Device simulation of CMOS Pixel Sensors with synopsys

Andrei Dorokhov
PICSEL group, IPHC

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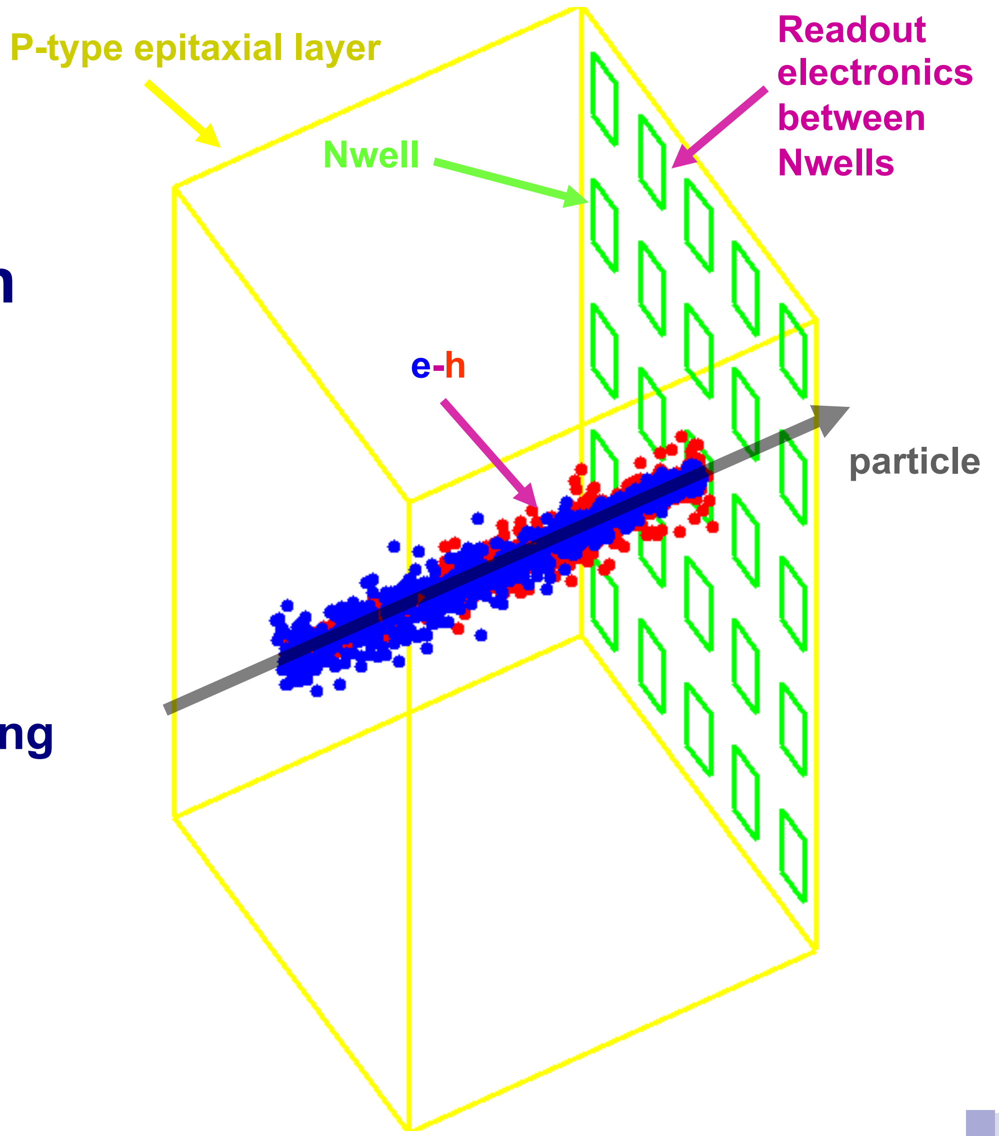
Contents

- **CMOS Pixel Sensors (CPS)**
- **Simulation with SYNOPSYS TCAD**
- **Simulation examples for CPS**

CMOS Pixel Sensors

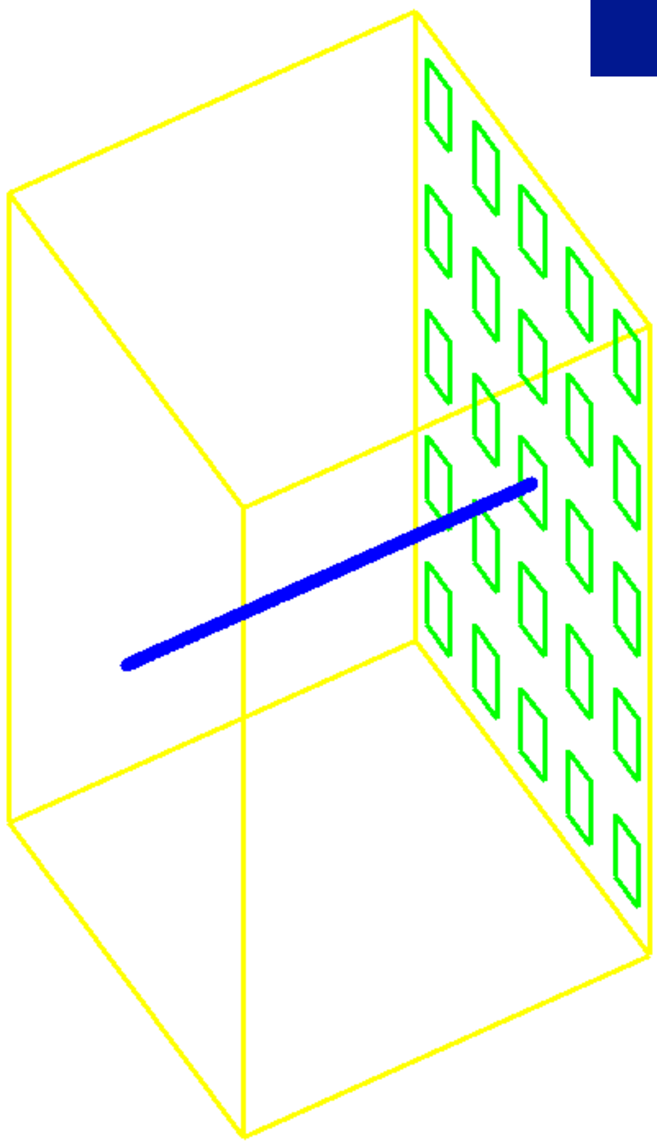
- **CPS (also known as Monolithic Active Pixel Sensors (MAPS)) are devices for charged particle or light detection**
  - **sensor and electronics are implemented in the standard CMOS substrate**
  - **electronics can perform the following tasks:**
    - **Correlated double sampling**
    - **Digitization**
    - **Discrimination**
    - **Zero suppression**
    - **…..**
    - **Storage**



CMOS Pixel Sensors

- CPS are under development by Strasbourg group since 1999
  - Many different prototypes (Mimosa**) have been optimized for:
    - noise and signal-to-noise ratio
    - charge collection efficiency for visible light and charged particles detection
    - power consumption
    - signal processing (discriminators, ADCs, zero suppression or compression logic)
    - radiation tolerance
    - speed
    - reliability

CPS: principle of operation



- energy of a particle transferred to creation of e-h pairs in silicon bulk (p-type epitaxial layer)
- moving electrons and holes induce current on sensing electrodes (Nwells)
- the current is converted to voltage on Nwell/Pepi diode capacitance

- physics processes describing the charge collection are very complex
  - device simulation is needed to understand them and to verify new ideas…

Andrei.Dorokhov@ires.in2p3.fr

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Simulation with Sentaurus TCAD from Synopsys

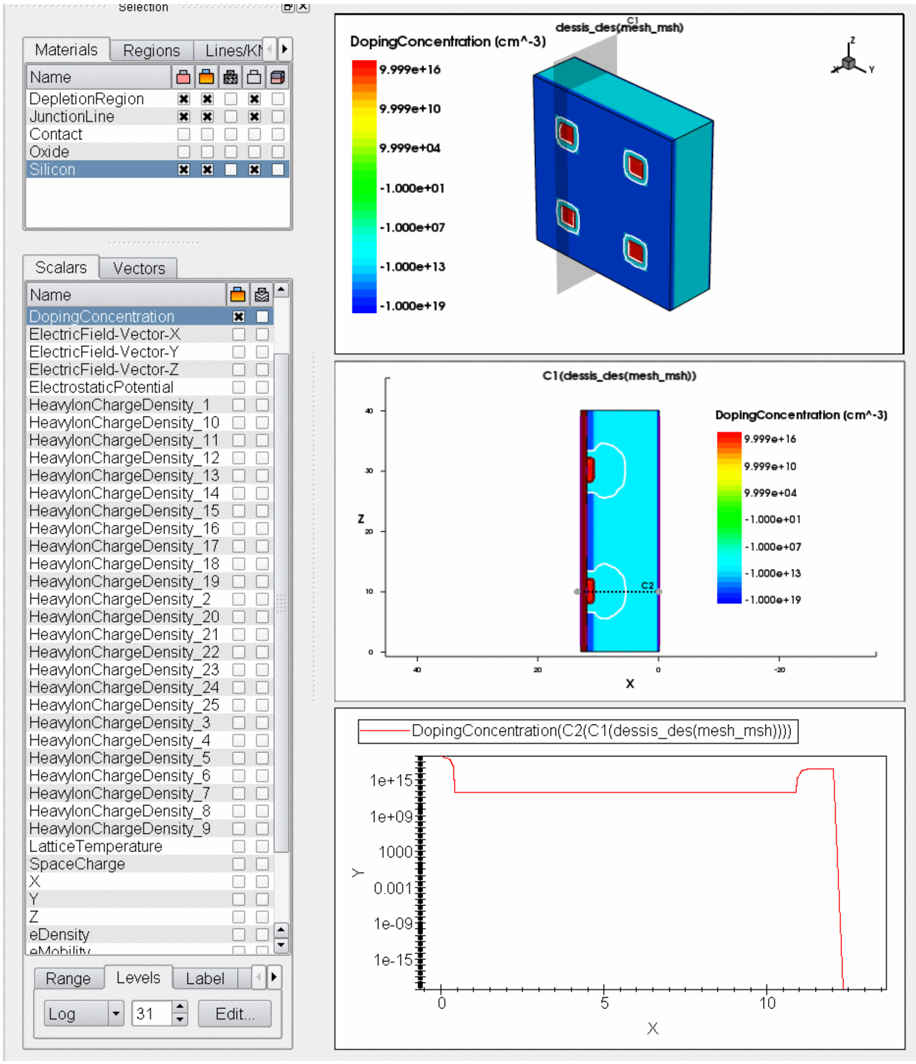
process simulation: temperature, pressure, velocity,....

used by FABs in order to improve fabrication of CMOS devices, the process parameters are unknown to us...

device simulation: fabricated device parameters - doping concentration, geometry, applied voltages, tracks of elementary particles

- basic properties:
  - electric field
  - potentials
  - leakage current
  - capacitance
- transient response on particle:
  - charge collection
  - collection time

Prepare for simulation: defining of doping profiles



- **mesh generator: " mesh" in Sentaurus**
- **two input files: boundary and doping**

Example of 3D boundary file:

Silicon "substrate"
{
cuboid [(0 0 0), (12 40 40)]
}
Contact "pixel_0_0"
{
rectangle [(12, 9.345, 9.345) (12, 10.655, 10.655)]
}
Contact "backplane_contact"
{
rectangle [(0, 1, 1) (0, 39, 39)]
}

Example of doping definition file:

Title "Pixel"
Definitions {
Constant "substrate"
{
Species = "BoronActiveConcentration"
Value = 1e13
}
AnalyticalProfile "NW" {
Species = "PhosphorusActiveConcentration"
Function = Erf(SymPos = 1, MaxVal = 1.0e +17, ValueAtDepth = 1e+13, Depth = 1.1)
LateralFunction = Gauss(Length = 0.02) }
}
Placements
{
Constant "substrate" {
Reference = "substrate"
EvaluateWindow
{
Element = cuboid [(0, 0, 0) (12, 40, 40)]
}
}
AnalyticalProfile "diode_0_0" {
Reference = "NW"
ReferenceElement
{
Element = rectangle [(12, 8.345, 8.345) (12, 11.655, 11.655)]
Direction = negative
}
}
}

Prepare for simulation: device simulation

- simulator: "dessis" in Sentaurus
- one input file: commands for simulation

Example of command file:

```
Physics {
      Temperature = 293.15
      Mobility( DopingDep HighFieldsat Enormal )
      Recombination( SRH(tunneling(Hurkx)) Auger surfaceSRH Radiative
TrapAssistetAuger )
      HeavyIon ("mip0") (
      PicoCoulomb
      Gaussian
      time=1.0e-9
      direction=(1,0,0)
      location=(0,36.6667,7.77778)
      wt_hi = 3
      length= 1000
      let_f = 1e-5
  )
}
......
Electrode {
      { Name="backplane_contact" Voltage=0.0 }
            { Name="pixel_0_0"   Voltage=1.8 }
}
.....
Solve {
      Coupled { Poisson Electron Hole Contact}
      Transient (
      InitialTime=0.0 FinalTime=300.0e-9
      InitialStep=0.1e-9 MinStep=1e-18 MaxStep=10.0e-9
      Increment=1.2
      )
      {
            Coupled { Poisson Electron Hole Contact}
                  Plot ( Time= ( 0; 1e-9; 1.2e-9; 1.5e-9; 2e-9; 5e-9; 10e-9; 20e-9;
50e-9; 150e-9; 300e-9 ) NoOverwrite )
      }
}
```

Declare which models will be used for simulation

Define particle track: HeavyIon or AlphaParticle models are available, however one can redefine model parameter values in order to incorporate other particles (m.i.p. in example)

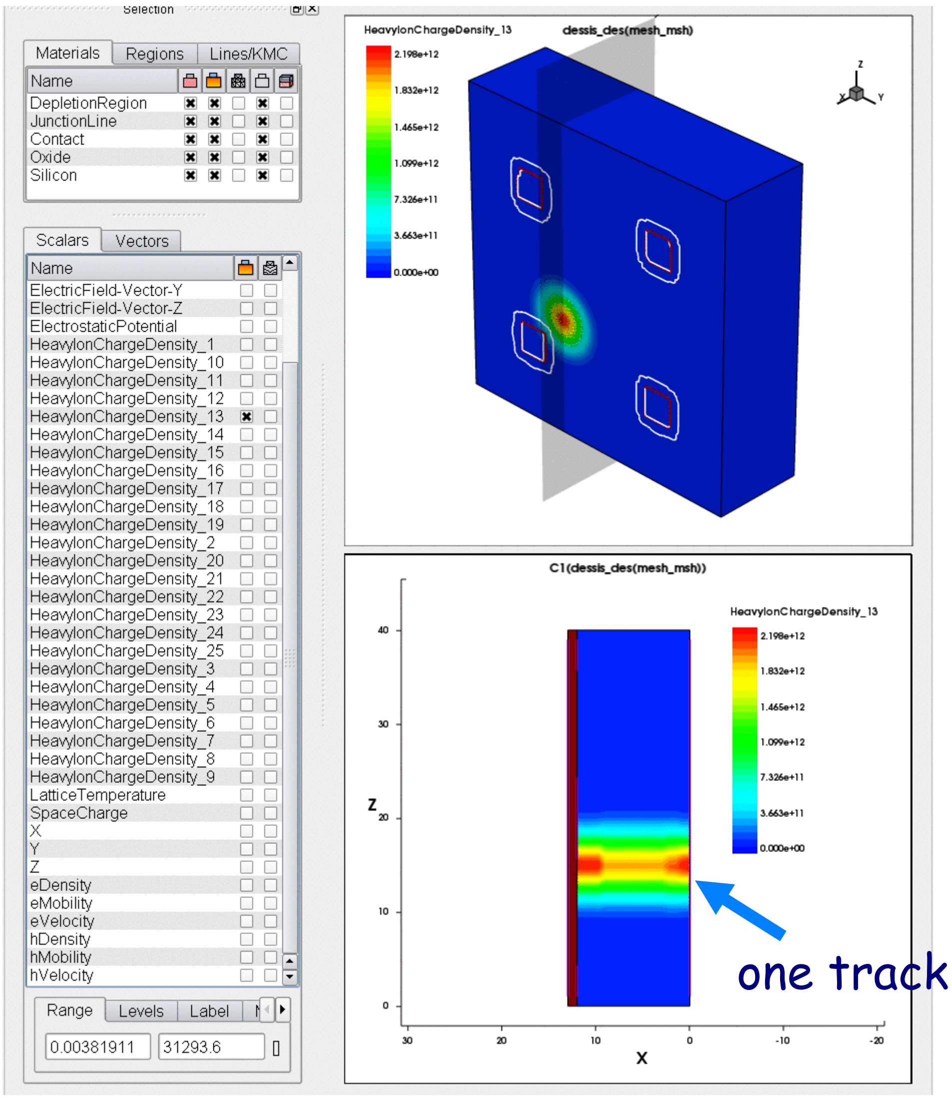
Set electrodes potentials (possible also current or charge)

Poisson and continuity equations : the currents on electrodes are known

$$\nabla \varepsilon \cdot \nabla \psi = -q\,(p - n + N_D - N_A)$$
$$\nabla \cdot \vec{J}_n = q\,R + q\,\partial n/\partial t$$
$$\nabla \cdot \vec{J}_p = q\,R + q\,\partial p/\partial t$$

Solve equations and plot them at several time points

Defining tracks of particles : multiple particles

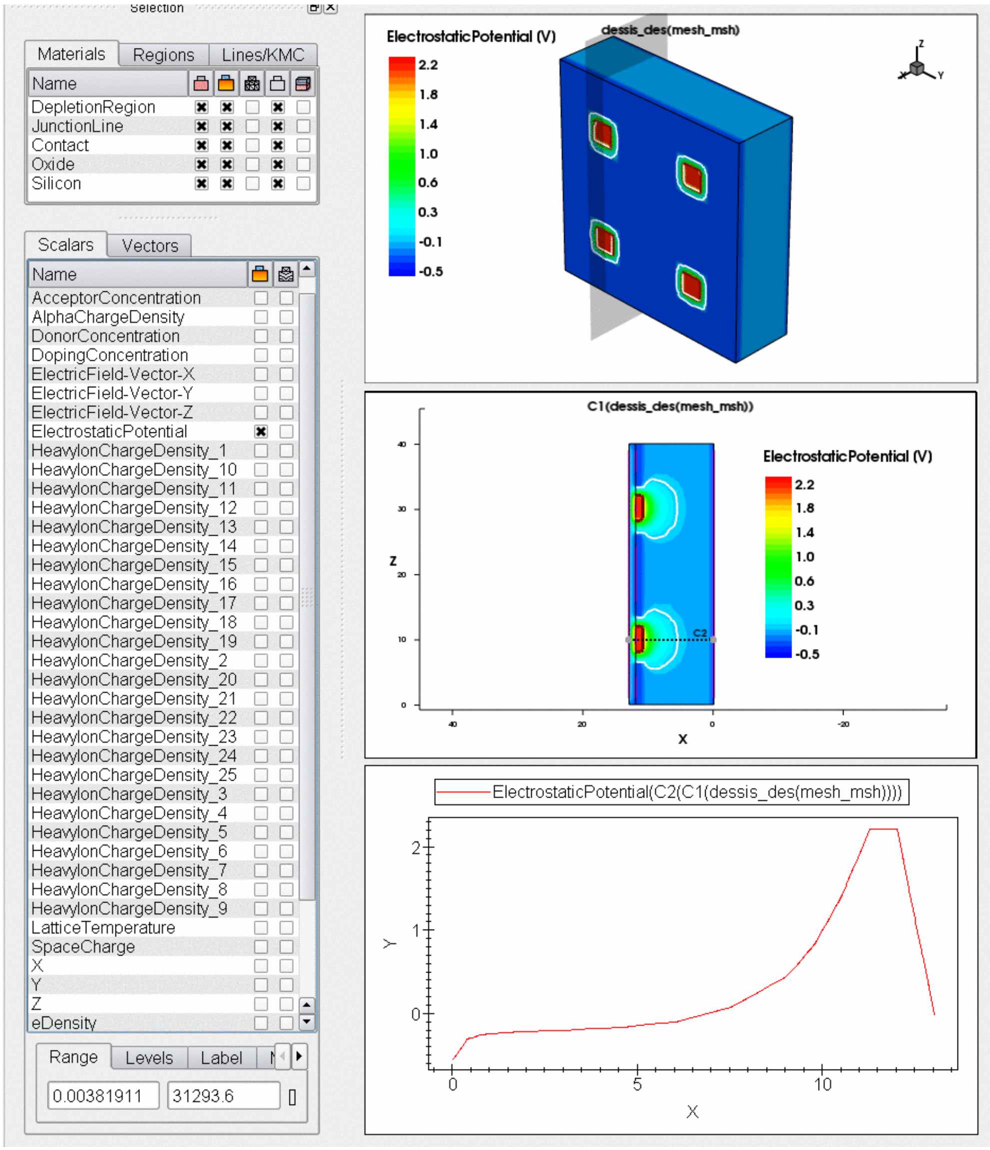


Heavy Ion is used to simulate m.i.p: parameters of energy deposition in silicon can be modified from default values in "dessis.par" file:

```
HeavyIon
{ * Generation by a Heavy Ion :
  * The temporal distribution is a Gaussian Function
  * The radial spatial distrbution can be a exponential, a gaussian function or
give by table
  * The spatial distribution along the path is coming from a table
  * G = LET(l)*R(r)*T(t)
  * LET(l) = a1 + a2*l + a3 exp(a4*l) + k'*[c1*(c2 + c3*l)^(c4) + Lf(l)]
  * with Lf(l) = { Lf1, Lf2, Lf3, ...}
  * Lfi are the Lf values for each length lengthi
  * if Radial_Exponential_Distribution;
  *        R(r) = exp[-(r/wt)]
  *      case 3D (unit pC/um) : k' = k / (2*pi*wt^2)
  *      case 2D (unit pC/um) : k' = k / (2*e*wt)
  *         if unit = Pairs/cm^3 => k' = k
  * if Radial_Gaussian_Distribution;
  *        R(r)= exp[-0.5*(r/wt)^2]
  *      case 3D (unit pC/um) : k' = k / (pi*wt^2))
  *      case 2D (unit pC/um) : k' = k / (e*wt*Sqrt(pi))
  *         if unit = Pairs/cm^3 => k' = k
  * with wt(l) = { wt1,  wt2,  wt3 ...}
  * wti are the wt values for each length lengthi
  * e = 1 um
     s_hi    = 100.0000e-12    # [s] default is 2.0e-12
#  * See the manual for more details.
}

HeavyIon ("mip0") {  s_hi    = 100.0000e-12    }
HeavyIon ("mip1") {  s_hi    = 100.0000e-12    }
HeavyIon ("mip2") {  s_hi    = 100.0000e-12    }
HeavyIon ("mip3") {  s_hi    = 100.0000e-12    }
...
...
```

Visualization of the results of simulation : DC solution

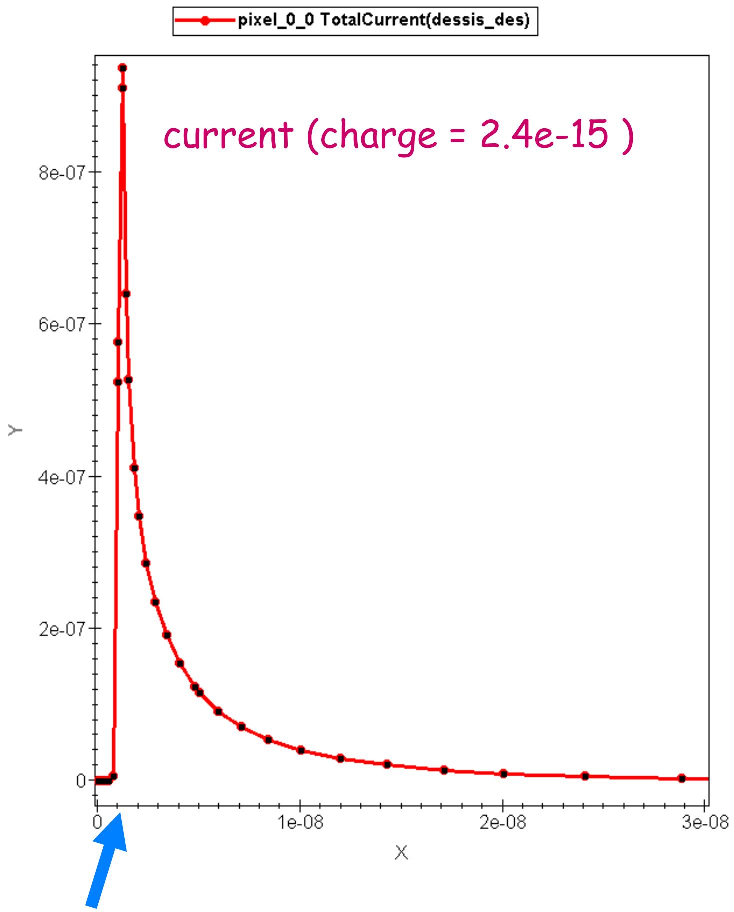


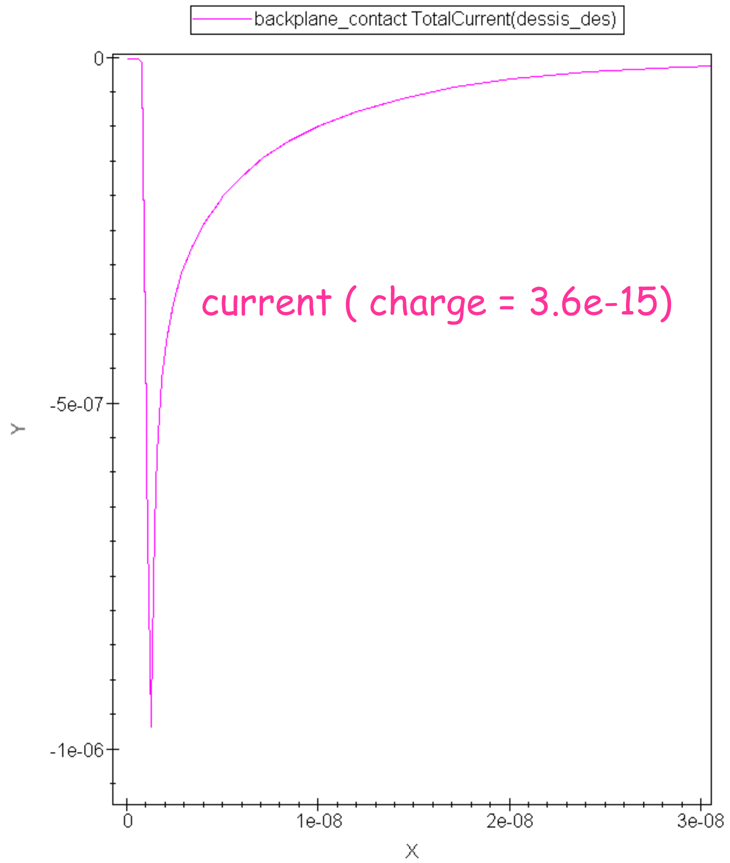
- **visualization with: "svisual" in Sentaurus**

DC solution is presented: electrostatic potential

Different zones can be displayed, for example the most important depletion zone (white color)

Charge transport : transient response

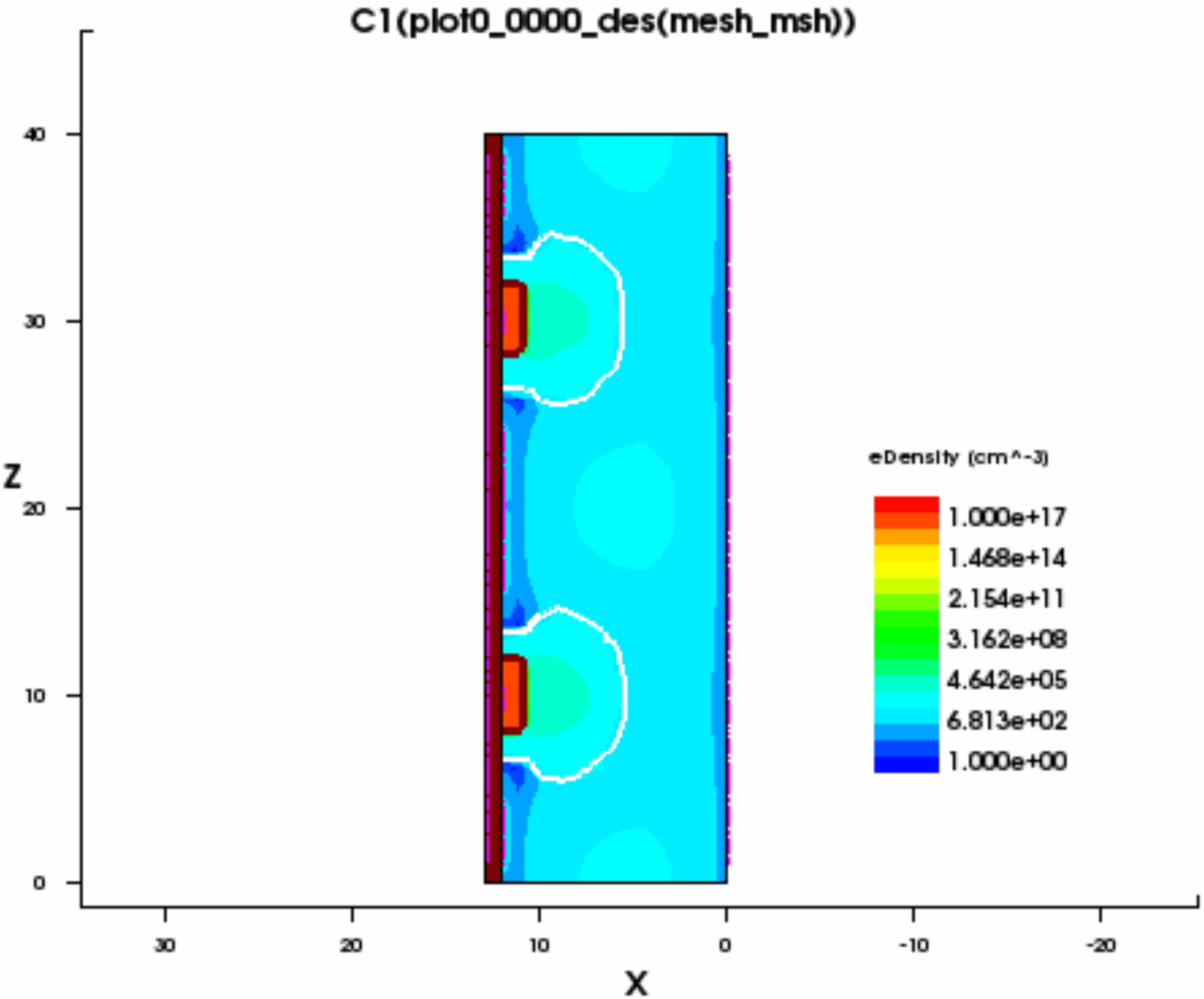




particles come at this moment

in average 67 % of total deposited by m.i.p. charge is collected, also one can find the typical charge collection time (<10 ns)

Charge transport in CPS: visualization of charge

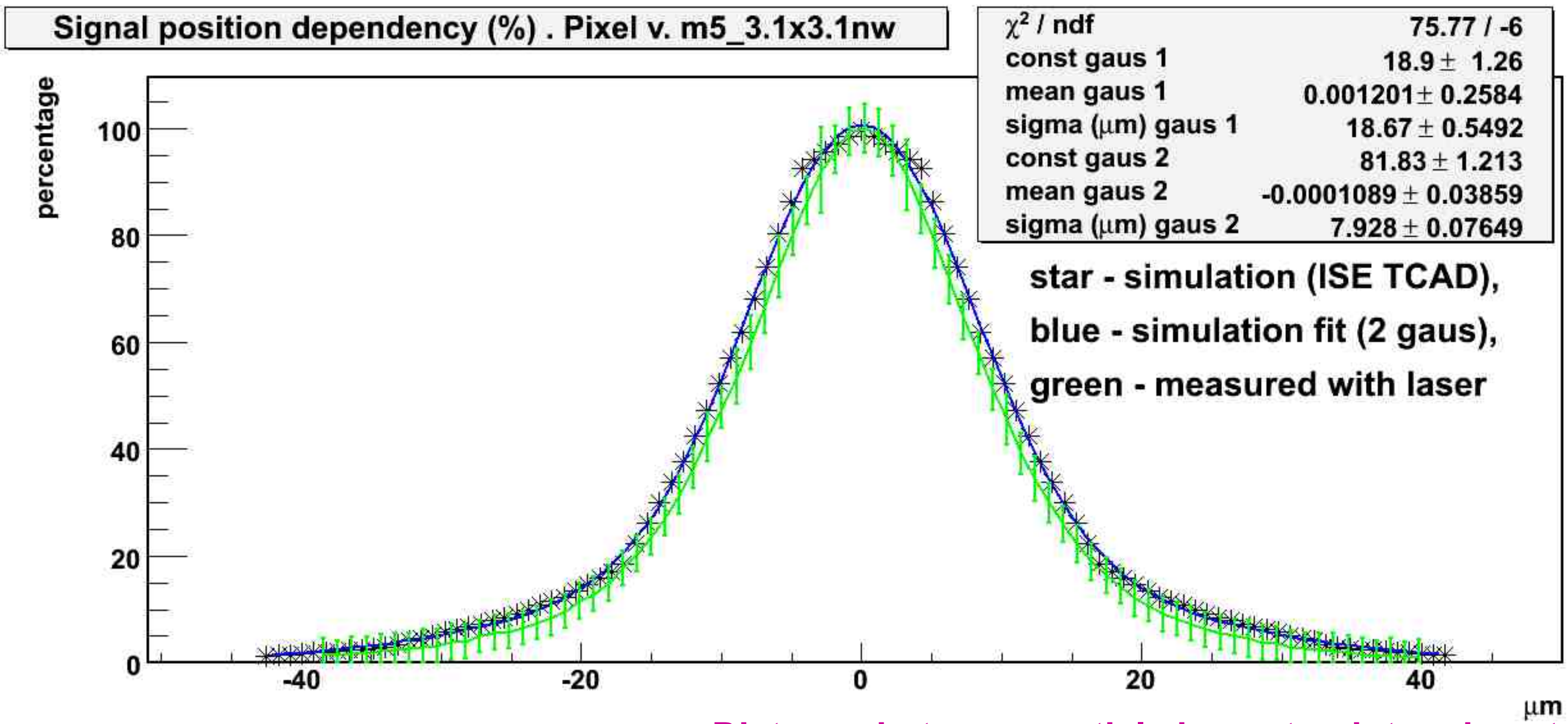


in TCAD is not possible to track charge created by the m.i.p, but excess of electron density can show the presence of charge created by the particle

The snapshots of electron density can be saved along the simulation, so one can see how the excess of charge evacuated bu the charge collections electrodes

Contents

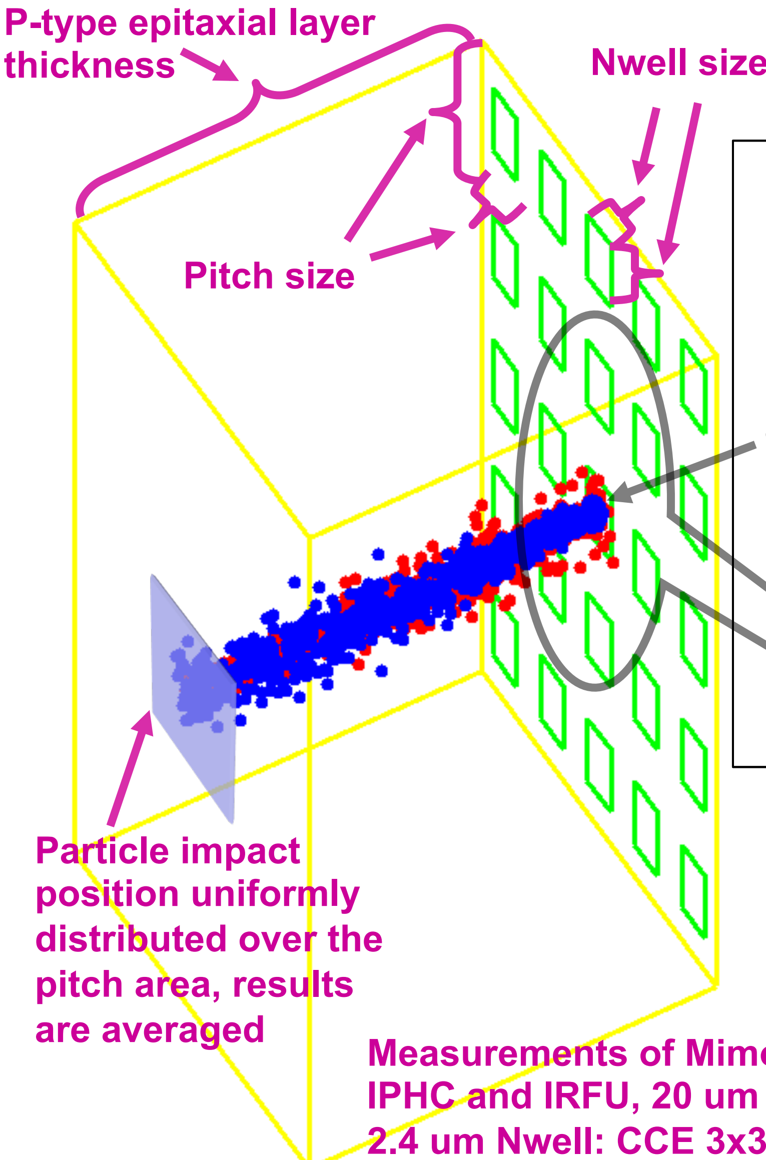
Example 1: Simulation of charge sharing

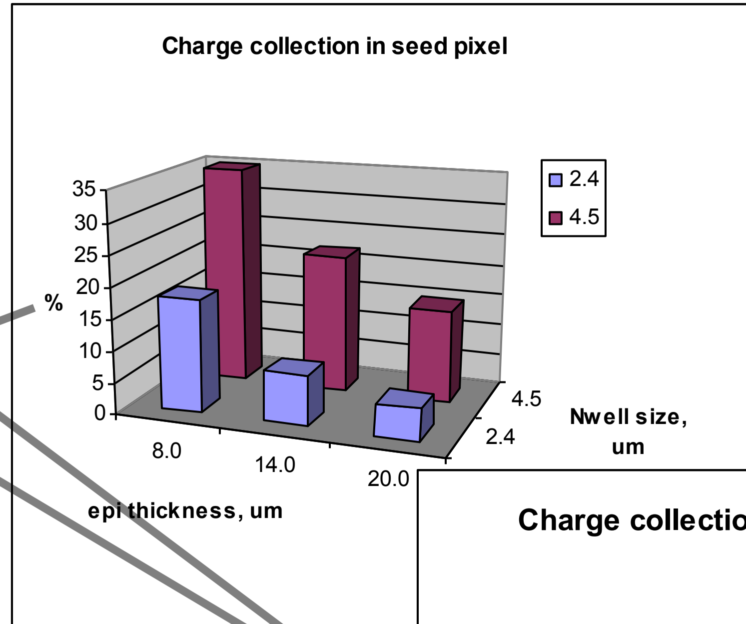


Distance between particle impact point and center of (3,3) pixel in 5x5 matrix

* Chip: Mimosa 5, developed at IPHC, Strasbourg
** Measurements with laser: at IPNL, Lyon

Example 2: Geometry influence on charge collection efficiency

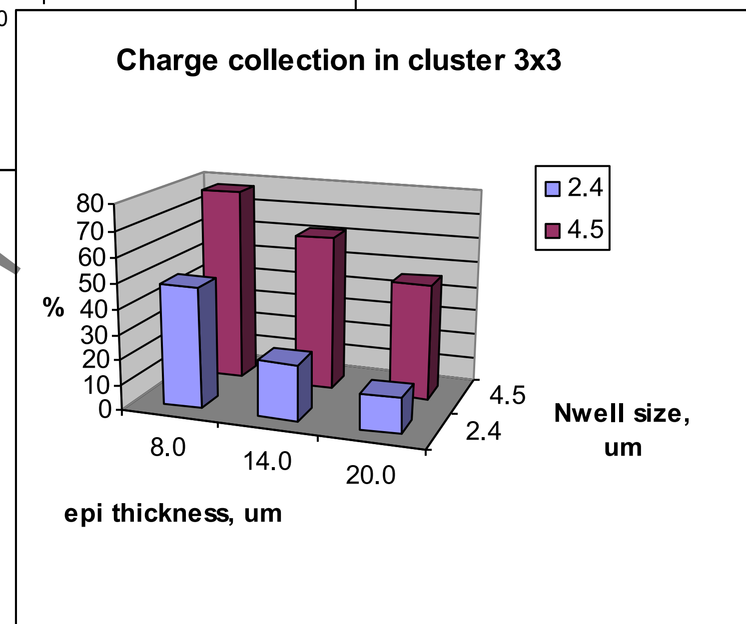




Optimisation for 14um:

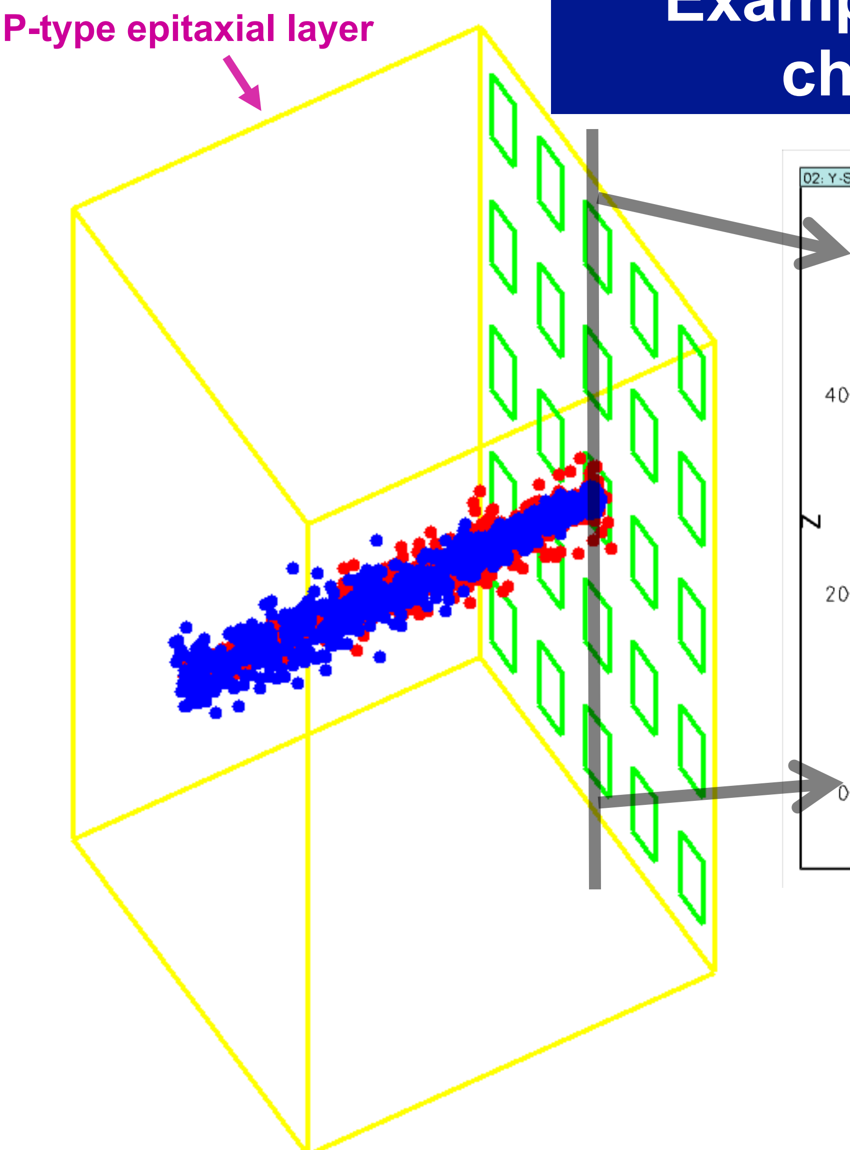
- $C_{2,4}$ =3 fF, $C_{4,5}$ = 6 fF
- $ENC_{4,5}/ENC_{2,4} \sim 2$
- signal ~ charge collection [%] : $S_{4,5}/S_{2,4} \sim 3$
- $(S/N)_{4,5}/(S/N)_{2,4} = 3/2$

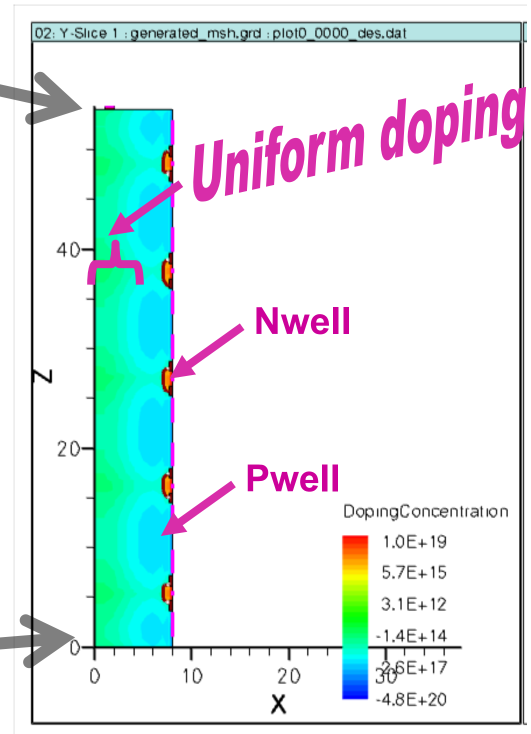
S/N higher with 4.5um

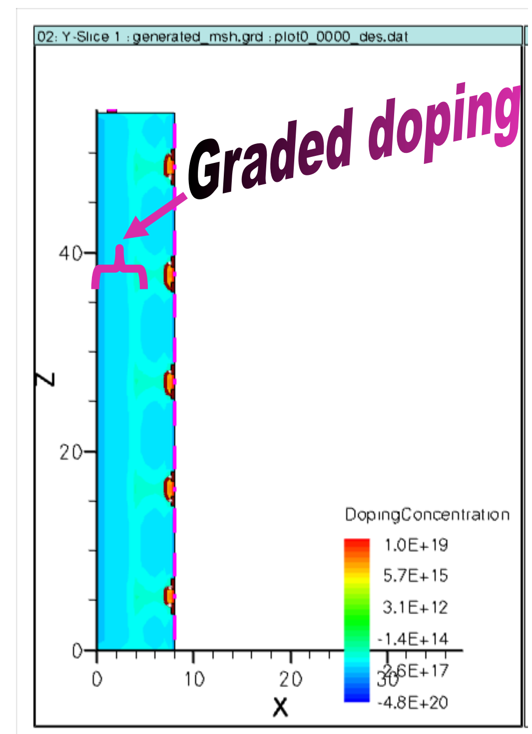


Measurements of Mimosa 16 developed at IPHC and IRFU, 20 um epi -
2.4 um Nwell: CCE 3x3 ~ 23%
4.5 um Nwell: CCE 3x3 ~ 52%

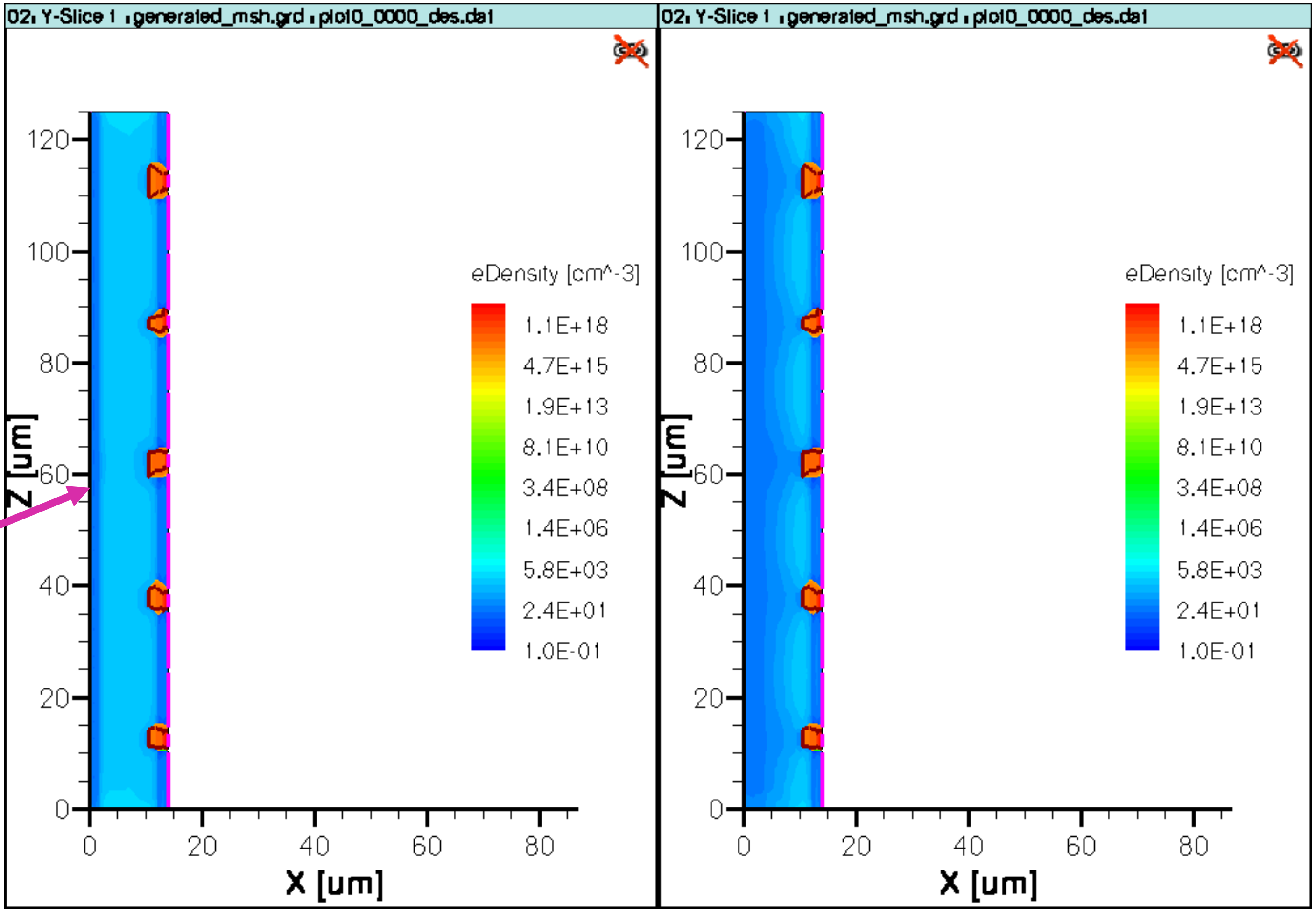
Example 3: epi doping influence on charge collection efficiency







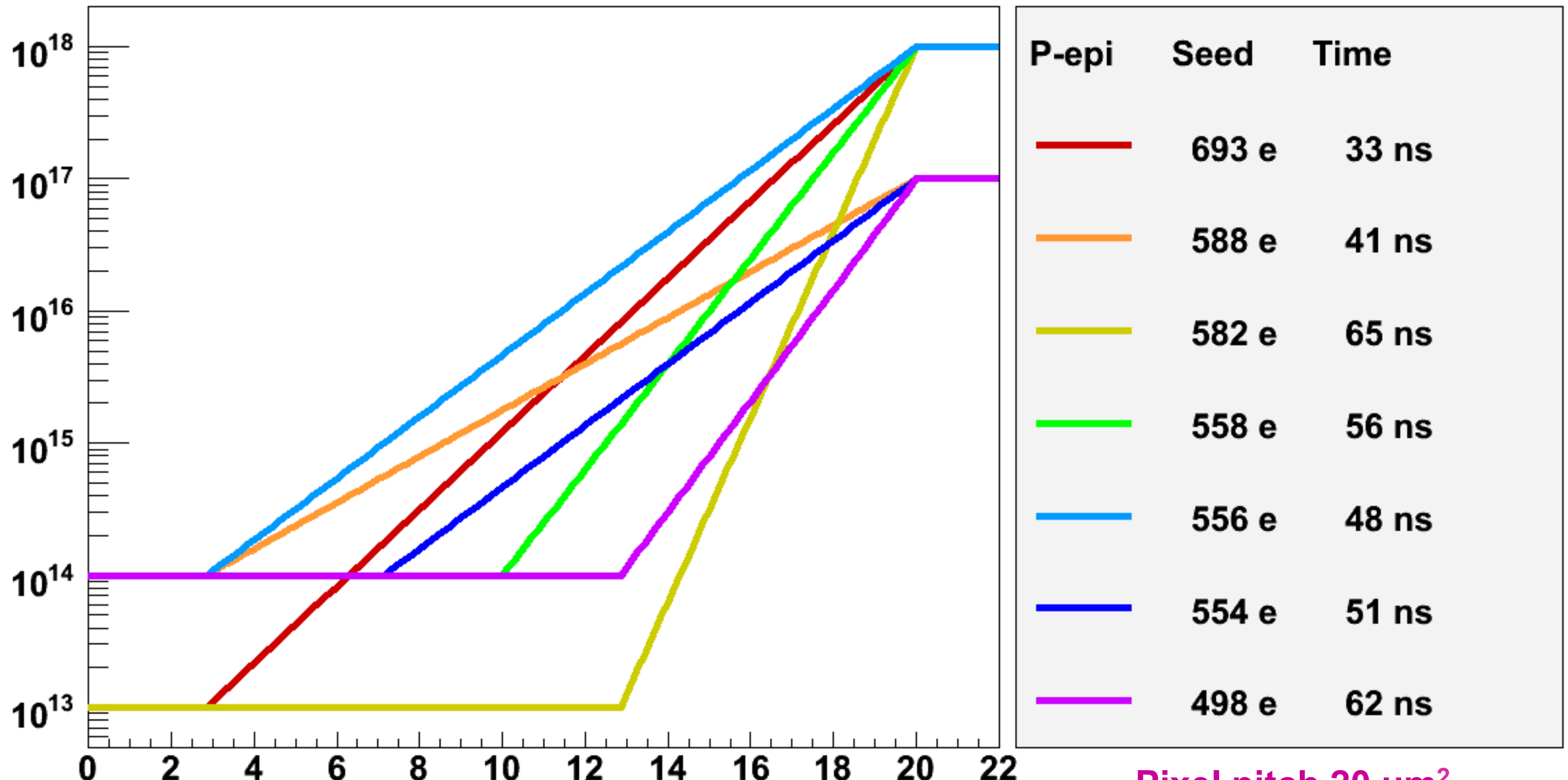
Example 3 :epi doping influence on charge collection efficiency



Excess of electrons from particle will be there

Example 3: epi doping influence on charge collection efficiency and collection time

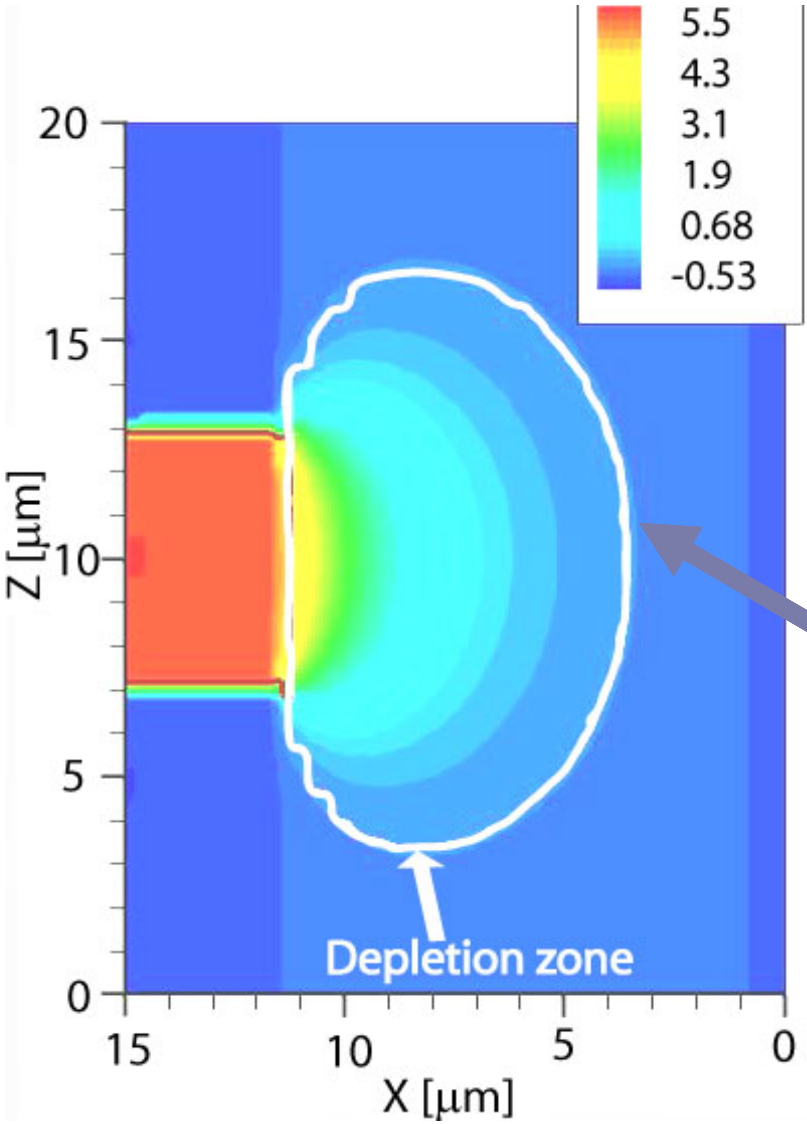
epi p-type doping concentration, cm^{-3}



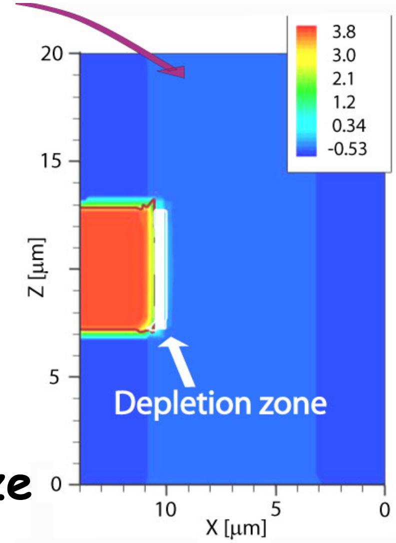
Distance from Nwell surface towards the bulk, um

Pixel pitch 20 um^2
Nwell 4 um^2

Example 4: epi doping influence on depletion

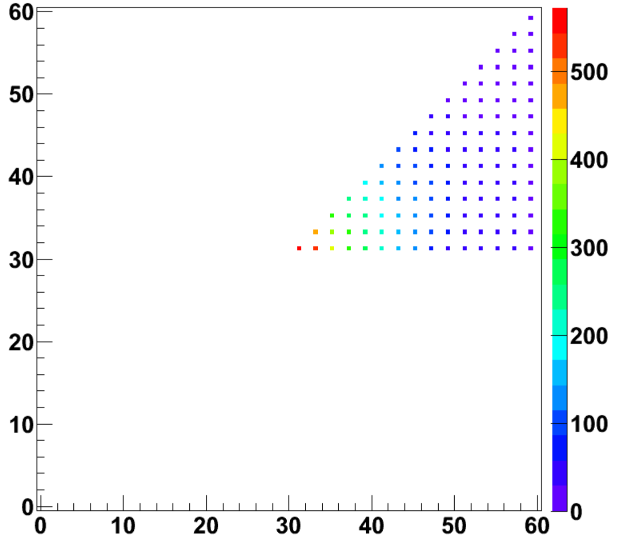


For comparison: standard CMOS technology, low resistivity P-epi

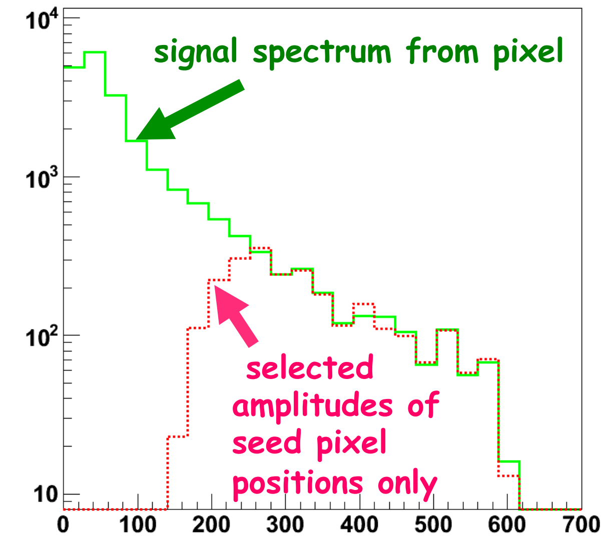


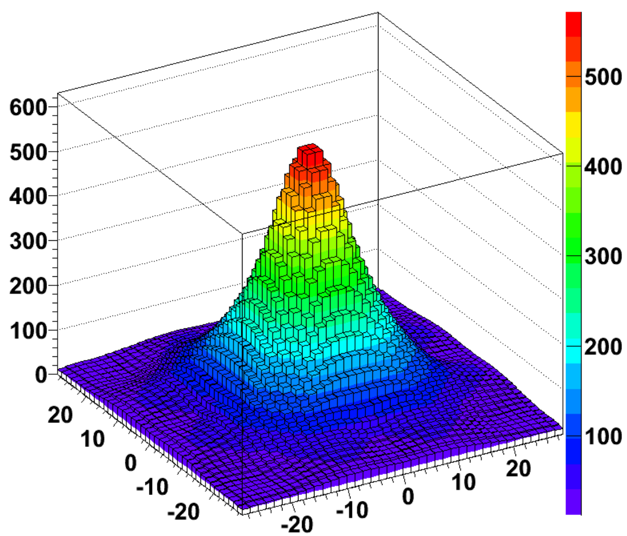
high resistivity P-epi: size of depletion zone size is comparable to the P-epi thickness-> show about x2 charge collected in seed, used in upgrade of STAR HFT detector

Example 5: charge collection vs position of track

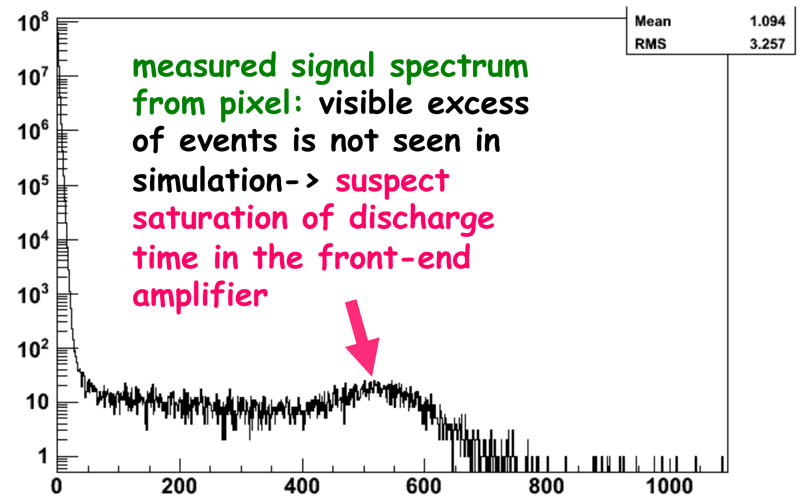


❖ simulated charge vs particle position in a 3x3 pixels of pitch 20um matrix





❖ interpolated results from simulation: charge vs distance between particle and central pixel



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Outlook

- **the following properties of semiconductor detectors can be extracted from simulation with TCAD:**
  - Charge collection efficiency
  - Collection time
  - Charge sharing
  - Capacitance
  - Electric field
  - Leakage current

- **the simulations can be used:**
  - for estimation of detector performance
  - optimization of front end electronics
  - verification of new ideas
  - complementary to measurements study