Device simulation of CMOS Pixel Sensors and microstrips

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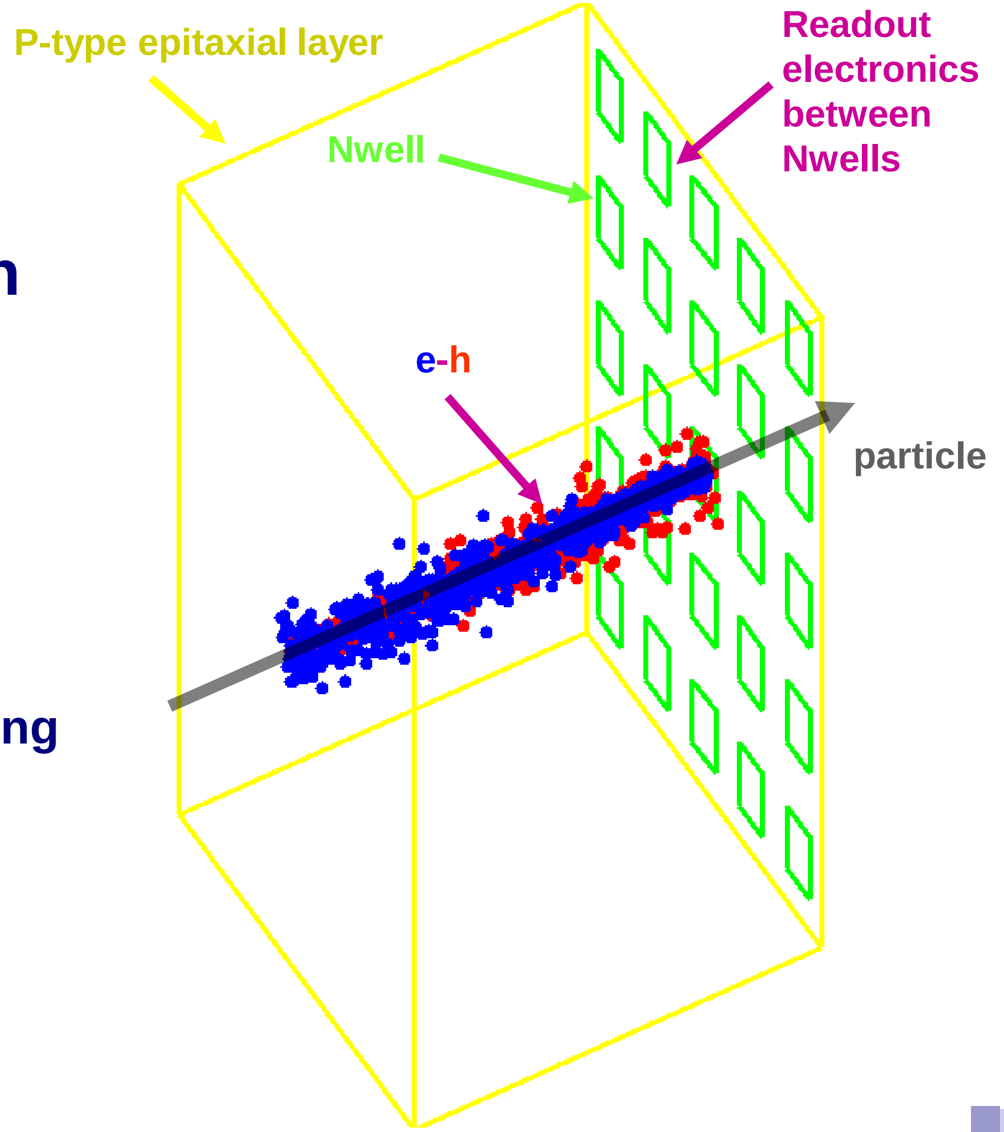
Contents

- **CMOS Pixel Sensors (CPS)**
- **Simulation with SYNOPSYS TCAD**
- **Simulation examples for CPS**
- **Microstrips detectors**
- **Example of simulation of microstrips with SILVACO INTERNATIONAL**

CMOS Pixel Sensors

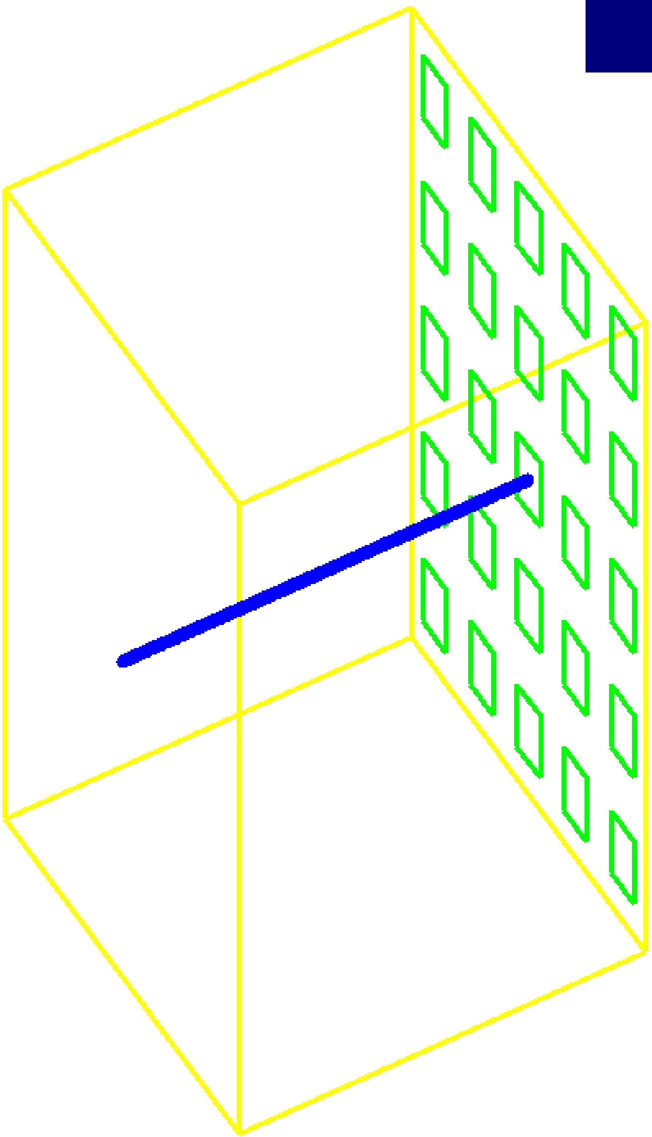
- **CPS (also known as Monolithic Active Pixel Sensors (MAPS)) are devices for charged particle or light detection**
  - **sensor and electronics are implemented in the standard CMOS substrate**
  - **electronics can perform the following tasks:**
    - **Correlated double sampling**
    - **Digitization**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

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Simulation with Sentaurus TCAD from Synopsys

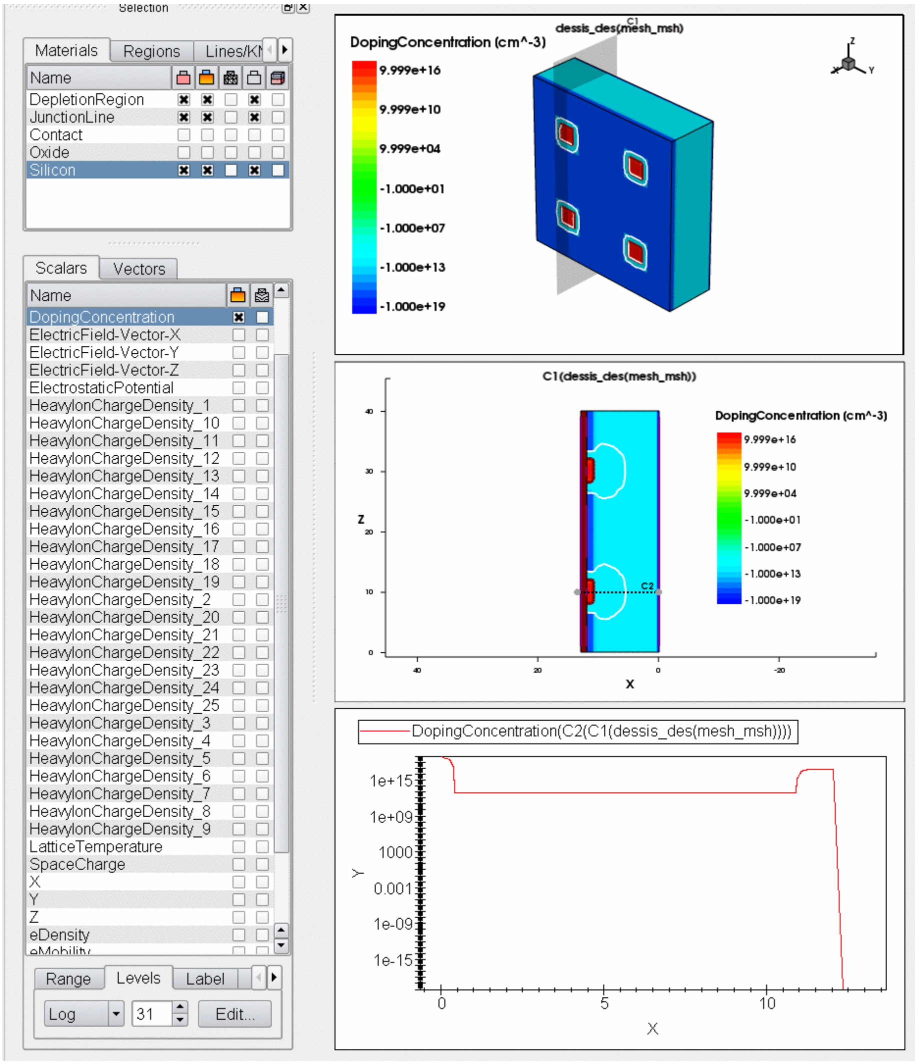
device simulation: fabricated device parameters - doping concentration, geometry, applied voltages, tracks of elementary particles

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

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

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

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**

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)

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

Poisson and continuity equations : the currents on electrodes are known

Solve equations and plot them at several time points

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 )
      }
}
```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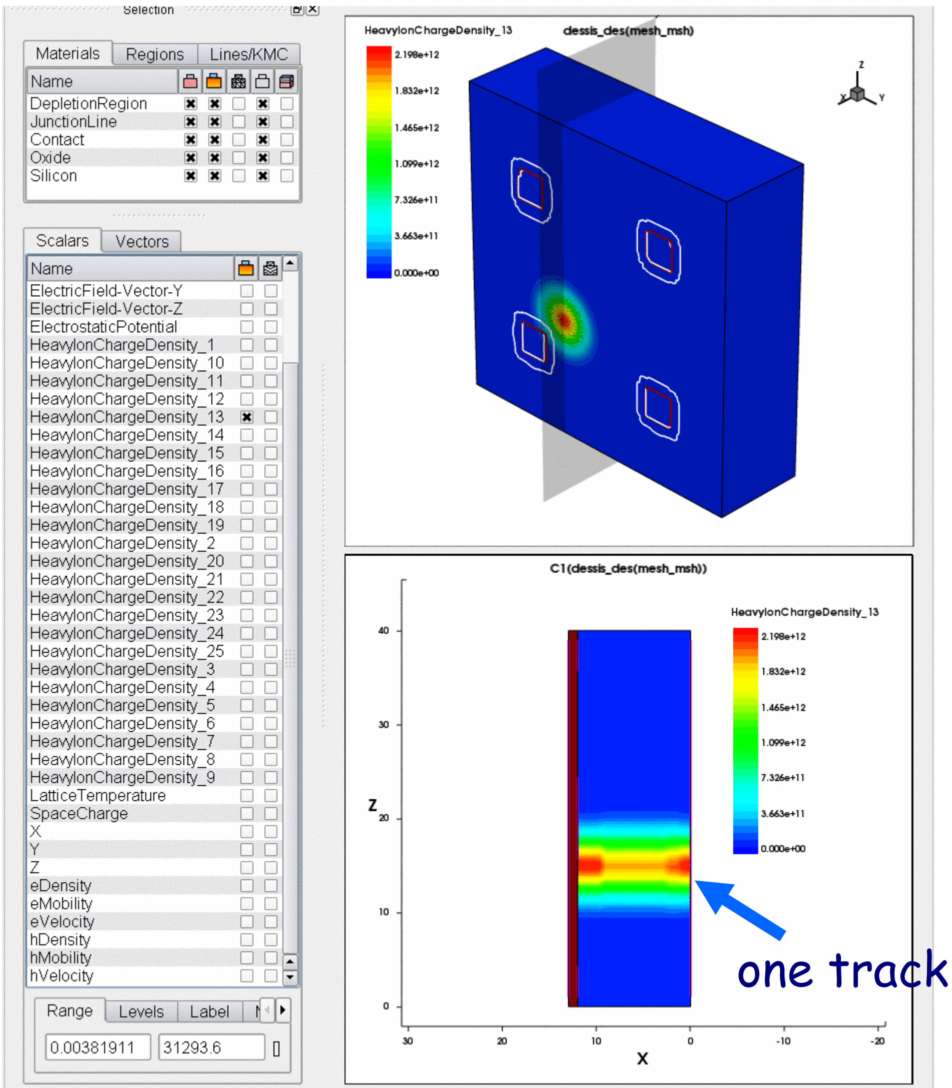
Defining tracks of particles : multiple particles

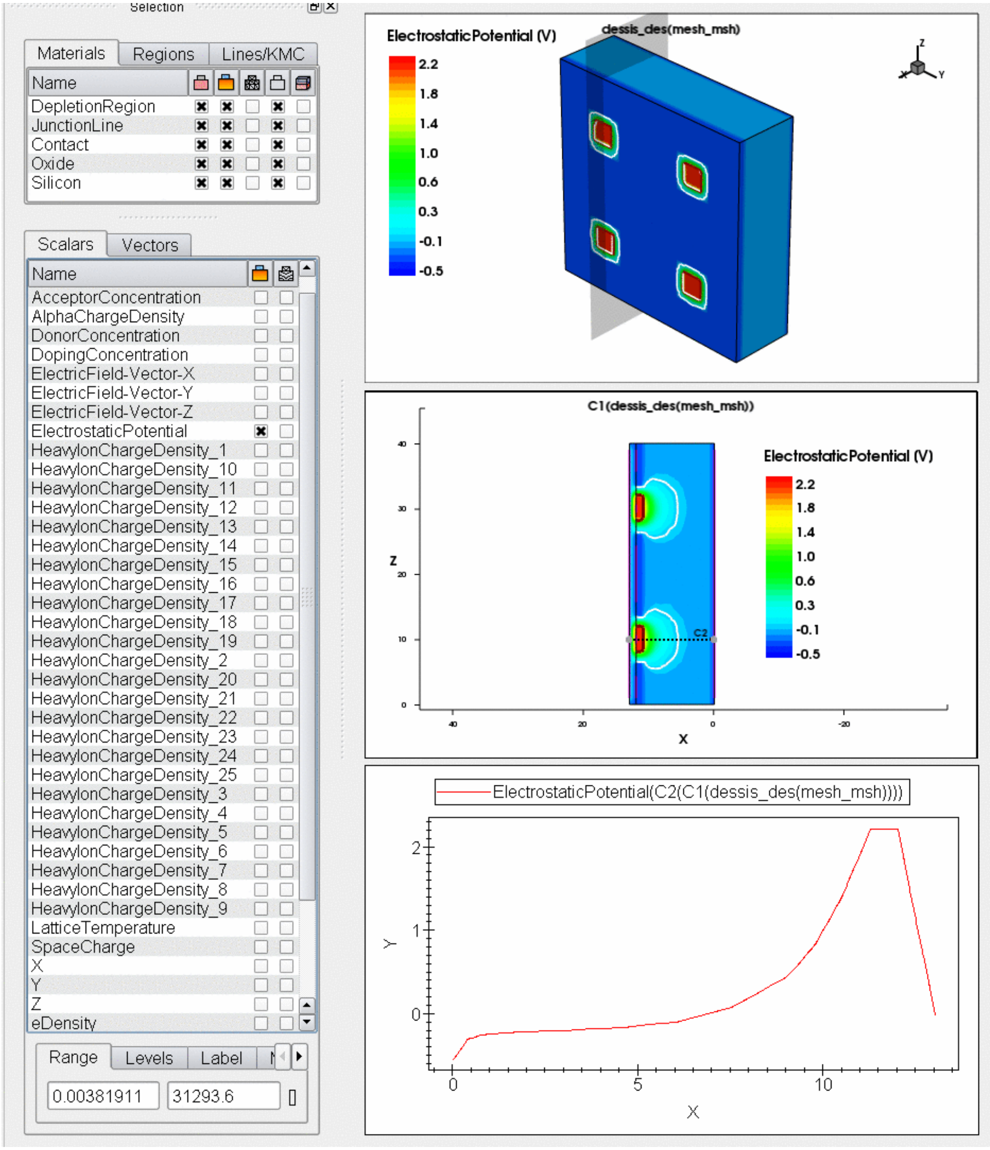


Heavy Ion is used to simulate m.i.p: parameters of energy deposition in silicon can be modified from default values in "dessis.par" file:

```
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)

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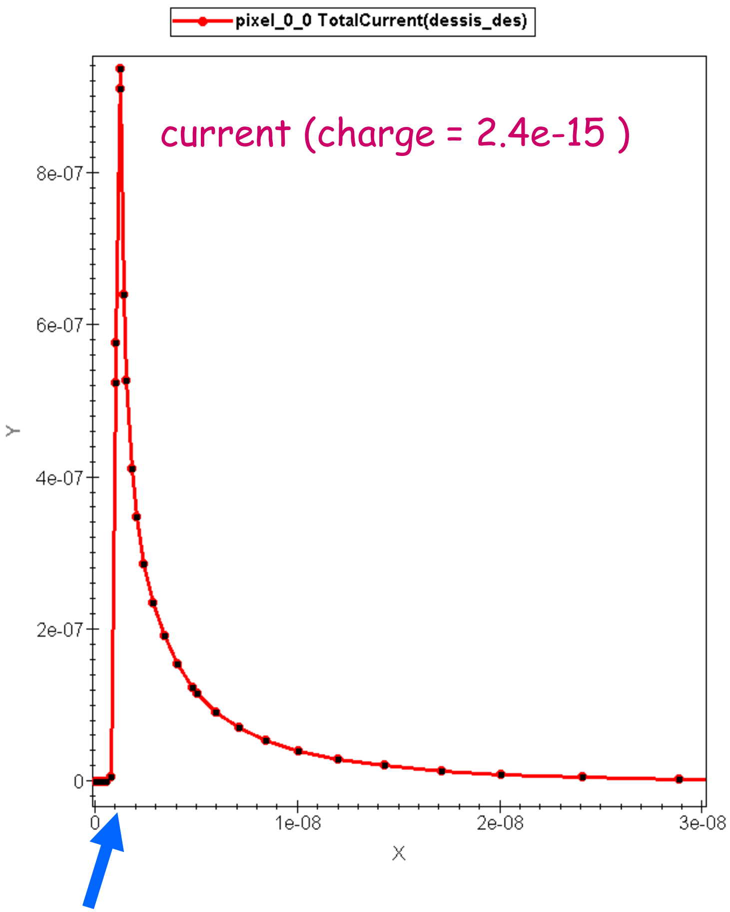
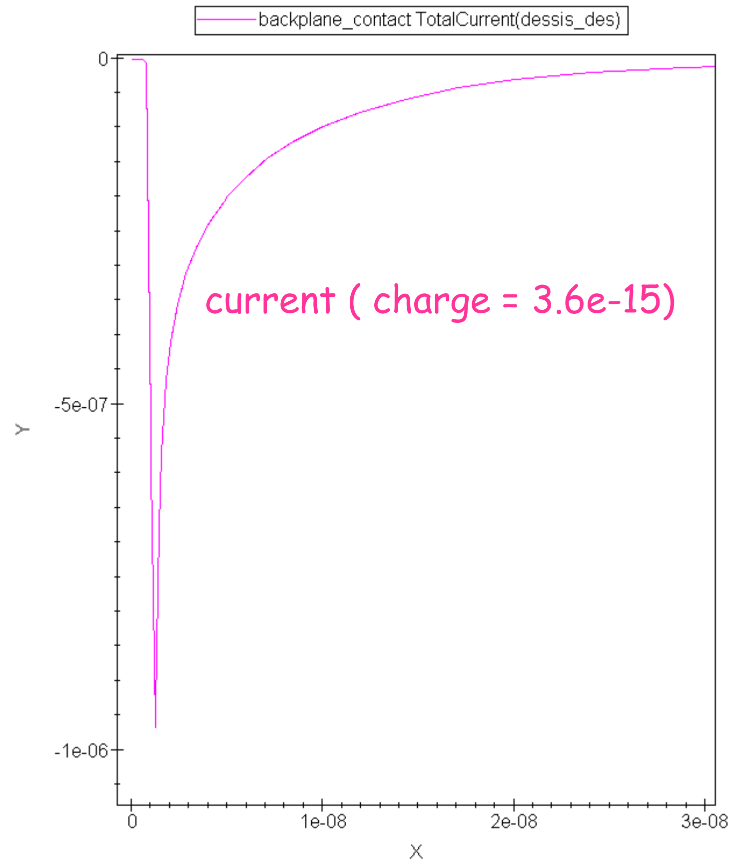
Charge transport : transient response

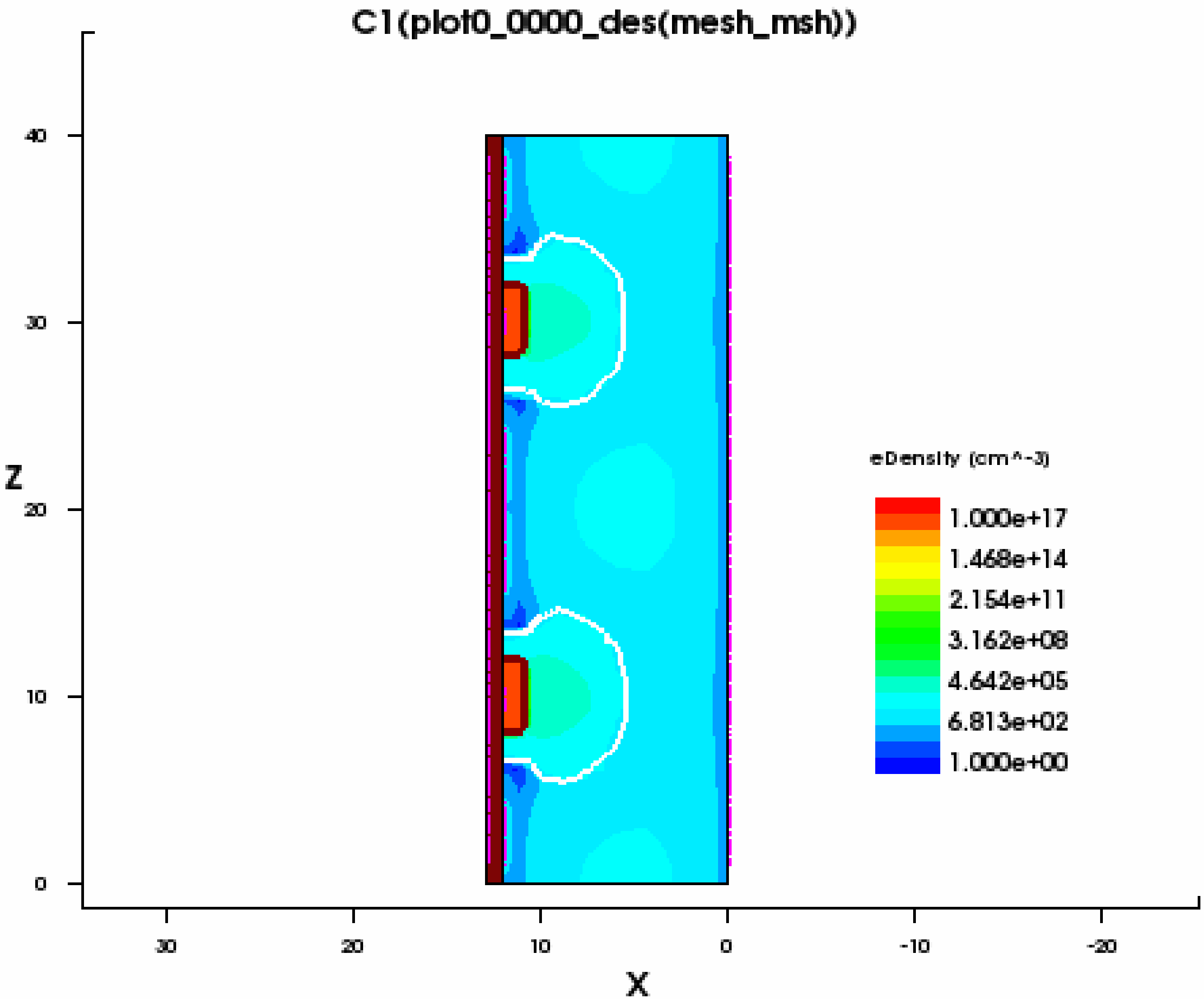




particles come at this moment

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

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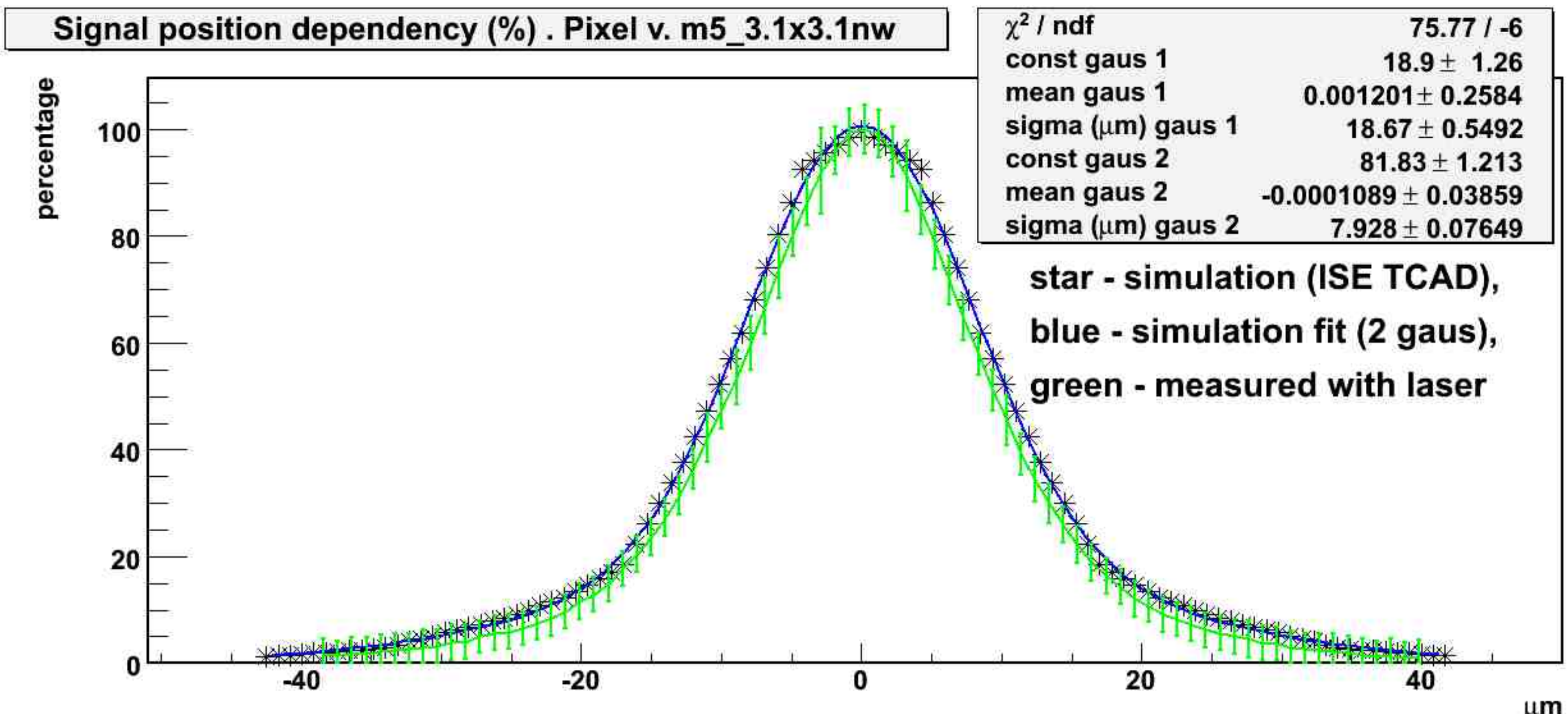
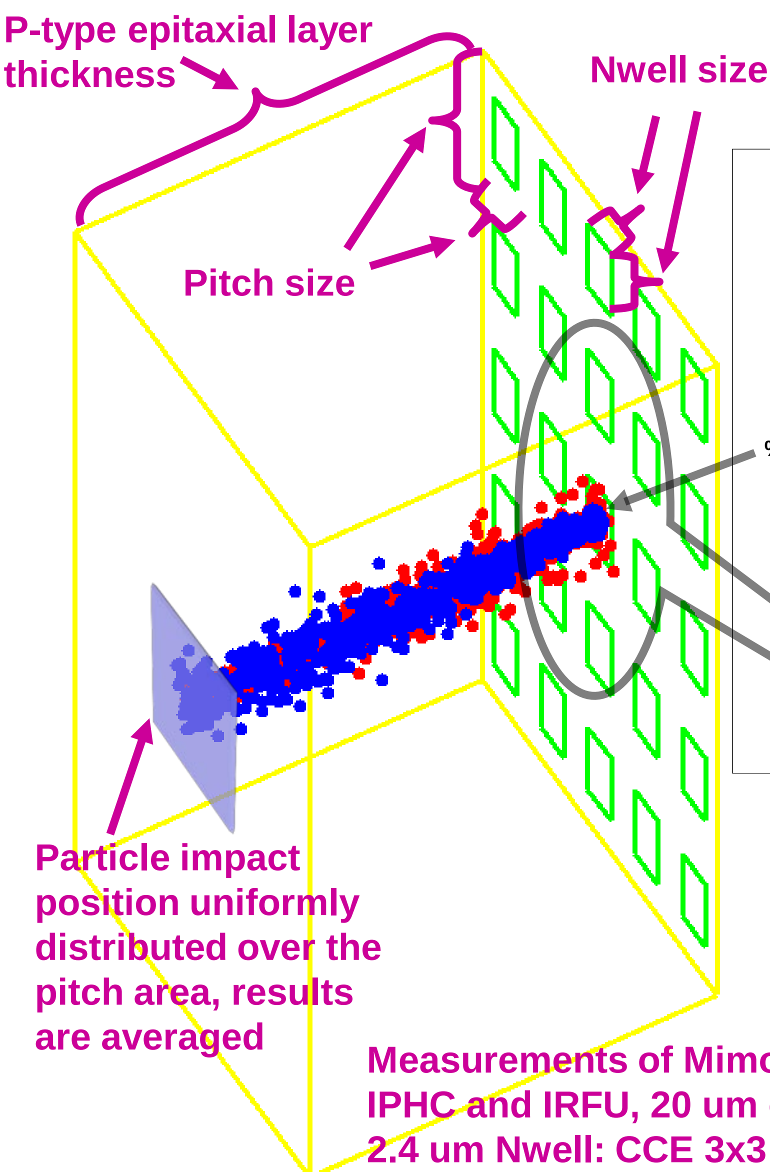
Example 1: Simulation of charge sharing

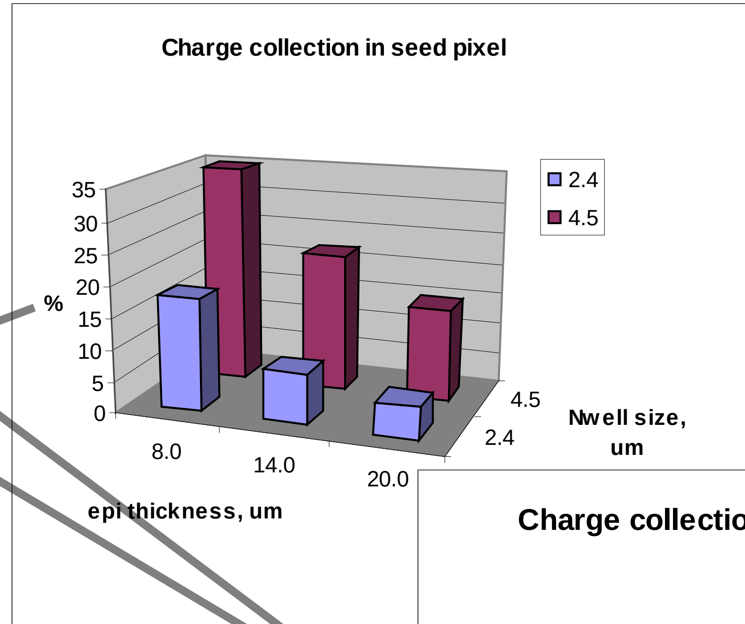


Distance between particle impact point and center of (3,3) pixel in 5x5 matrix

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

Example 2: Geometry influence on charge collection efficiency

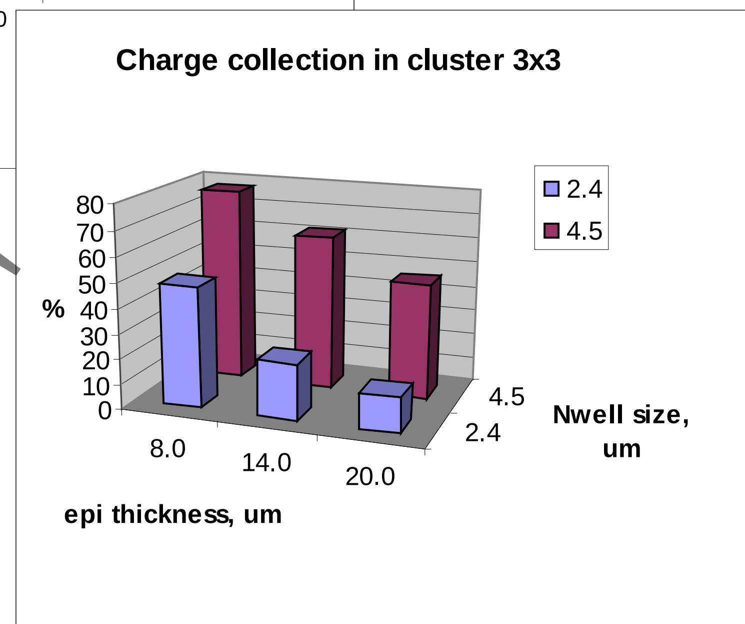




Optimisation for 14um:

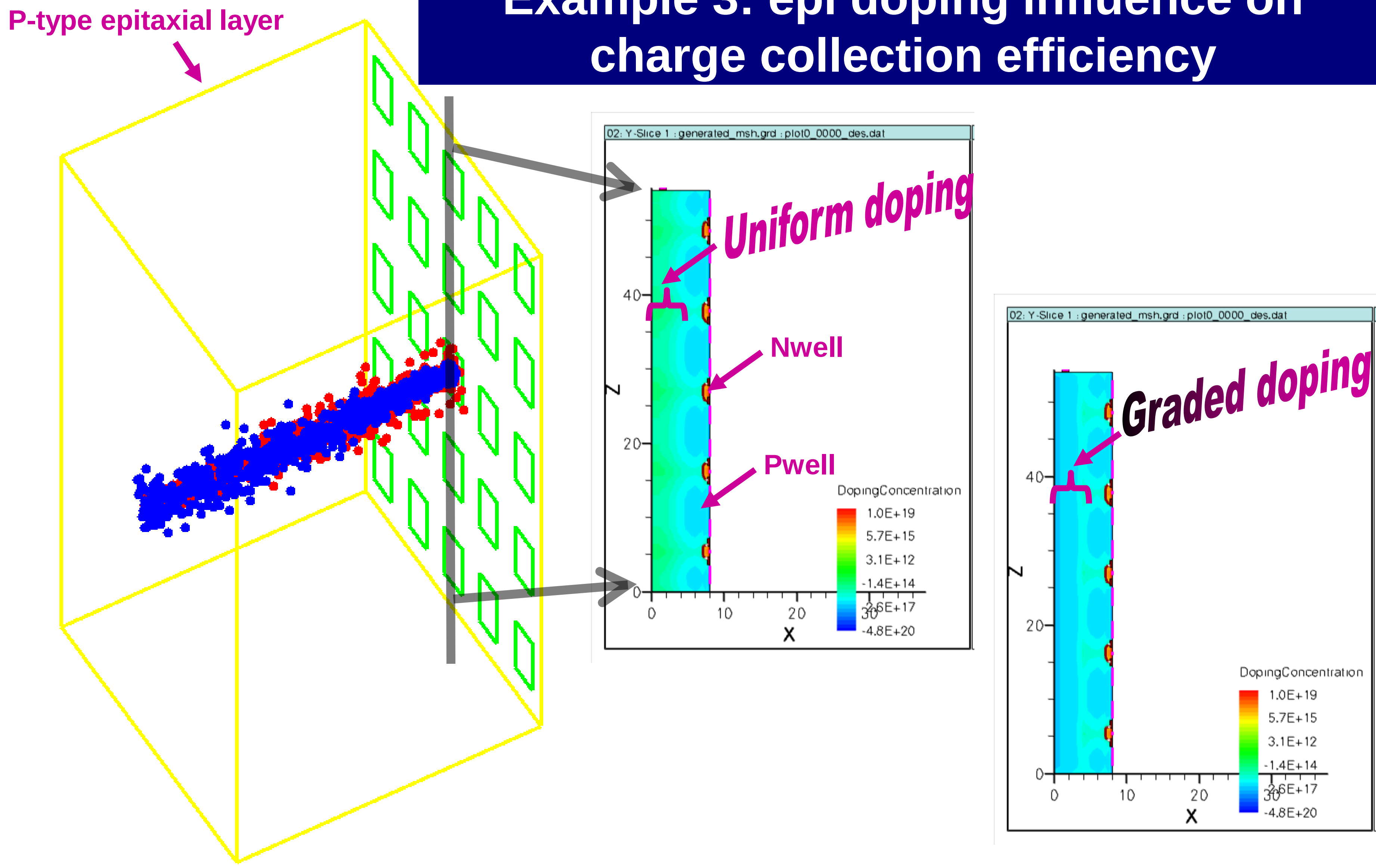
- $C_{2,4}$ =3 fF, $C_{4,5}$ = 6 fF
- $ENC_{4,5}/ENC_{2,4} \sim 2$
- signal ~ charge collection [%] : $S_{4,5}/S_{2,4} \sim 3$
- $(S/N)_{4,5}/(S/N)_{2,4} = 3/2$

S/N higher with 4.5um

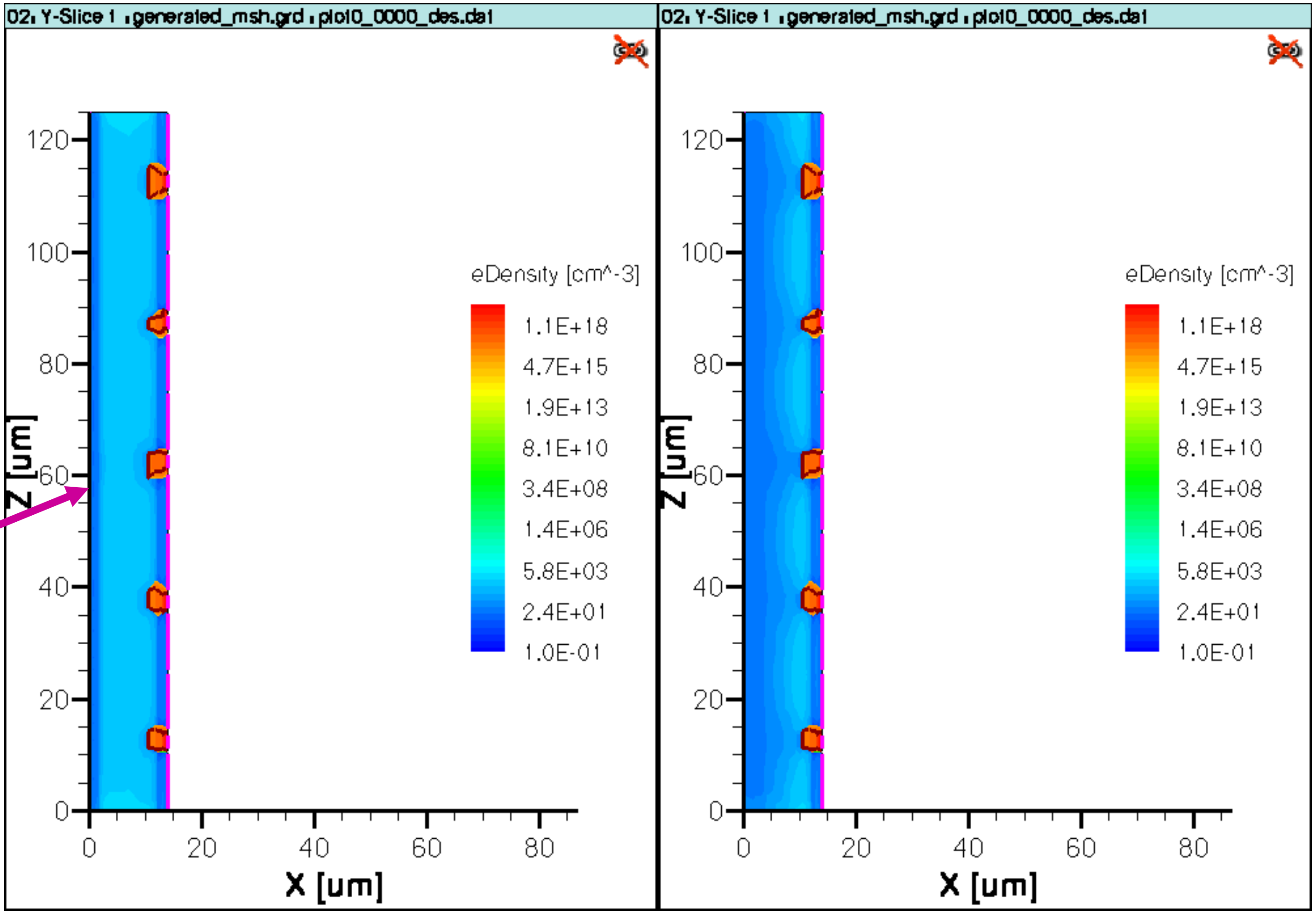


Measurements of Mimosa 16 developed at IPHC and IRFU, 20 um epi -
2.4 um Nwell: CCE 3x3 ~ 23%
4.5 um Nwell: CCE 3x3 ~ 52%

Example 3: epi doping influence on charge collection efficiency



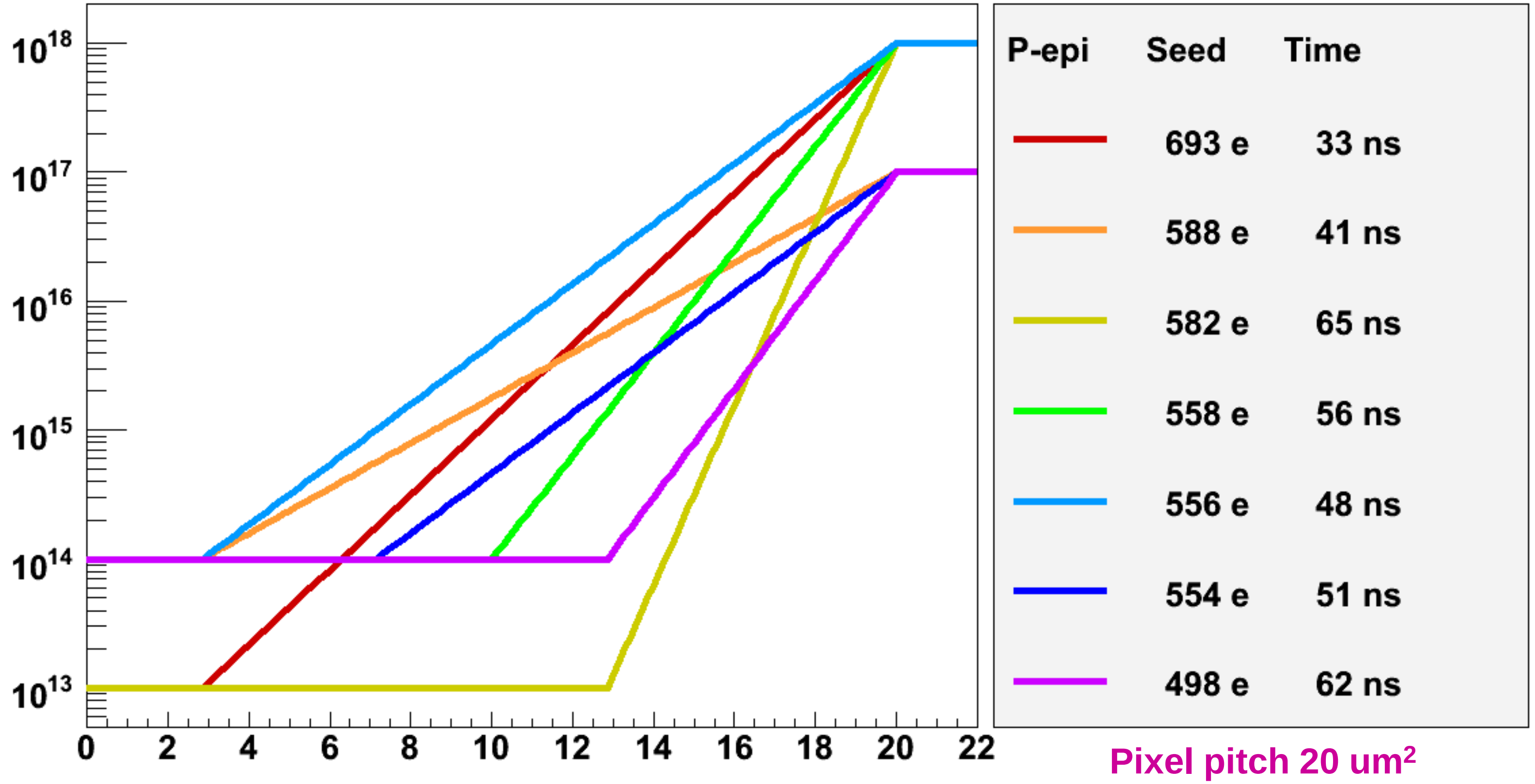
Example 3 :epi doping influence on charge collection efficiency



Excess of electrons from particle will be there

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

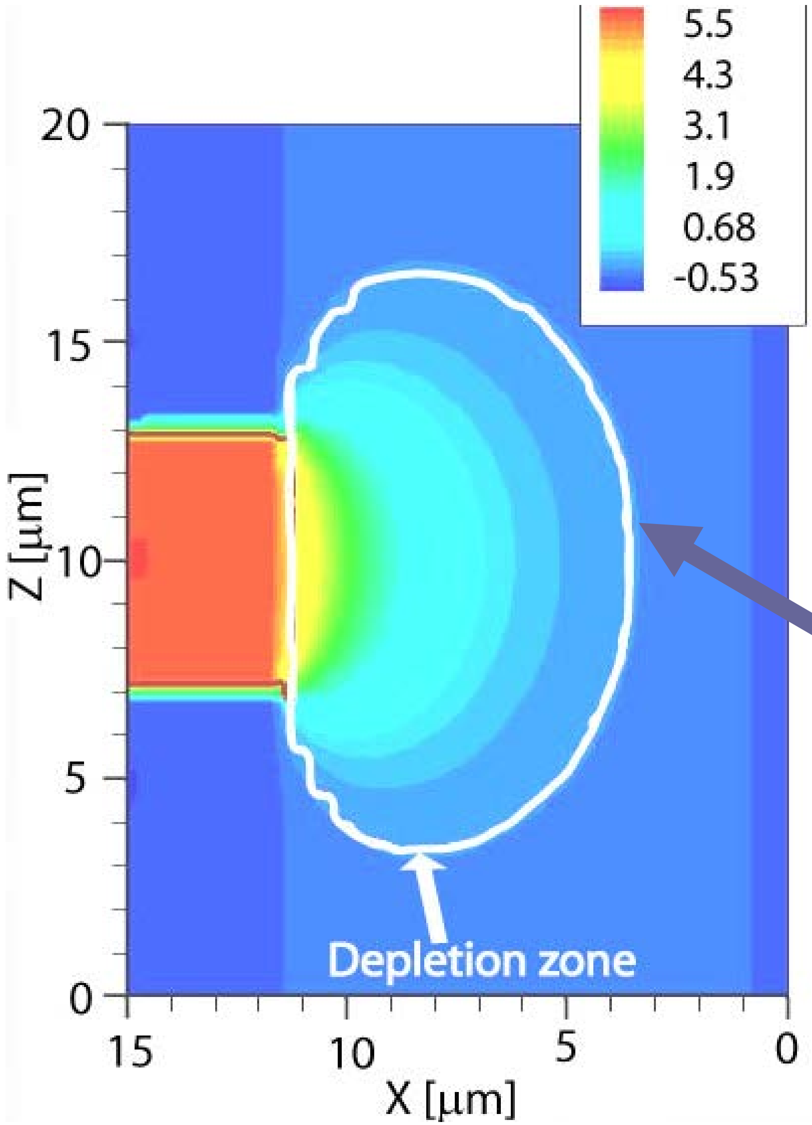
epi p-type doping concentration, cm^{-3}



Distance from Nwell surface towards the bulk, um

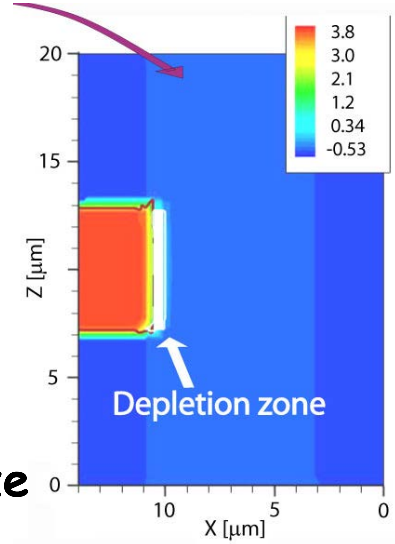
Pixel pitch 20 um^2
Nwell 4 um^2

Example 4: epi doping influence on depletion

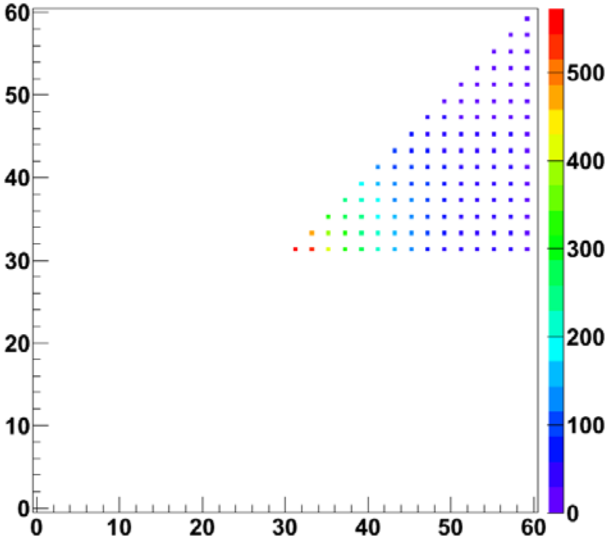


high resistivity P-epi: size of depletion zone size is comparable to the P-epi thickness-> show about x2 charge collected in seed, used in upgrade of STAR HFT detector

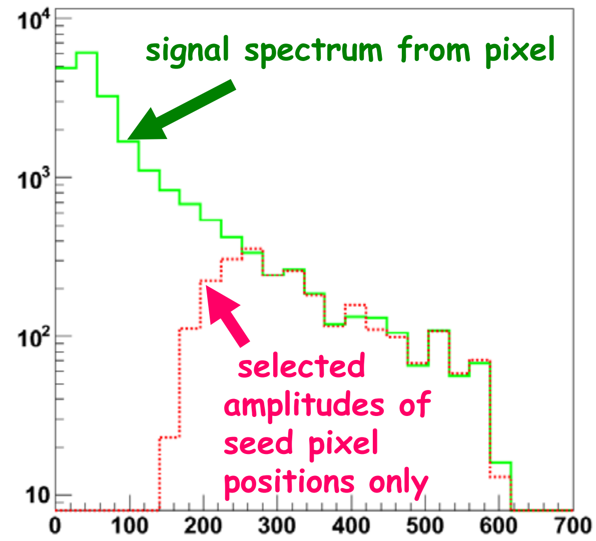
For comparison: standard CMOS technology, low resistivity P-epi

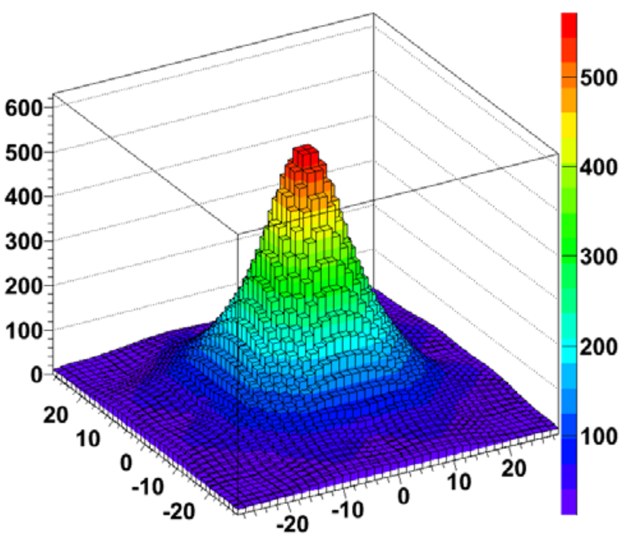


Example 5: charge collection vs position of track

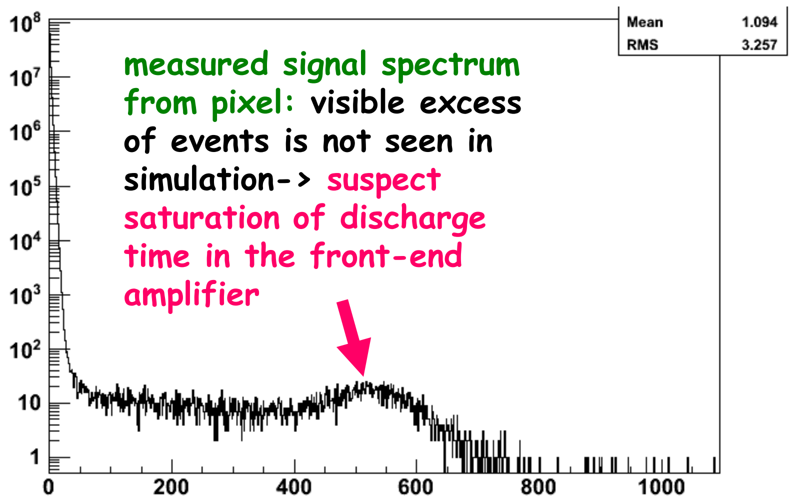


❖ simulated charge vs particle position in a 3x3 pixels of pitch 20um matrix





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



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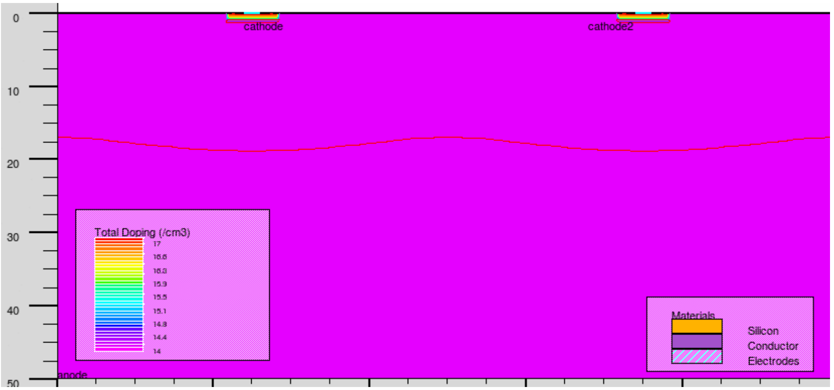
microstrips detectors



- **microstrip detectors:**
  - used for particles position detection
  - energy of a particle transferred to creation of e-h pairs in silicon depleted bulk
  - the electrons and holes drift (and diffuse) in the silicon bulk
  - Induce current on sensing electrodes (strips)
- **difference from CPS:**
  - 2D device (there are combinations of X and Y usually used)
  - readout electronics is separated from detector volume
  - substrate is fully depleted
- **as it is 2D device -> so 2D simulation is usually sufficient...**

simulation of semiconductor detectors with Silvaco

- definition of the simulation flow very similar to Senaurus TCAD, however the input files syntax is different....
- mesh generation and simulation in one command file
- using "atlas" software from Silvaco

Define device geometry, regions

Define electrodes geometry

Define doping ...

Declare physical models, numerical parameters ...

Voltages on electrodes, DC solution, save results

AC frequency sweep, save results

```
go atlas
mesh space.mult=1

x.mesh loc=0.00 spac=0.2
x.mesh loc=50.00 spac=0.2

y.mesh loc=0.00 spac=0.2
y.mesh loc=2.00 spac=0.2
y.mesh loc=50.00 spac=1
eliminate columns x.min=0 x.max=50 y.min=2.0 y.max=50

region  num=1  silicon

electr  name=cathode  x.min=12  x.max=13  y.min=0  y.max=0
electr  name=anode  x.min=0  x.max=50  y.min=50  y.max=50
electr  name=cathode2  x.min=37  x.max=38  y.min=0  y.max=0

doping  uniform p.type conc=1e14  x.min=0 x.max=50 y.min=0 y.max=50
doping  gauss n.type conc=1e17 junc=1 rat=0.01 x.min=11  x.max=14 y.min=0  y.max=0
doping  gauss n.type conc=1e17 junc=1 rat=0.01 x.min=36  x.max=39 y.min=0  y.max=0

model    conmob  fldmob  srh
method newton dt.max=10e-6 TSTEP.INCR=1.1

log outfile=device_dc.log

solve      init
solve      vanode=0  vstep=-10  vfinal=-50  name=anode

save outf=device_dc.str

log outfile=device_ac.log
solve ac freq=1 fstep=10 MULT.F nfstep=10
save outf=device.str

quit
```

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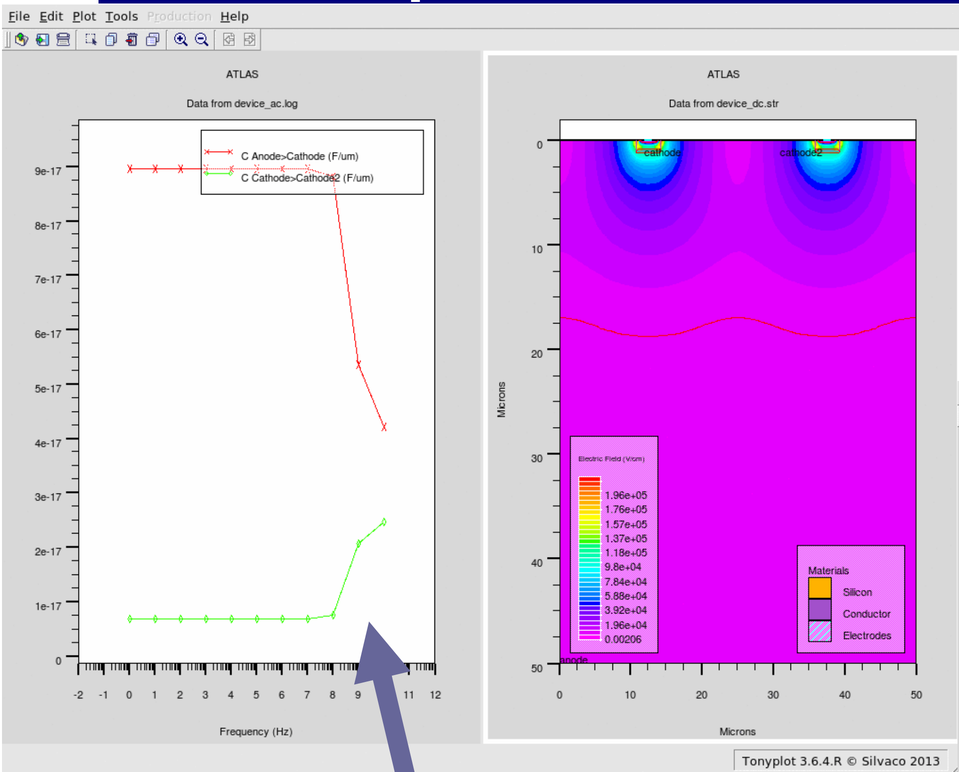
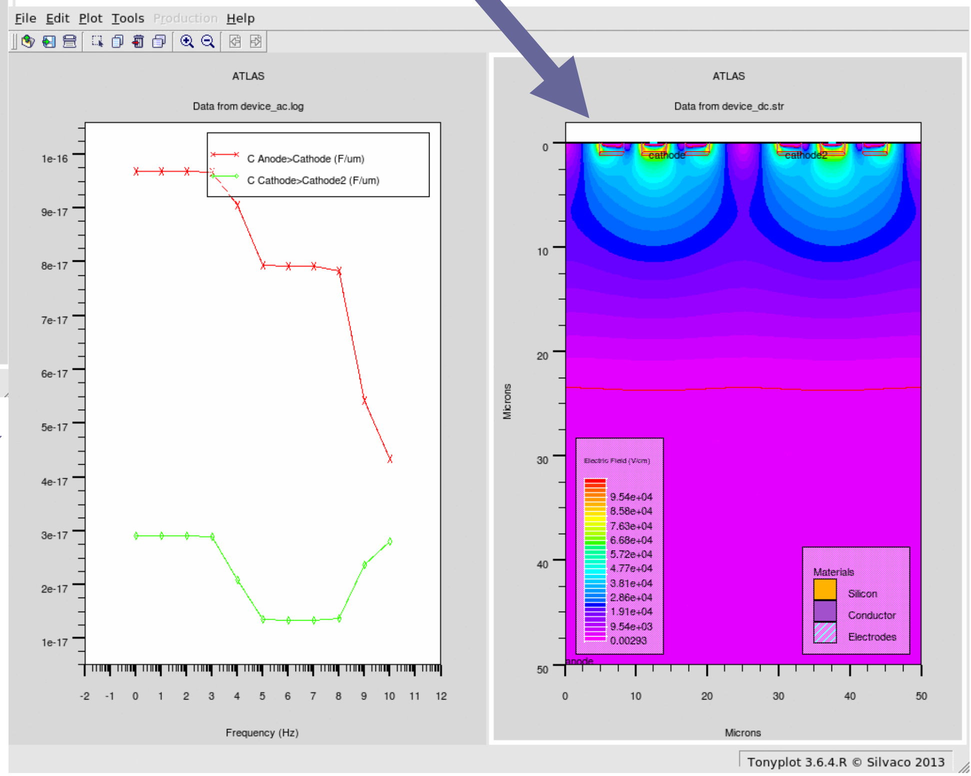
Example 1: simulation of microstrips with Silvaco



use Silvaco Tonyplot to display the results

- electric field for two cases: simple strips and strips with intermediate diffusion strips
- the second case has more uniform and deep depletion, also the maximum of electric field is lower-> charge collection, breakdown, ...



- the strip to substrate and strip-to-strip capacitance as a function of frequency -> can be used for charge and gain calculation

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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