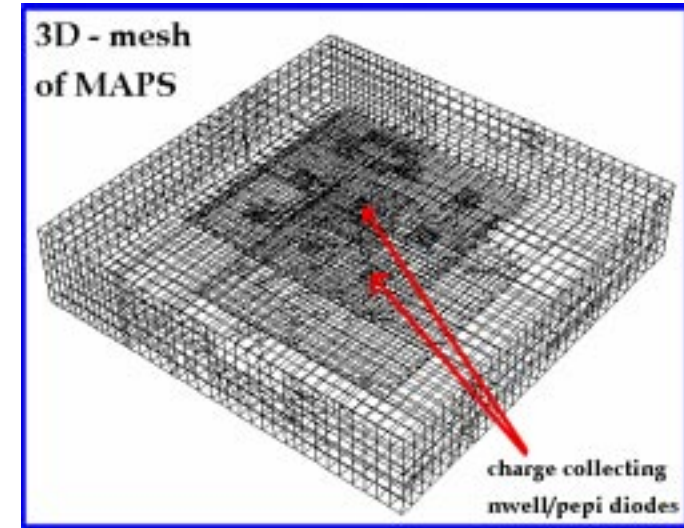


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Simulation with ISE-TCAD package

Charge Collection Simulation

Simulations determine the electrical behaviour of a 2D or 3D representation of a physical detector device. Terminal currents, voltages and charges are computed based on a set of physical device equations describing carrier distribution and conduction mechanisms. A device is defined by its mesh (grid), discretized doping information, its contacts and finally by the physical model.

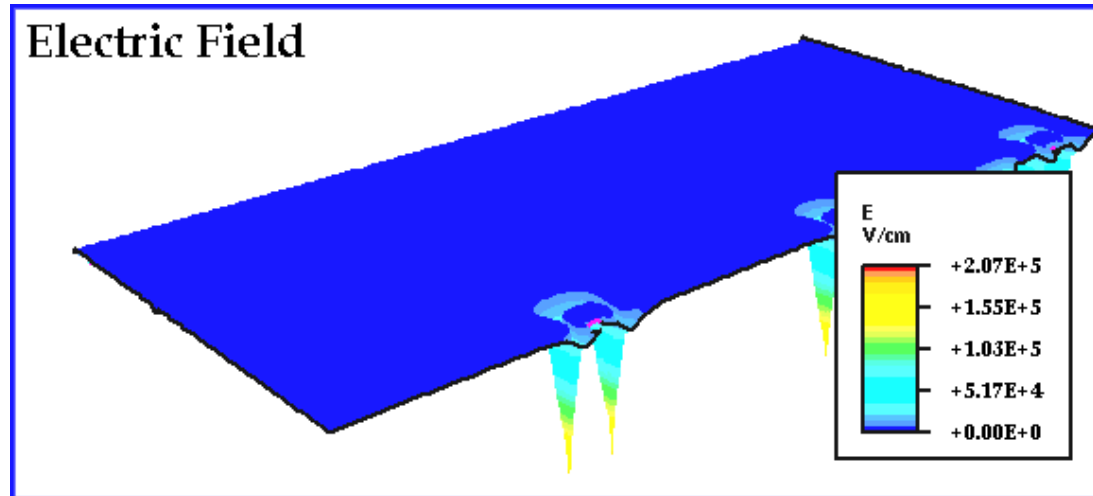
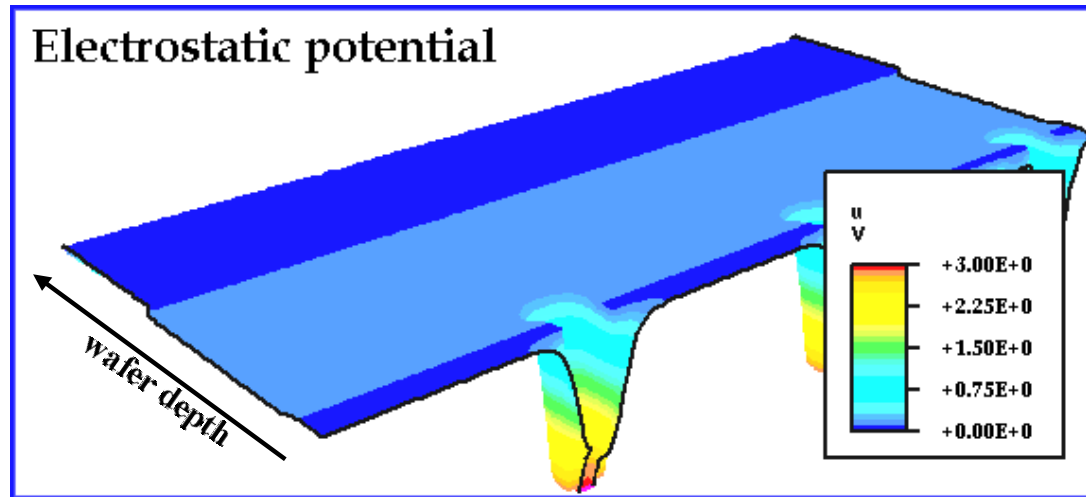


The doping dependence of the SRH lifetimes - modeled with the Scharfetter empirical relation

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Simulation with ISE-TCAD package

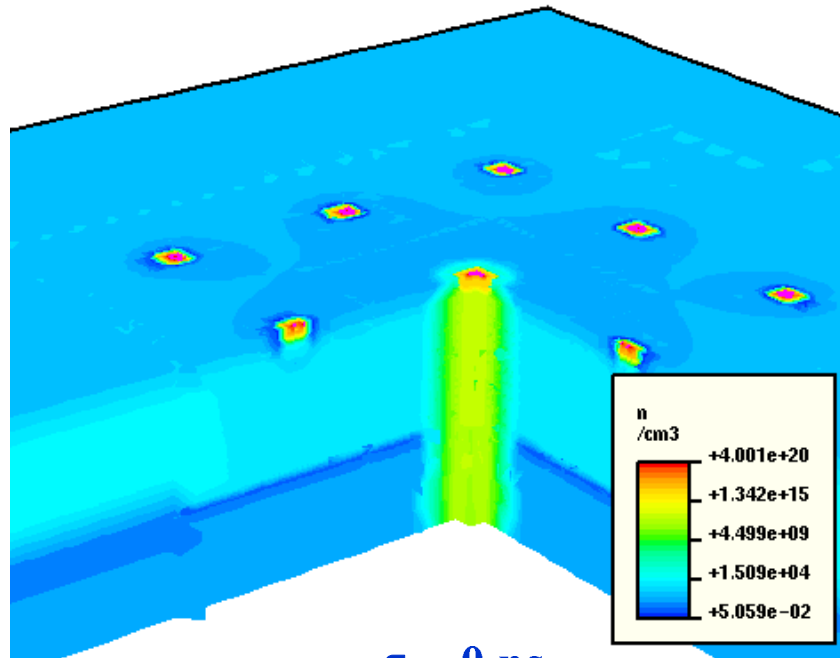
Charge Collection Simulation



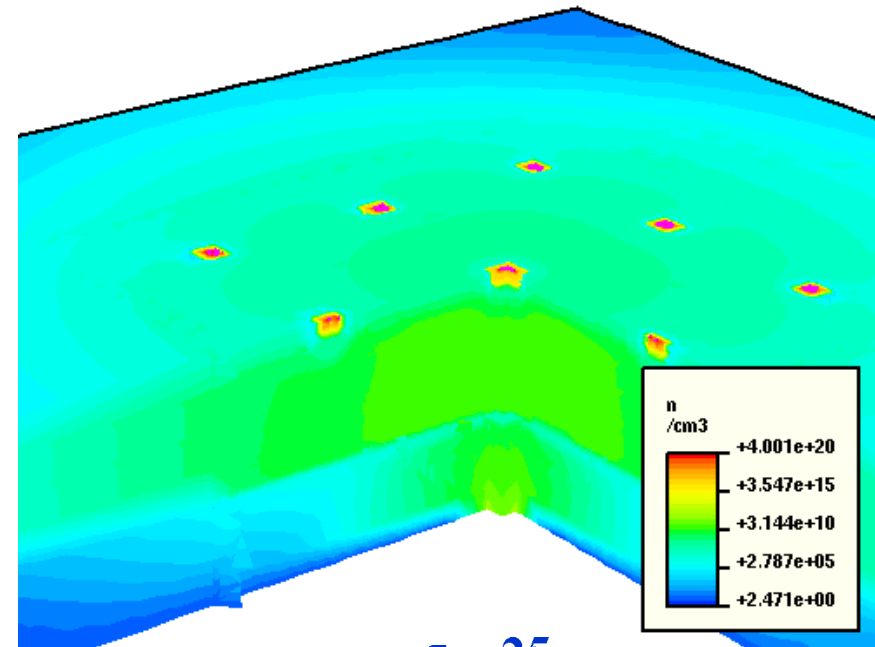
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Charge Collection Simulation

3-D device simulation with ISE-TCAD package



$\tau = 0 \text{ ns}$



$\tau = 25 \text{ ns}$

Carrier concentration

Parameters

- epitaxial layer thickness
- diode size (*geometry*)
- recombination time (*carriers lifetime*) ...

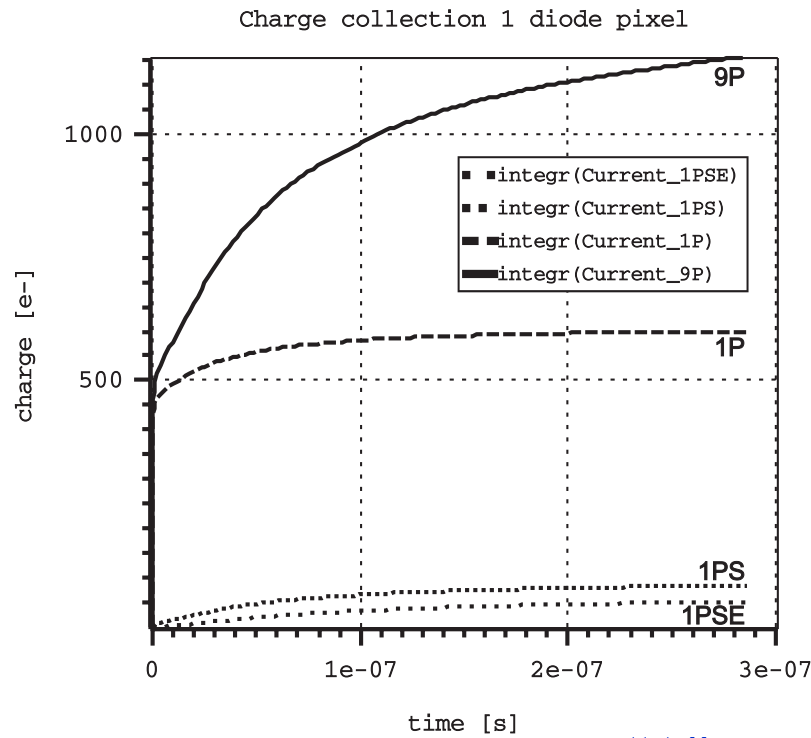
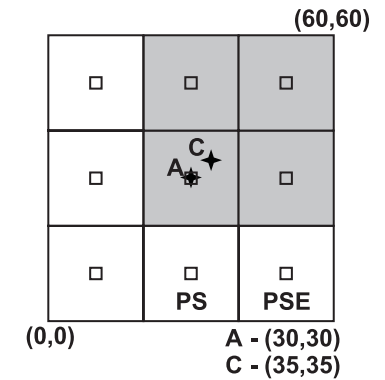
Unknown

- substrate contribution

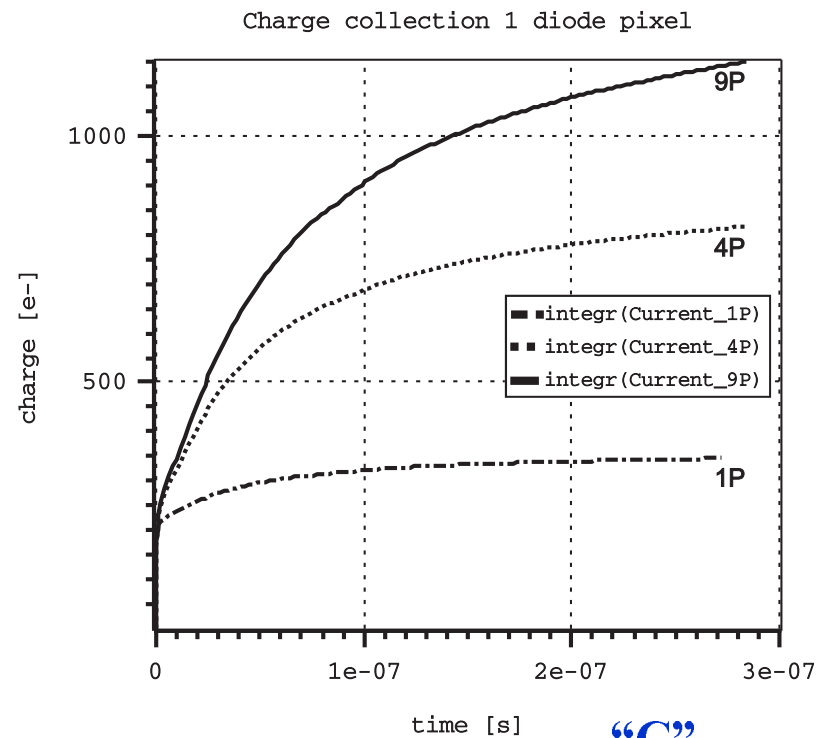
MIMOSA I

Charge Collection Simulation

- ▶ 3-D device simulation with ISE-TCAD package
- ▣ charge collection versus time as a function of a hit position



“A”

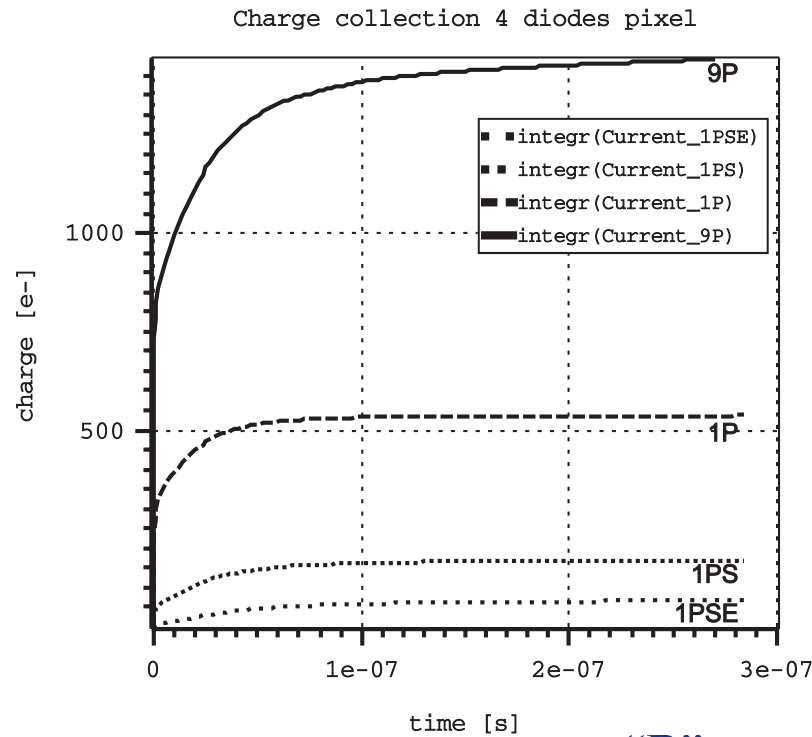
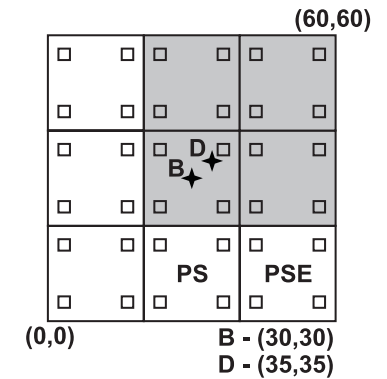


“C”

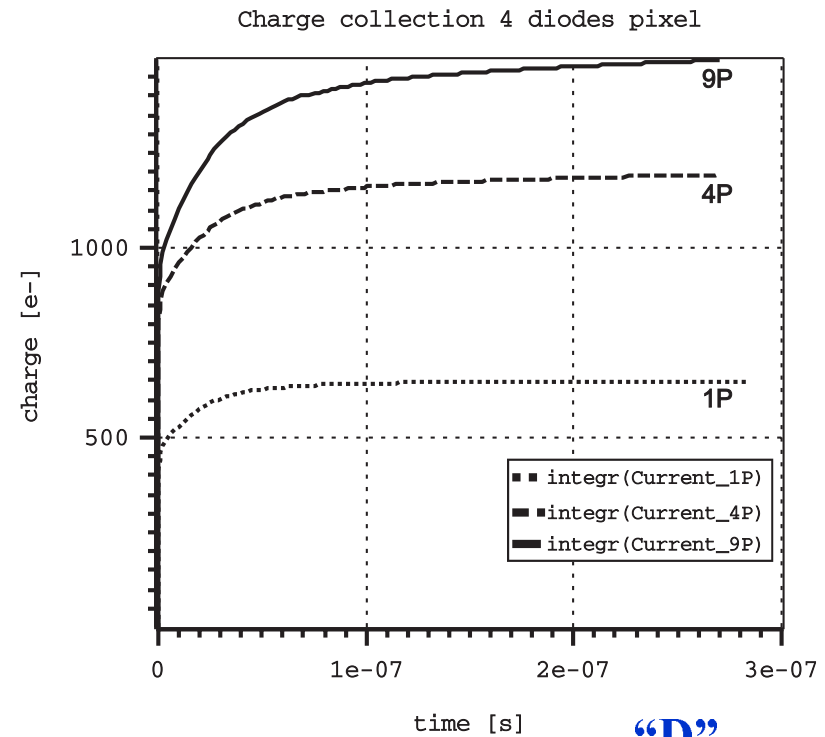
MIMOSA I

Charge Collection Simulation

- ▶ 3-D device simulation with ISE-TCAD package
- charge collection versus time as a function of a hit position



“B”



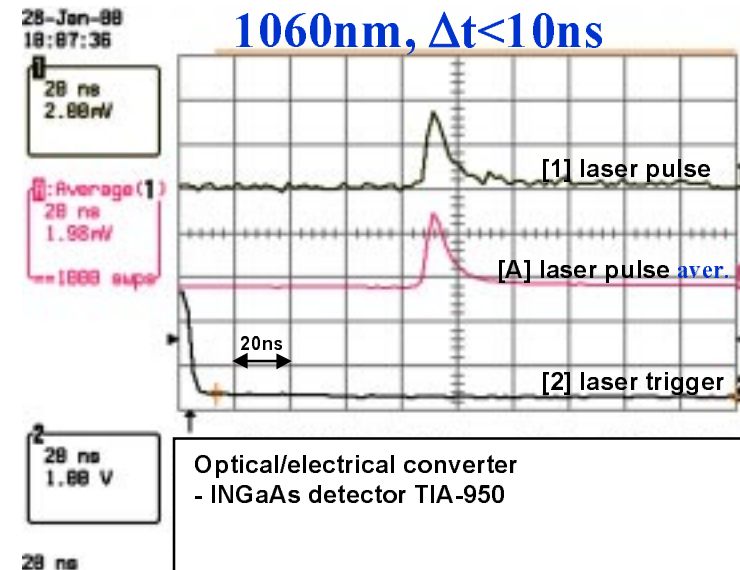
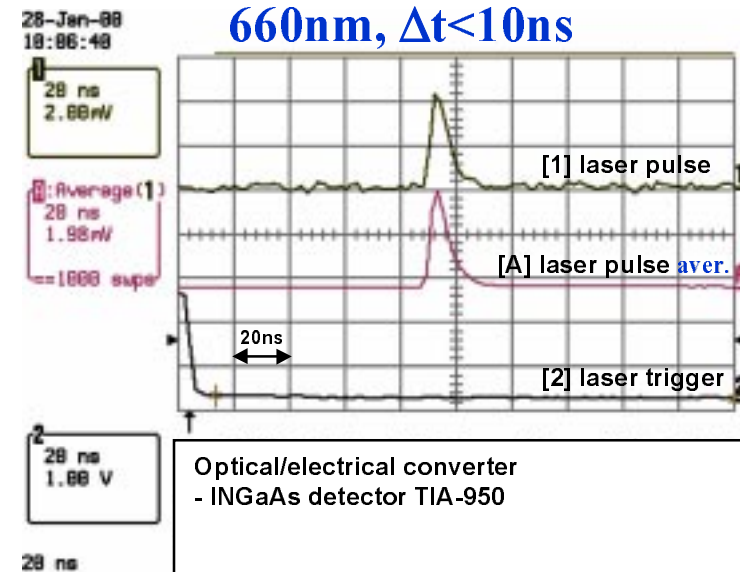
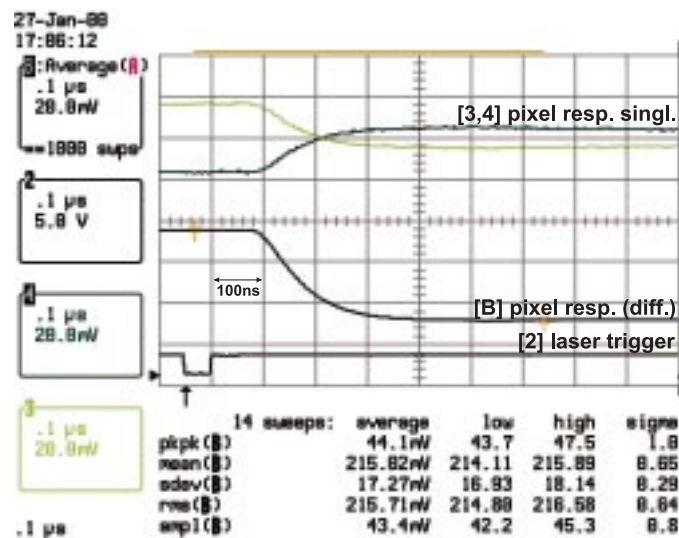
“D”

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Charge Collection Measurements

- ▶ **Laser set-up for strip detector evaluation (CERN - RD42)**
- ❑ **Use of laser diodes for MIP simulation:**
 - 660nm and 1060nm pulse laser diodes
 - rise time = 0.2ns
 - pulse width = 8.5ns
 - spot size = 10µm (FWHM)
 - delay after trigger = 65ns

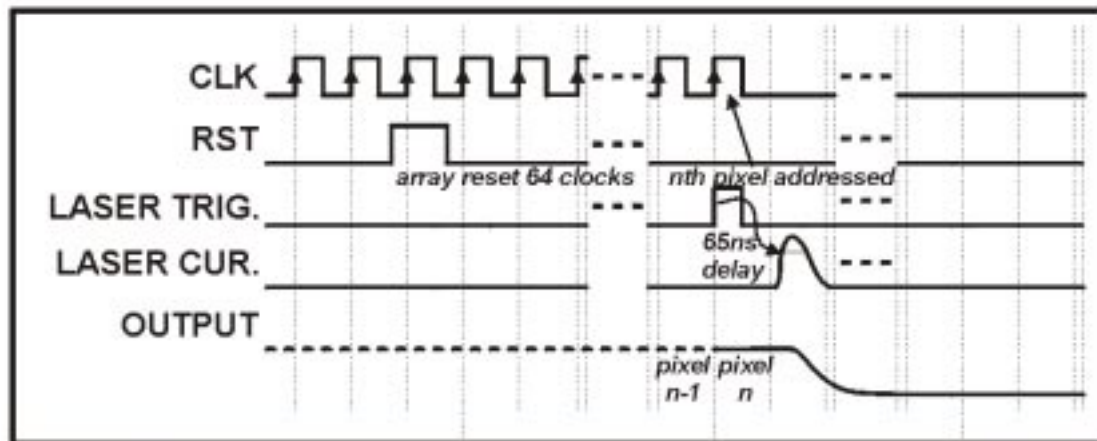
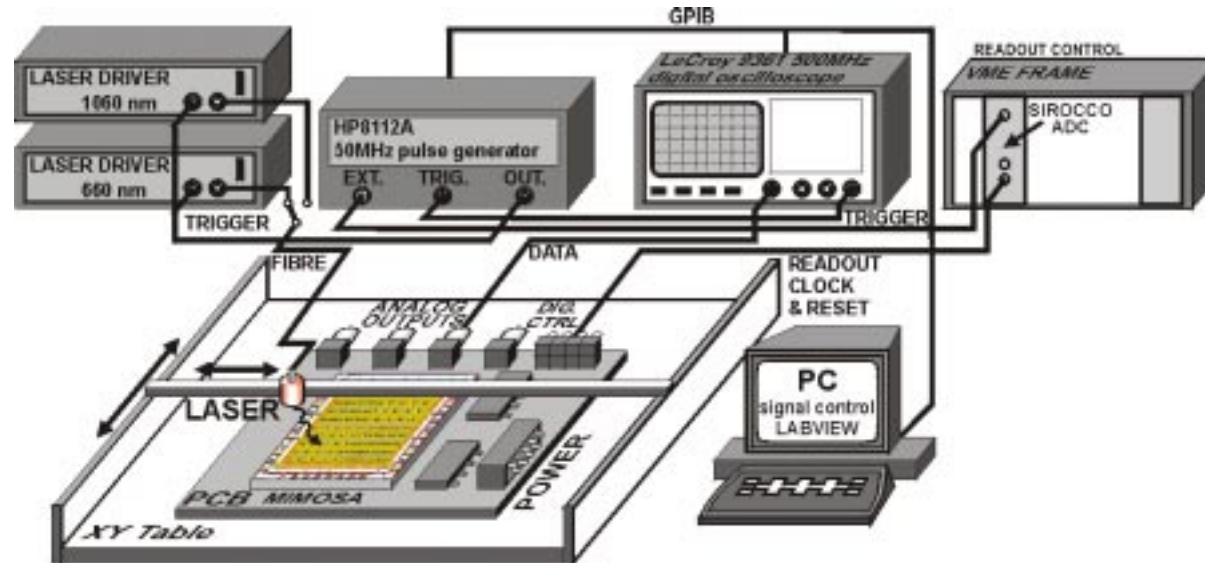
1P - type
pixel
response



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▶ Test set-up

Charge Collection Measurements



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Charge Collection Measurements

pixel level signal deconvolution

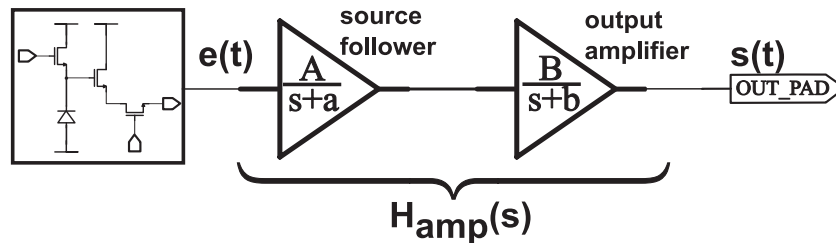
Transfer function of the on chip amplifier (*readout chain*):

$$H_{\text{amp}}(s) = \frac{A}{s+a} \cdot \frac{B}{s+b}$$

Where:

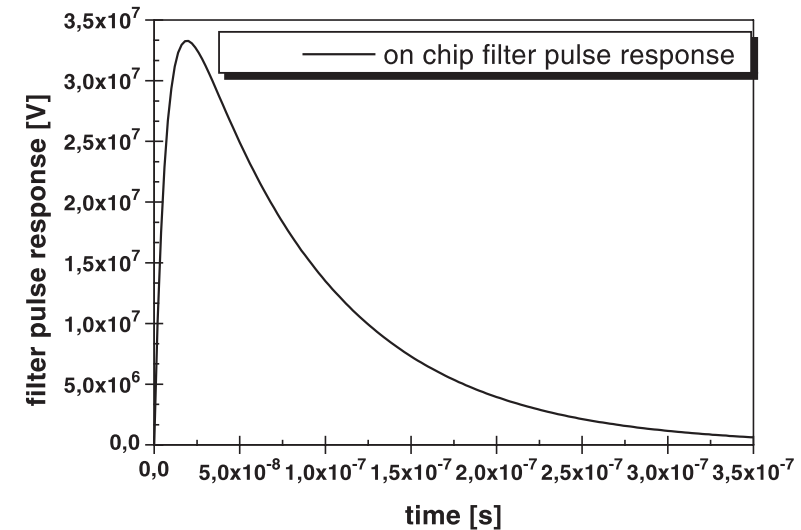
$$A = (128.55E + 6), \quad B = (45.58E + 6)$$

$$a = (139.13E + 6), \quad b = (12.31E + 6)$$



$$S(s) = H_{\text{amp}}(s) \cdot E(s) \Rightarrow E(s) = \frac{S(s)}{H_{\text{amp}}(s)}$$

Pulse response of the on chip amplifier:c



$$E(s) = \frac{1}{A \cdot B} [s^2 \cdot S(s) + (a+b) \cdot s \cdot S(s) + a \cdot b \cdot S(s)]$$

⇓

$$e(t) = \frac{1}{A \cdot B} \left[\frac{d^2 s(t)}{dt^2} + (a+b) \frac{ds(t)}{dt} + a \cdot b \cdot s(t) \right]$$

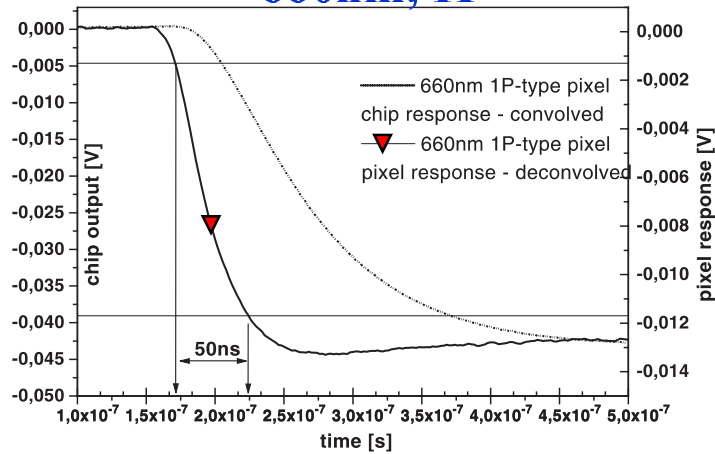
Equation is solved for $e(t)$ using discrete differentiation of the measured signal

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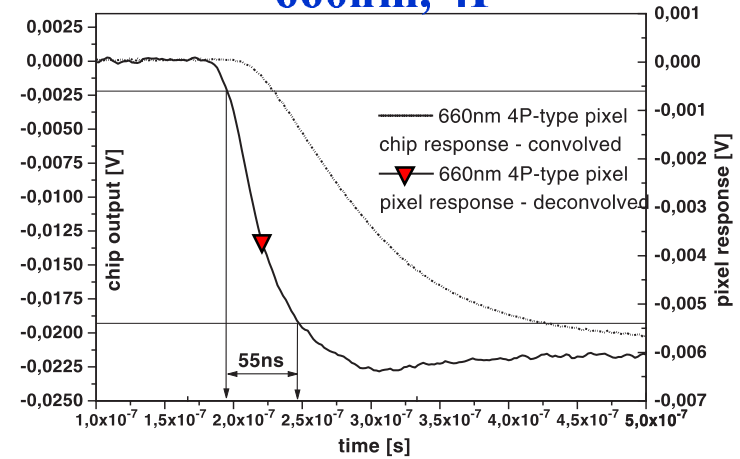
Charge Collection Measurements

▶ results

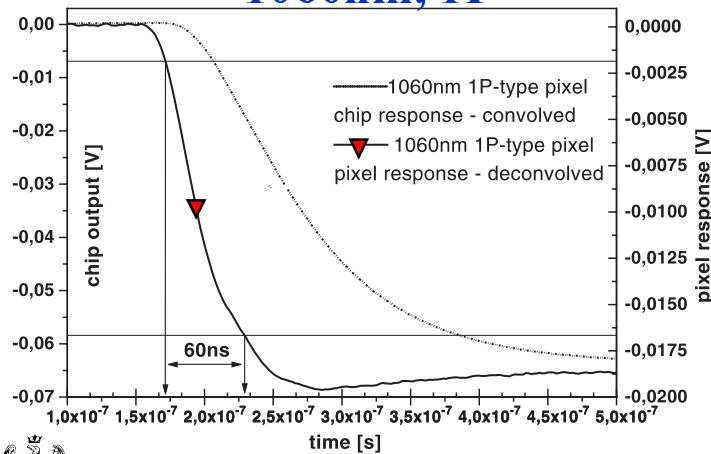
660nm, 1P



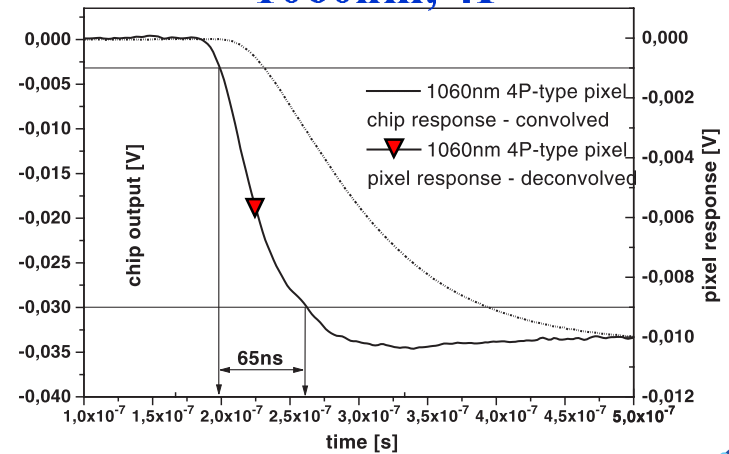
660nm, 4P



1060nm, 1P



1060nm, 4P



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◉ 15 μ m (epitaxial layer) => 1100 e⁻ (peak)

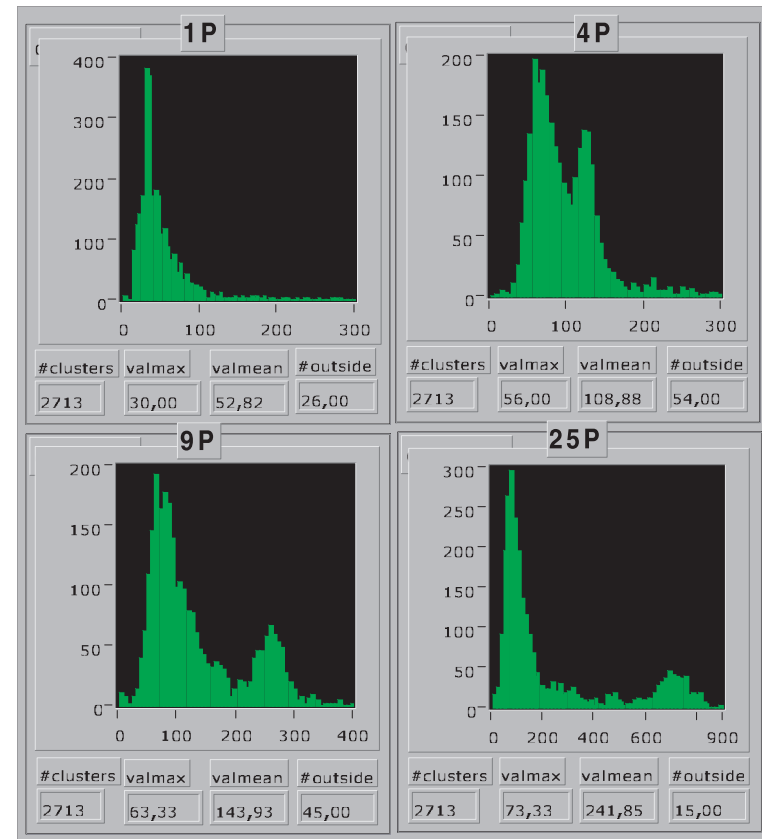
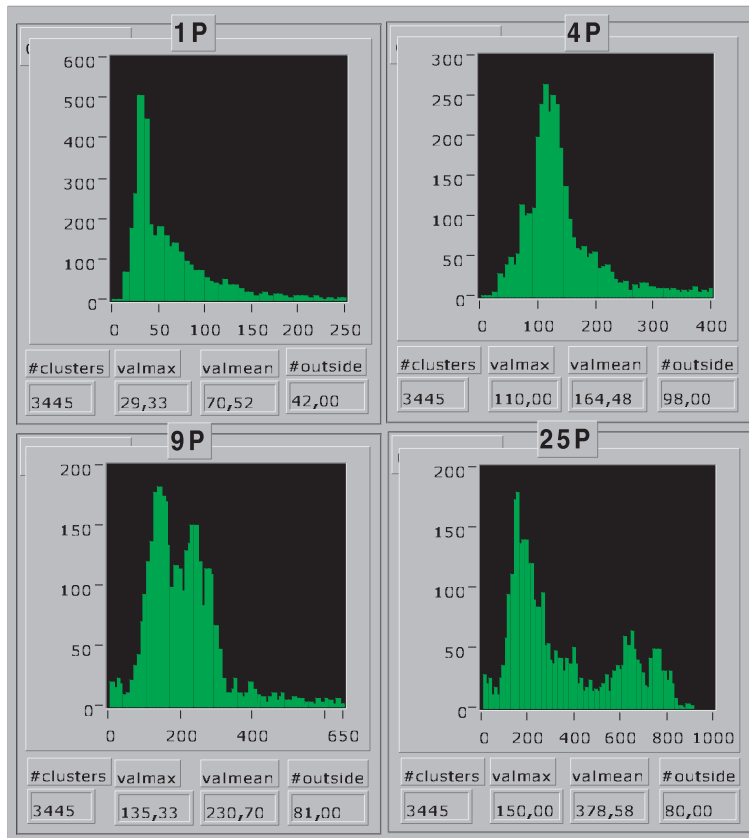
Tracking tests: 120GeV/c pions - online data monitor display

❑ no alignment with reference detectors tracks

Preliminary results
beam test 01.06 - 04.06 2000

1P - gain=5.90/ADC
12000 events, noise=3,52ADC

4P - gain=14.85e/ADC
10000 events, noise=3,11ADC



Conclusion and prospects:

- ▶ ISE-TCAD package simulates transient process of achieving the equilibrium state after a particle passage
 - ❑ it does not allow effective MC simulation (*small volume limited*)
 - ▶ More detailed knowledge of technological properties (*doping profiles, layer thickness*) of the fabrication processes is needed
 - usually silicon foundry confidential data
 - ▶ Detailed simulation + big structures = **CPU time** ↗↗↗
 - ▶ Quantitative results of device simulation using ISE-TCAD package tally with measurements (SNR=20÷30, charge collection time <100ns (*for one pixel*))
-
- ▶ Near future: rad-tolerant device (MIMOSAII) with some new features (coming soon) - charge collection dependence on the epitaxial layer thickness
 - ▶ Longer perspective: other types of active elements (photofet, photogate ...)