Device and process TCAD simulation experiences at Fondazione Bruno Kessler

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CMM
CENTRE FOR MATERIALS AND MICROSYSTEMS

Fondazione Bruno Kessler (FBK)

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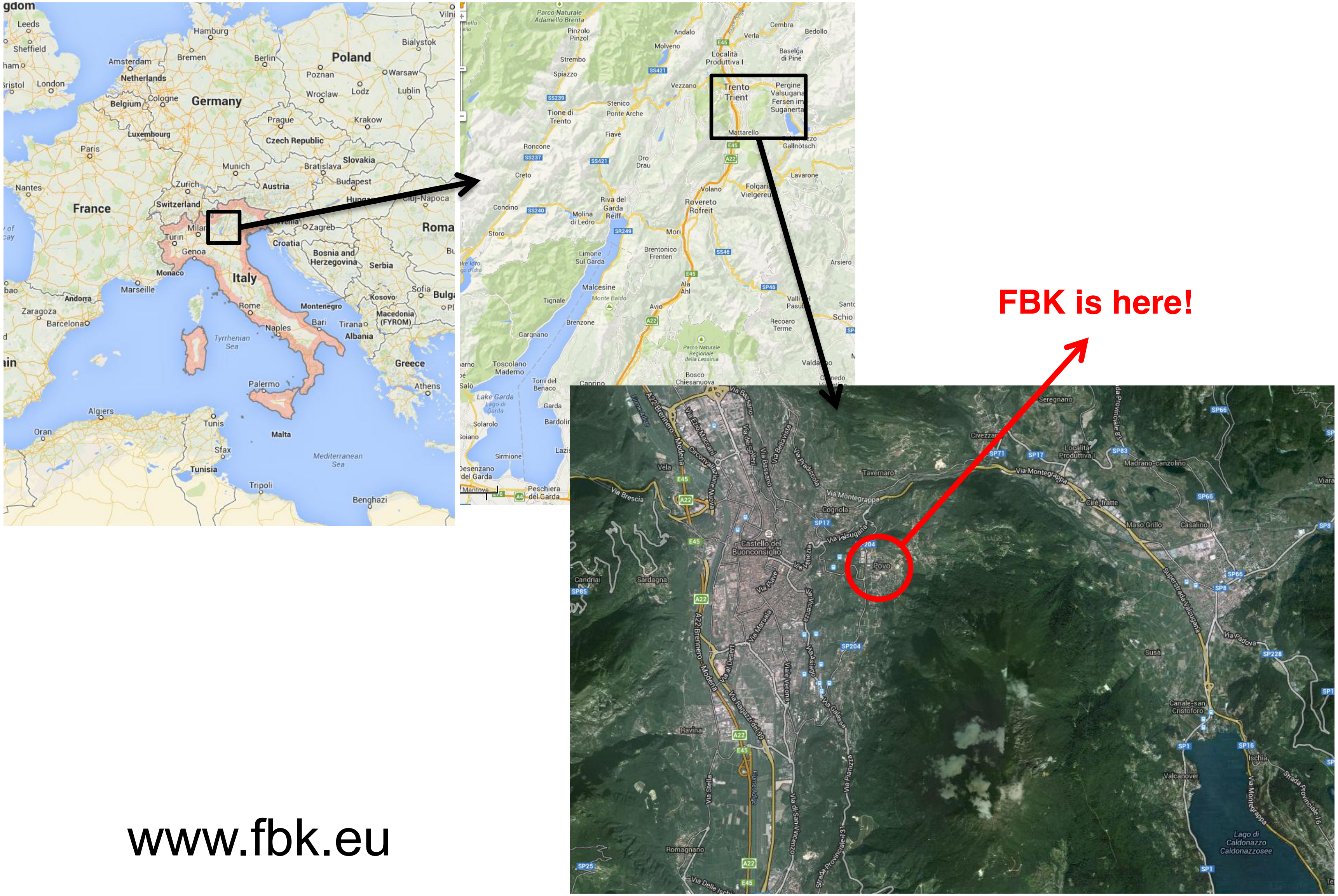


FBK is here!

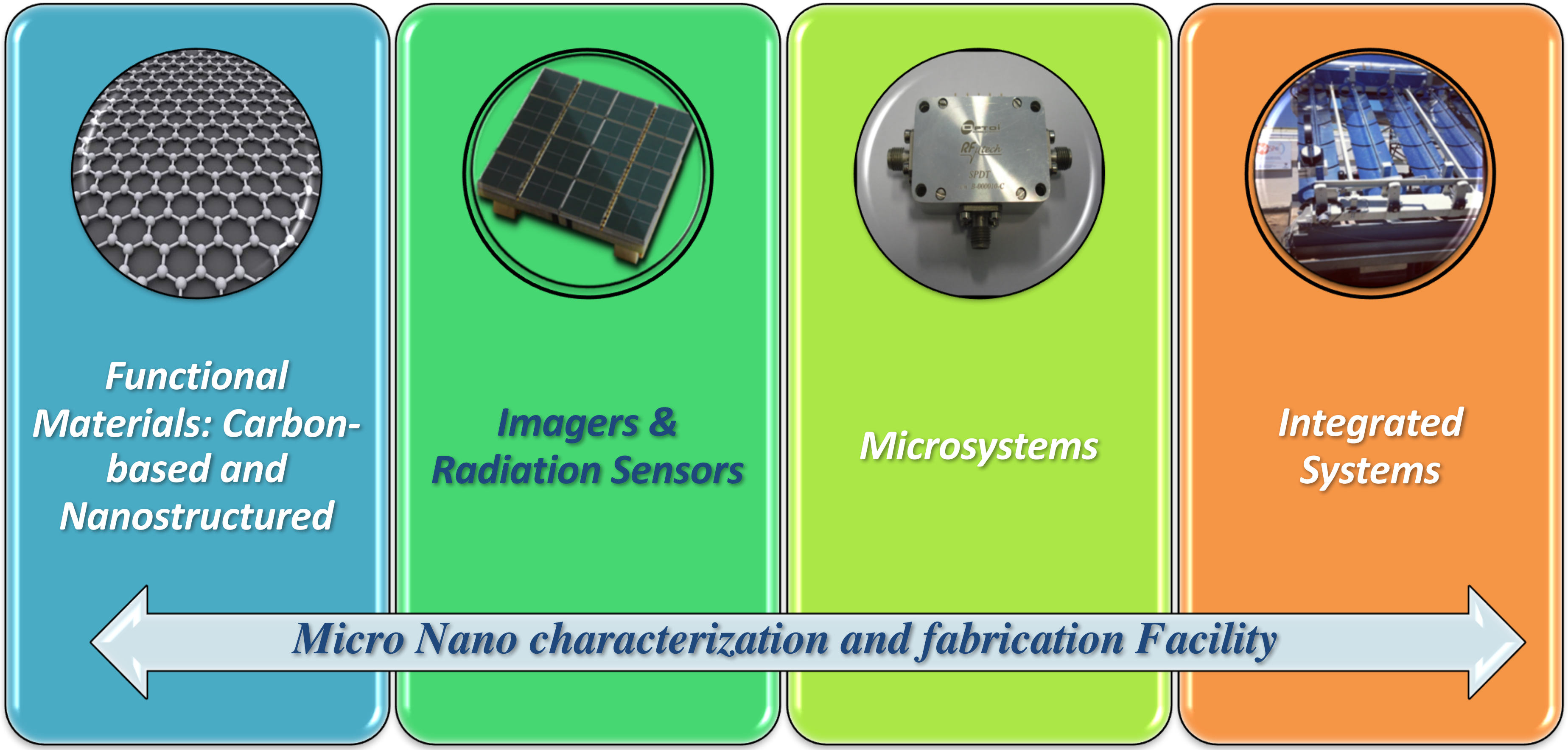
www.fbk.eu

Fondazione Bruno Kessler (FBK)

FBK Organization

- **Scientific and Technological Area**
  - **CMM** – Centre for Materials and Microsystem
  - **ICT** – Centre for Information Technology
  - **ECT*** – European Centre for Theoretical Physics
  - **CIRM** – International Center for Mathematical Research
- **Humanities Area**
  - **ISIG** – Centre for Italian-German Historical Studies
  - **ISR** – Centre for Religious Sciences
  - **IRVAPP** – Research Institute for the Evaluation of Public Policies
  - **CERPEG** – Research Center on War, Peace and International Change

CMM: The Four Research Lines



Functional Materials: Carbon-based and Nanostructured

Imagers & Radiation Sensors

Microsystems

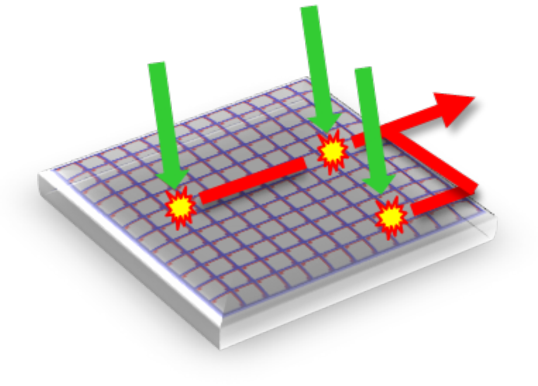
Integrated Systems

Micro Nano characterization and fabrication Facility

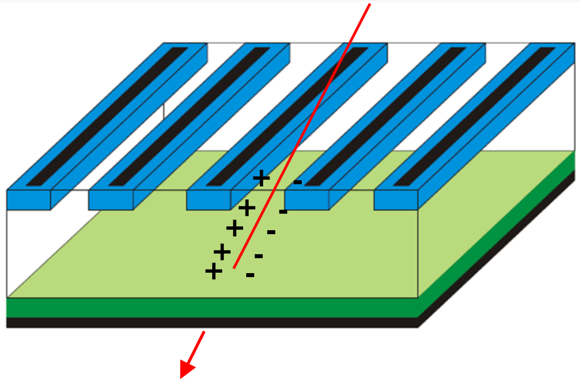
Research topics

Two main platforms:

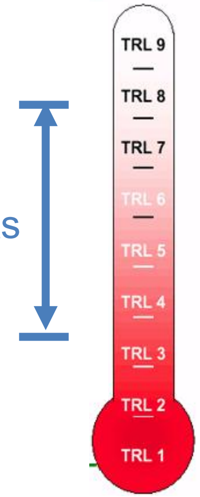
Single-photon light sensors



High-energy radiation detectors



various developments

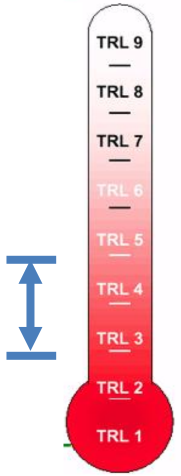


R&D initiatives on:

TeraHertz detectors

Low-power imaging

Graphene-based detector



Research Units

The activity is carried out in two Research Units:

IRIS
INTEGRATED RADIATION AND IMAGE SENSORS

~20 people
(electronic eng, physicists)

MNF
MICRO NANO FACILITY

~40 people
(physicists, chemists, technicians)

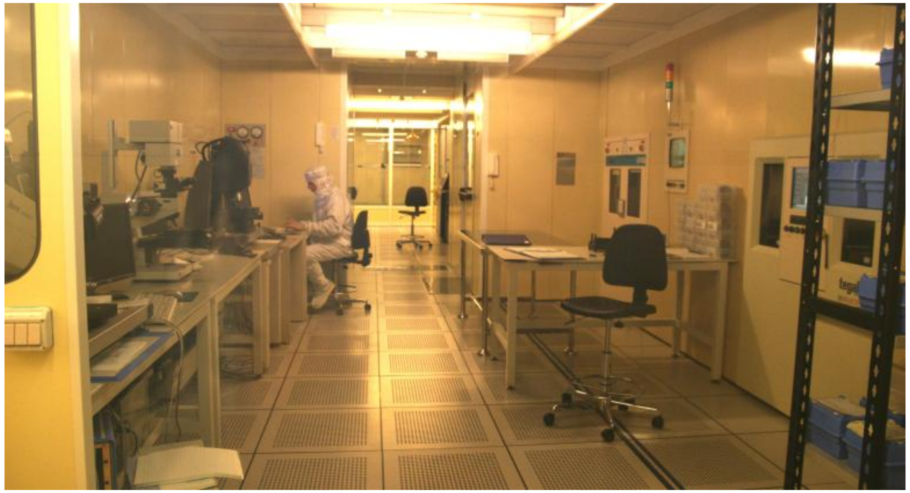
CMM: Micro Nano characterization and fabrication Facility (MNF)

ISO 9001-2008

Two separate clean rooms

- 500m^2 of clean room (class 10-100)
- 200m^2 of clean area (class 100-1000) equipped for MEMS technology

6-inch wafers (Si, Quartz, Glass) – 0.35 um processing

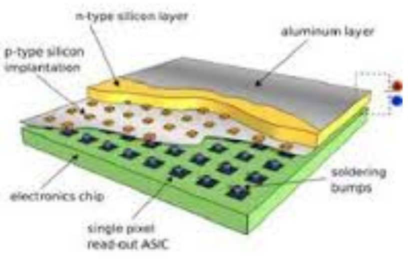


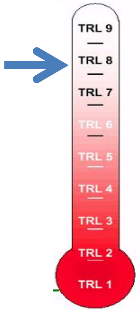
- Dry/wet oxidation
- sputtering Metallization
- Diffusion
- LPCVD
- PECVD
- Projection lithography: CD 2μm
- Stepping lithography: CD 350nm
- Ion Implantation
- Dry/wet etching

Technologies

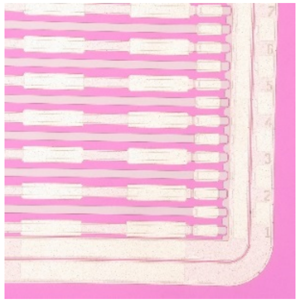
Silicon-based detector in full-custom technology

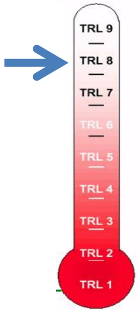
SPD
silicon pixel detctors



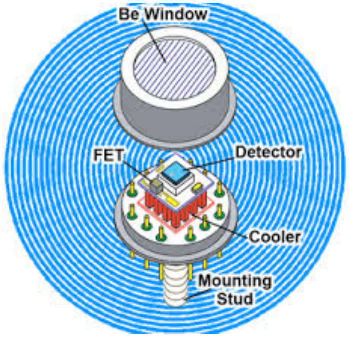


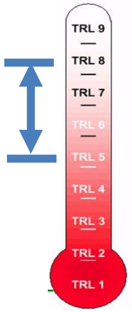
SSD
silicon strip detectors



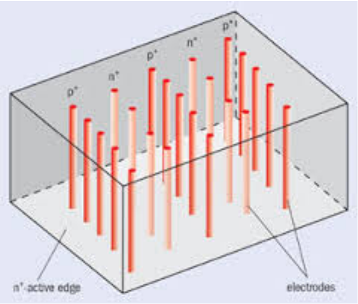


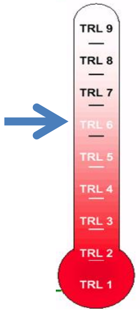
SDD
silicon drift detectors



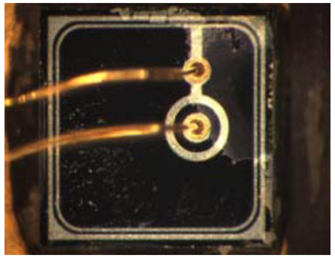


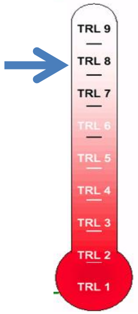
3D detectors



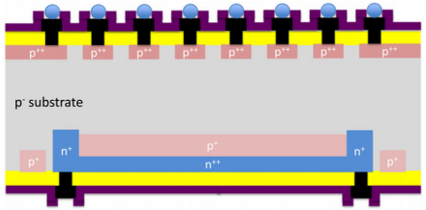


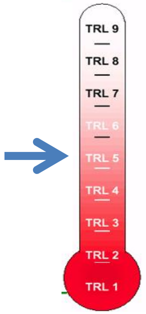
PIN Photodiodes
and phototransistors





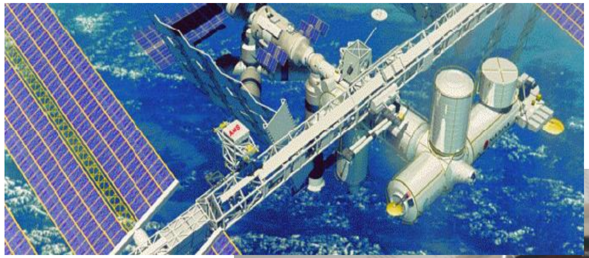
Avalanche
photodetectors



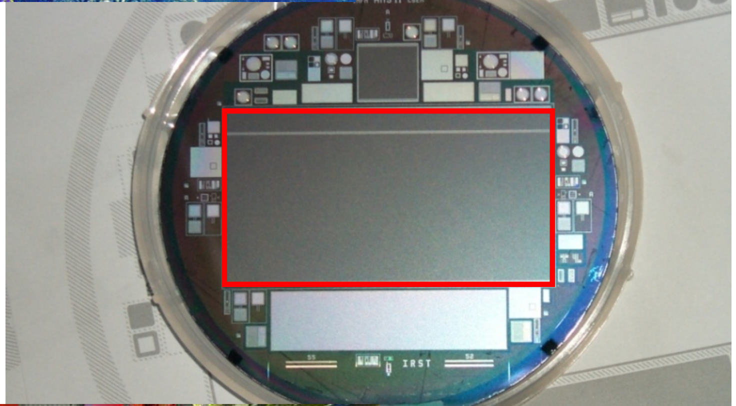


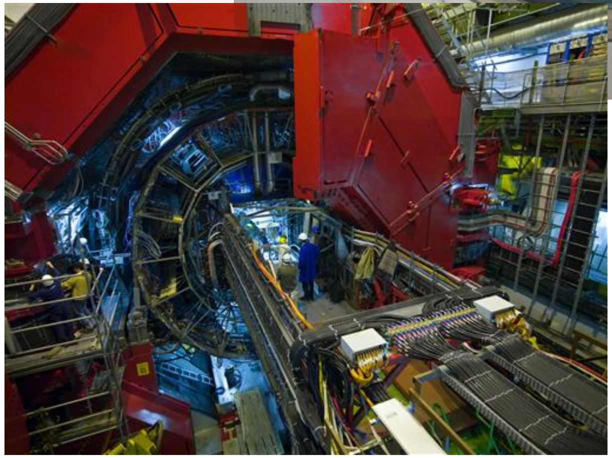
Silicon Strip Detectors

AMS experiment (@ISS)



700 detectors

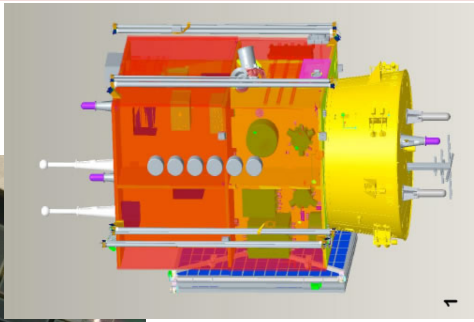


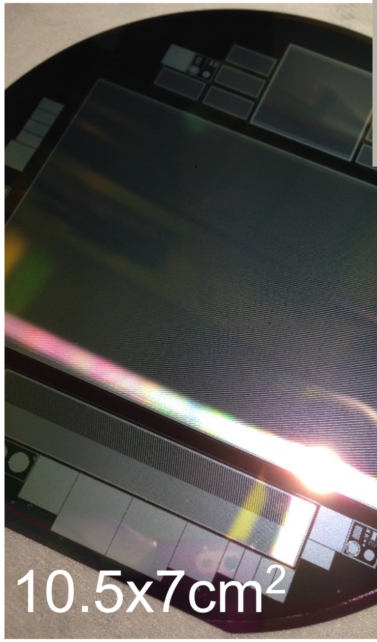


600 detectors

ALICE experiment (@LHC)

Limadou experiment (@CSES)



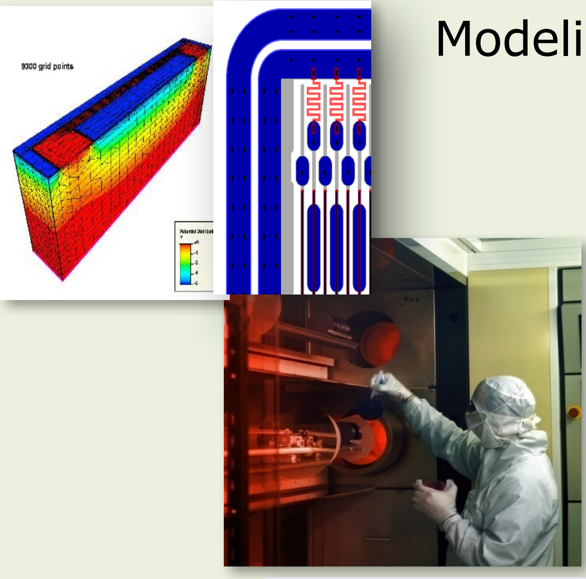


10.5x7cm^2

Custom productions for industry

Technologies & Competencies

Full Custom Silicon Technology



Modeling-design

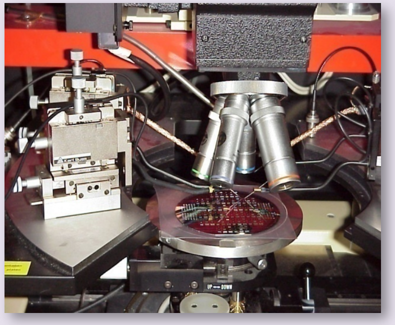
In-house production

State-of-the art CMOS Technologies

Analog and Digital IC Design

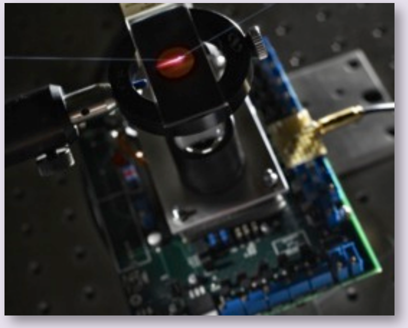
130nm-350nm external Fab

Parametric Testing



Functional Testing

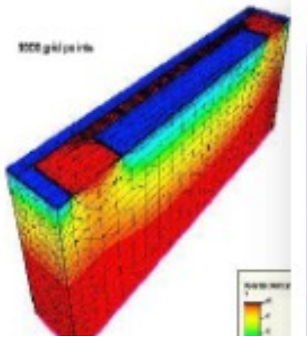
Prototyping



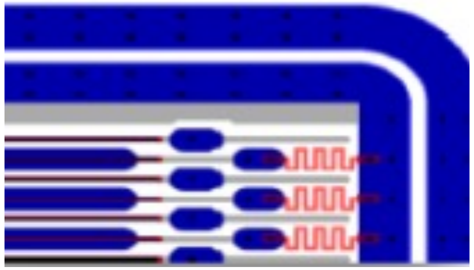
Workflow for device developing

New device concept

TCAD simulation (proof of concept)

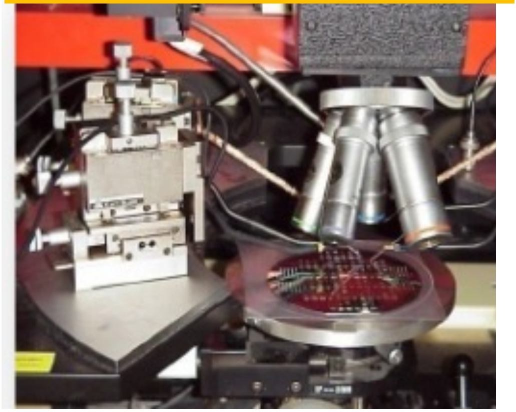


Design

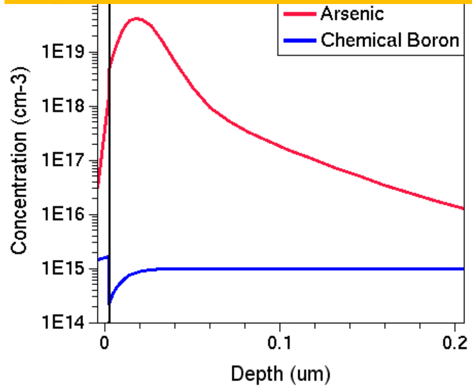


Microfabrication

Testing



Simulation tuning & validation



Why TCAD simulations?

- **Very powerful tool for:**
    - design optimization of the device
    - Problem solving
    - Deep understanding of the device physics

- **Simulating sensors:**
    - Avoid trivial errors and mistakes
    - Reduce the number of splits and iterations during the fabrication (save time & money)

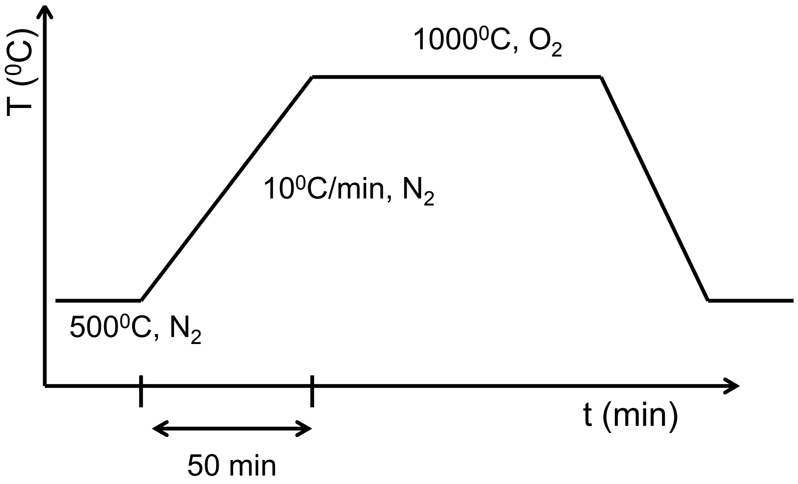
Simulations

- **Process technology Simulations**
    - Example 1: Oxidation
    - Example 2: Trench Oxidation LOCOS
    - Example 3: Ion Implants
- **Device Simulations**
    - Case Study 1: Multi Guard Ring Design for silicon detectors
    - Case Study 2: Silicon Solar Cells for CPV

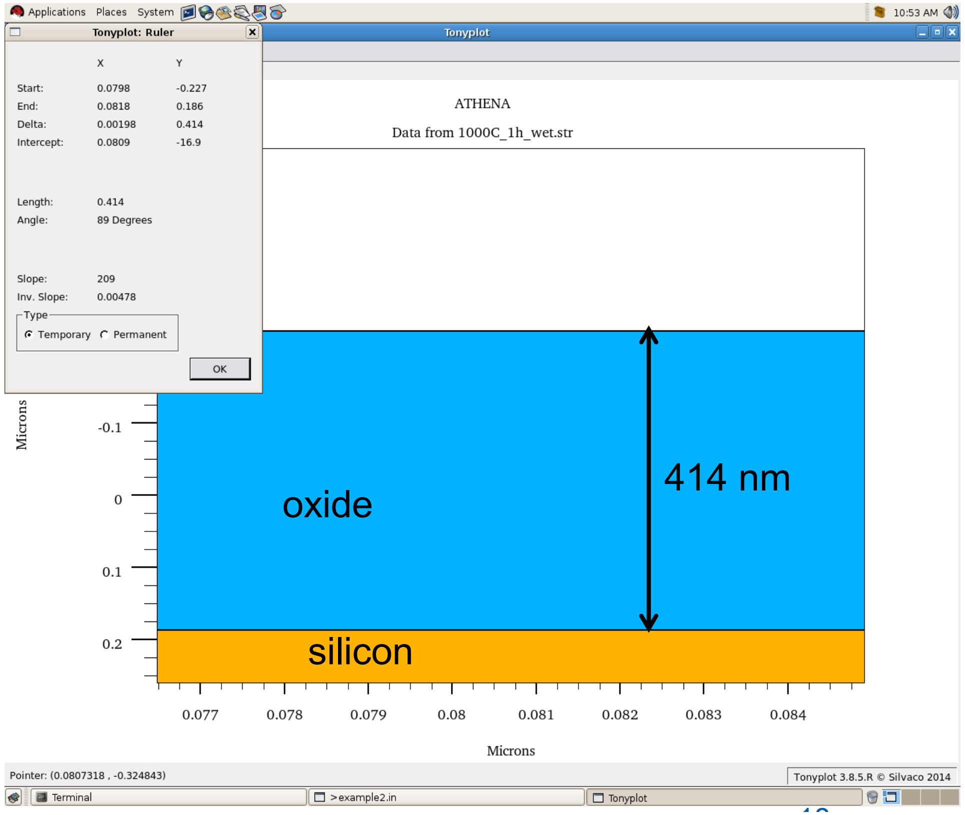
Process Technology Simulations

• Example 1: Oxidation

Well known process. Silvaco is not striclty required



```
#
diffus time=50 temp=500 t.final=1000 nitro
#
diffus time=120 temp=1000 dryo2
```



```
                X          Y
Start:          0.0798     -0.227
End:            0.0818     0.186
Delta:          0.00198    0.414
Intercept:      0.0809     -16.9

Length:         0.414
Angle:          89 Degrees

Slope:          209
Inv. Slope:     0.00478
Type
● Temporary  ○ Permanent
OK
```

```
Pointer: (0.0807318 , -0.324843)
```

• Problem (doping inversion)

n-type wafers (1e12 atoms/cm-3) after the oxidation turn into p-type!!!

Process Technology Simulations

- **Example 1: Oxidatior**

We supposeda Boron contamination in the furnace (less than 1 ppm)

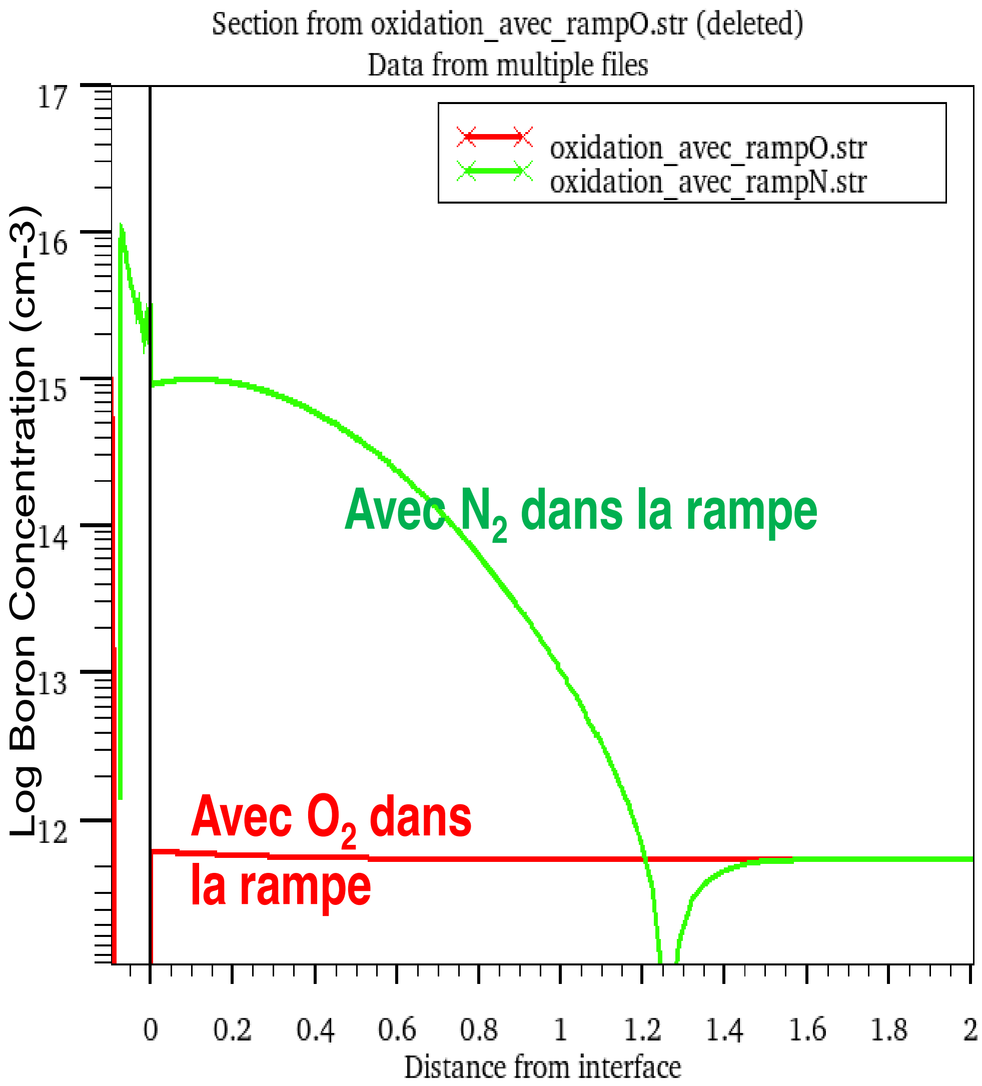
```
#
diffus time=50 temp=500 t.final=1000 nitro c.boron=1.0e16
#
diffus time=120 temp=1000 dryo2

struct outf=oxidation_avec_rampN.str
```

Introducing O2 during ramp-up step

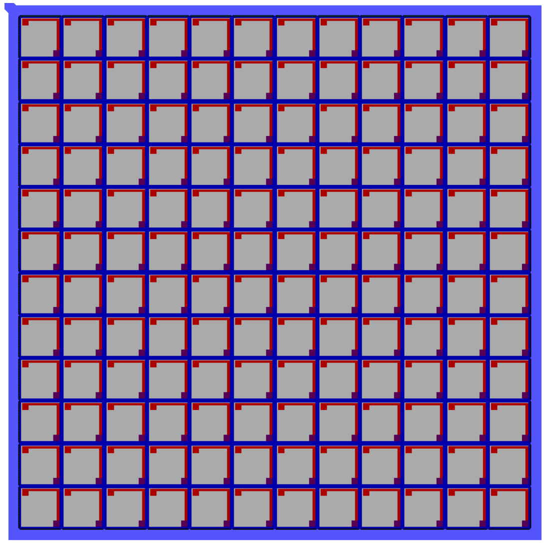
```
#
diffus time=50 temp=1000 t.final=1000 dryo2 c.boron=1.0e16
#
diffus time=120 temp=1000 dryo2

struct outf=oxidation_avec_rampO.str
```

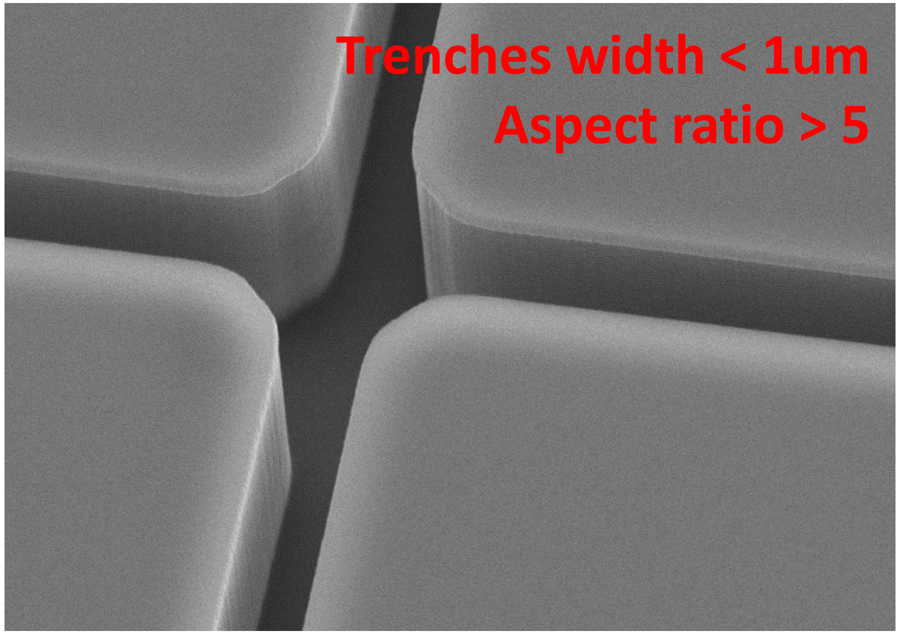


Process Technology Simulations

- **Example 2: Trench Oxidation (LOCOS)**



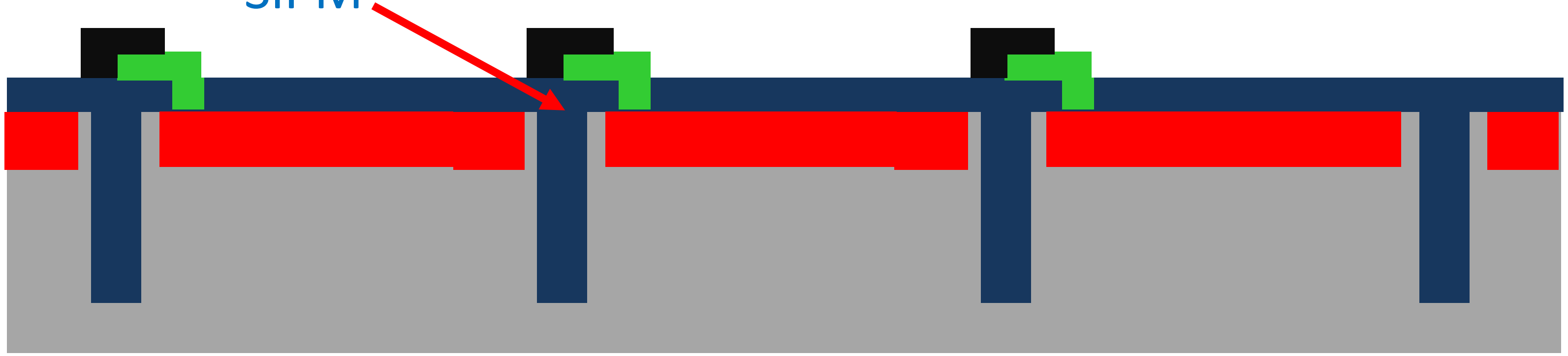
SiPM (matrix of SPADs connected in parallel)



Trenches width < 1um

Aspect ratio > 5

Trench for SPAD isolation in a SiPM



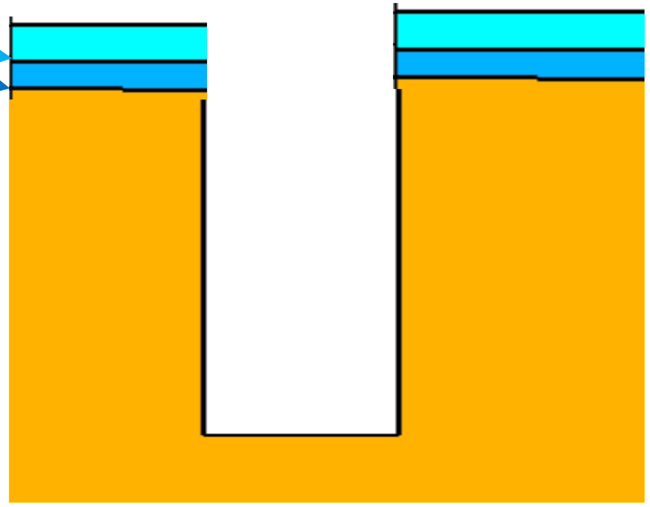
Process Technology Simulations

• Example 2: Trench Oxidation (LOCOS)

Oxidation of the trench internal surfaces. We would oxidize only the trenches but not the wafer top surface.

"***LOCOS***" stands for "**Local Oxidation of Silicon**"
The areas of the **Si** that are not to be oxidized must be protected by SiN that does not allow oxygen diffusion.

```
deposit oxide thick=0.02 dy=0.001
deposit nitride thick=0.03 dy=0.001
etch nitride  start x=2.2 y=-0.05
etch cont x=2.8 y=-0.05
etch cont x=2.8 y=0
etch done x=2.2 y=0
etch oxide  start x=2.2 y=-0.05
etch cont x=2.8 y=-0.05
etch cont x=2.8 y=0
etch done x=2.2 y=0
etch silicon  start x=2.2 y=0
etch cont x=2.8 y=0
etch cont x=2.8 y=3
etch done x=2.2 y=3
```

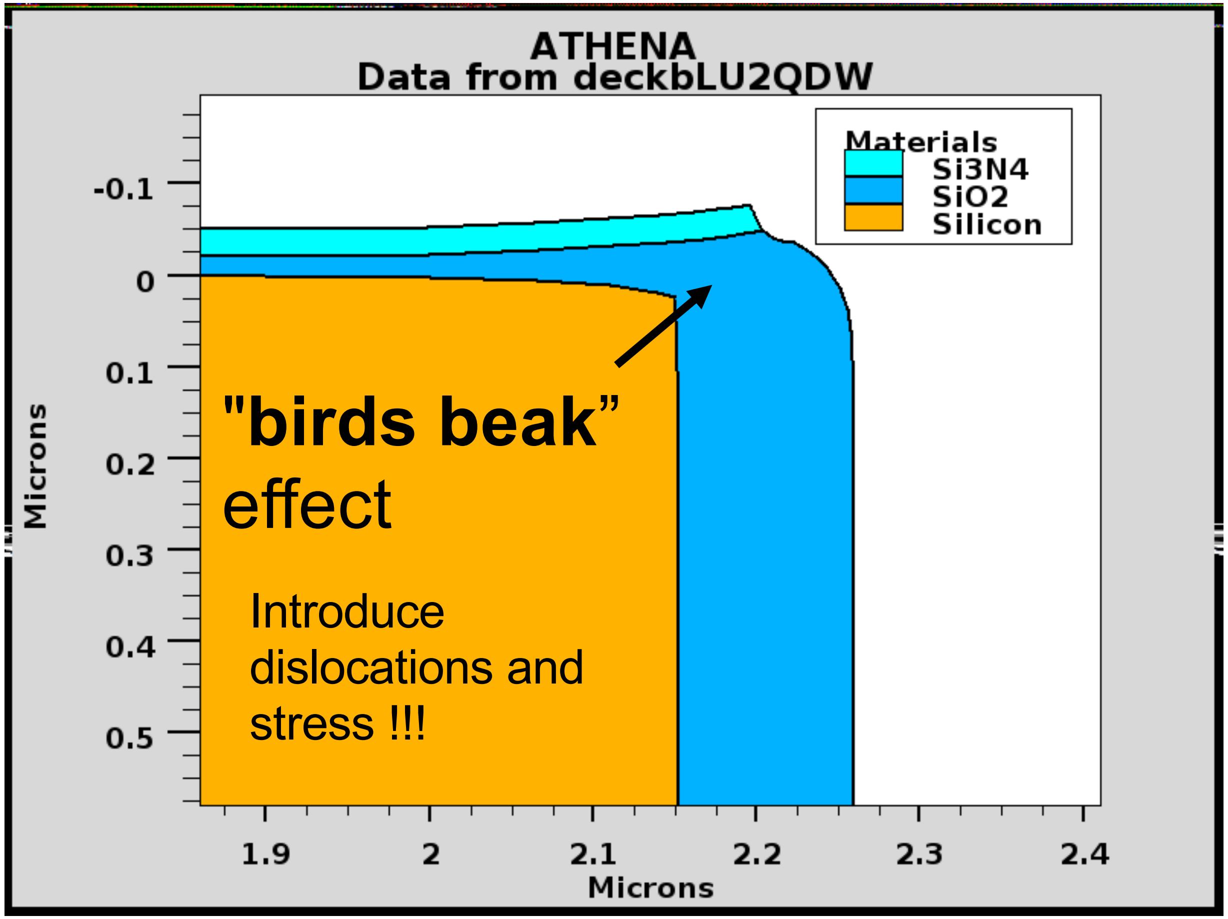


Process Technology Simulations

- **Example 2: LOCOS**

Dry Oxiation

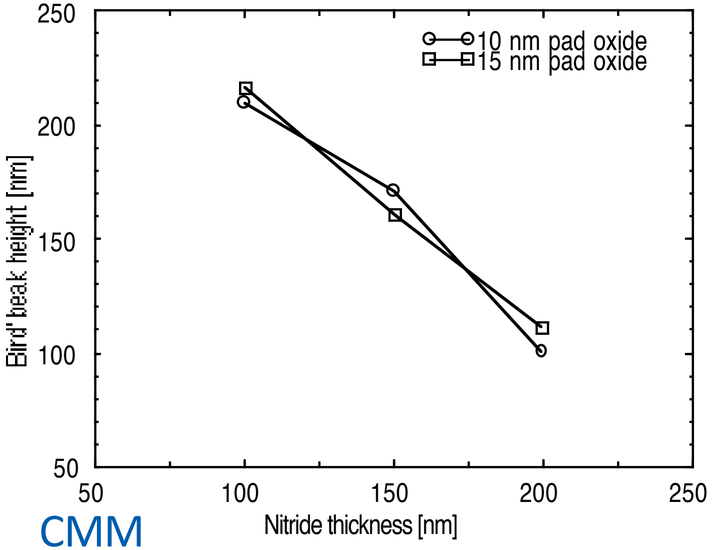
```
diffus time=150
temp=1000 dry
```



"birds beak" effect

Introduce dislocations and stress !!!

Birds beak height dependance on oxide and nitride thickness

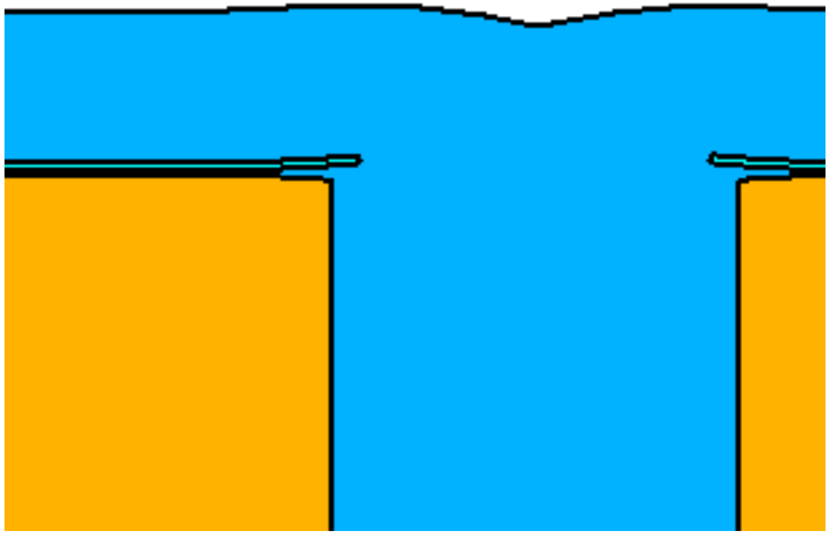


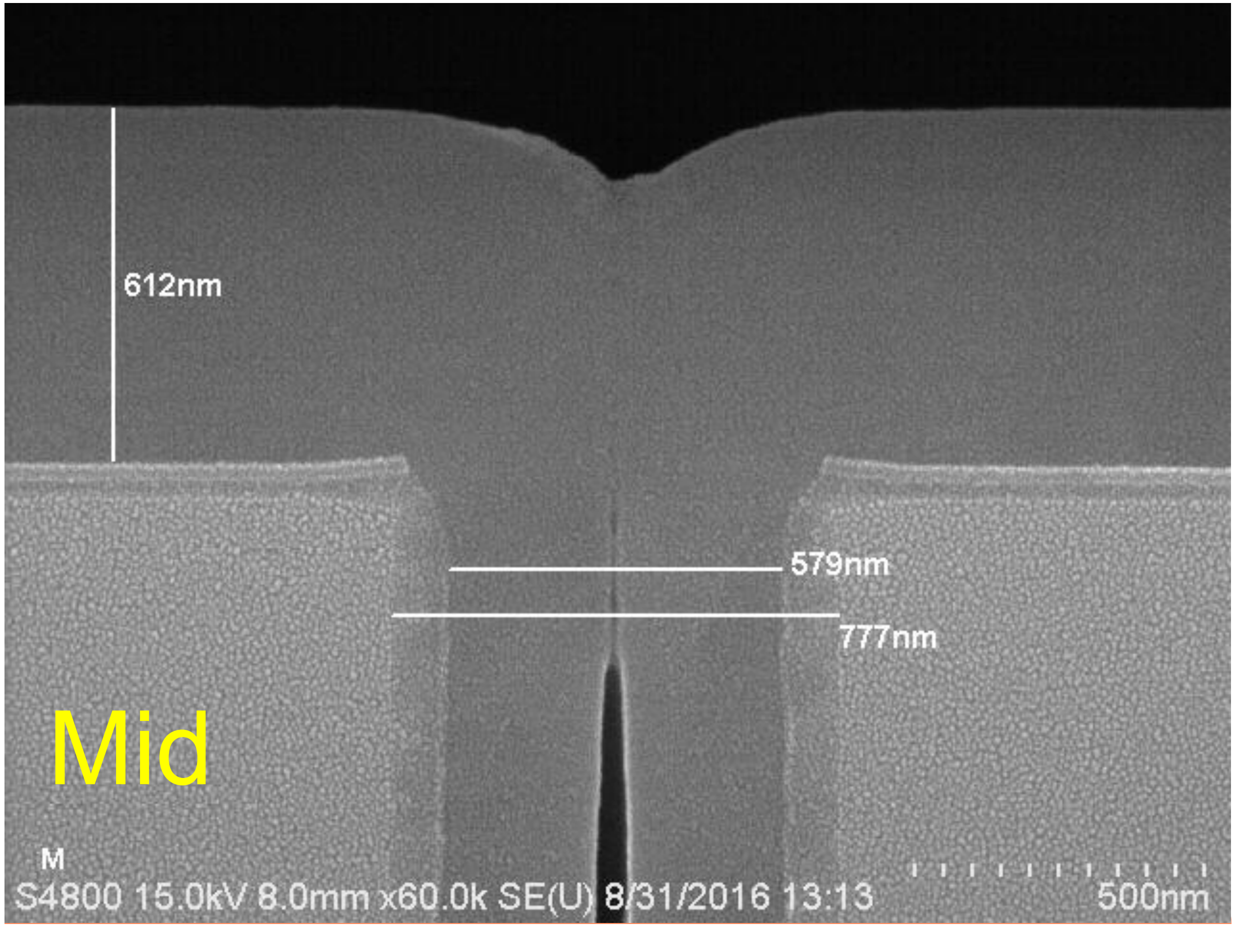
Structure optimization

Process Technology Simulations

- **Example 2: LOCOS**

Realization of the
Optimized structure





Process Technology Simulations

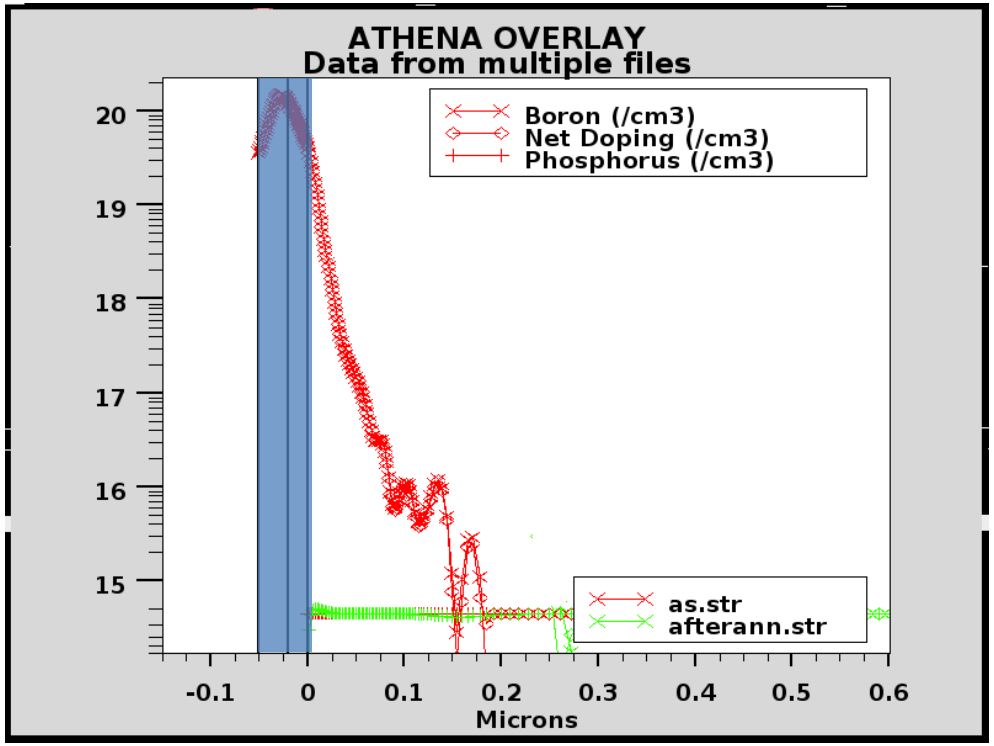
- **Example 3: Shallow junction for UV sensitive photodetcors**

UV light generated carriers in the first nm of Silicon

Is striclty necessary to create a shallow junction in order to increse the QE in the VUV range

Low energy Boron implant through a screen oxide layer

```
deposit oxide thick=0.05 dy= 0.001
implant boron dose=5e14 energy=10
tilt=7 rotation=0 crystal unit.damage \
dam.factor=0.8 monte n.ion=100000
smooth=0.4
```



Process Technology Simulations

- **Example 3: Shallow junction creation for UV sensitive photodet.**

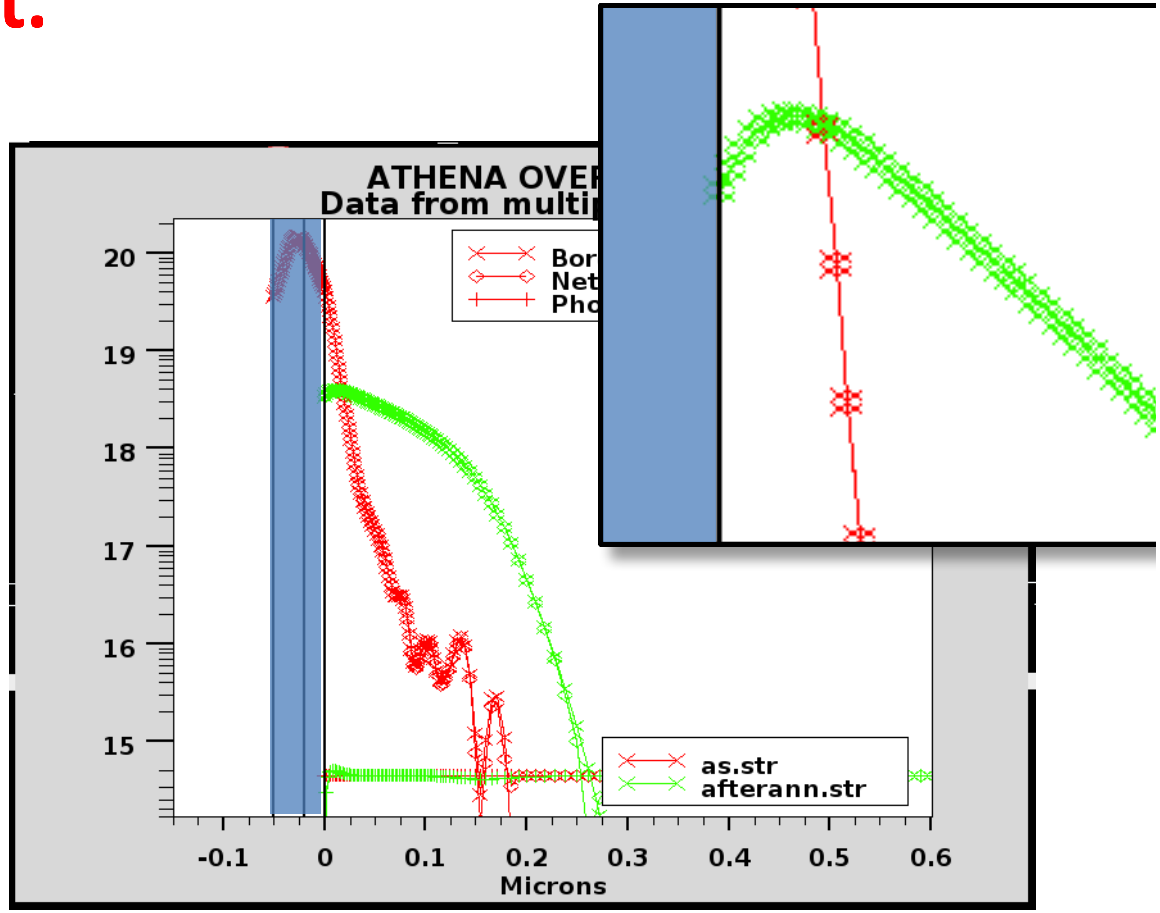
Activation and diffusion

```
method full.cpl high.conc cluster.dam
grid.oxide=0.001

diffus time=30 temp=850 nitro
```

Dopant re-distribution

Solution?
Low theramal budget
RTA annealing!



Segregation coefficent
m<1 for boron

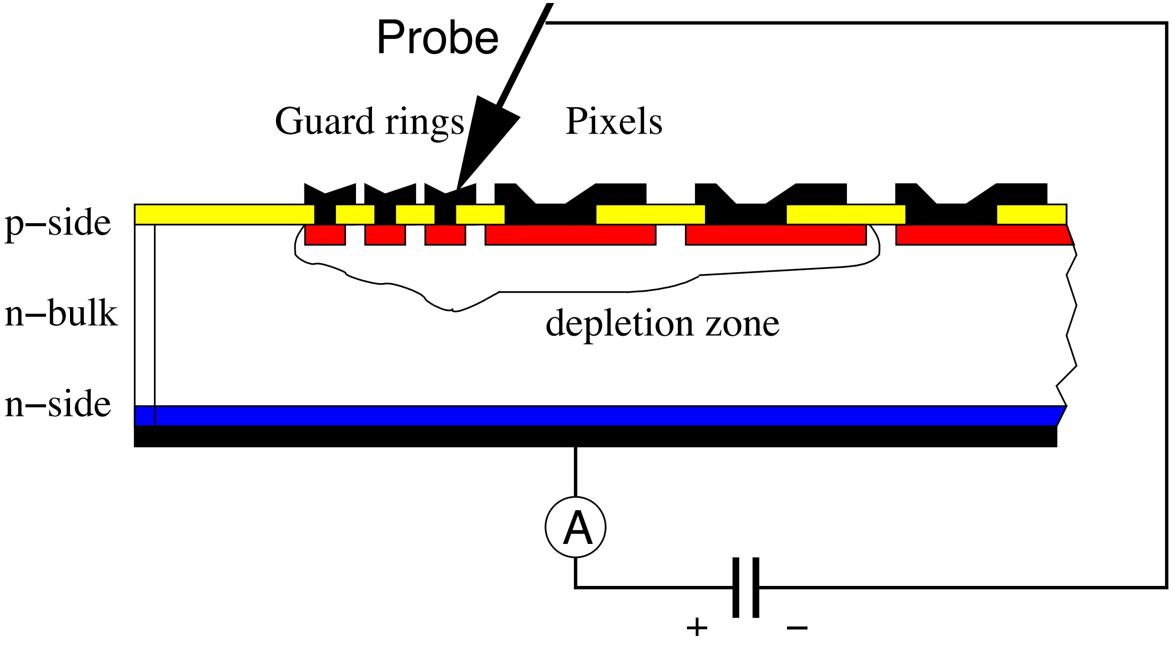
Device Simulations

- **Case study 1: Multi Guard Ring design**

In future HEP experiments Si tracking detectors will be operated in a very harsh radiation environment, which leads to surface damage in Si detectors which in turn change the full depletion voltage and the Breakdown Voltage

GOAL: design detectors with Breakdown Voltage > 1000V also after radiation damage

Multi Guard Ring structure



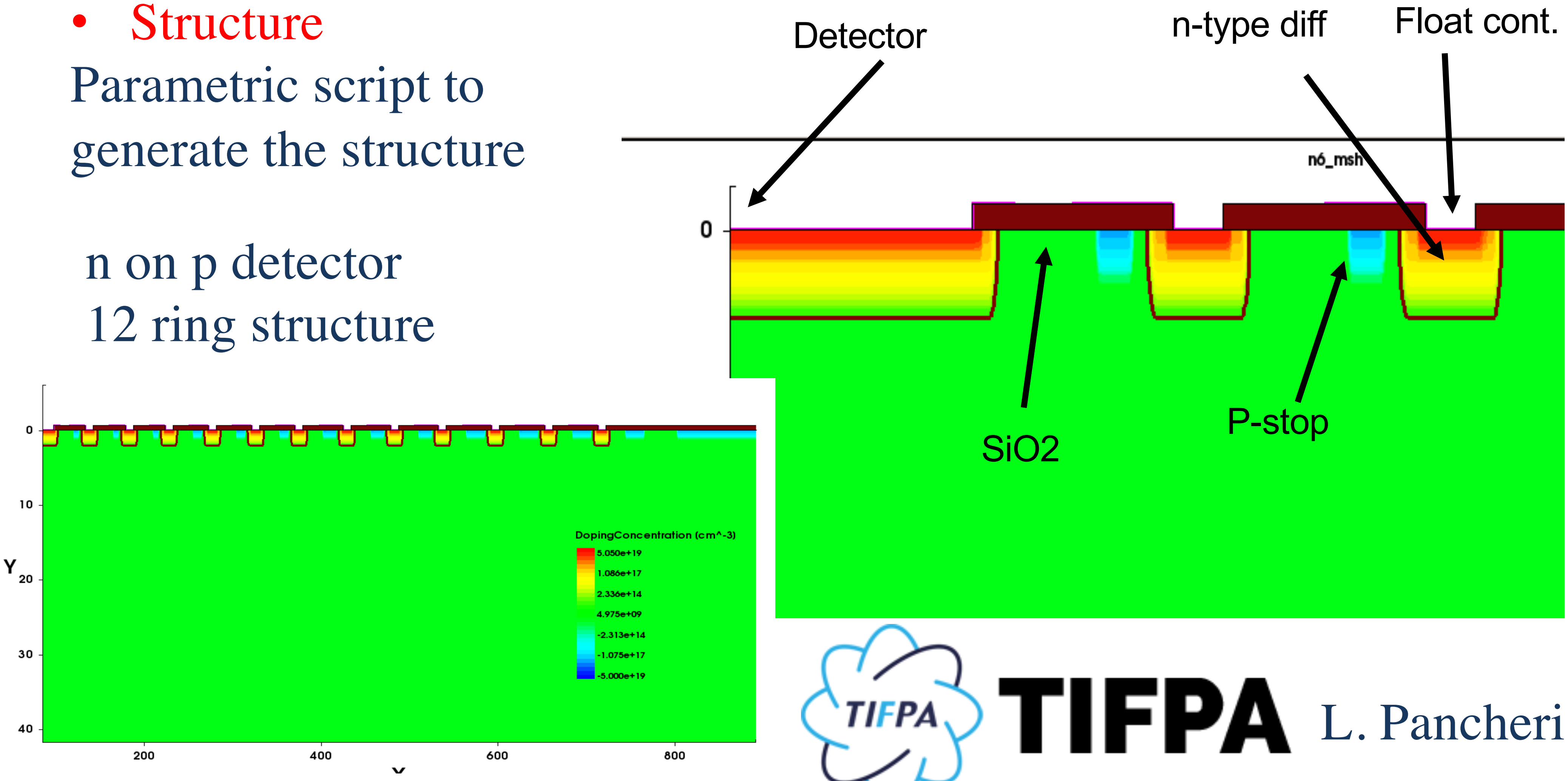
Device Simulations

- **Case study 1: Multi Guard Ring design**

- Structure

Parametric script to generate the structure

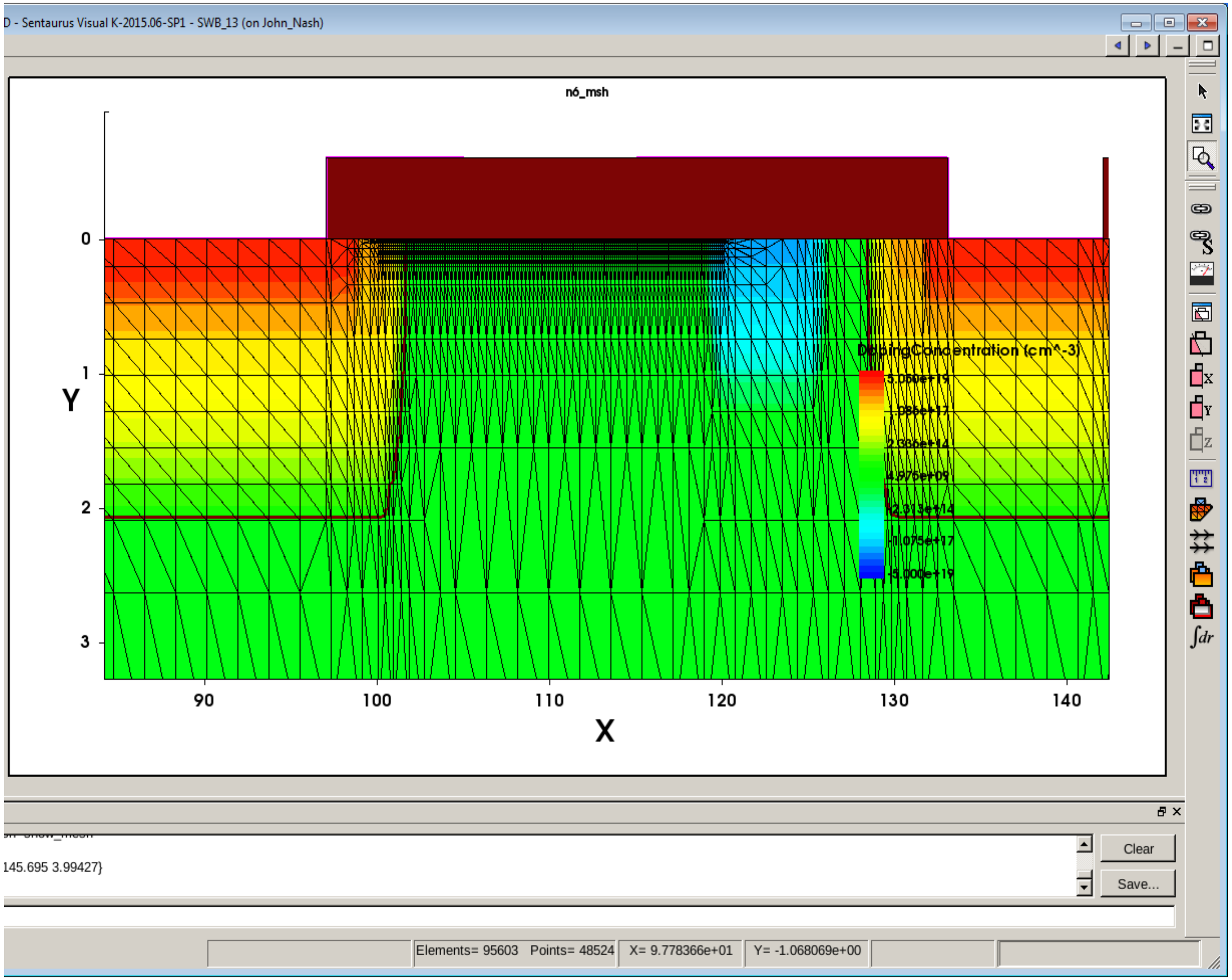
n on p detector
12 ring structure



Device Simulations

- **Case study 1: Multi Guard Ring design**

- Mesh refinement:
Very critic under the oxide due to the high Electric field



```
145.695 3.99427}
```

```
Elements= 95603   Points= 48524   X= 9.778366e+01   Y= -1.068069e+00
```

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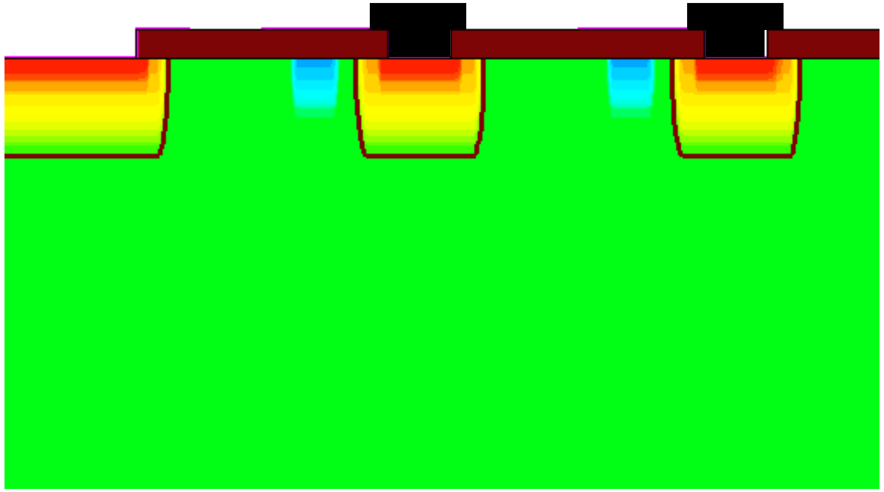
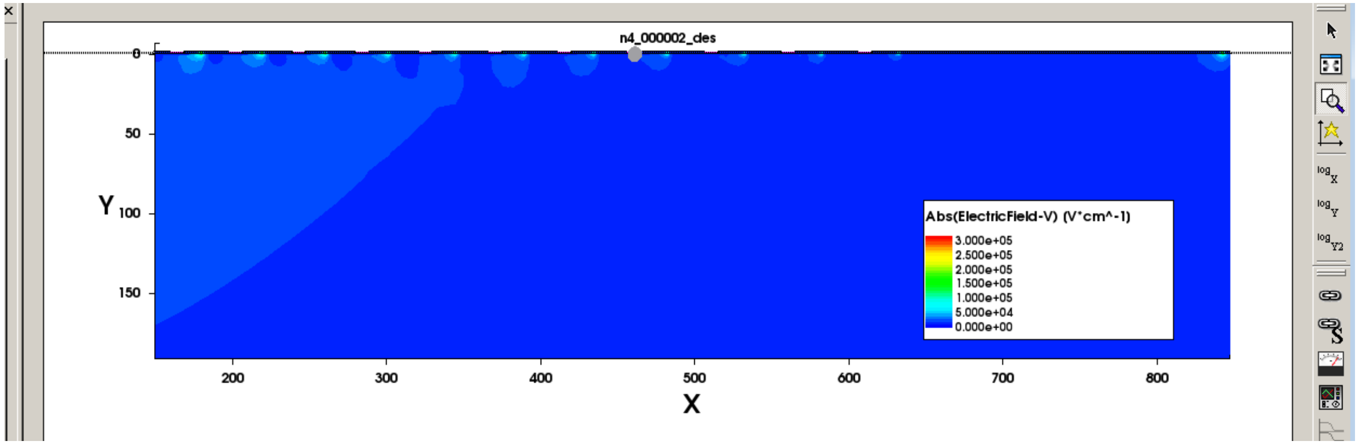
Device Simulations

- **Case study 1: Multi Guard Ring design**

- First structure:

No Field Plate on the guard ring



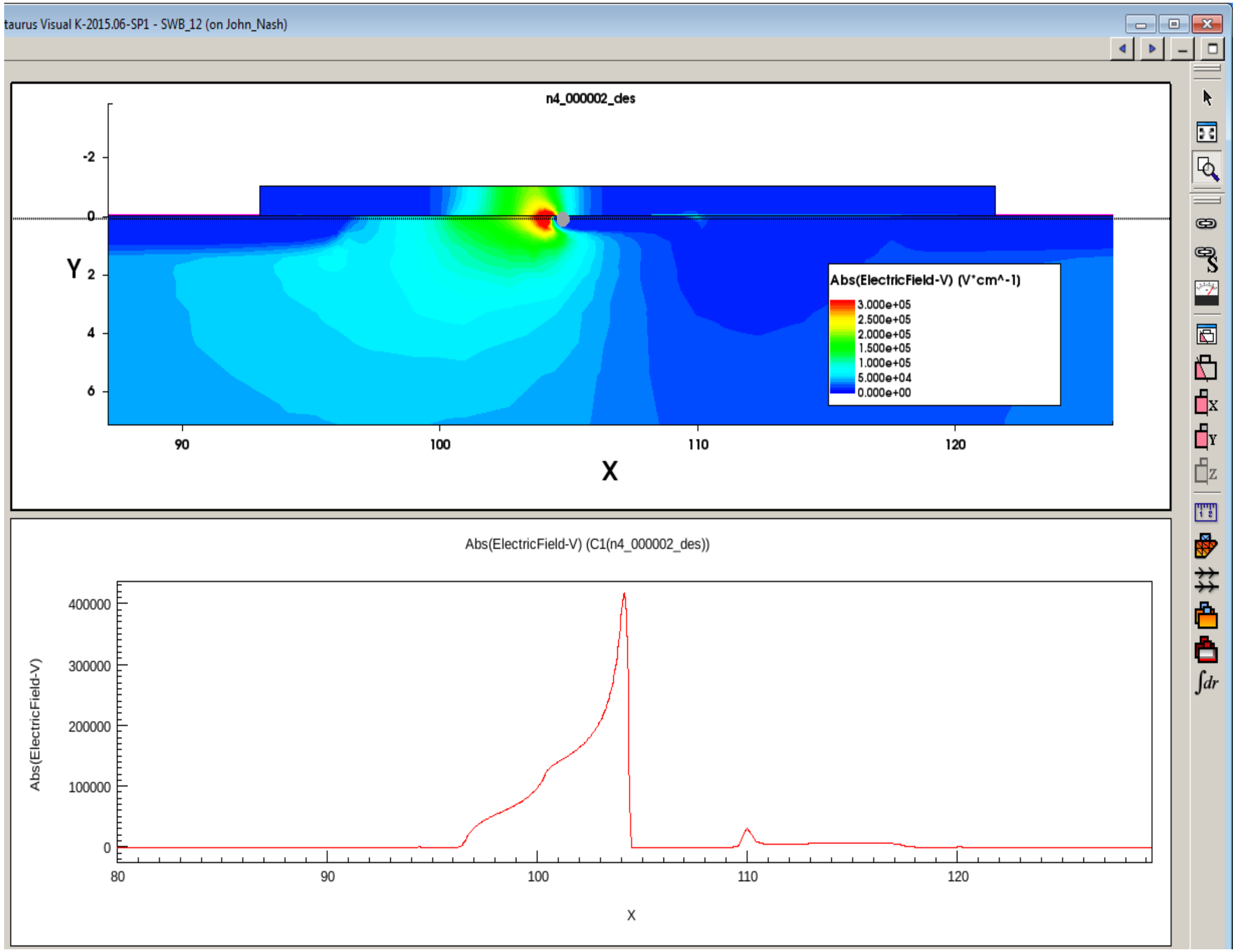


well working for not-irradiated devices.

But after irradiation…

Device Simulations

- **Case study 1: Multi Guard Ring design**



- Irradiated device

Increase oxide charge from 5e10 to (Nox=1e12)

the breakdown voltage falls down to 470V !

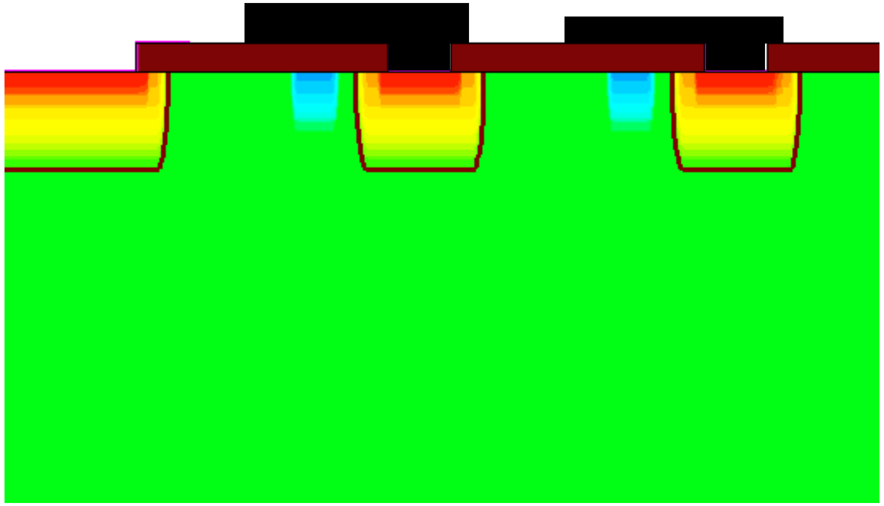
Device Simulations

- **Case study 1: Multi Guard Ring design**

- Optimized structure

Tuned parameters:

- Guard ring pitch
- P-stop width
- Field Plate



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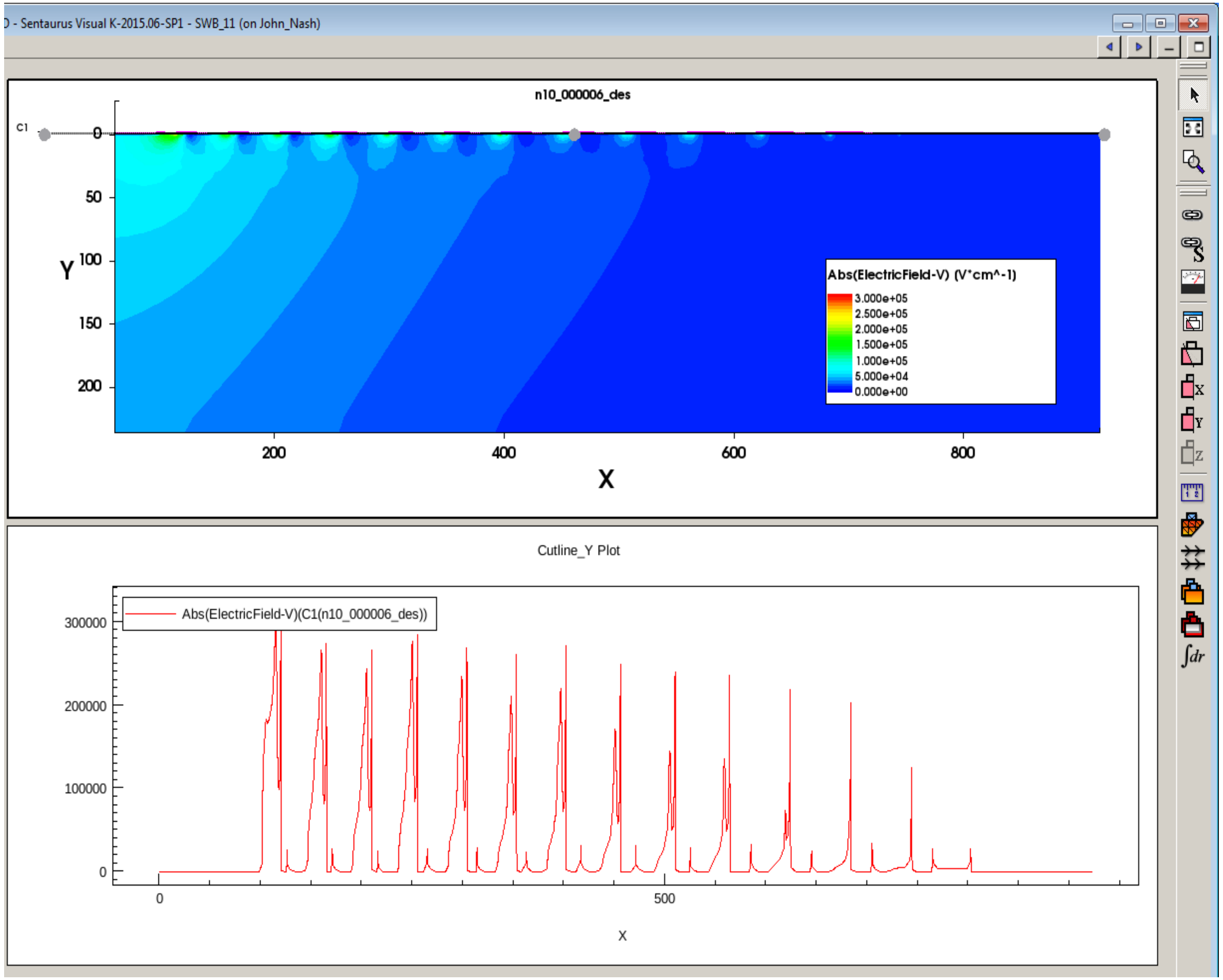
Device Simulations

- **Case study 1: Multi Guard Ring design**

- Optimized structure:



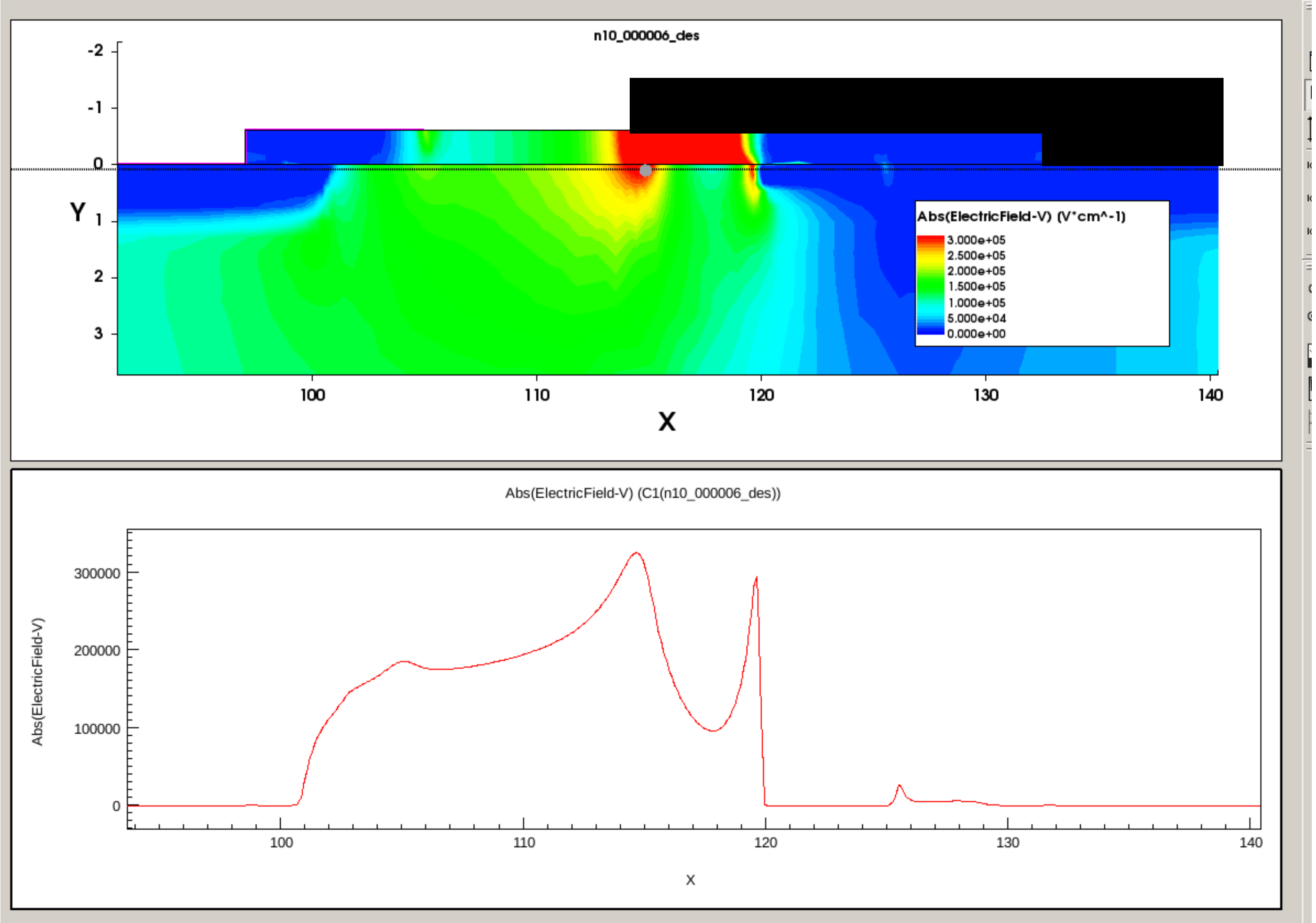
Breakdown = 1270 Volts
After irradiation!

Device Simulations

- **Case study 1: Multi Guard Ring design**

- Optimized structure:

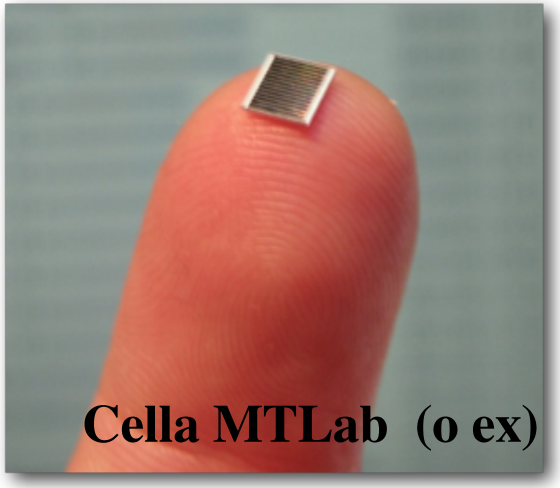
Detail of the Electric Field at the first guard ring



Device Simulations

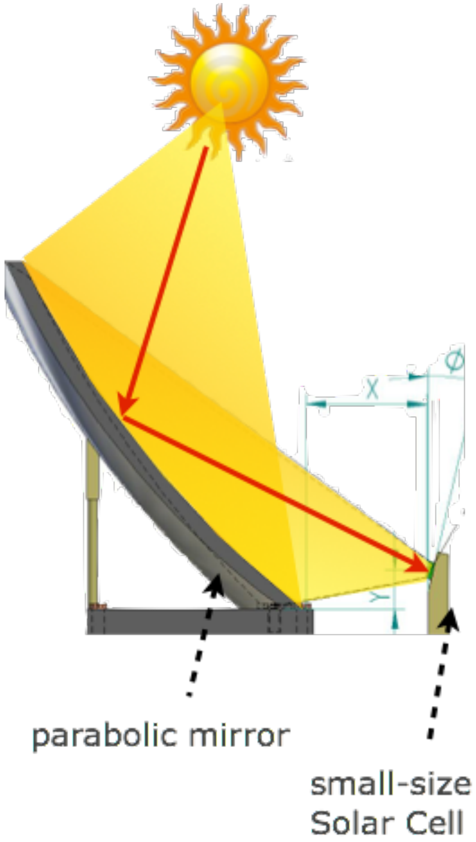
- **Case study 2: Silicon Solar Cell for CPV**

Project HCSC (2009)
Project iSiCPV (2012-2014)



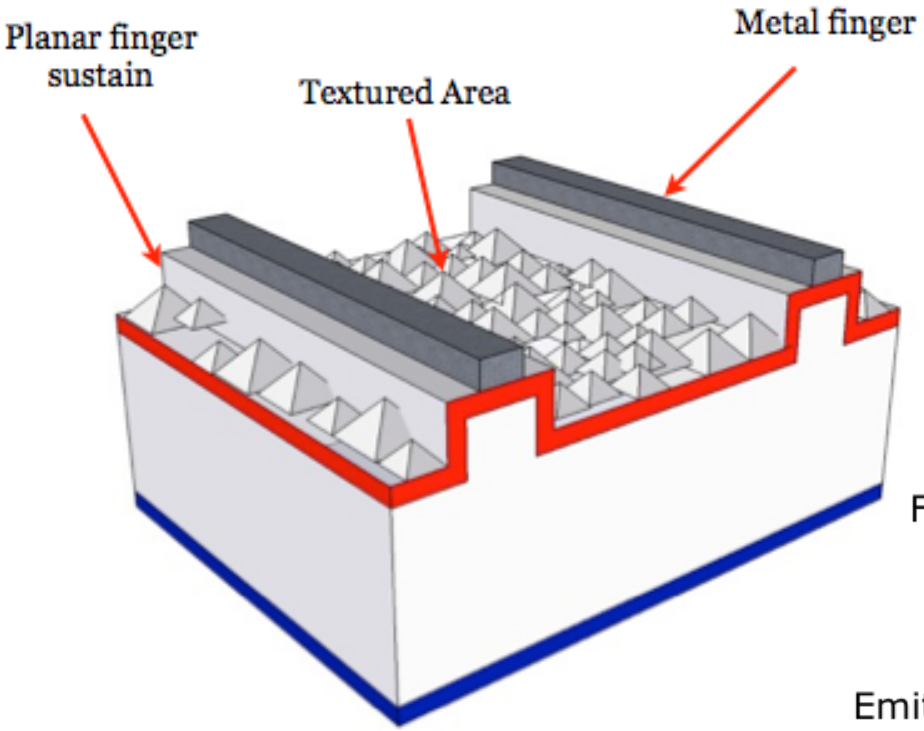
System Characteristics:

- Small mirrors 7 cm high.
- The illuminated spot size is about 16mm² wide.
- The light is concentrated at ≈ 160 Suns.
- Many assemblies can be used to obtain a solar panel of standard dimensions.

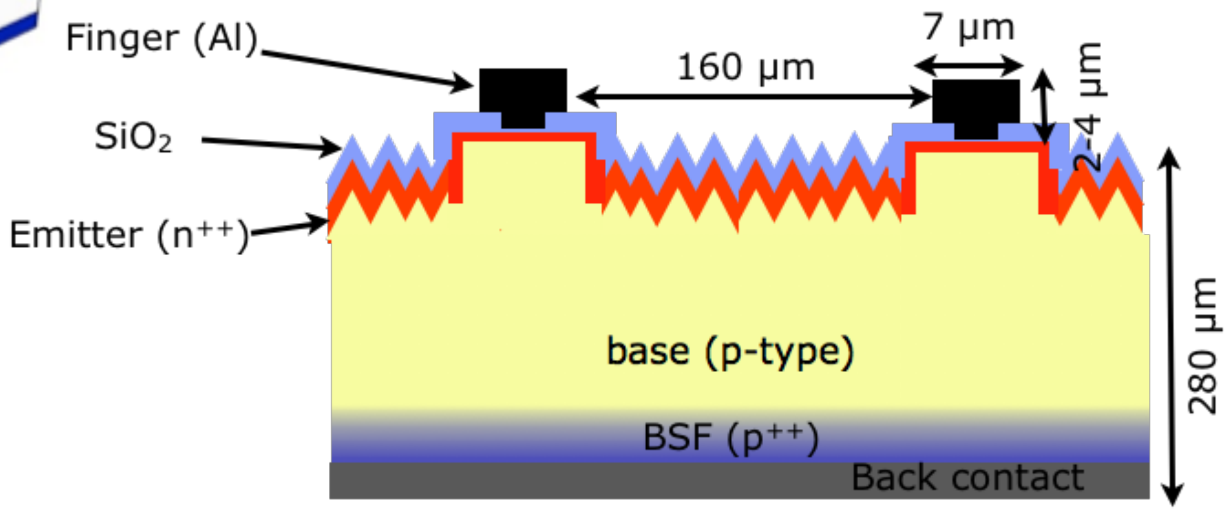


Device Simulations

- **Case study 2: Silicon Solar Cell for CPV**

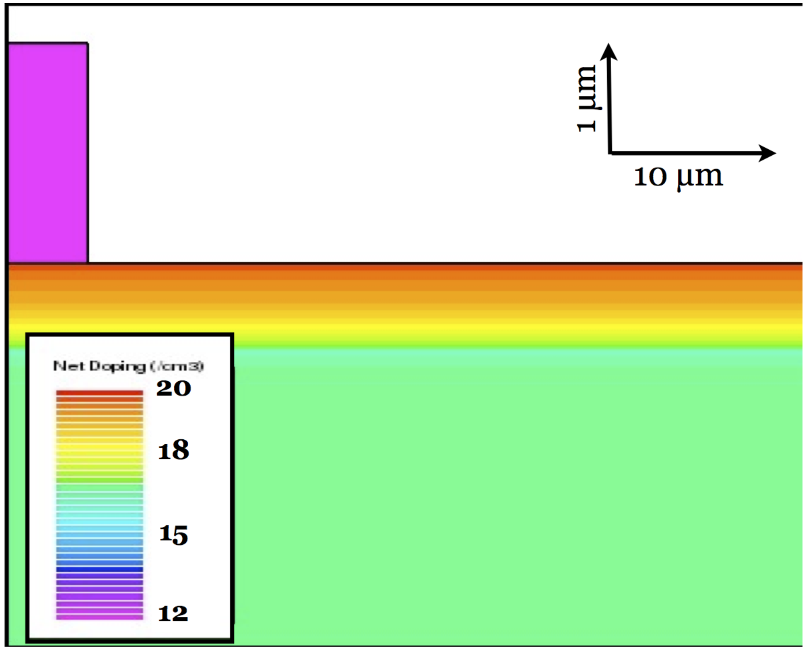


PESC =
Passivated Emitter Solar Cell



Device Simulations

- Case study 2: Silicon Solar Cell for CPV



Optimized Parameters:

- Base doping
- Cell thickness
- Back surface Field doping
- Front metal grid geometry
- Finger Spacing

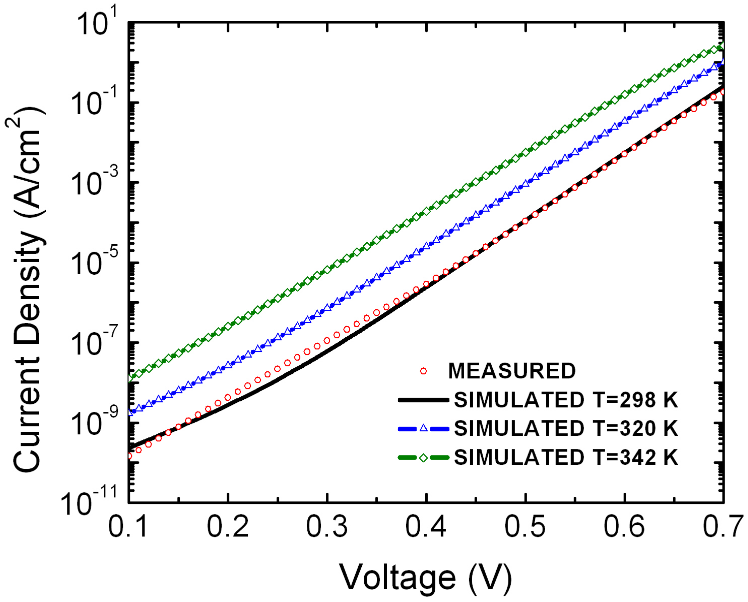
```
#wafer thickness
set wb= 280
#finger spacing
set pitch= 80.0
#metal thickness
set hm= 4.0
#Finger width
set wf= 5.0

#Material and Doping
# bulk doping
set dop_bulk = 3.255e+16
set BSFp = 0

# bulk lifetime
set tau = 1e-4
```

Device Simulations

Case study 2: Silicon Solar Cell for CPV

- Simulations tuning with real experimental values

Recombination parameters	
Bulk minority carrier lifetime	60 μm
Front surface (passivated) recombination velocity	10^3 cm/s
Recombination velocity at the metal-silicon interface	$3 \cdot 10^6$ cm/s



```
# SET  MATERIAL
material Silicon TAUN0=$tau
TAUP0=$tau nc300=3.2e19
nv300=1.83e19 eg300=1.119
copt=1.1e-14
material material=aluminum
real.index=1.39
imag.index=1.51
```

```
# DOPING
doping phosphor
x.min=0
x.max=$pitch
y.min=0 ascii
infile=phos_sims.do
p
doping boron
conc=$BSFp x.min=0
x.max=$pitch
y.max=$wb junc=$wb-
1.5 gauss
```

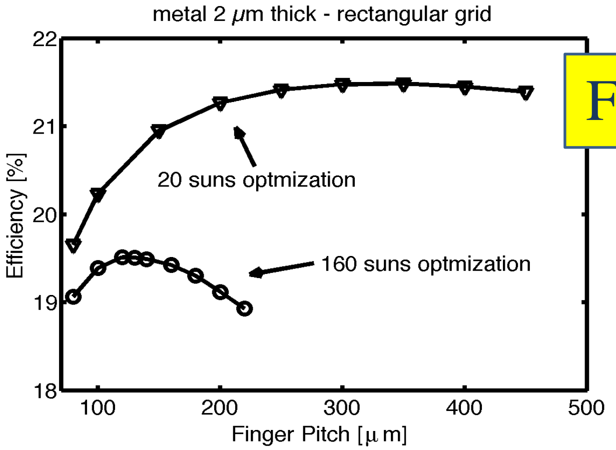
```
# SURFACE RECOMBINATION
interface x.min=0.0
x.max=$pitch y.min=-0.1
y.max=0.1 S.X S.N=5e3
S.P=5e3
interface x.min=0 x.max=$wf
y.min=-0.1 y.max=0.1 S.X
S.N=3.e6 S.P=3.e6
interface x.min=0
x.max=$pitch y.min=$wb-0.1
y.max=$wb+0.1 S.X S.N=3.e6
S.P=3.e6
```

Device Simulations

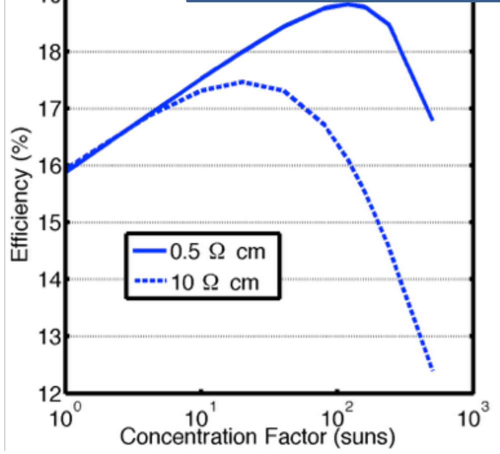
- **Case study 2: Silicon Solar Cell for CPV**

… a lot of suimulations

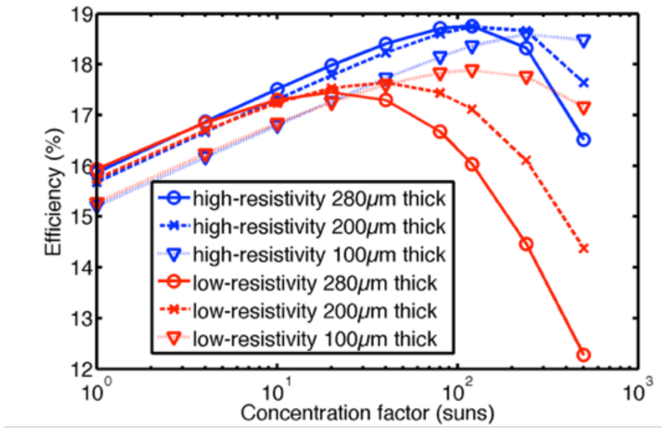
Finger pitch



Substrate resistivity

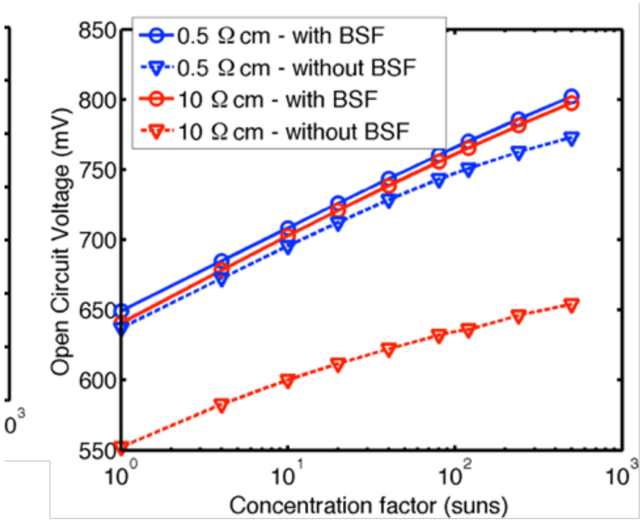


Substrate thickness



- Thick substrate is preferible at low-concentration
- Thin substrates show higher efficiency under high-concentrated light.

Back Surface Field

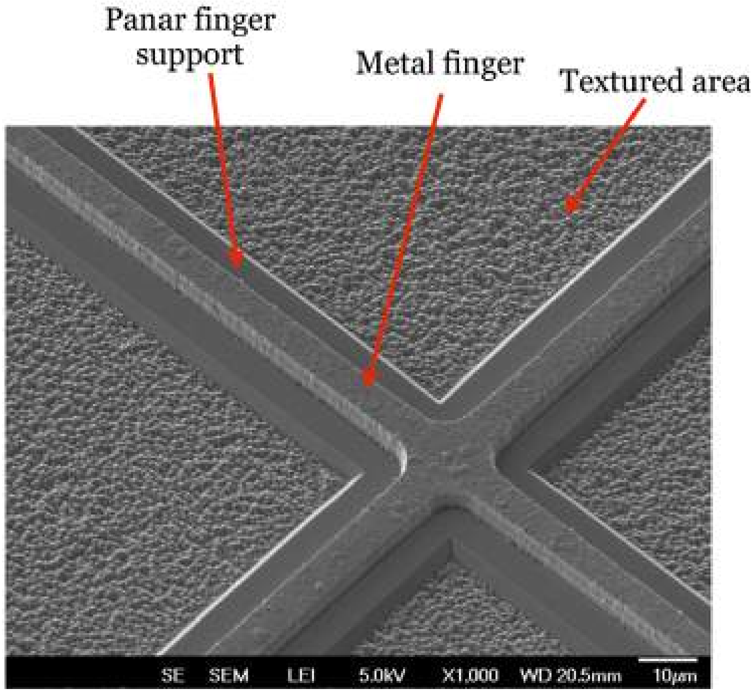


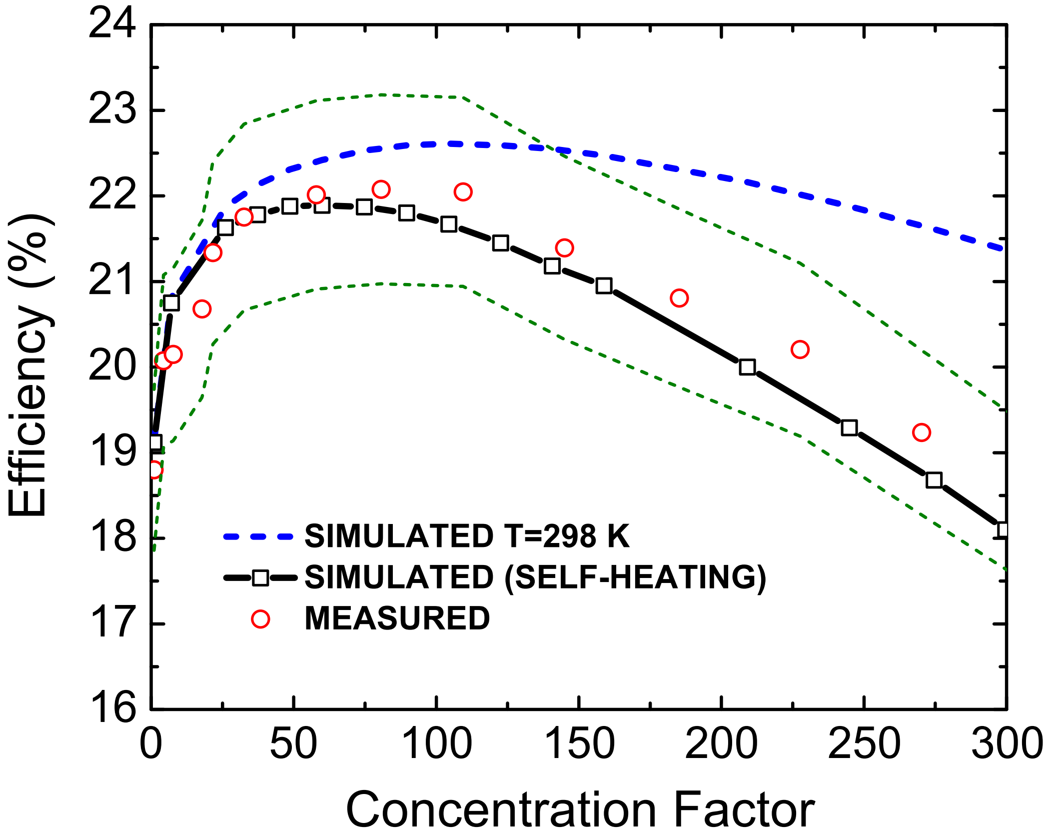
Device Simulations

- **Case study 2: Silicon Solar Cell for CPV**

- Final Step:

fabrication of the optimized solar cell & characterization





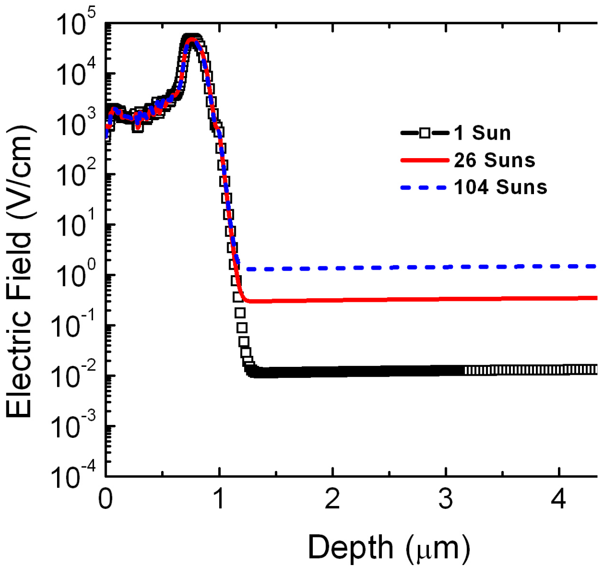
Device Simulations

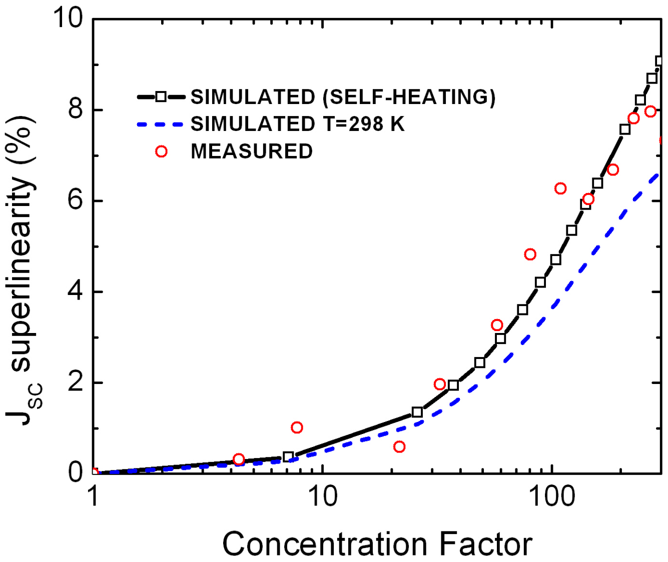
• Case study 2: Silicon Solar Cell for CPV

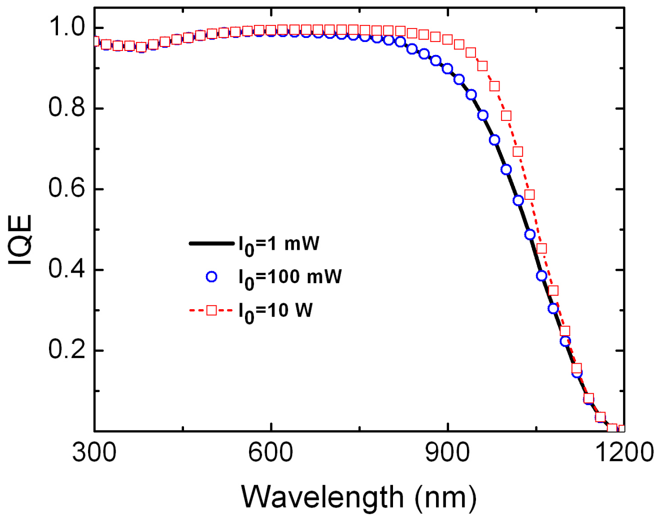
- Consideration:

TCAD simulation is not only a powerful tool for device optimization.

New effects of Jsc super-linearity under concetrated light investigated by means of TCAD simulations







G. Paternoster et al., “Fabrication, characterization and modeling of a silicon solar cell optimized for concentrated photovoltaic applications”, Solar Energy Materials and Solar Cells, Volume 134, March 2015, Pages 407-416.

Thank you for your attention!