

SIM-DéTECTEURS 2014 LPNHE - Paris

École de simulation de détecteurs silicium

du 15 au 17 septembre 2014

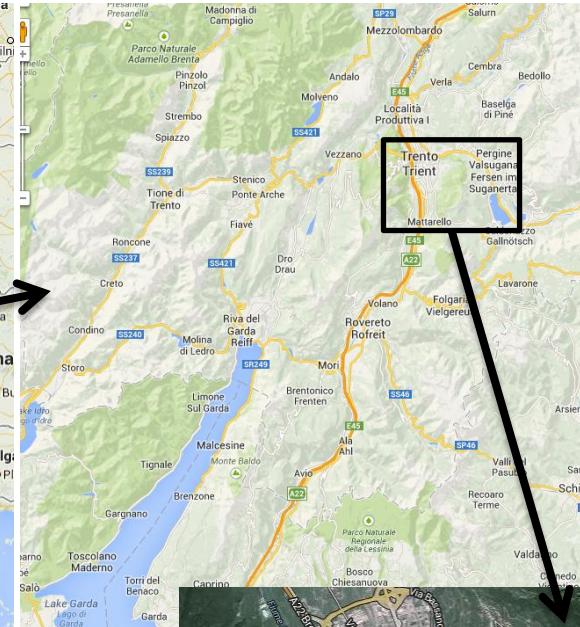
Bruno Maloyer - LAL Orsay



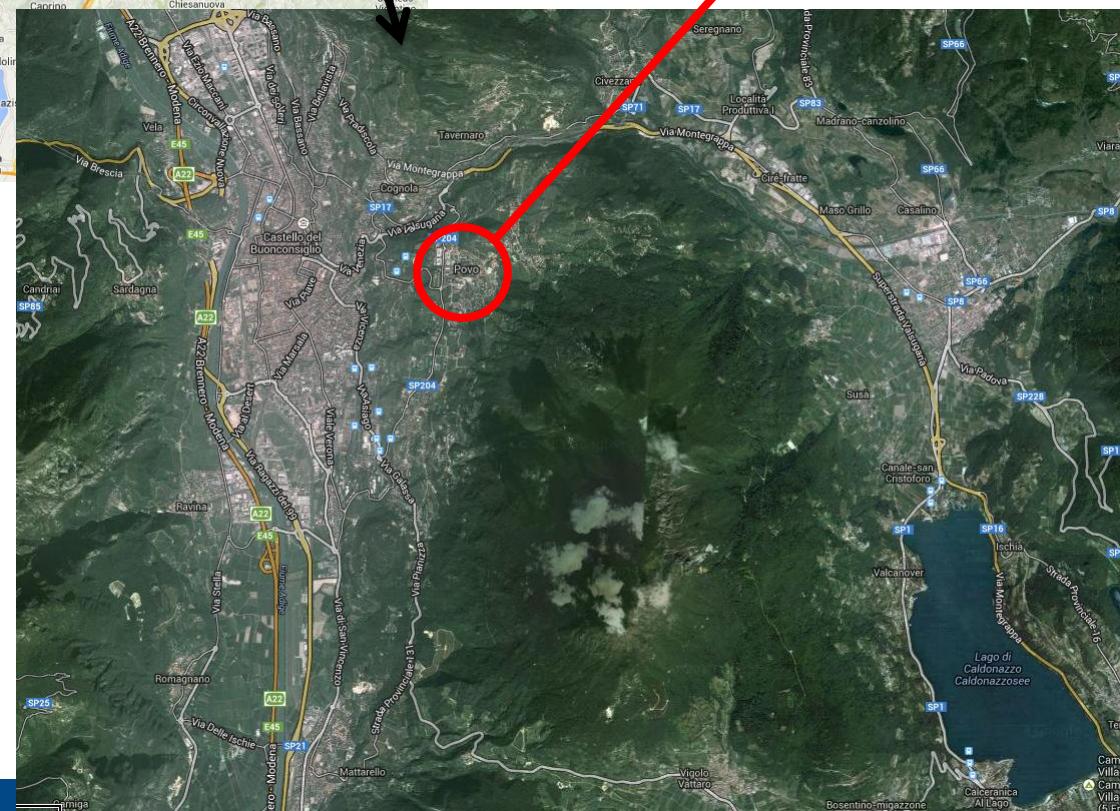
Expérience pratique de simulation dans la fonderie FBK

Gabriele Giacomini
FBK (Trento, Italie)
mercredi 17 septembre 2014





FBK is here!



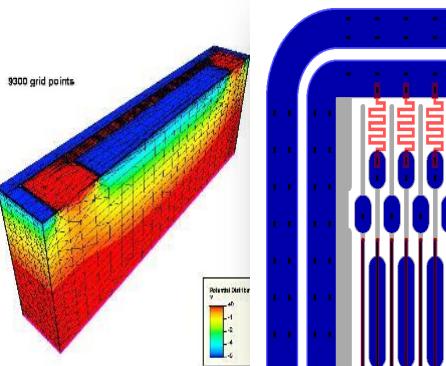
www.fbk.eu

Centre for Materials and Microsystems
<http://cmm.fbk.eu>

MTLab Fabrication Facility
<http://mtlab.fbk.eu>

Silicon Facility Expertise

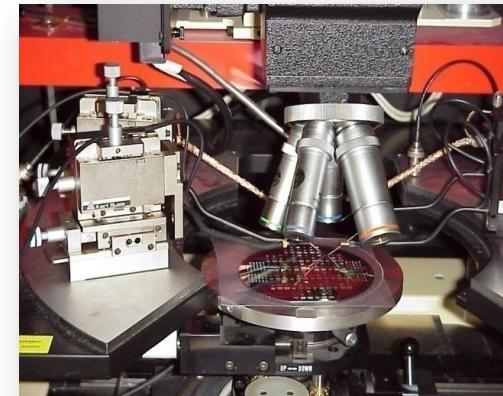
TCAD simulation
CAD design



Fabrication



Device testing

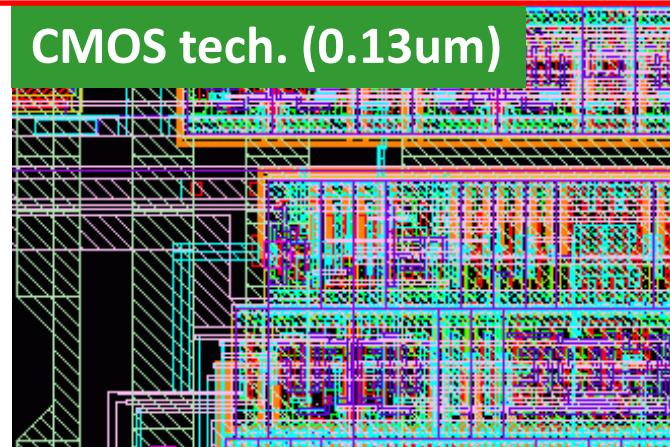


Material Characterization:

- XPS
- SIMS
- ToF-SIMS
- TXRF
- AFM
- SEM

Custom CMOS design
Development of ROIC by
exploiting state of the
art CMOS tech
(external services)

CMOS tech. (0.13um)



MTLab Facility: MicroFabrication Area

Two separate clean rooms

- 500m² of clean room (class 10-100)
- 200m² 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



Centre for Materials and Microsystems

Silicon Radiation Sensors

<http://srs.fbk.eu>

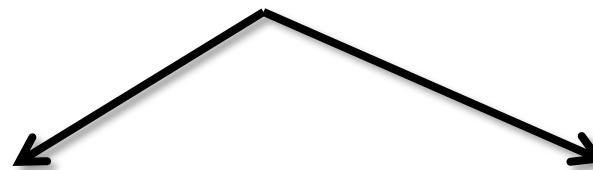


IRIS

Integrated Radiation and Image Sensors
<http://iris.fbk.eu>

SRS activity

Development of silicon radiation sensors



Sensors on high-resistivity substrates

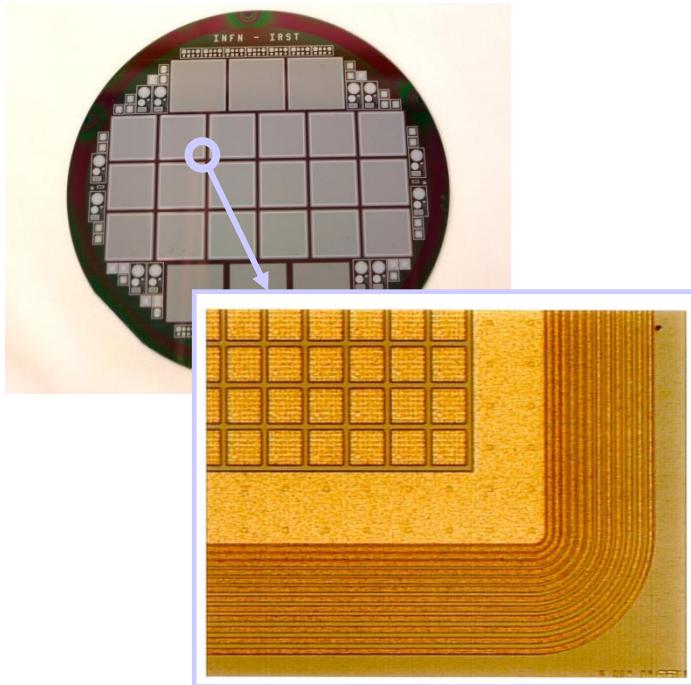
- pixel detectors
- strip detectors
- drift detectors
- 3D detectors

Sensors with internal gain for light detection

- Silicon Photomultipliers
- SPADs

Pixel detectors

Medipix 1&2

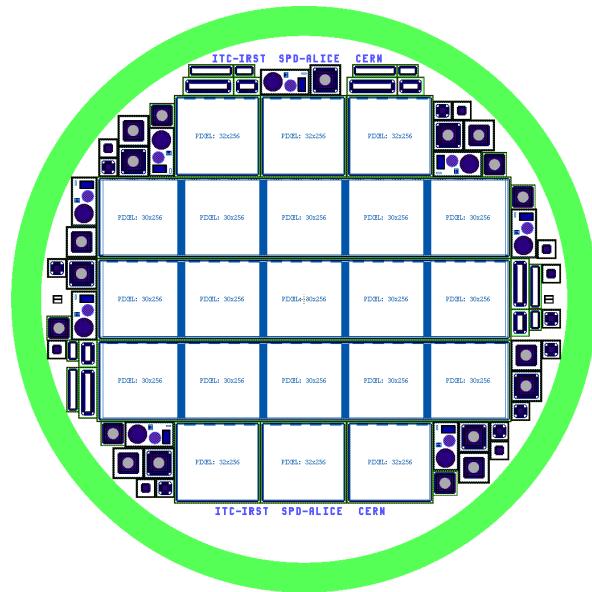


- Medipix1: pixel size 170x170 μm^2
- Medipix2: pixel size 55x55 μm^2

Substrate thick.: up to 1.5mm

Leakage current ~100pA/cm² for 300 μm substrates

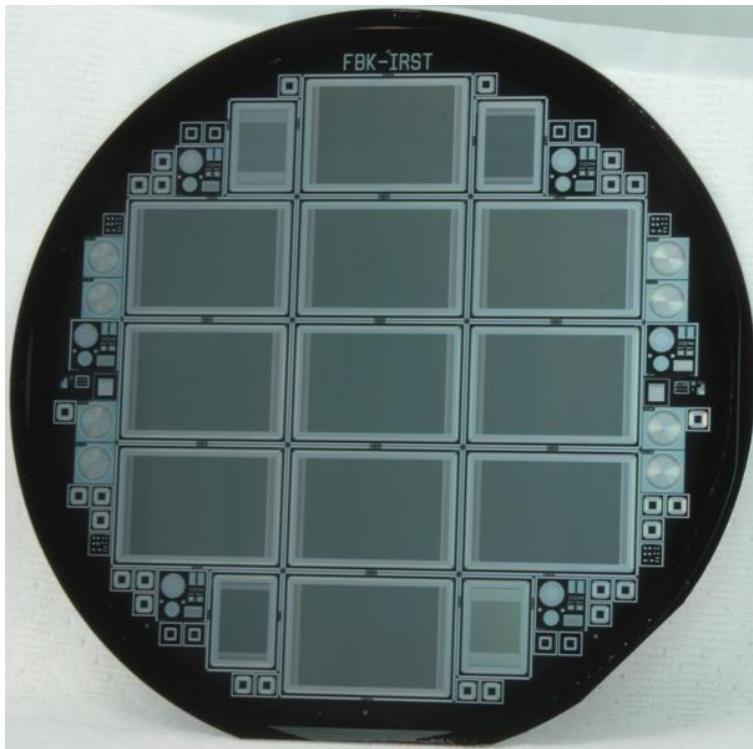
NA48/ALICE experiment



- ALICE SPD layout
- pixel size 50x400 μm^2

Substrate thickness: 200 μm

Strip Detectors: single side

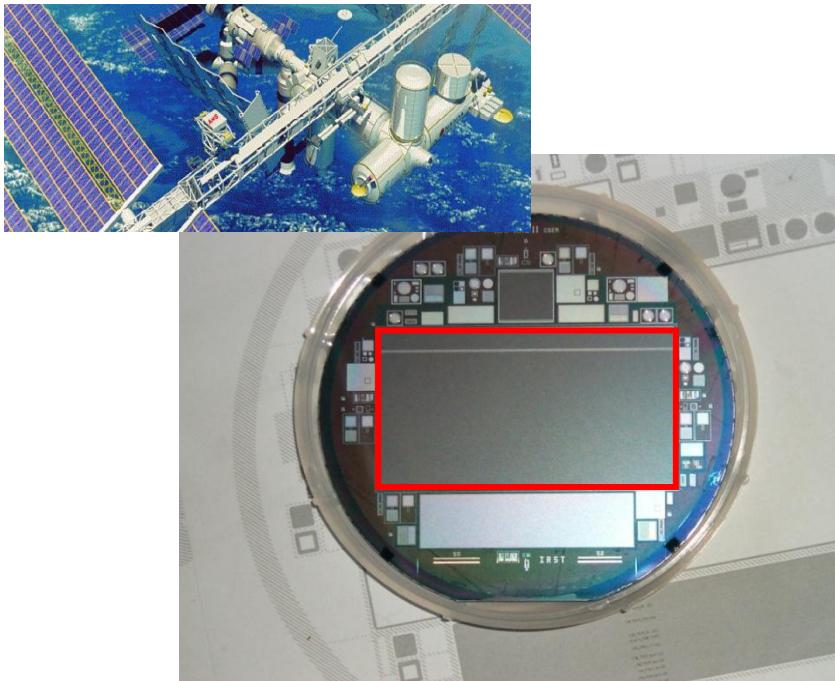


Custom development of strip detectors:

- DC/AC coupled,
- very low leakage,
- high yield

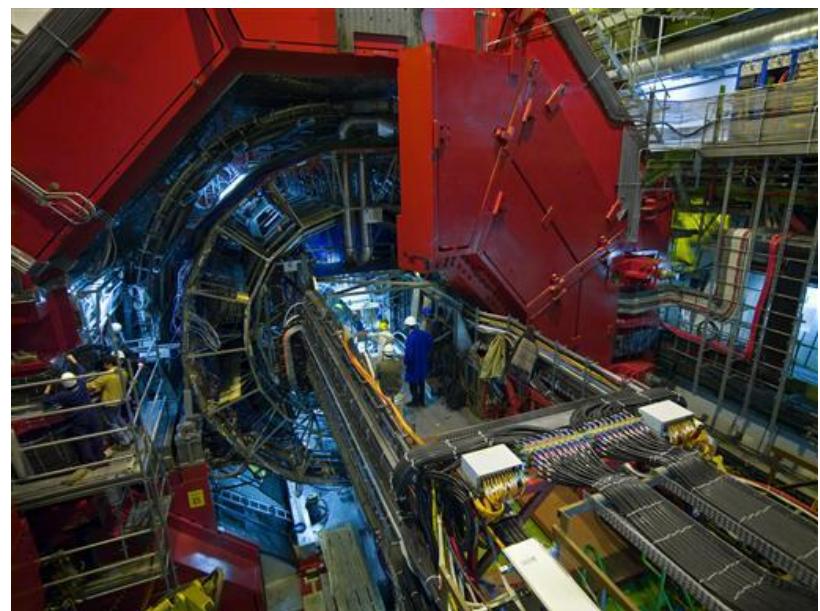
Strip Detectors: double side

AMS experiment (@ISS)



700 large-area double-sided
in-spec detectors fabricated
in 2002-2004.

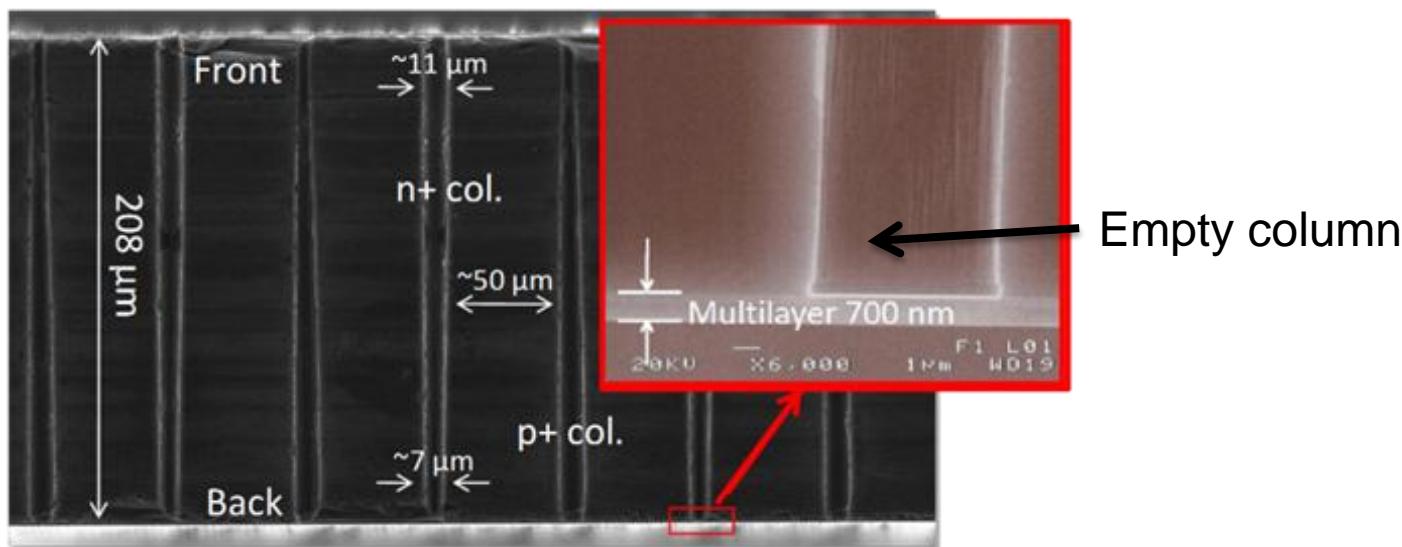
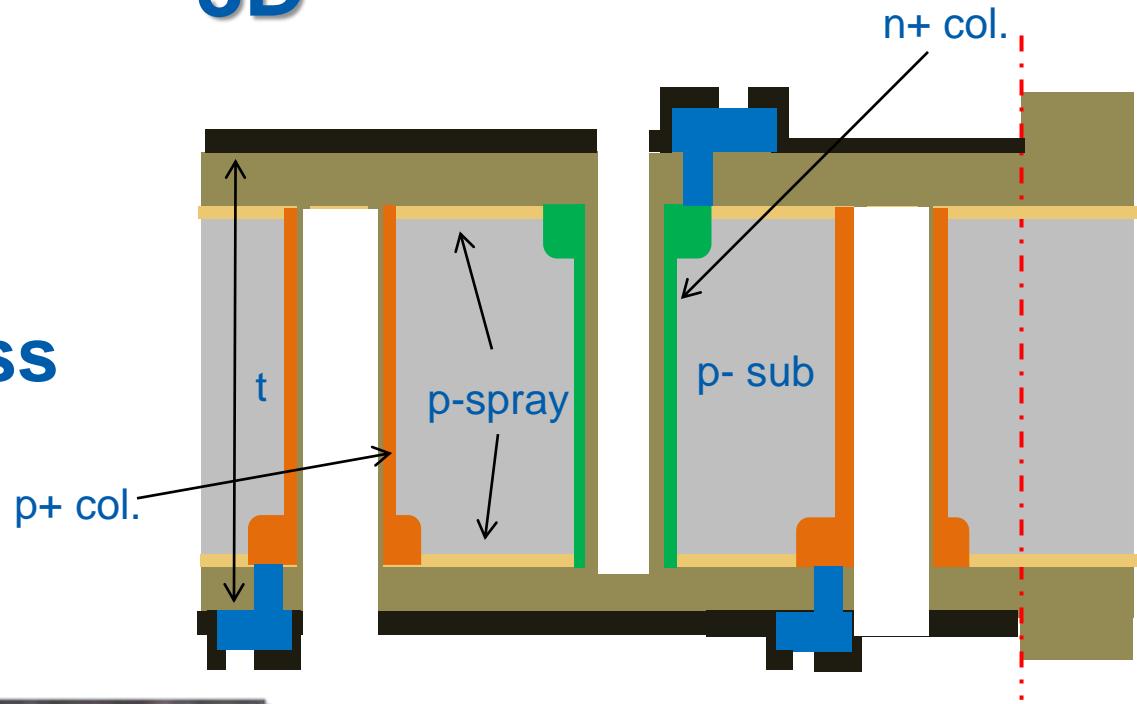
ALICE experiment (@LHC)



600 large-area double-sided
in-spec detectors fabricated
in 2003-2005.
ALICE Industrial Awards in 2006

3D

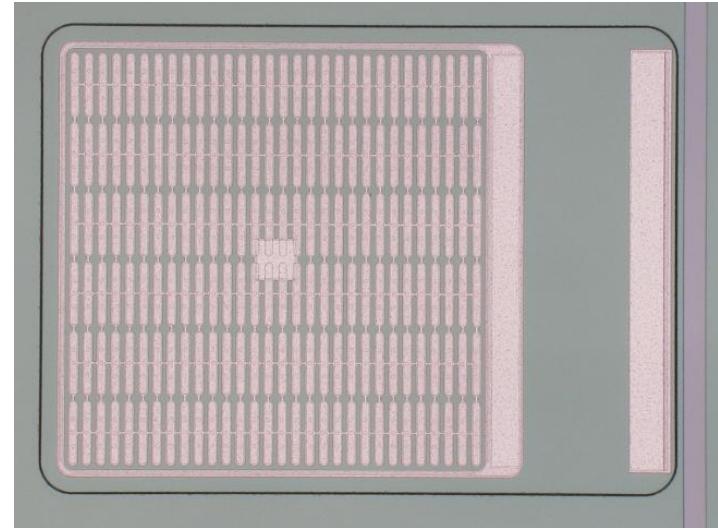
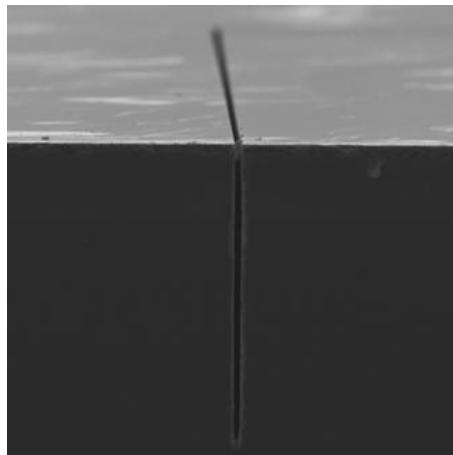
Double side fabrication process



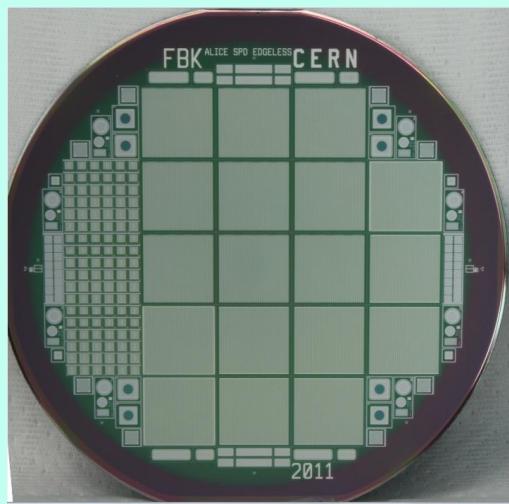
- p-implanted silicon
- n-diffused silicon
- p-diffused silicon
- Aluminum metal
- dielectric
- silicon
- PECVD overglass

Active edge

- 4.5 μm wide trench
- 200 μm deep
- polysilicon filled



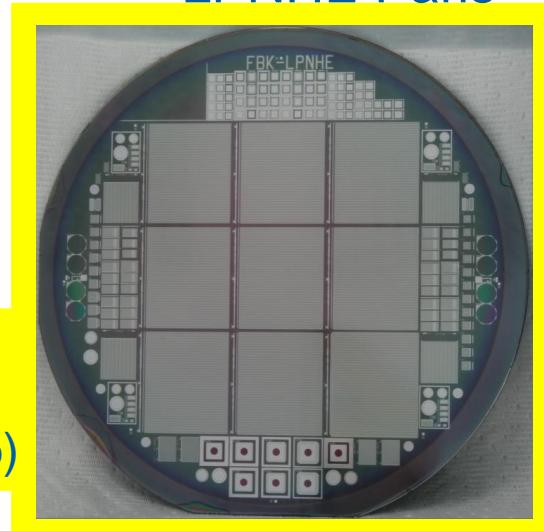
INFN-BA, CERN



pixel sensors compatible with
ALICE ROC
(epi wafers, 100 μm thick + sub)

- pixel sensors compatible with
ATLAS FE-I4
(200 μm -thick FZ + waf-bond sub)

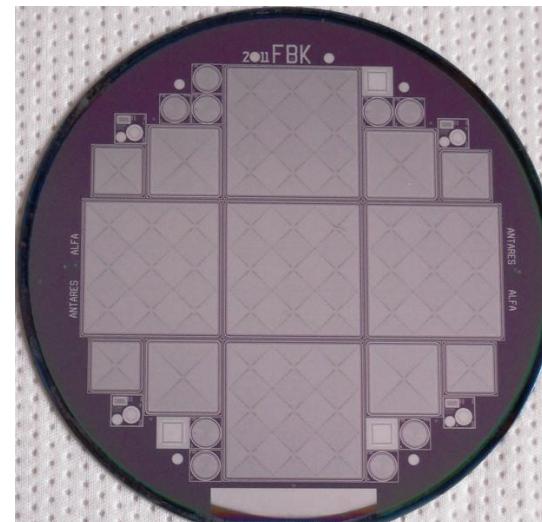
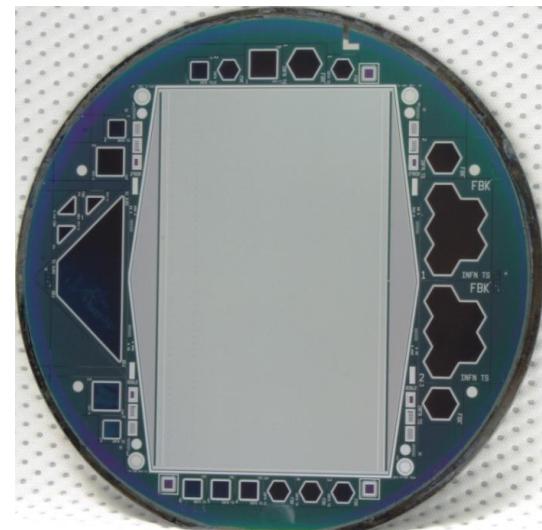
LPNHE Paris



Silicon Drift Detectors

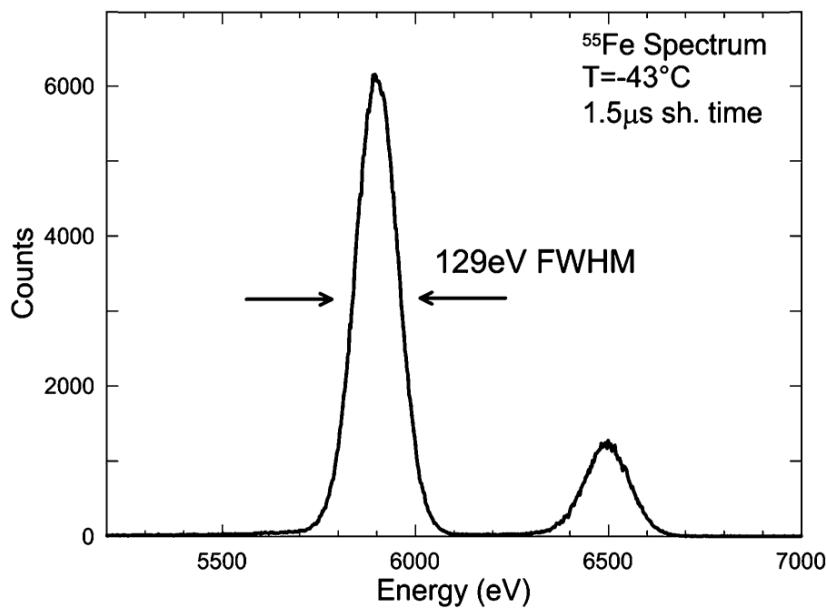
2 public project:

- INFN/INAF (2011-)
development of very large
linear SDD for astrophysics experiment
- ESA - PoliMi (2010-2012)
development of gamma ray spectrometer
based on SDD coupled to LaBr_3 scintillator



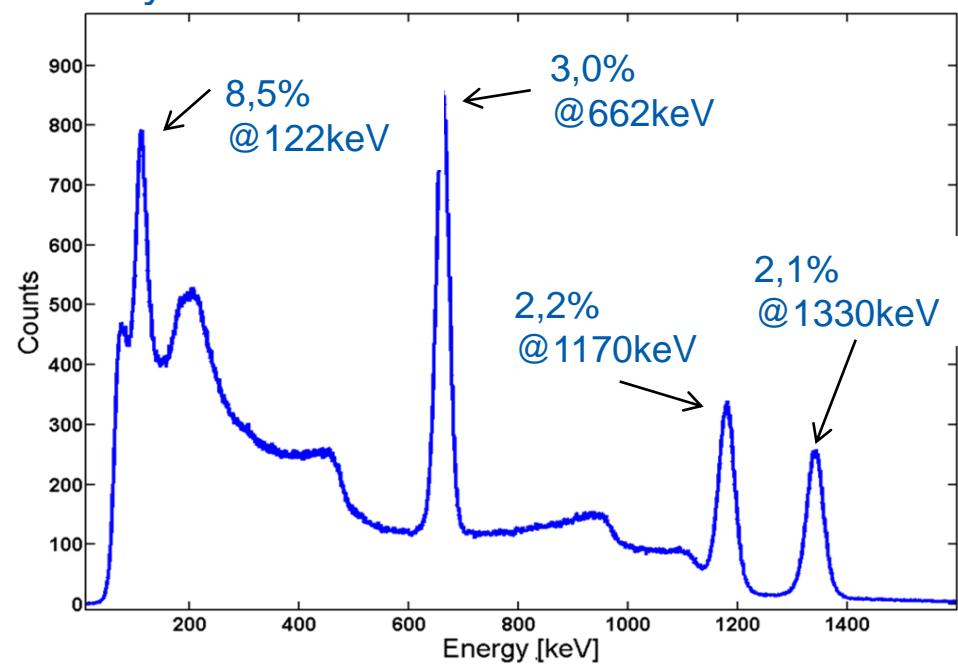
Silicon Drift Detectors

X-ray detector



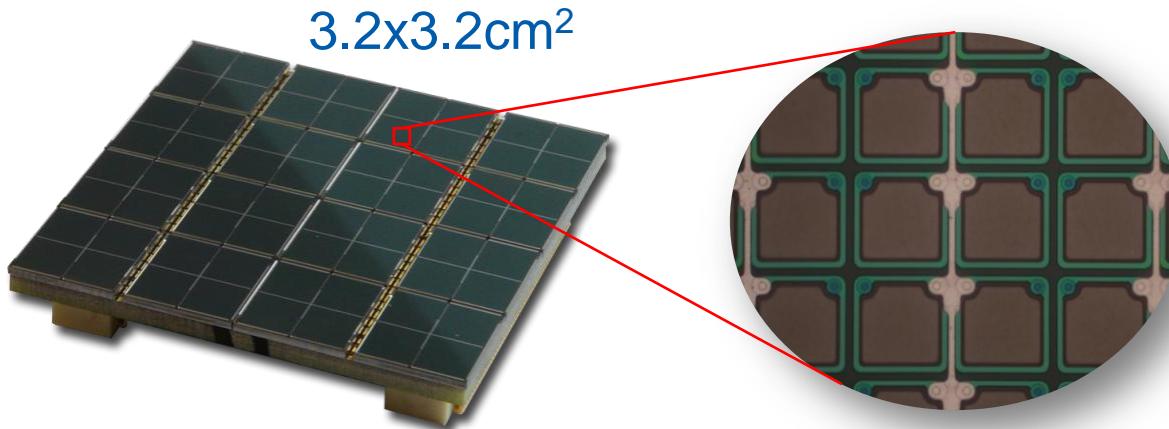
gamma spectrometer

⁵⁷Co, ¹³⁷Cs, ⁶⁰Co spectra measured with the SDD coupled to a 1" LaBr₃ crystal



Energy resolution @ 662keV measured with a PMT = 3.2%

Silicon photomultiplier



SiPM

array of tiny SPADs
connected in parallel
to give proportional
information

Main Current Projects

EU projects:

- Sublima (2010 – 2014)
- Insert (2014 - ...)

National projects:

- with INFN (2013-2015)

Application fields:

detection of faint light with high
time resolving capability:

- nuclear medicine
- biology
- physics experiments
- instrumentation for material analysis

Simulations des parts de la fabrication

- oxidation and diffusion
 - exemple: deux problems a resoudre
- ARC
- Implantation 1D
 - comment l'utiliser dans DEVEDIT

Comportement des détecteurs

- explication de problèmes mesuré dans les détecteurs réels
 - exemple: effet de l' humidité
- développement des nouvelle détecteurs
 - exemple: XAMPS (transient)
- détermination des propriétés dynamiques
 - exemple: temps de dérive des électrons dans une SDD
- beaux images pour les publications
 - exemple: PT in SDD

Simulations des parts de la fabrication:

- oxydation and diffusion
 - exemple: deux problèmes à résoudre
- ARC
- Implantation 1D
 - comment l'utiliser dans DEVEDIT

Comportement des détecteurs

- explication de problèmes mesuré dans les détecteurs réels
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- beaux images pour les publications
 - exemple: PT in SDD

oxydation

Bien étudié: SILVACO n'est pas nécessaire.
 on line calculateur: <http://www.cleanroom.byu.edu/OxideTimeCalc.phtml>

Pour oxyder on fait une diffusion:

```

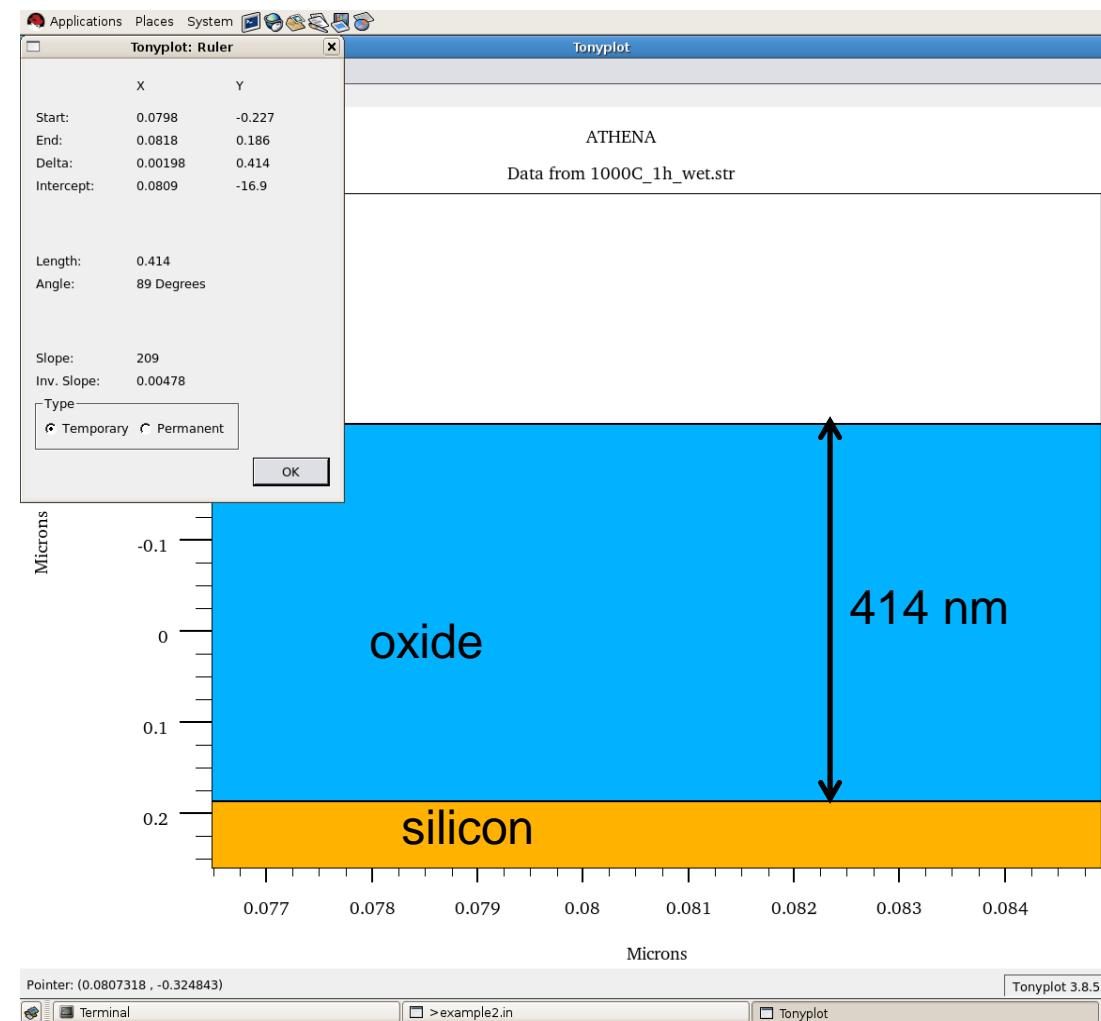
go athena simflag = "-P 2"
# mesh define
line x loc=0.00 spac=0.10
line x loc=0.5 spac=0.10
line y loc=0.00 spac=0.002
line y loc=0.25 spac=0.002
line y loc=0.5 spac=0.005
line y loc=20 spac=1

# init wafer

init silicon c.phosphor=5.5e11 orientation=100 two.d
method two.dim grid.oxide=0.002 gridinit.ox=0.001
#
diffus time=60 temp=1000 weto2
# nous pouvons lever l'oxide:
# etch oxide all

struct outfile=1000C_1h_wet.str
tonyplot 1000C_1h_wet.str

quit
  
```



Problème I:

Le wafer est *n*-type mais nous le trouvons *p*-type après l'oxydation

```

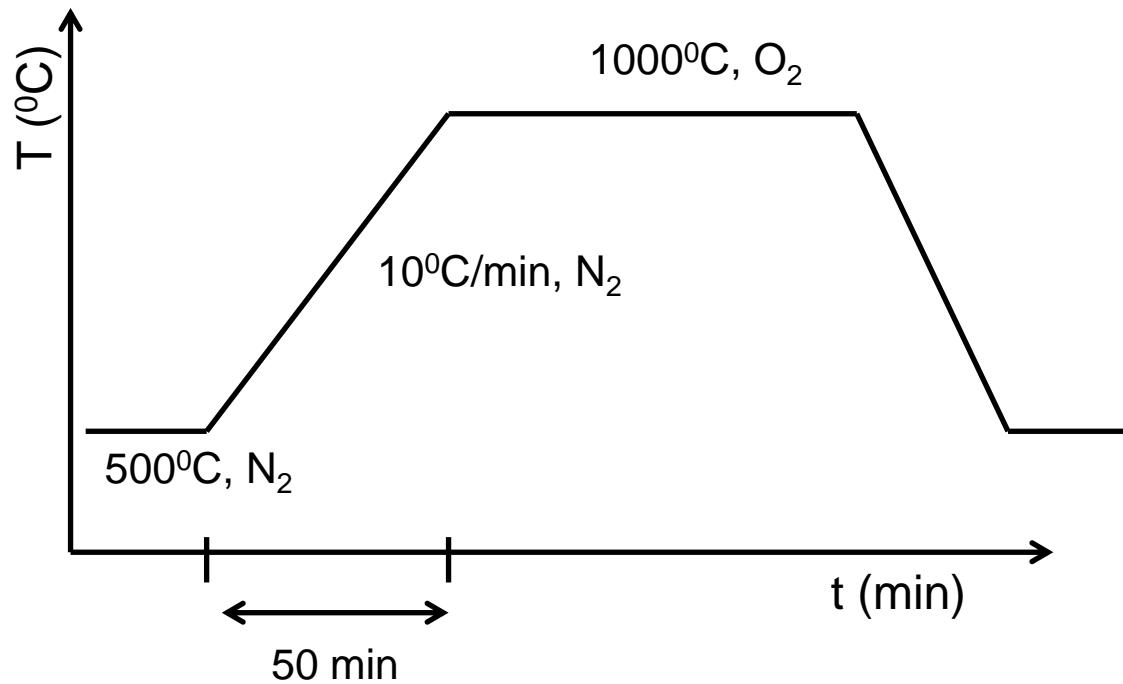
go athena simflag = "-P 2"
# mesh define
line x loc=0.00 spac=0.10
line x loc=0.5 spac=0.10
line y loc=0.00 spac=0.002
line y loc=0.25 spac=0.002
line y loc=0.5 spac=0.005
line y loc=20 spac=1

# init wafer
init silicon c.phosphor=5.5e11 orientation=100 two.d
method two.dim grid.oxide=0.002 gridinit.ox=0.001
# la rampe
diffus time=50 temp=500 t.final=1000 nitro
# croissance de l'oxide
diffus time=120 temp=1000 dryo2

struct outf=oxidation.str

quit
  
```

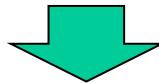
Pour faire croire l'oxide sur le silicon, on y fait une oxydation après une rampe, qui porte la fournaise à la correct température:



Problème I

Partant de la normal oxidation:

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



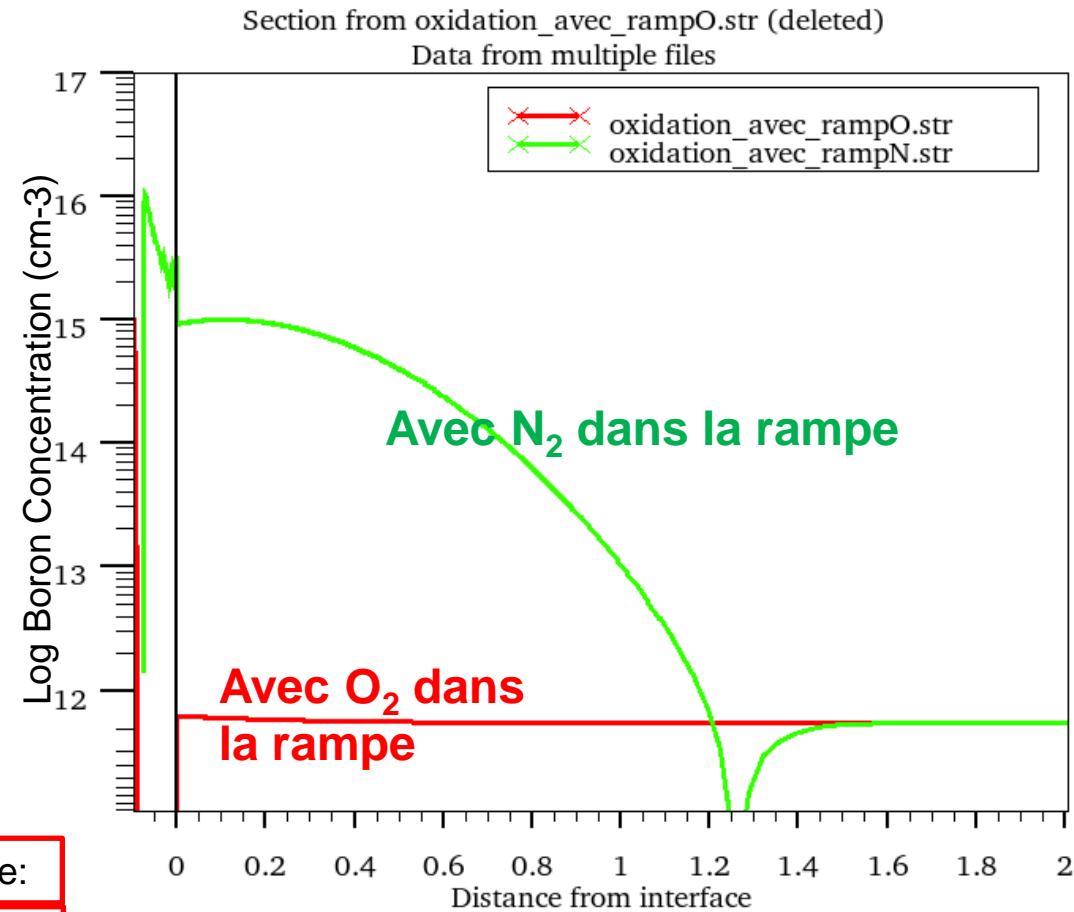
Nous pouvons penser qu'il y a une contamination de boron dans la fournaise (seulement 1 ppm):

```
#  
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
```



Nous la faisons inoffensive avec O₂ dans la rampe:

```
#  
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
```



Pas d'inversion!

Problème II:

Nous n'avons pas de contact parmi un *p*-poly et un *p*-silicon

```

go athena simflag = "-P 2"
# mesh define
line x loc=0.00 spac=0.10
line x loc=0.5 spac=0.10
line y loc=0.00 spac=0.002
line y loc=0.25 spac=0.002
line y loc=0.5 spac=0.005
line y loc=20 spac=1

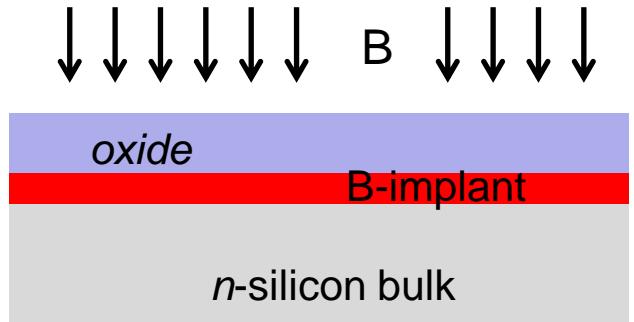
# init wafer

init silicon c.phosphor=5.5e11 orientation=100 two.d
method two.dim grid.oxide=0.002 gridinit.ox=0.001
#
deposit oxide thick=0.1
#
implant boron dose=1e15 energy=20 rotation=0 tilt=7 amorph
#
etch oxide all
#
deposit polysilicon thick=0.50 divisions=100
#
implant bf2 dose=1e14 monte energy=50 rotation=0 tilt=7 amorph
#
diffus time=20 temp=800 nitro
#
struct outfile=800C_20min.str
tonyplot 800C_20min.str

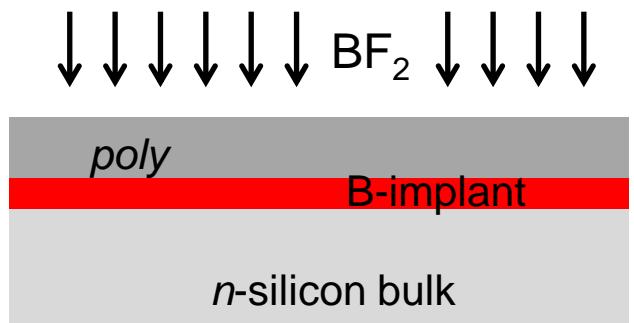
quit
  
```

(a) {
 (b) {
 (c) {

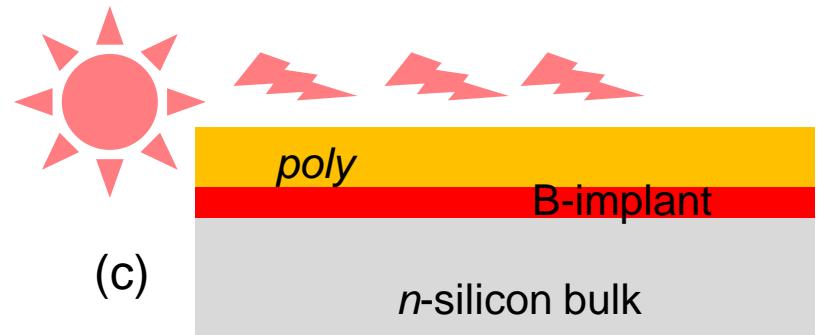
(a)



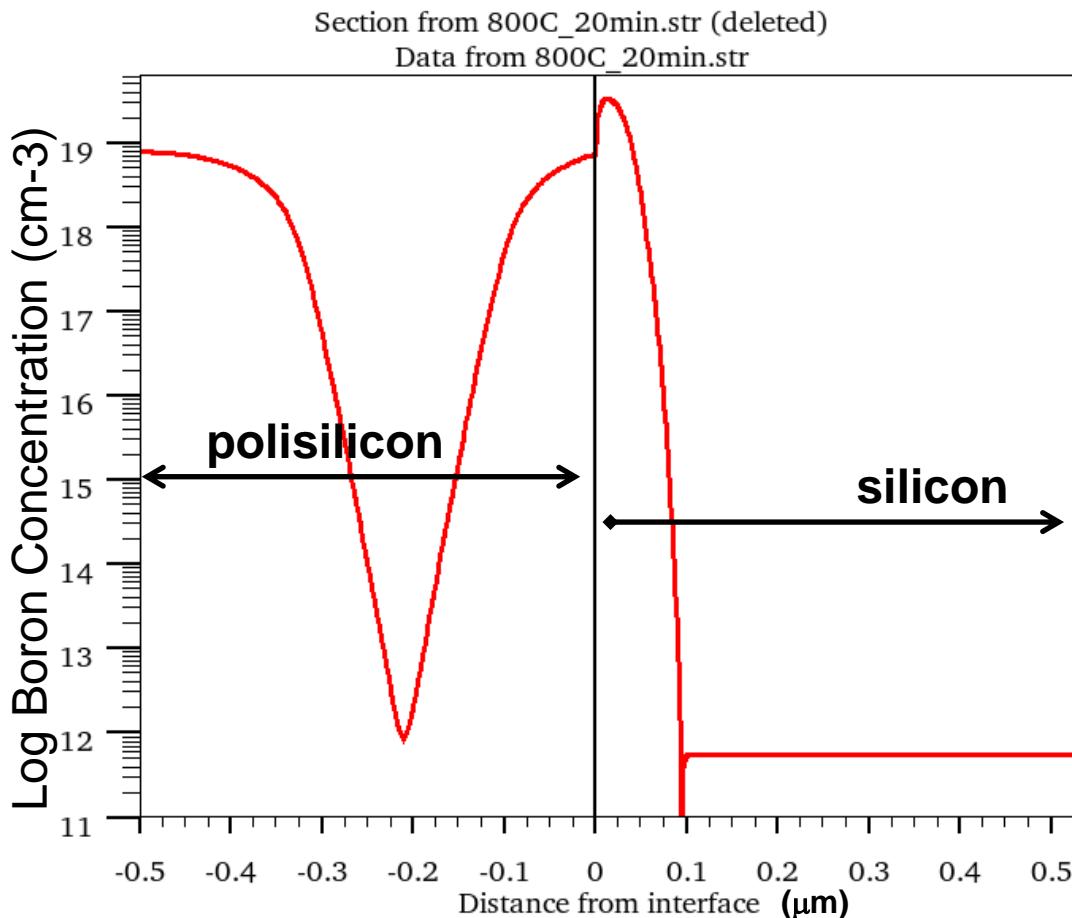
(b)



(c)

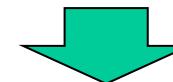


Problème II: nous avons mesure' que il n'y a pas de contact !
 → La simulation nous dit que le poly n'a pas assez de B dans le polisilicon!



Essayons de changer la temperature et/ou la duree' de la diffusion:

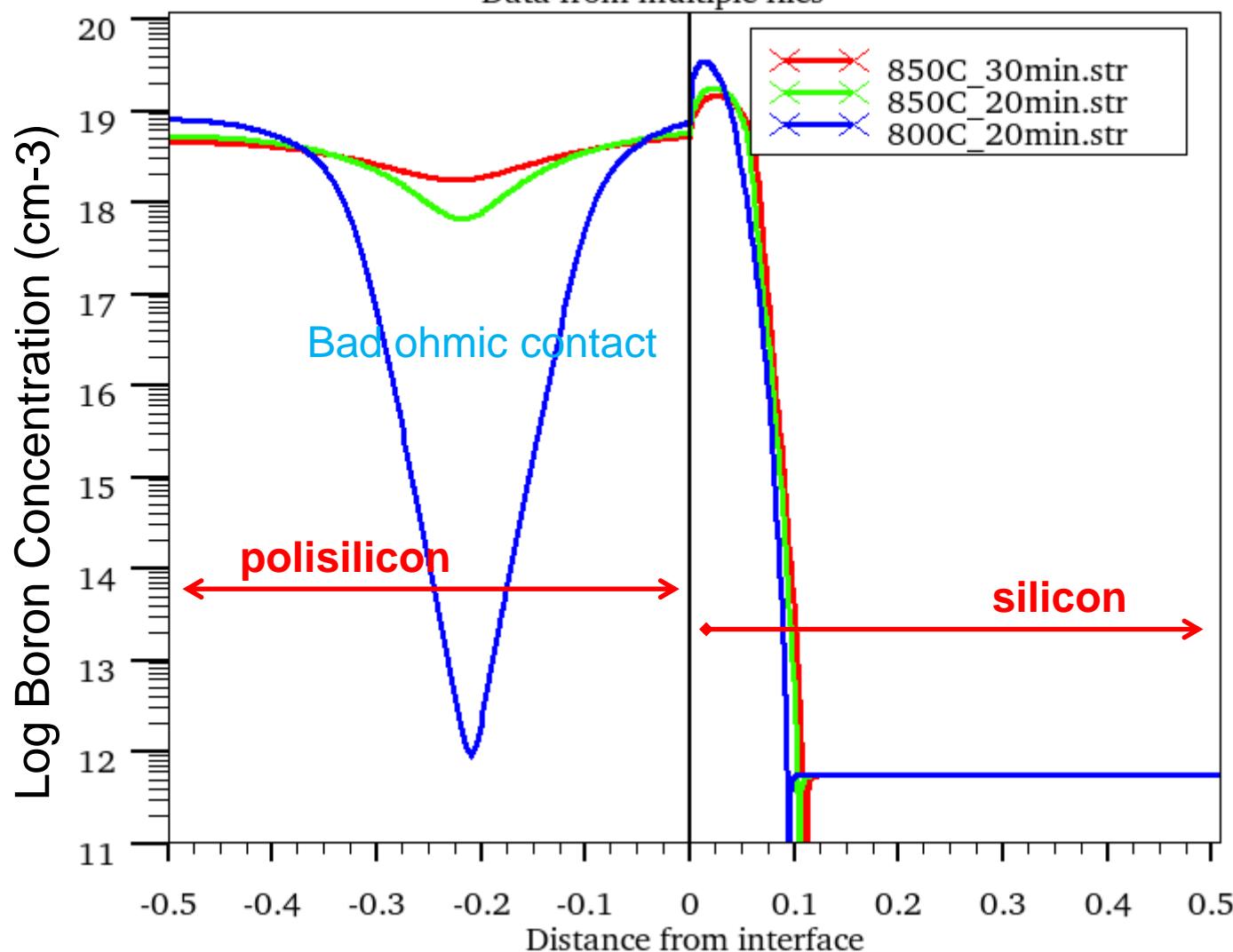
diffus time=20 temp=800 nitro



- A. diffus time=20 temp=850 nitro
- B. diffus time=30 temp=850 nitro

Problème II

ATHENA OVERLAY
 Data from multiple files



Anti Reflective Coating (ARC)

```

go atlas simflag="-P 2"
mesh space.mult=1.0
x.mesh loc=0.0 spacing=10.0
x.mesh loc=10.0 spacing=10.0
y.mesh loc=0.0 spacing=0.1
y.mesh loc=500.0 spacing=0.2
region num=1 material=Silicon
elec name=cathode bottom
doping uniform conc=1e14 n.type
# define a beam (be sure to include REFLECT parameter)
beam num=1 x.origin=5.0 y.origin=-260.0 angle=90.0 \
    front.refl reflect=5 min.w=-2 max.w=2 \
    min.power=0.001

# define anti-reflective coating
# layer 1 is top layer
# layer 2 is underneath layer 1

#nitride
interface optical material=nitride ar.thick=0.02 coating=1 layer=1
#oxide
interface optical material=oxide ar.thick=0.02 coating=1 layer=2

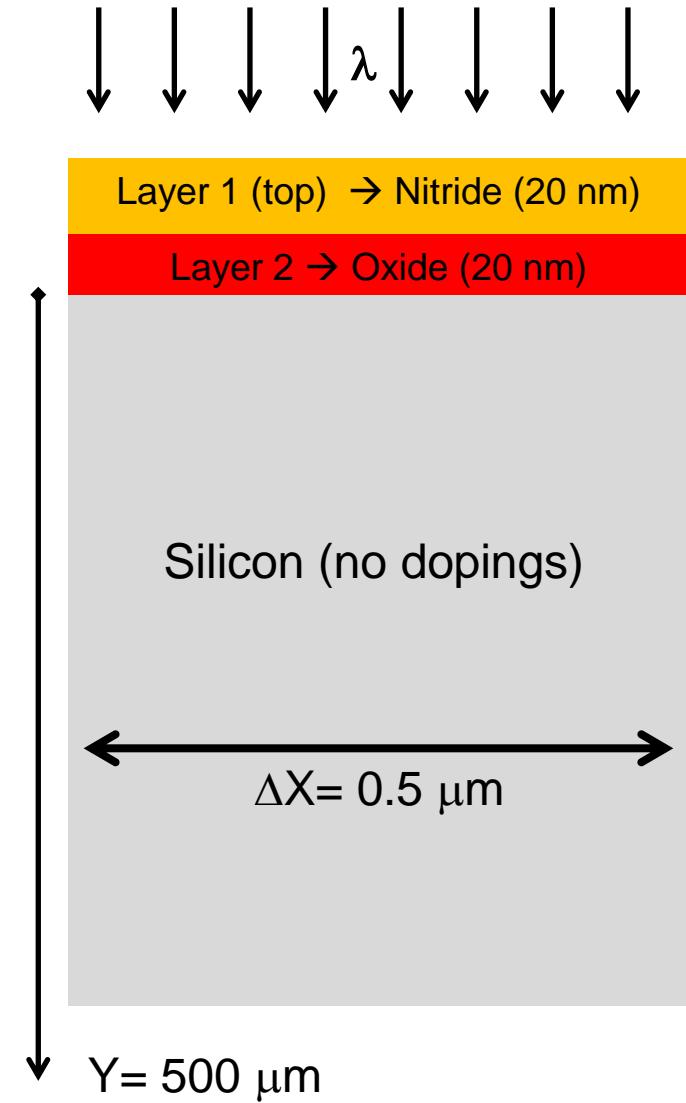
solve init

log outf=ARC.log

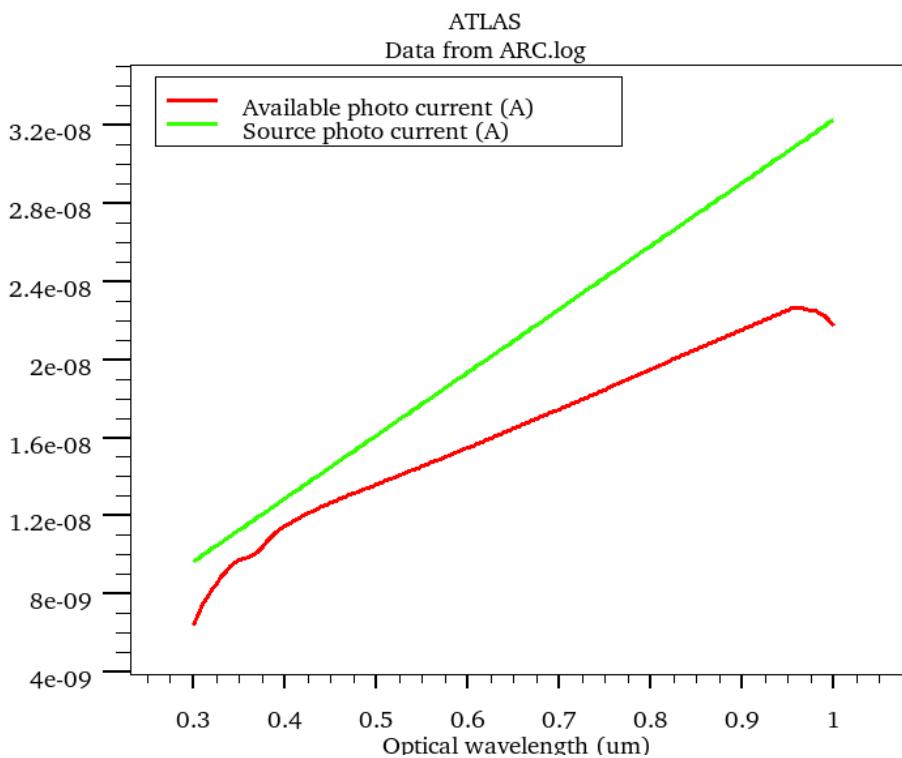
solve b1=1 lambda=0.3 index.check
solve b1=1 lambda=0.305 index.check
solve b1=1 lambda=0.31 index.check
# and so on ...
Solve b1=1 lambda=0.99 index.check
solve b1=1 lambda=0.995 index.check
solve b1=1 lambda=1 index.check

quit

```

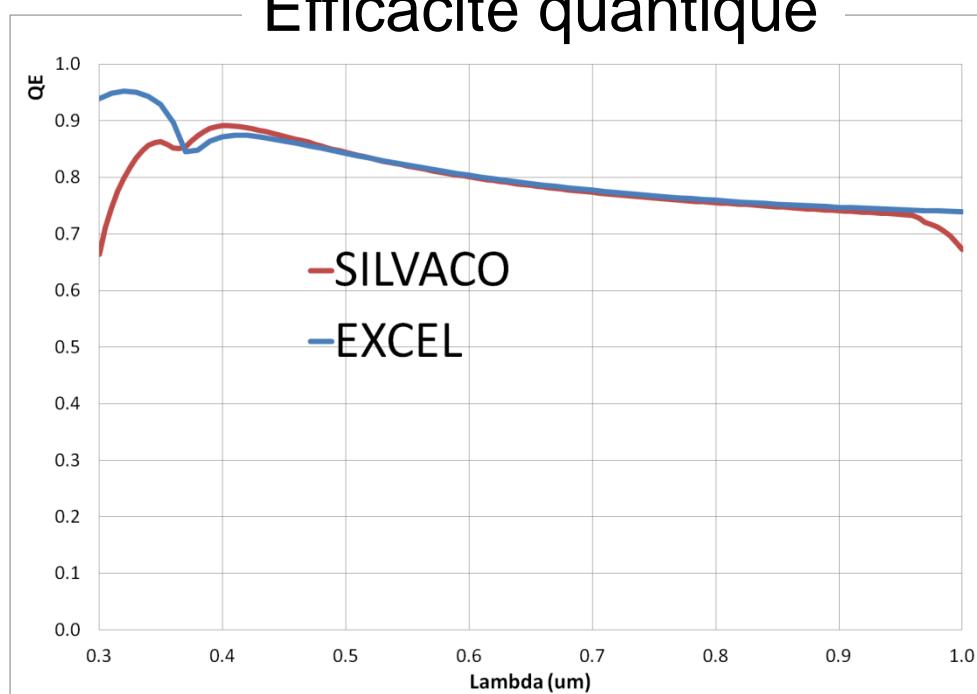


Anti Reflective Coating (ARC)



QE = $\frac{\text{available photo current}}{\text{source photo current}}$

Efficacité quantique



Excel se trompe:
il ne considère pas les
nombres complexes

Implantation ionique

```

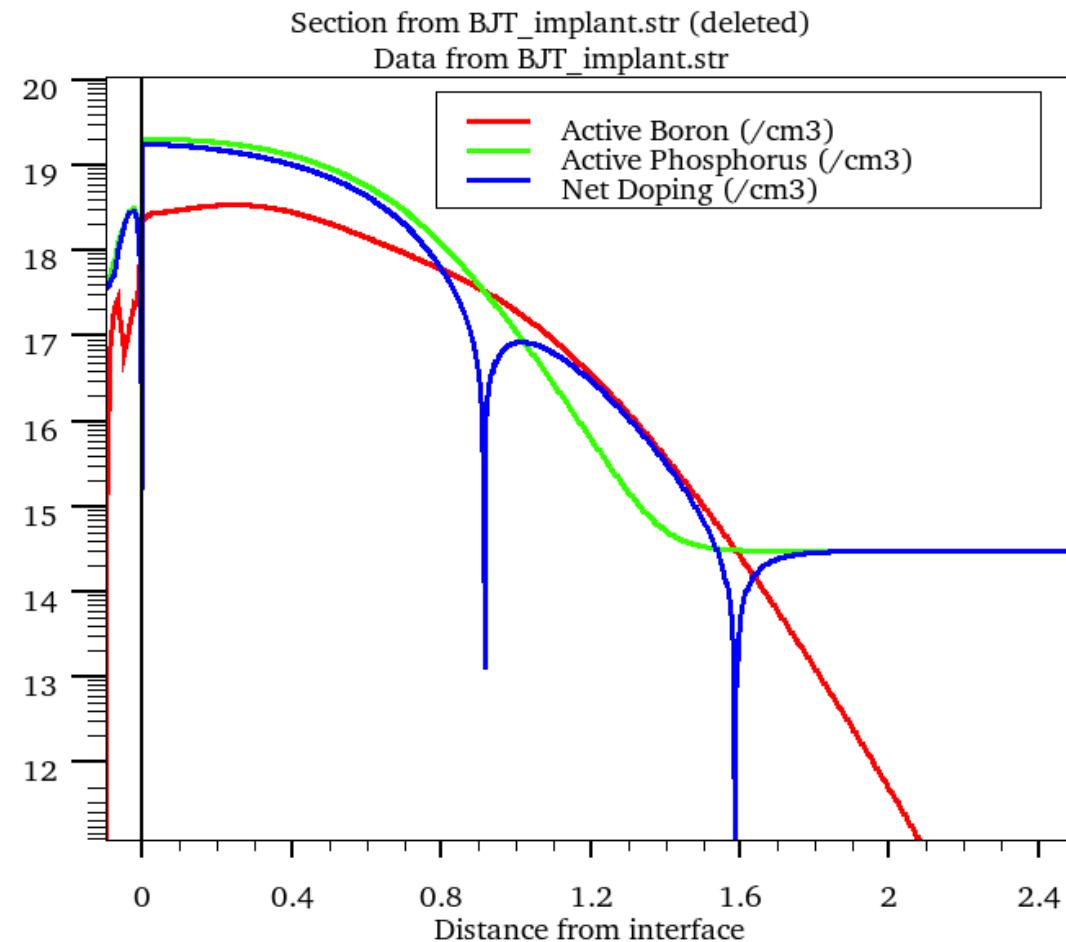
go athena simflag = "-P 2"

# mesh define
line x loc=0.00 spac=0.10
line x loc=0.5 spac=0.10
line y loc=0.00 spac=0.002
line y loc=0.25 spac=0.002
line y loc=0.5 spac=0.005
line y loc=4 spac=0.01
line y loc=20 spac=1

# init wafer
init silicon c.phosphor=3e14 orientation=100 two.d
method two.dim grid.oxide=0.002 gridinit.ox=0.001
#
deposit oxide thick=0.1
#
implant boron dose=2e14 energy=130 monte rotation=0 tilt=7 amorph
#
diffus time=35 temp=1050 nitro
implant phosphor dose=1e15 energy=200 monte rotation=0 tilt=7 amorph
#
diffus time=90 temp=1050 nitro
diffus time=20 temp=900 nitro
#etch oxide all
struct outfile=BJT_Implant.str

quit

```



Implantation ionique

Comment utiliser le profile dans Devedit - I

```

go athena simflag = "-P 2"

# mesh define
line x loc=0.00 spac=0.10

line x loc=0.5 spac=0.10
line y loc=0.00 spac=0.002

line y loc=0.25 spac=0.002

line y loc=0.5 spac=0.005
line y loc=4 spac=0.01
line y loc=20 spac=1

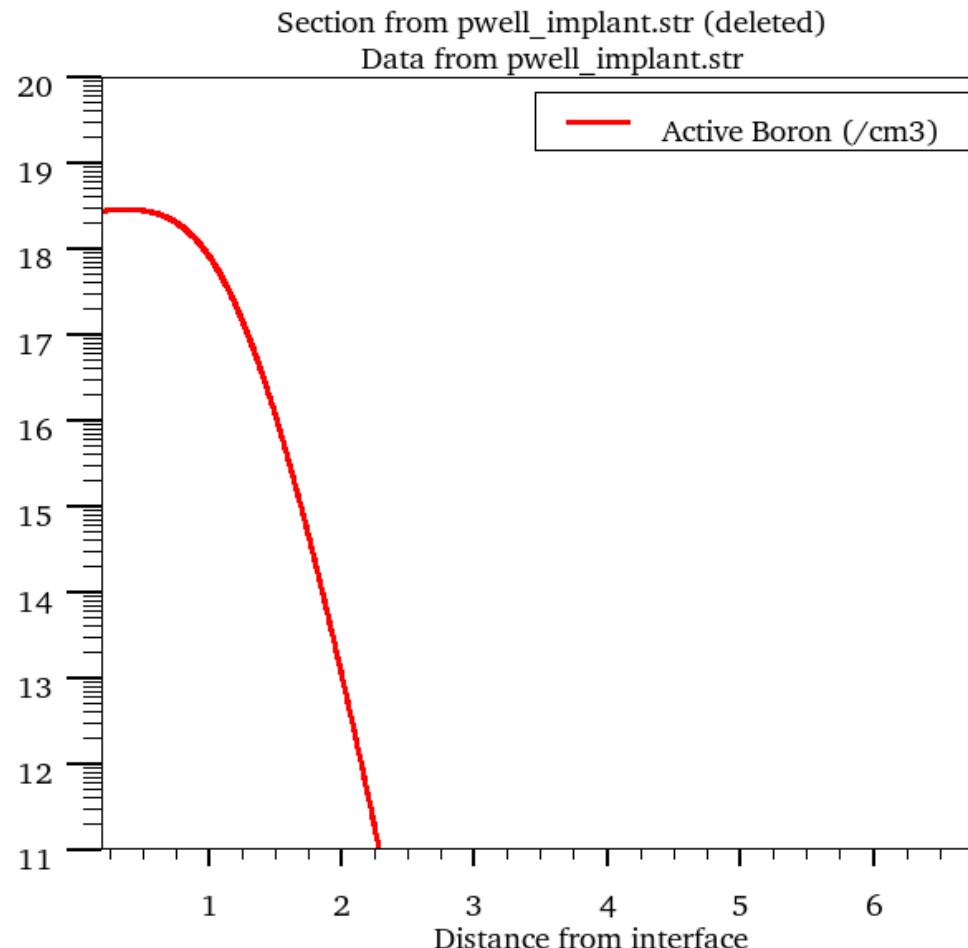
# init wafer
init silicon c.phosphor=3e14 orientation=100 two.d
method two.dim grid.oxide=0.002 gridinit.ox=0.001
#
deposit oxide thick=0.1
#
implant boron dose=2e14 energy=130 monte rotation=0 tilt=7 amorph
#
diffus time=35 temp=1050 nitro
#implant phosphor dose=1e15 energy=200 monte rotation=0 tilt=7 amorph
#
diffus time=90 temp=1050 nitro
diffus time=20 temp=900 nitro
etch oxide all

extract name="boron" sheet.res material="Silicon" mat.occno=1 x.val=0.2 \
region.occno=1

struct outfile=pwell_Implant.str

quit

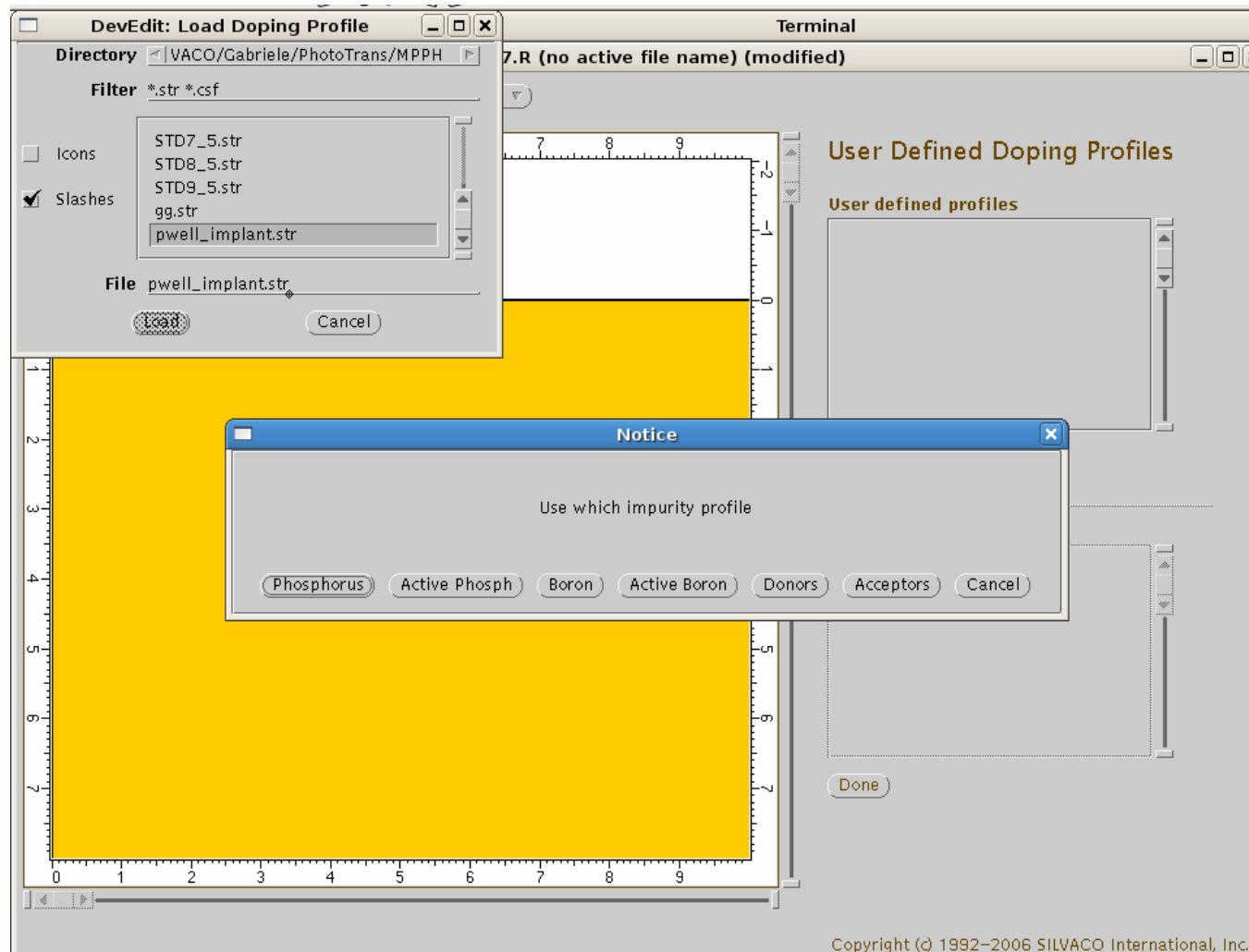
```



Pendant la fabrication, nous pouvons mesurer la "sheet resistance" de l'implantation

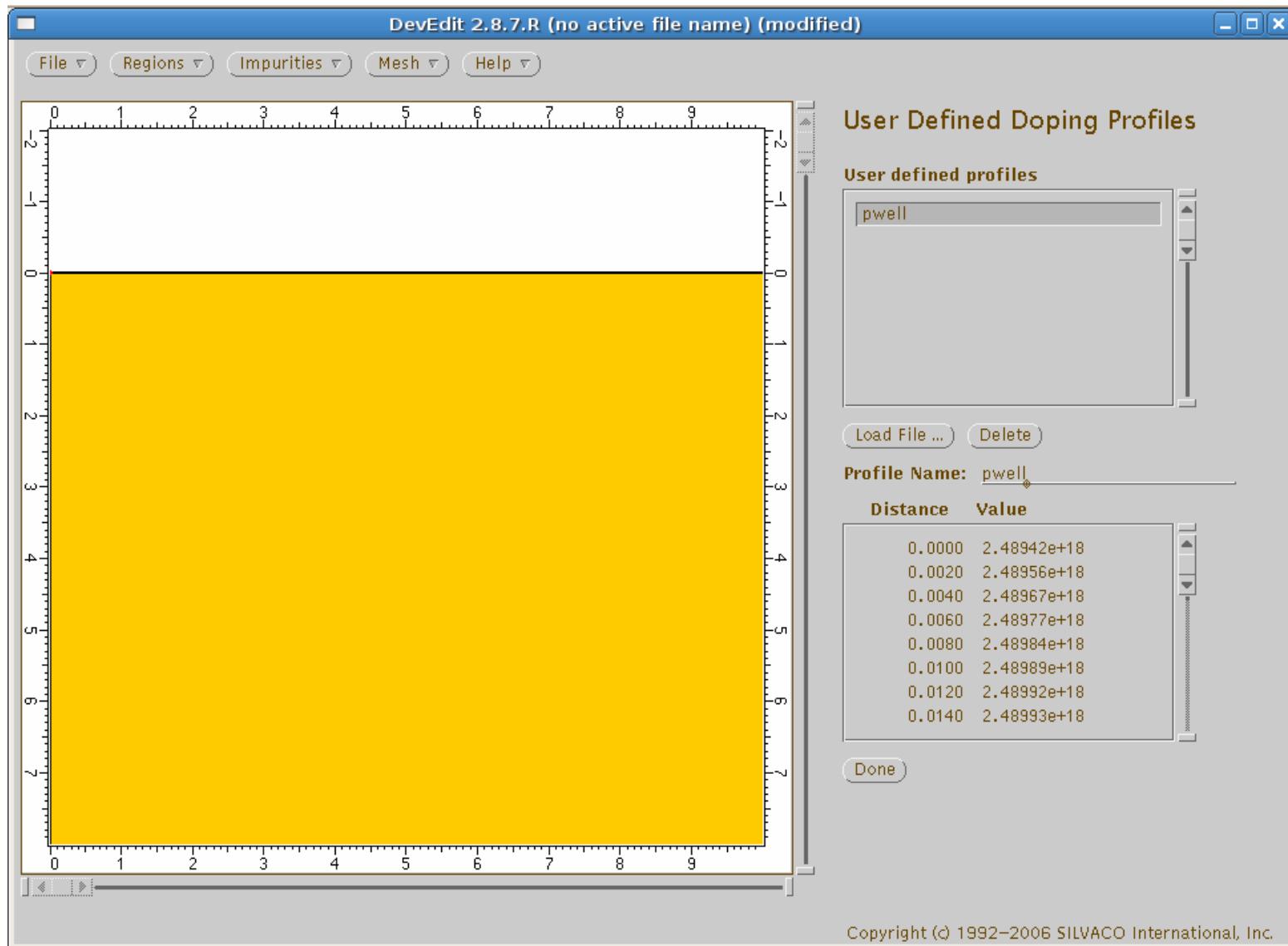
Implantation ionique

Comment utiliser le profile dans Devedit - II
 Impurities → Doping Profiles → Load ...



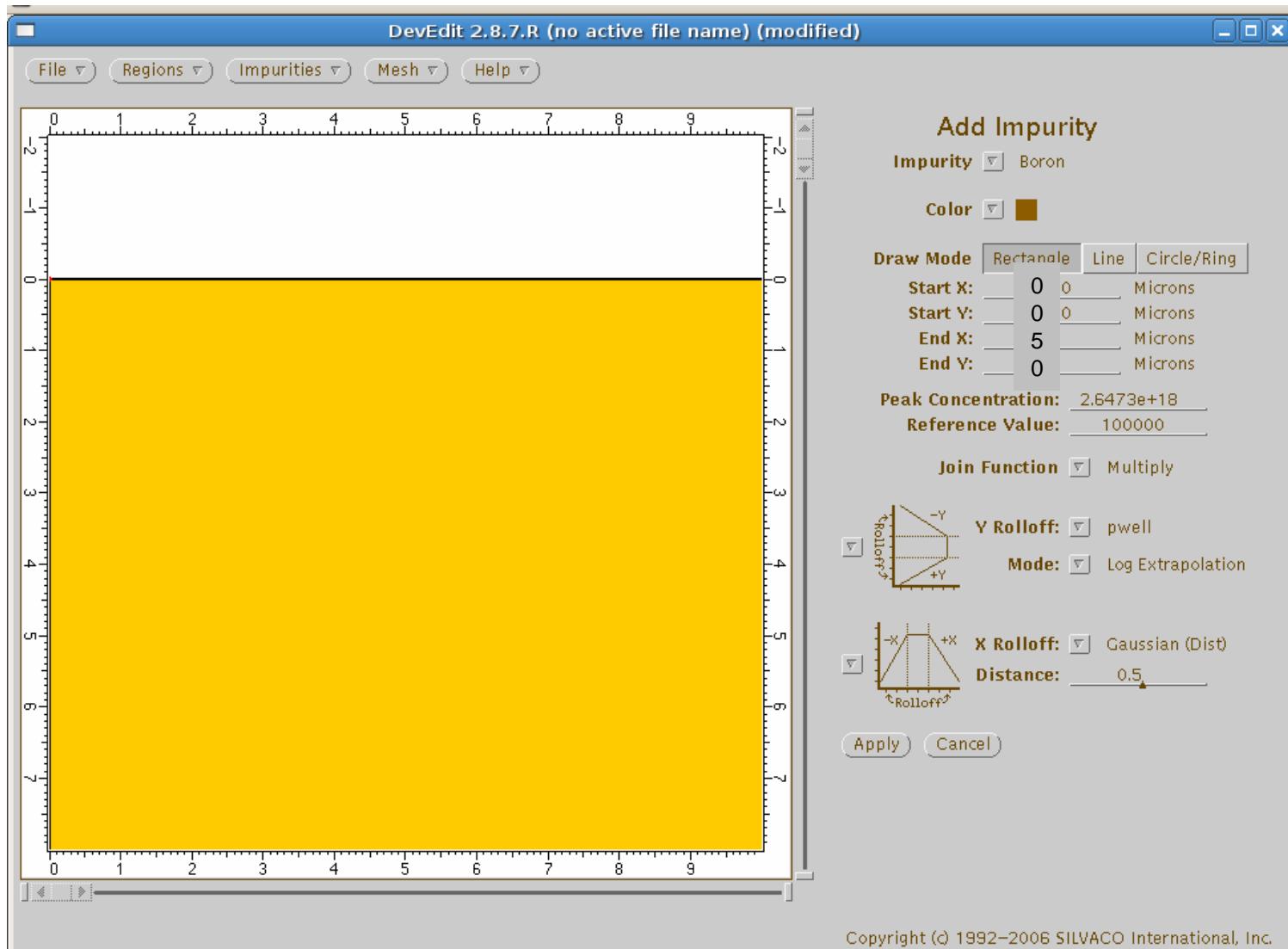
Implantation ionique

Comment utiliser le profile dans Devedit - III



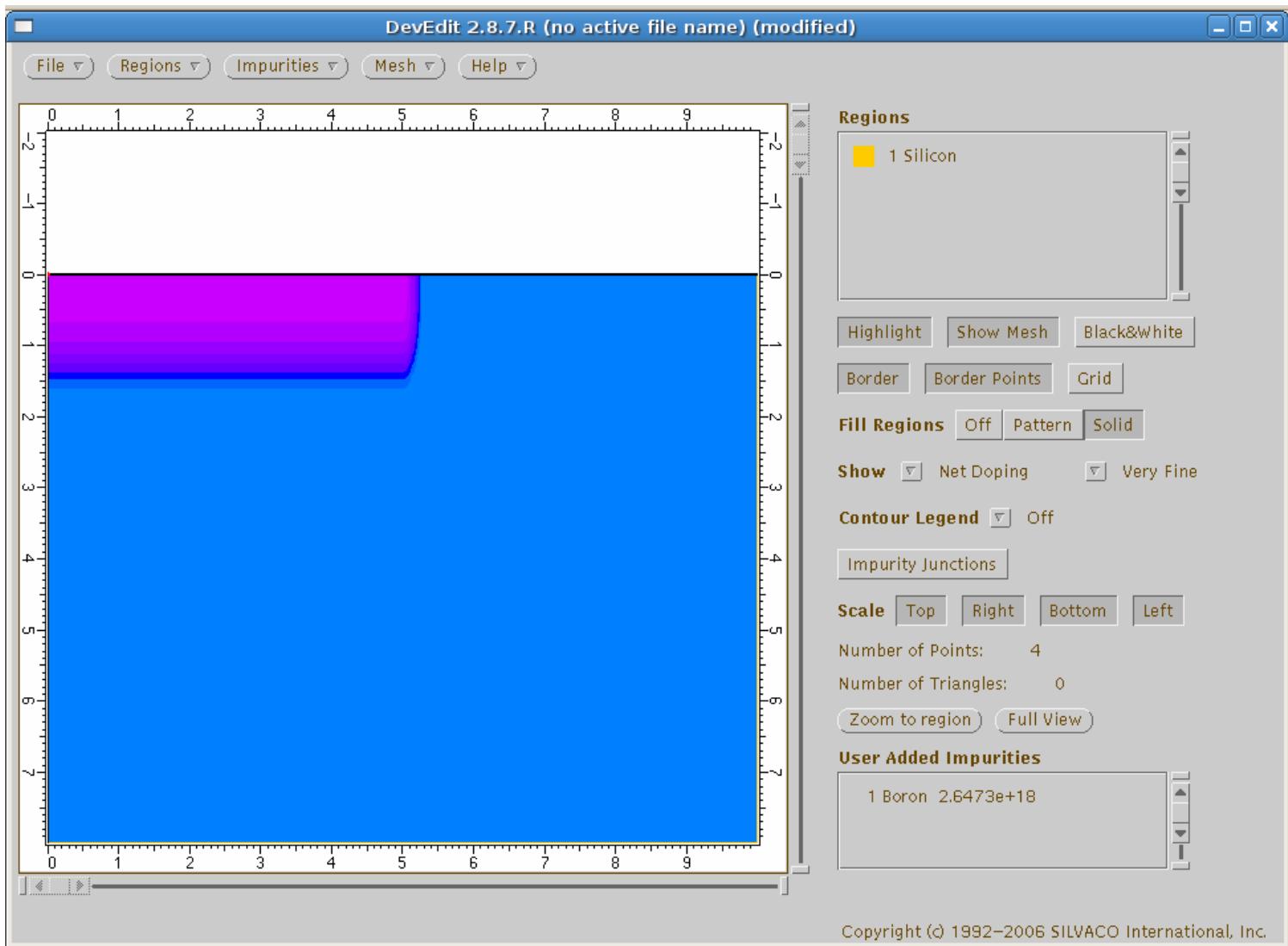
Implantation ionique

Comment utiliser le profile dans Devedit - IV



Implantation ionique

Comment utiliser le profile dans Devedit - V



Simulations des parts de la fabrication:

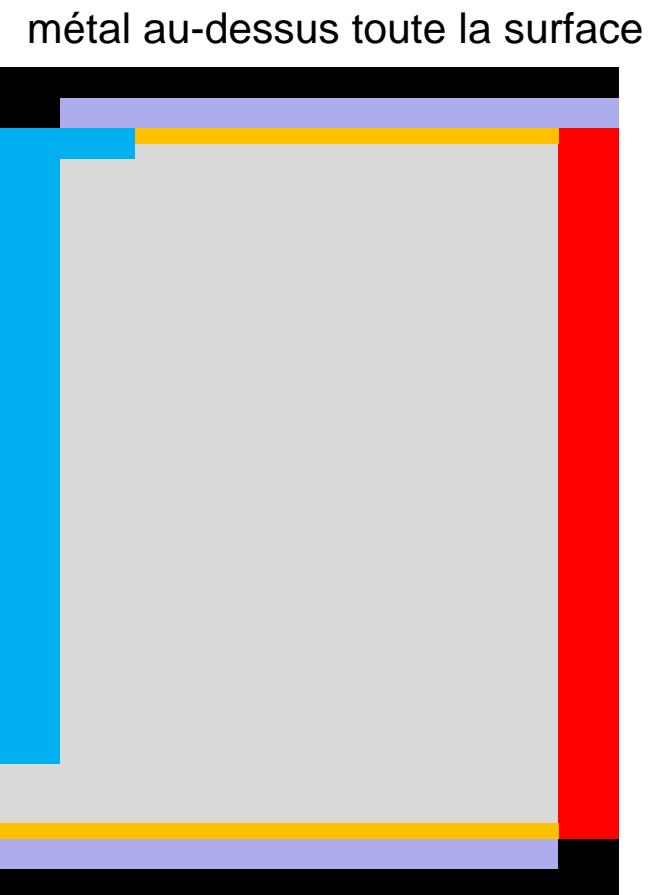
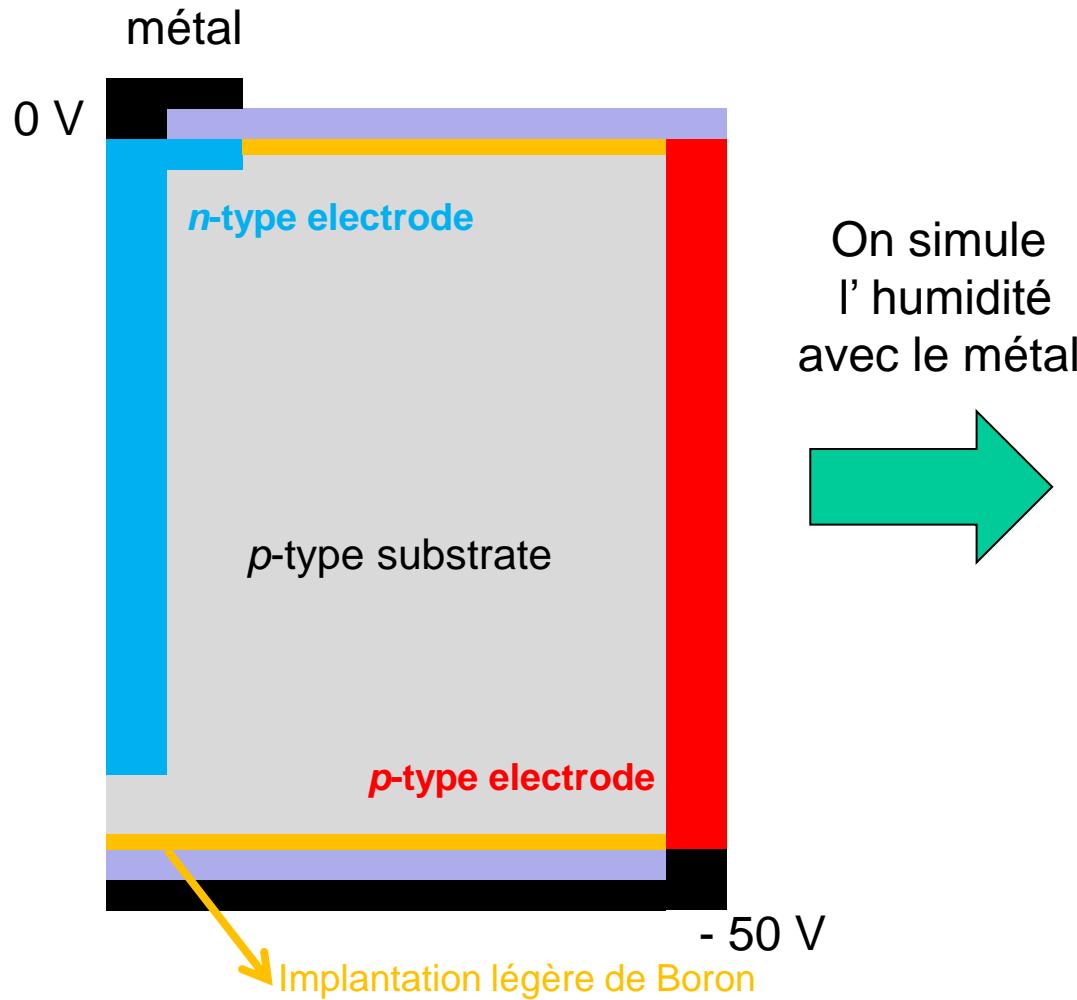
- oxidation and diffusion
 - exemple: deux problems a resoudre
- ARC
- Implantation 1D
 - comment l'utiliser dans DEVEDIT

Comportement des détecteurs

- explication de problèmes mesuré dans les détecteurs réels
 - exemple: effet de l' humidité
- développement des nouvelle détecteurs
 - exemple: XAMPS (transient)
- détermination des propriétés dynamiques
 - exemple: temps de dérive des électrons dans une SDD
- beaux images pour les publications
 - exemple: PT in SDD

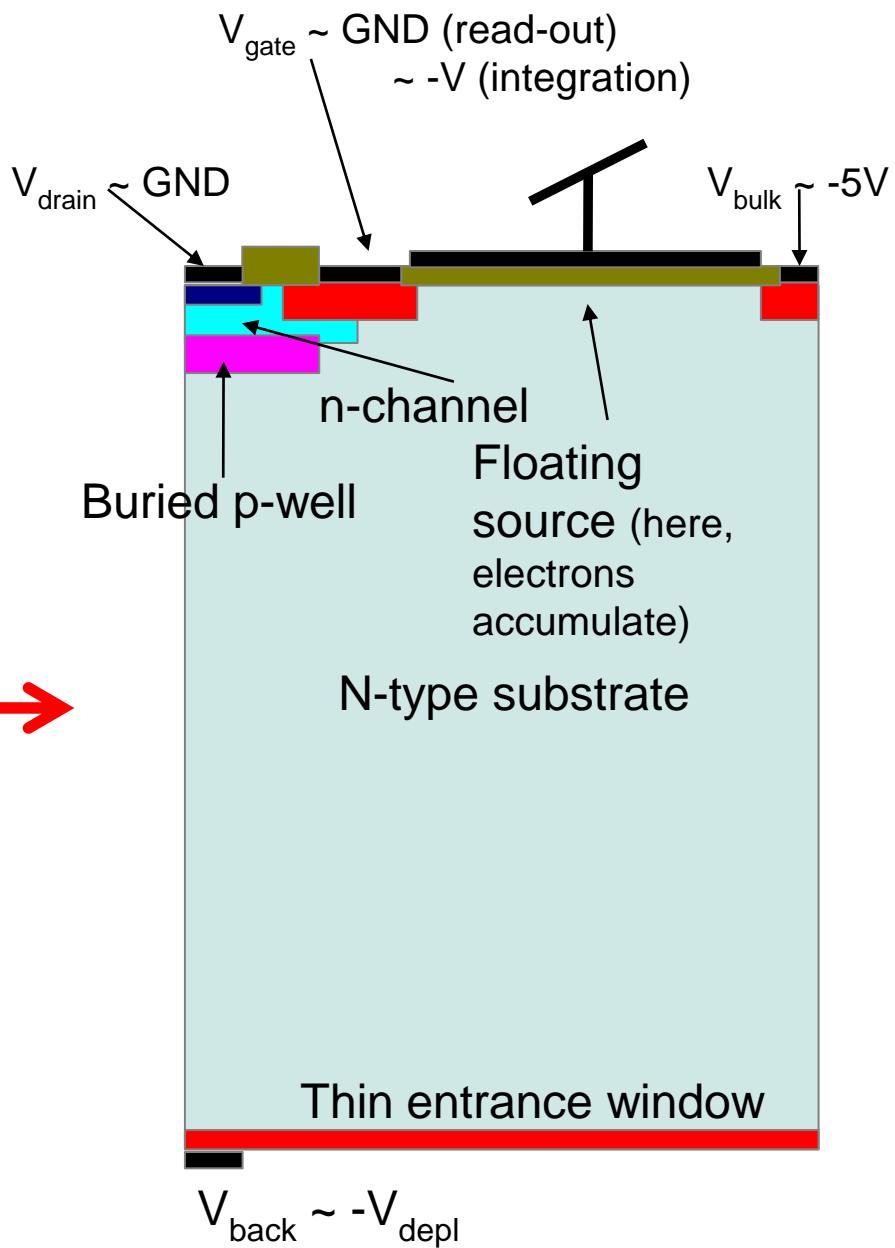
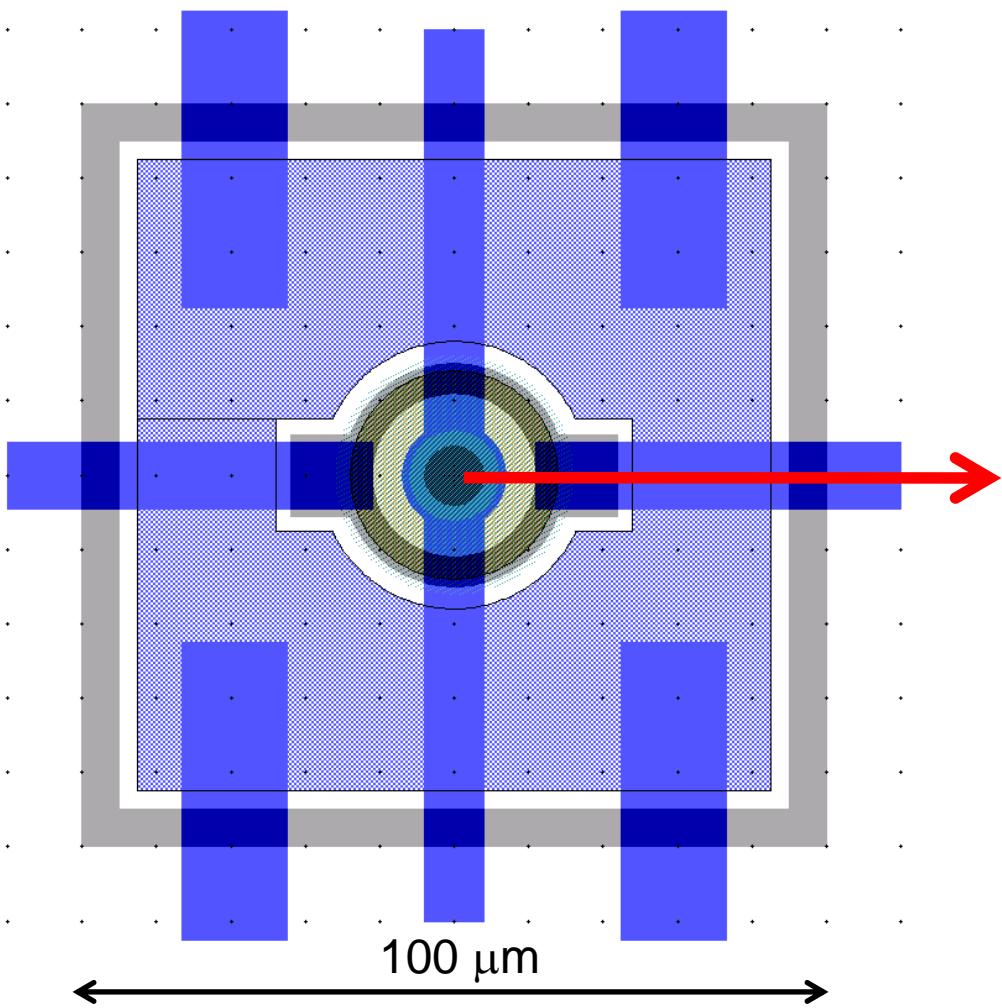
I - Effet de l' humidité dans un 3D

La courant dépend de l'humidité: avec une humidité élevée il y a un cassage



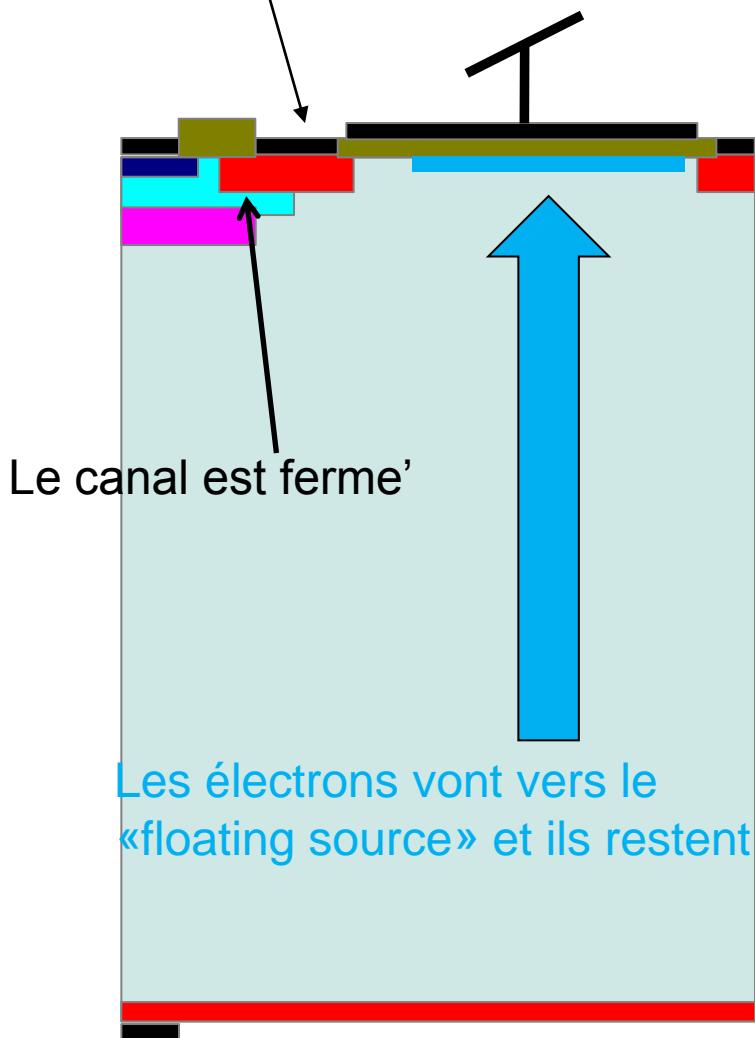
II - XAMPS (BNL)

→ un interrupteur

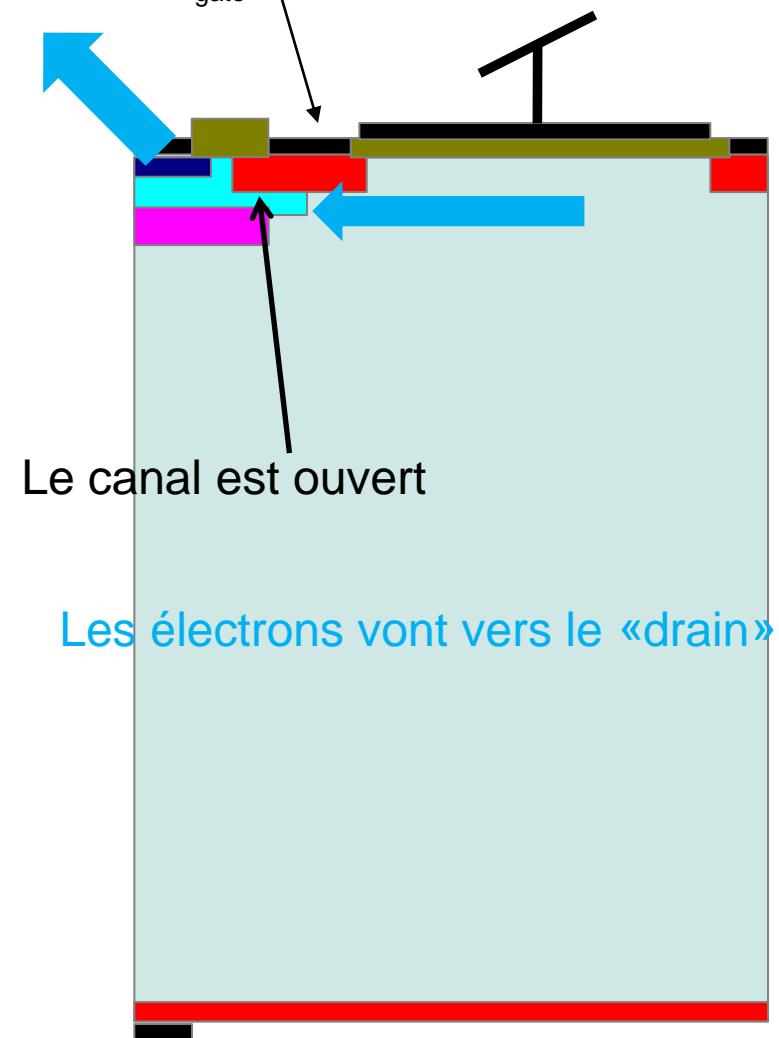


Le détecteur travaille en 2 manières

$V_{gate} \sim -10\text{ V}$ (integration)



$V_{gate} \sim \text{GND}$ (lecture)



II - XAMPS

go atlas simflag="-P 2"

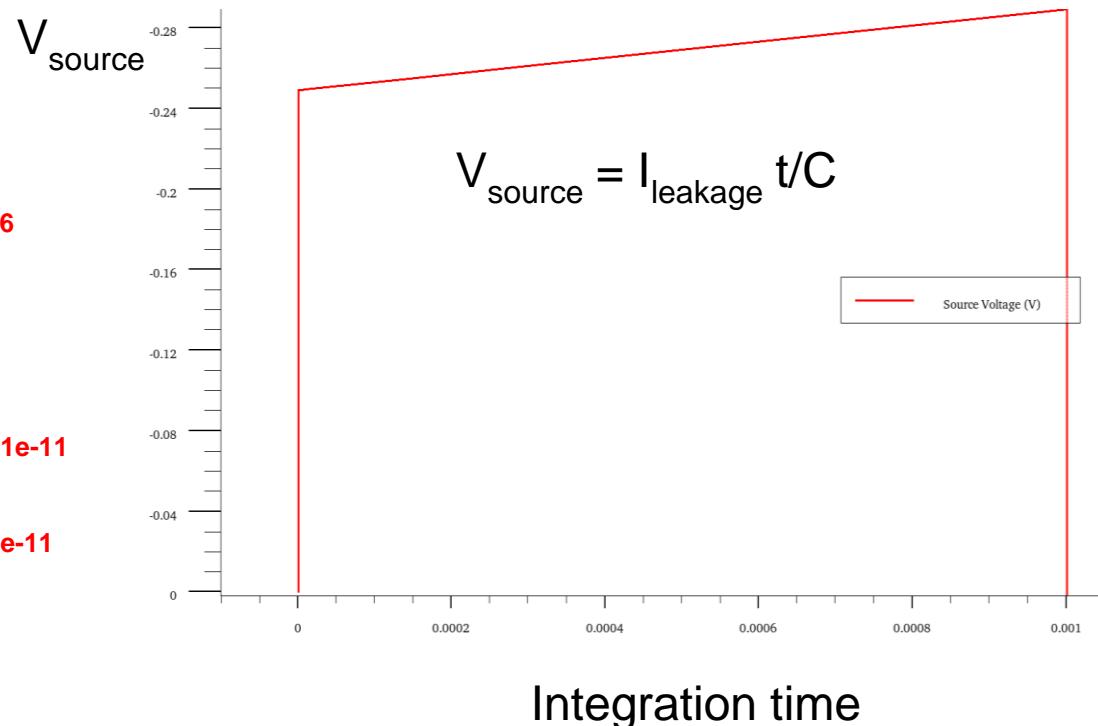
mesh infile=XAMPS.str cylindrical

```

contact name=drain neutral
contact name=gate neutral
contact name=bulk neutral
contact name=substrate neutral
contact name=source current
contact name=collector neutral
#
material region=1 taun0=1e-4 taup0=1e-4
interface qf=3e11
models bipolar
#
method newton
solve init
#
solve vsubstrate=0 vstep=-5 vfinal=-75 name=substrate
solve vbulk=0 vstep=-1 vfinal=-10 name=bulk
solve vgate=0 vstep=-1 vfinal=-2 name=gate AC freq=1e6
#
log outf=XAMPS_transient.log
#
solve vgate=-2 ramptime=1e-6 tstop=1e-6 tstep=1e-11
save outf=XAMPS_AT_1us.sta
#
solve vgate=-10 ramptime=1e-8 tstop=1.001e-3 tstep=1e-11
save outf=XAMPS_AT_1ms.sta
#
solve vgate=-2 ramptime=1e-8 tstop=1.002e-3 tstep=1e-11
#
quit

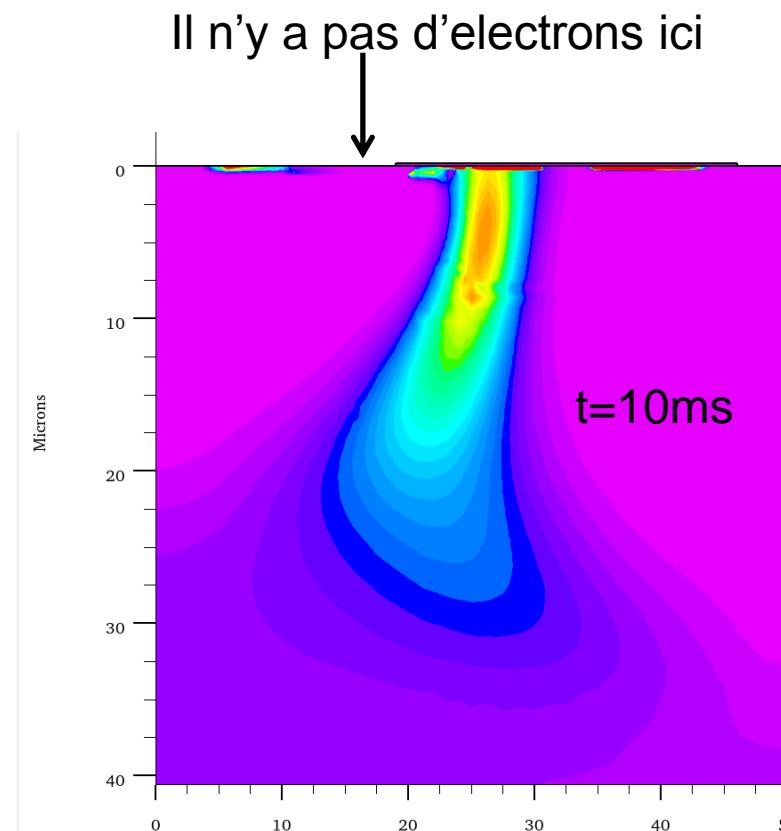
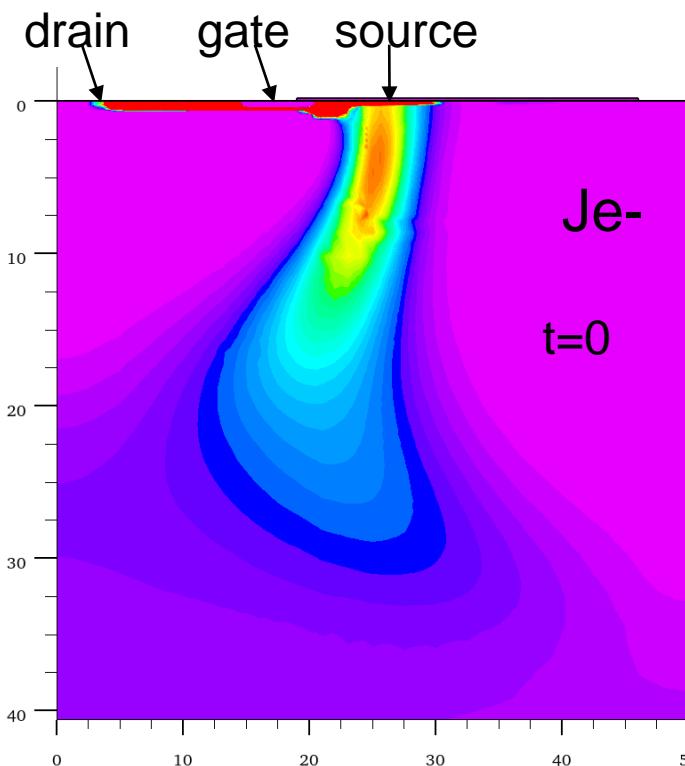
```

- @ $t=0$, $V_{\text{gate}} = -2 \text{ V}$ et le canal est ouvert:
→ La “source” est à GND, comme le drain
- @ $t>0$, $V_{\text{gate}} \sim -10 \text{ V}$ et le canal est fermé:
→ la courant reste dans le source



II - XAMPS

Dans une situation stationnaire, les électrons ne peuvent pas rester dans la source mais il doivent aller dans le drain: ils ont fait la source assez négative qu'elle puisse ouvrir le canal.
 → La simulation doit être un transient



III – Temps de dérive dans une SDD

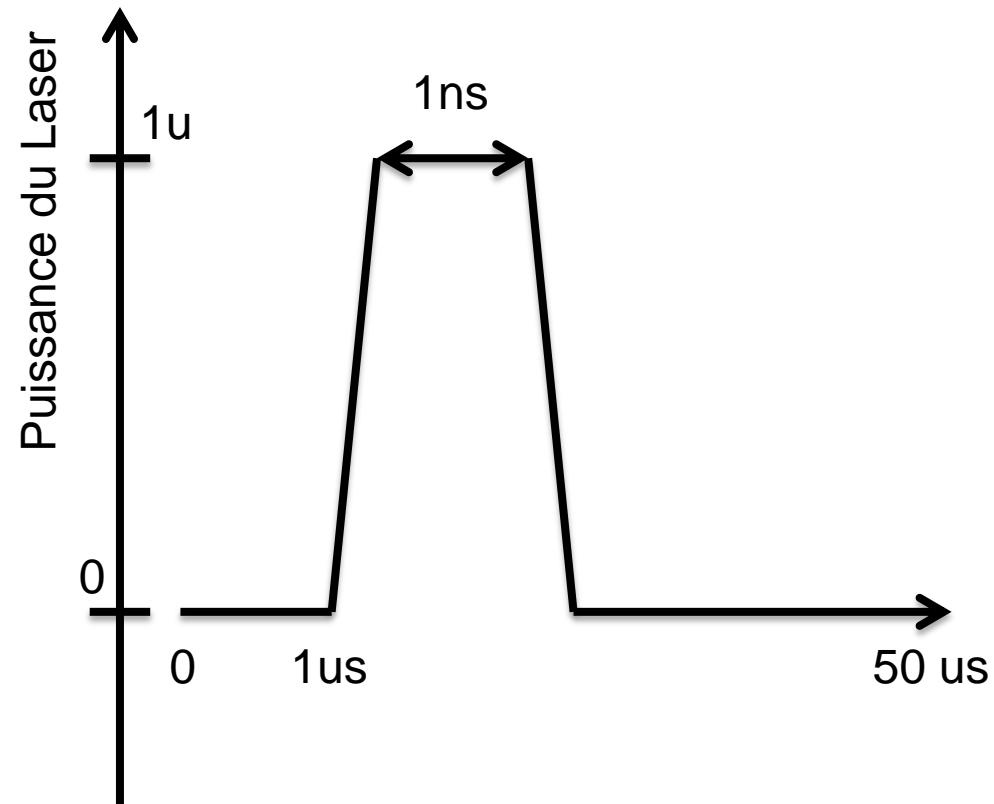
```

go atlas simflag="-P 2"
mesh infile=SDD.str cylindrical
contact name=anode neutral
# other electrodes ...
contact name=cathode neutral
#
material region=1 taun0=1e-3 taup0=1e-3
#
models bipolar temp=250
method newton maxtraps=20

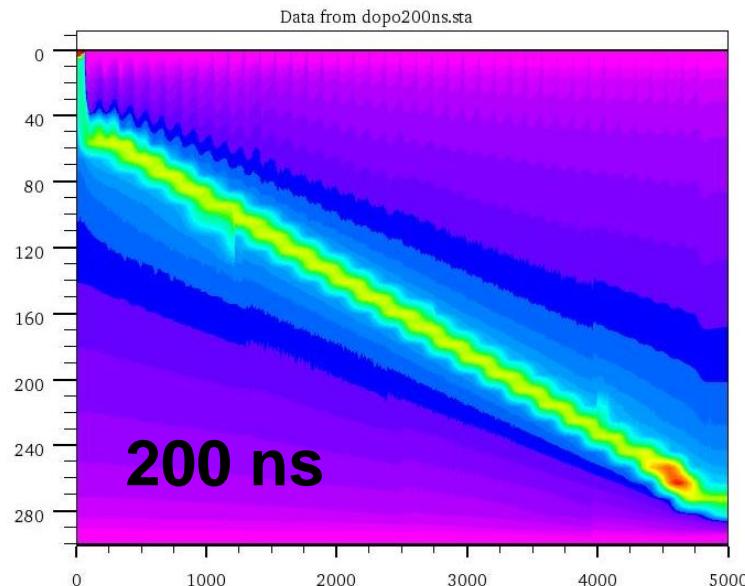
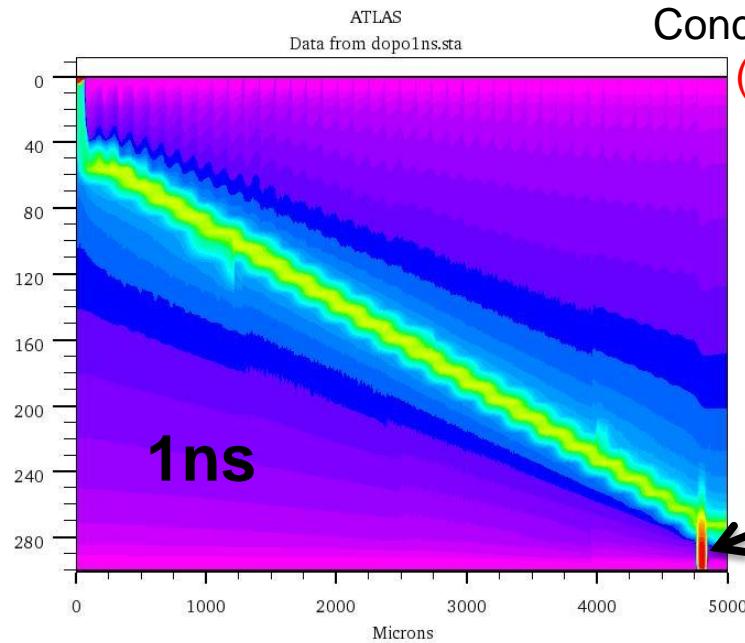
solve      init
solve vcathode=0 vstep=-2 vfinal=-134 name=cathode
outf=SDD_infile

# DEUXIEME simulation:
go atlas simflag="-P 2"
mesh infile=SDD.str cylindrical
contact name=anode neutral
# other electrodes ...
contact name=cathode neutral
#
material region=1 taun0=1e-3 taup0=1e-3
#
models bipolar temp=250
method newton maxtraps=20 dt.max=1e-8
#
beam num=1 x.origin=4800 y.origin=451 angle=270 xmin=-20 xmax=20 rays=200 → SDD est stimulé par un Laser
#
solve      init
load infile=SDD_infile

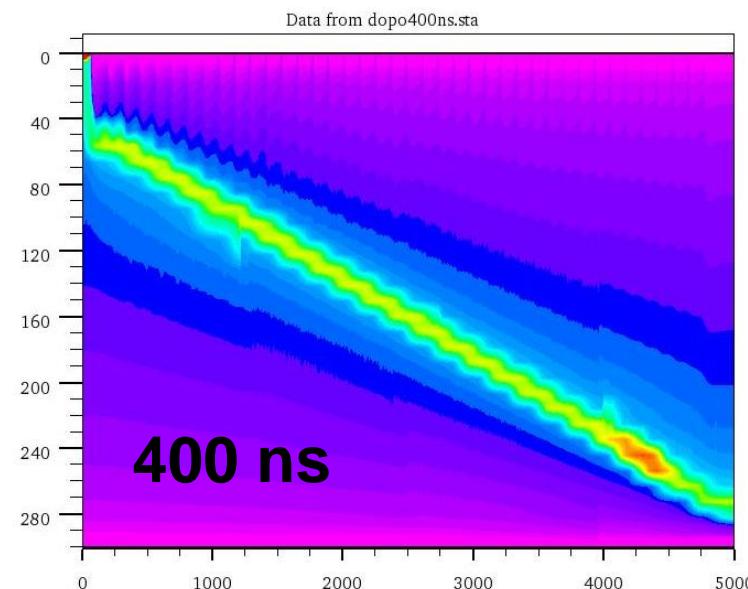
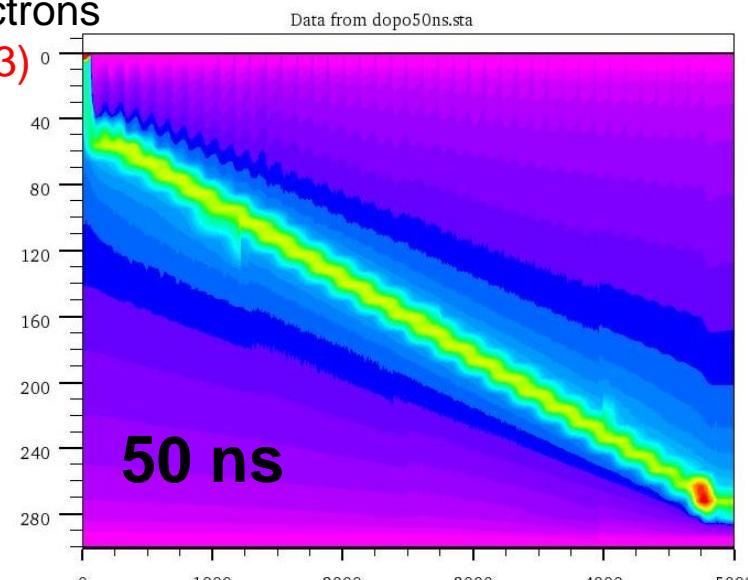
log outf=SDD_transient.log
solve B1=0 ramptime=1e-10 tstop=1e-6 tstep=1e-12
solve B1=1e-6 lambda=0.7 ramptime=1e-10 tstop=1.001e-6 tstep=1e-12
solve B1=0 ramptime=1e-10 tstop=50e-6 tstep=1e-15
quit
  
```



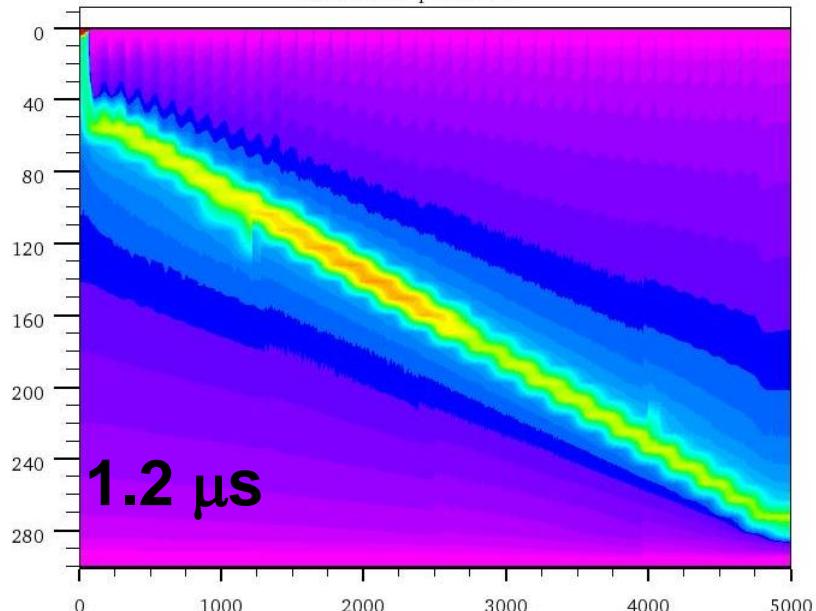
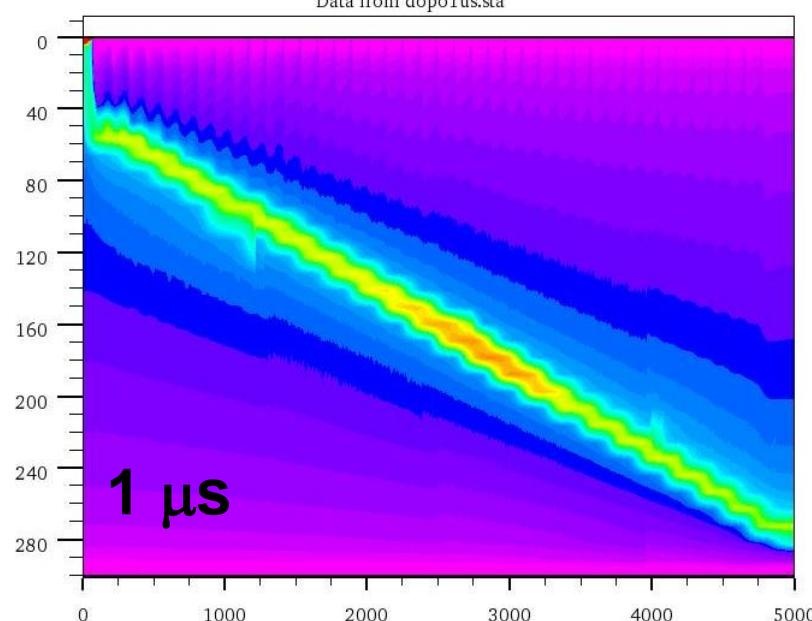
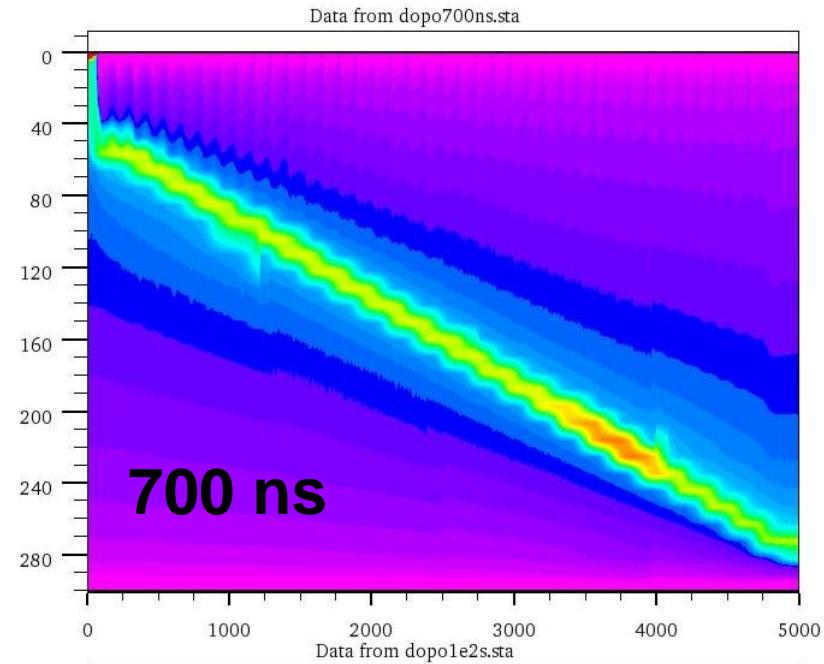
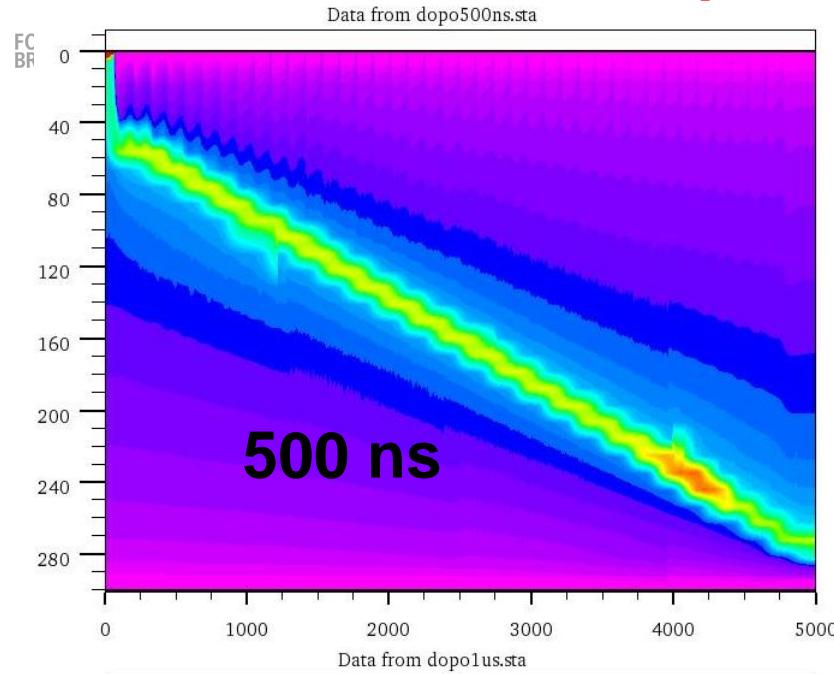
III – Temps de dérive dans une SDD



Concentration des électrons
(rouge = 1e-8 cm⁻³)

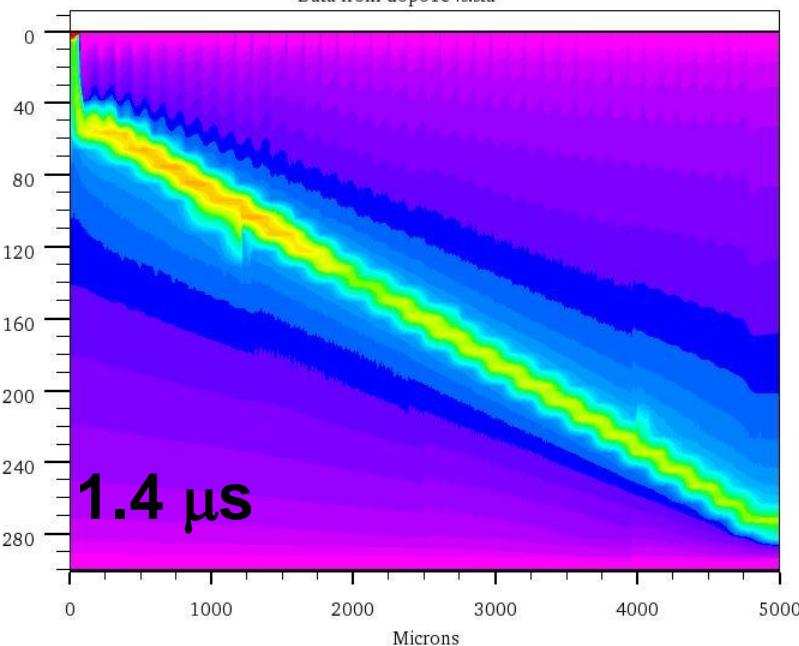


III – Temps de dérive dans une SDD

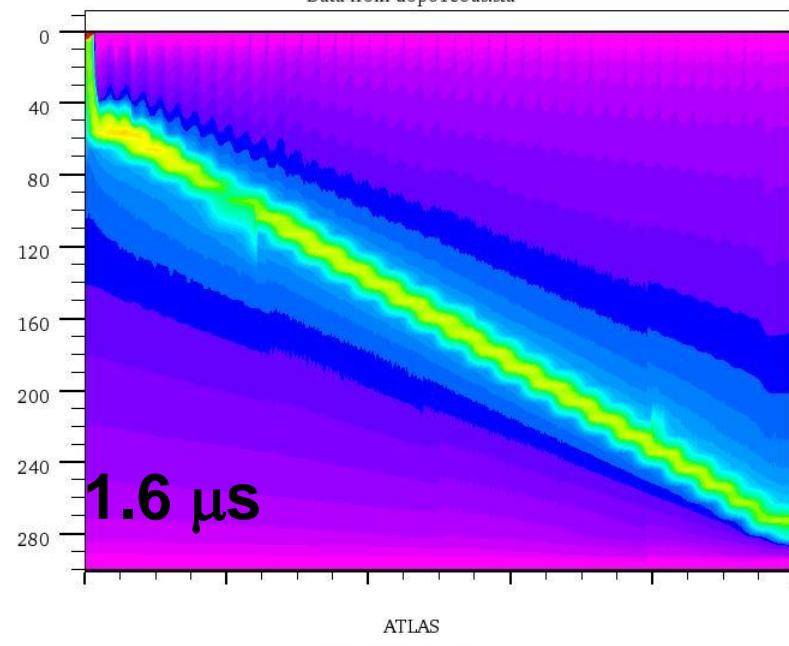


III – Temps de dérive dans une SDD

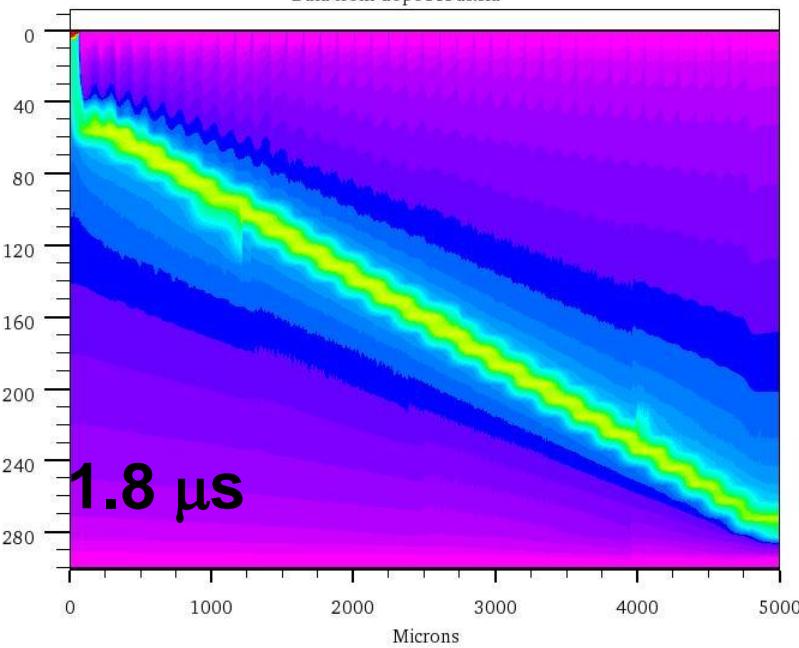
Microns



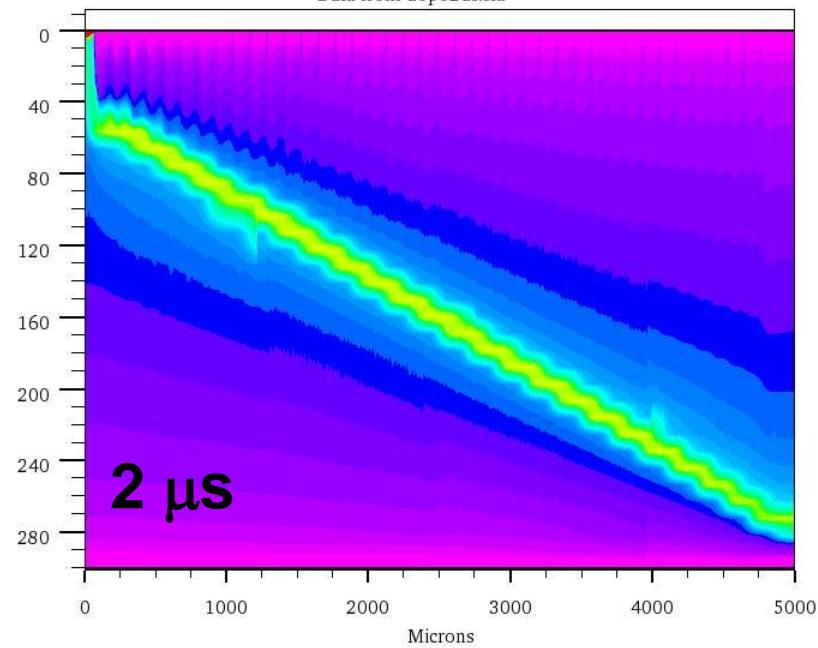
Microns



Microns

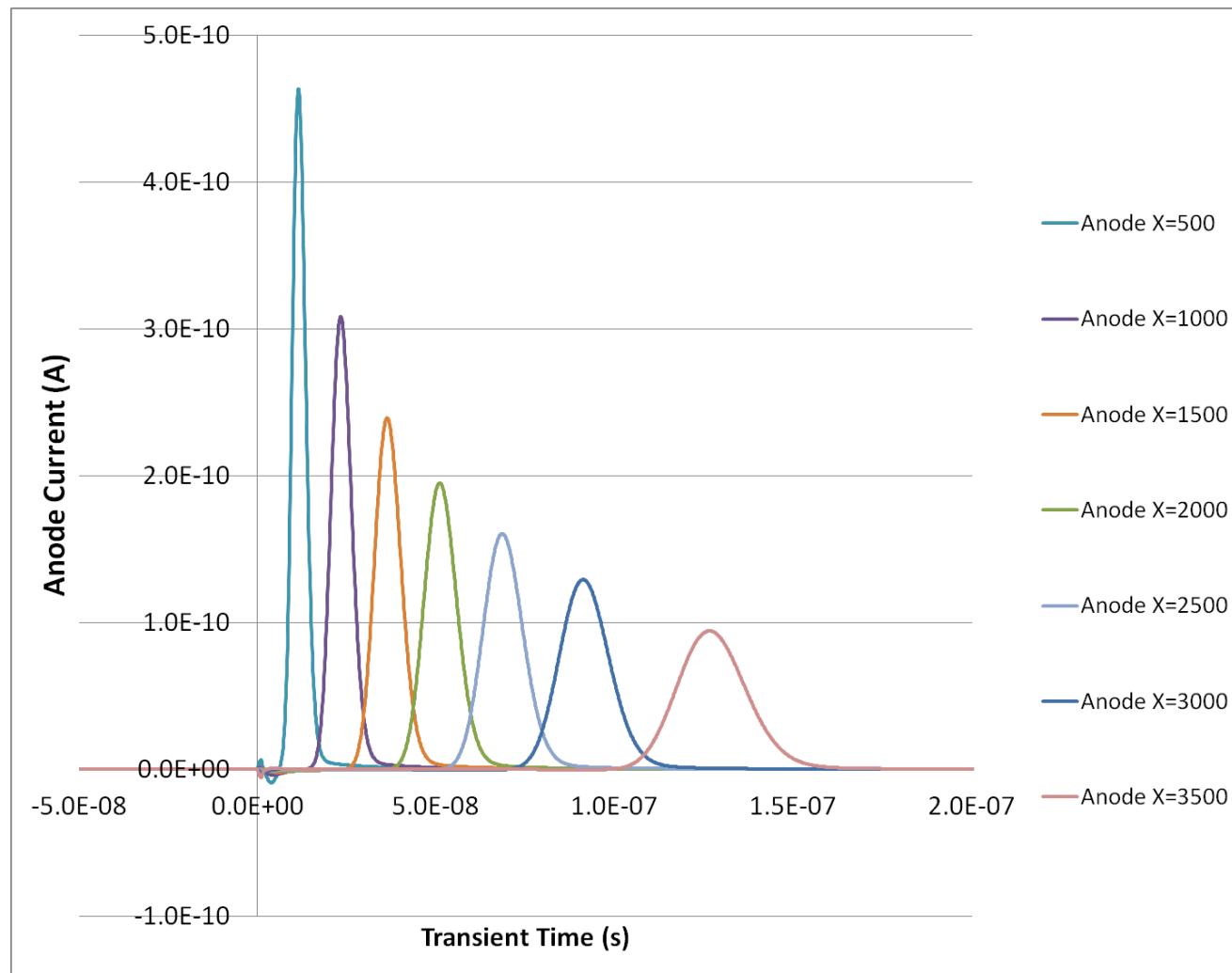


Microns



III – Temps de dérive dans une SDD

Courant à l'anode



L'intégral des impulsions de courant est le même (la charge du laser c'est la même)

IV - Jolies figures pour les publications

SDD avec polarization par punch-through

