16th Trento Workshop on Advanced Silicon Radiation Detectors

# Parametric Process Simulation for In, Ga & B

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CERN

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# •Introduction – Motivation

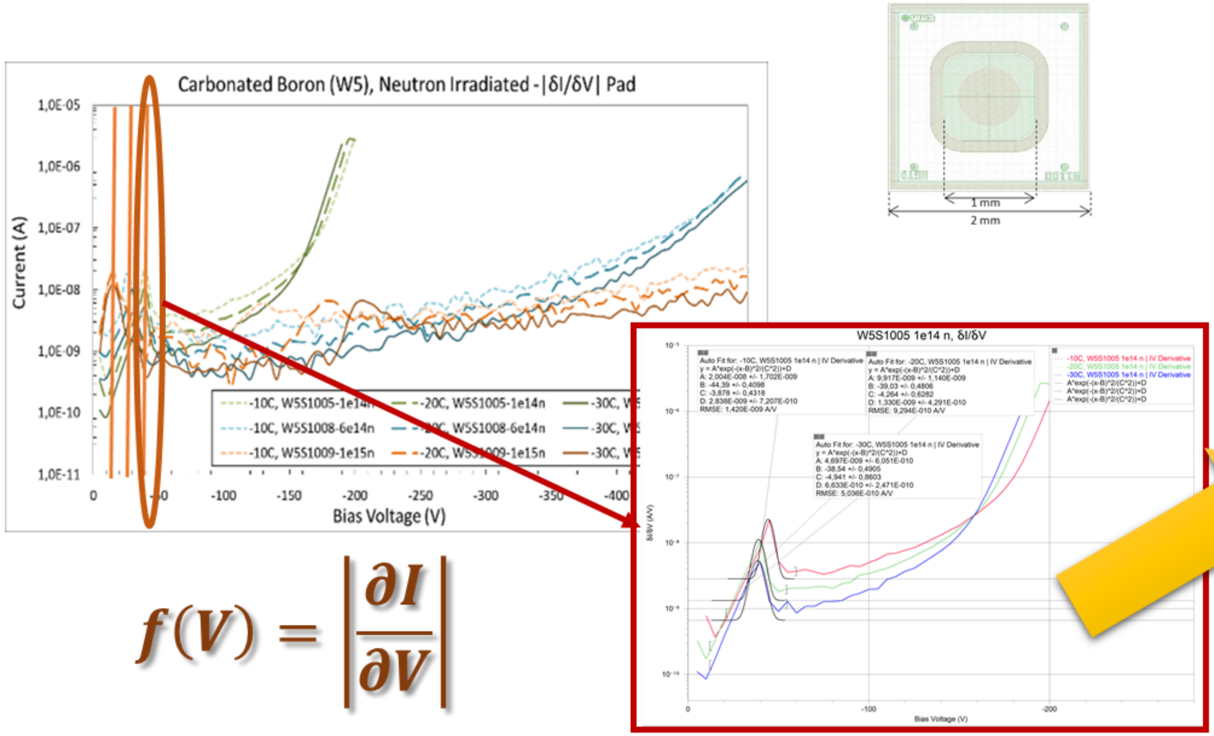
- ✓ 1x1 mm$^2$ CNM diodes, runs 10478 (W4 & W5) and 10924 (W6)
  - ✓ 50 μm on 250 μm 4” SoI wafers
  - ✓ **Boron**, **Boron + Carbon** diffused and **Gallium** implanted gain layer
- ✓ Irradiations:
  - ✓ 23 GeV PS protons
  - ✓ fast (~10MeV) neutrons at JSI
  - ✓ 5 fluences: 1e14, 6e14, 1e15, 3e15, 6e15 $n_{eq}/cm^2$
- ✓ Tested at -10C, -20C and -30C

30 sensors x 3 temp.
90 Series of measurements!!

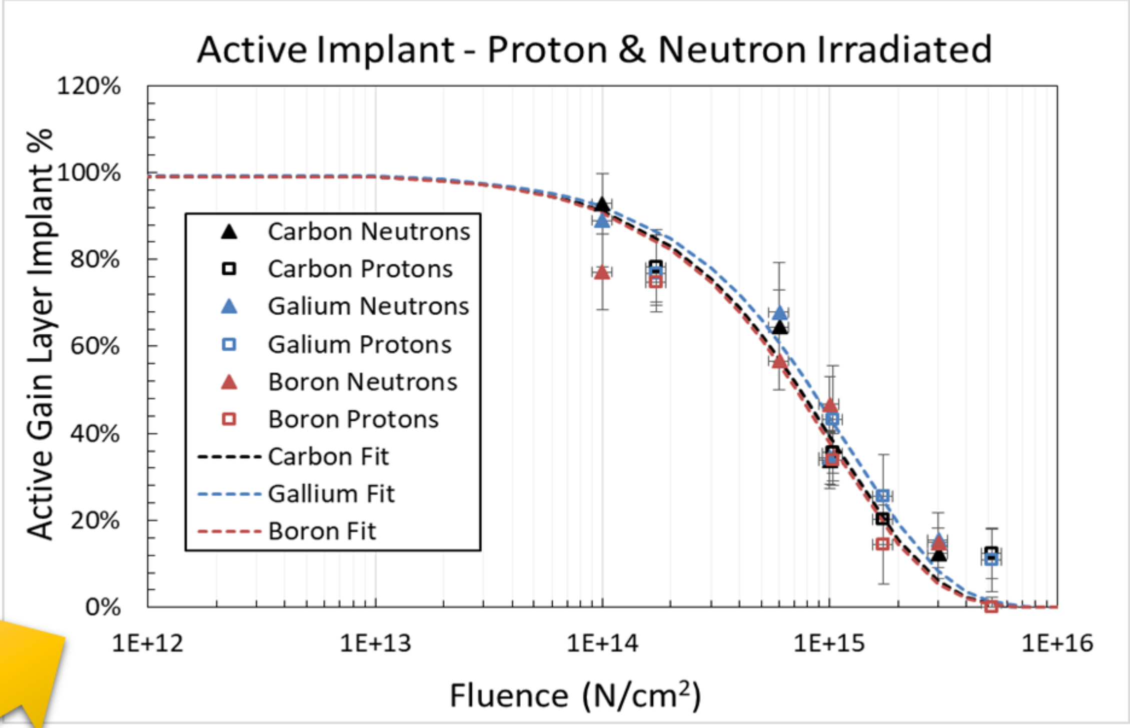
Gkougkousis V., RD50 Workshop Talk, June 2020: link

- Depletion voltage by Gaussian fit on IV derivative
- Repeated for -10, -20 & -30°C
- Active dopant extrapolated

$$G(\%) = e^{-C_G \Phi}$$



$$f(V) = \left|\frac{\partial I}{\partial V}\right|$$

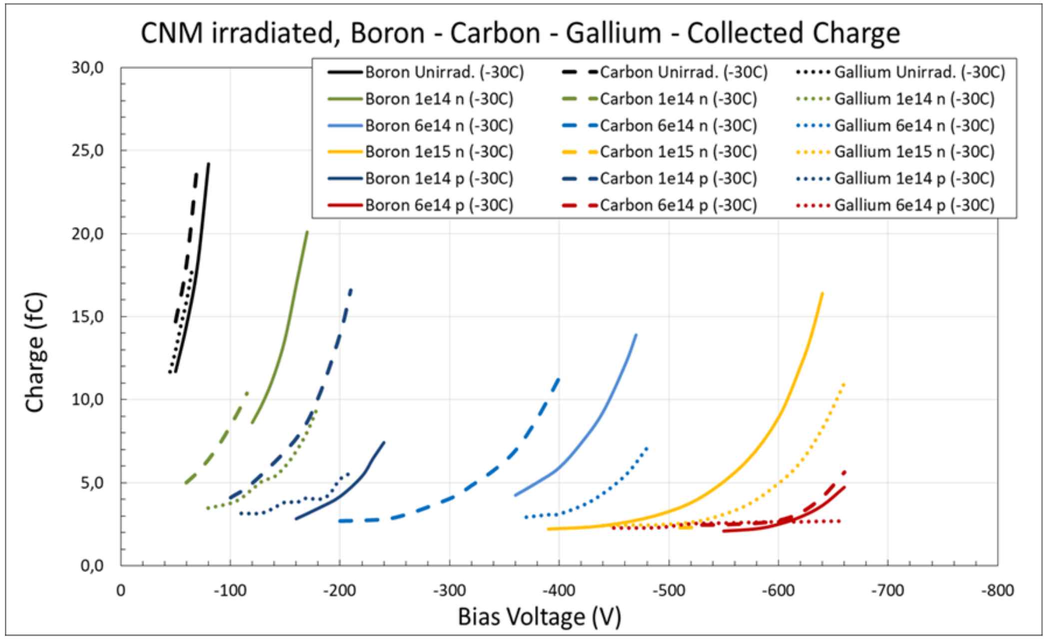


**No active dopant difference between different implantation types – neutron/proton**

# •Introduction - Motivation

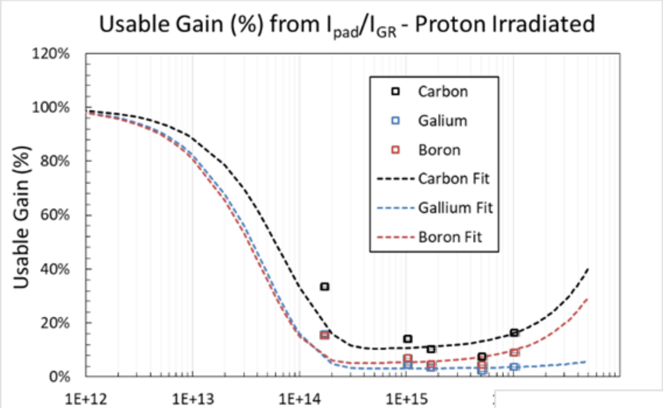
**Method 1: Charge Collection**

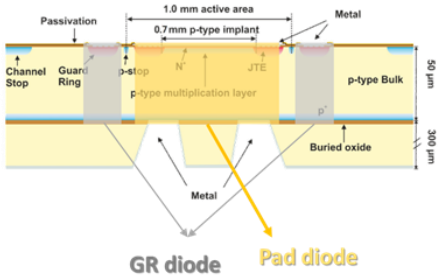
- ✓ Collected charge measured with MIPs
  - ✓ 5k events, beta measurements with Sr90
  - ✓ **Repeated in -10°C, -20°C -30°C with concurrent results**



- ✓ Usable gain estimated by comparing GR-pad leakage current
  - ✓ GR – gain region share same cathode
  - ✓ Separate removal factors for Protons/ neutrons
  - ✓ **Exponential behavior in depleted region**

**Method 2: GR-Pad IV fit estimation**





Acceptor level introduction rate

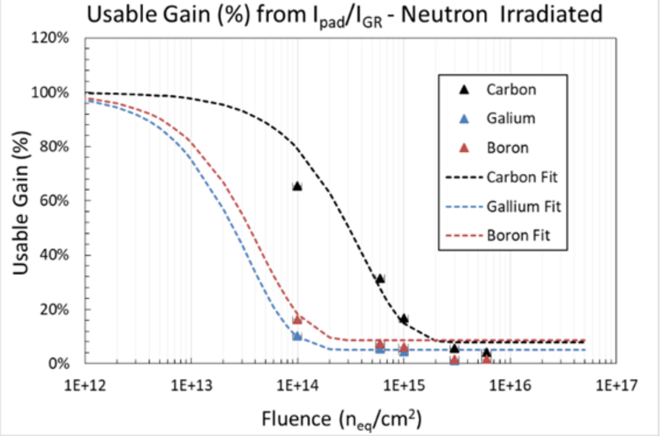
$$N_{eff}(\Phi) = N_{eff_0} - N_c\left(1 - e^{-c\Phi}\right) + g_c\Phi$$

Removable dopant

Effective dopant concentration

Initial dopant concentration

Gain extraction constant



**Both methods agree: Gallium ~20% worse, Carbon ~ 20% better wrt Boron sensors calibrated to perform equally**

**Acceptor removal in all three cases is the same (same fraction of active dopant from $V_{GL}$), trapping is not (different gain for same fluence, starting from the same point)**

# •Introduction

Four main mechanism for irradiated LGADs

**Substrate**

1. Reduced primary charges induced in substrate (reduced lifetime) → $^{1}/_{\tau} = \beta \times \Phi$
2. Acceptor re-introduction rate → $N_{G_\Phi} = N_{G_0} \mathrm{e}^{-c\Phi}$

**Gain Layer**

3. Reduced active implant in gain layer due to acceptor removal → $N_{Act.} = G \times \Phi$
4. **Reduced mobility within gain layer** → **Gain reduction larger than anticipated from acceptor removal (~factor of 1.5)**

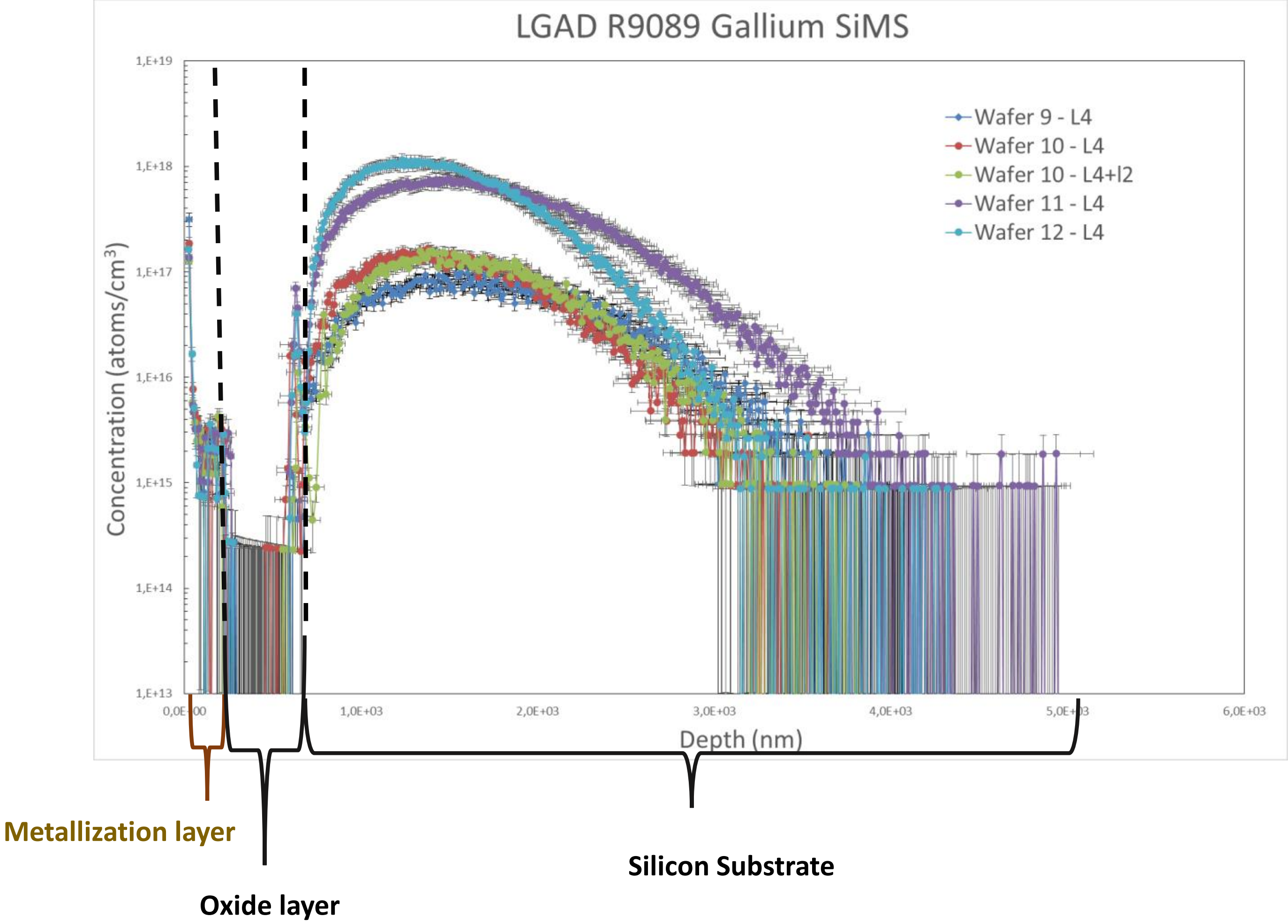
Indium or Indium-Aluminum?

- ✓ Defect Engineering method, similar with Carbon effect
- ✓ No acceptor removal improvement anticipated
- ✓ Idea from thin solar cell community, D.J. Paez et. al. (link)
- ✓ Used in space applications
- ✓ Demonstrated to have larger radiation resistance in electron radiation
- ✓ Because of higher atomic mass, should be less prone to displacement defects (in theory, practice will be different….)

# •Standard Candle Process

*Typical Profiles*

- ✓ New process optimization require standard profile as a reference
- ✓ Use Secondary Ion Mass Spectroscopy (SiMS )profiles form LGAD gain layers
- ✓ Target Boron and Gallium process (well understood)
- ✓ Accuracy of 1e15/cm$^3$



| Gallium Nominal Parameters | | | |
|---|---|---|---|
| **Nominal Dose [atoms/cm$^2$]** | **Anealing Temp [°C]** | **Anealing Time [min]** | **Implant. Energy [KeV]** |
| 1,00E+14 | 1100 | 180 | 195 |
| 1,00E+14 | 1100 | 100 | |
| 1,00E+14 | 1100 | 100 | |
| 1,00E+15 | 1100 | 180 | |
| 1,00E+15 | 1100 | 100 | |

## Target optimization parameters

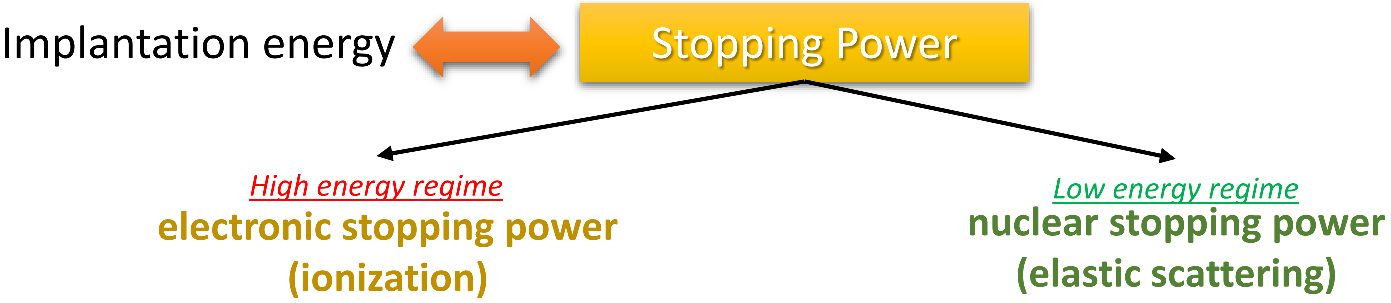
- ✓ Implantation energy
- ✓ Implantation dose
- ✓ Screen oxide layer thickness
- ✓ Diffusion Time
- ✓ Tilt Angle

# •Implantation Parameters – Energy 1

31 69.723
**Ga**
Gallium
[Ar] $3d^{10}4s^{2}4p^{1}$
Post-Transition Metal

5 10.811
**B**
Boron
[He] $2s^{2}2p^{1}$
Metalloid

49 114.818
**In**
Indium
[Kr] $4d^{10}5s^{2}5p^{1}$
Post-Transition Metal

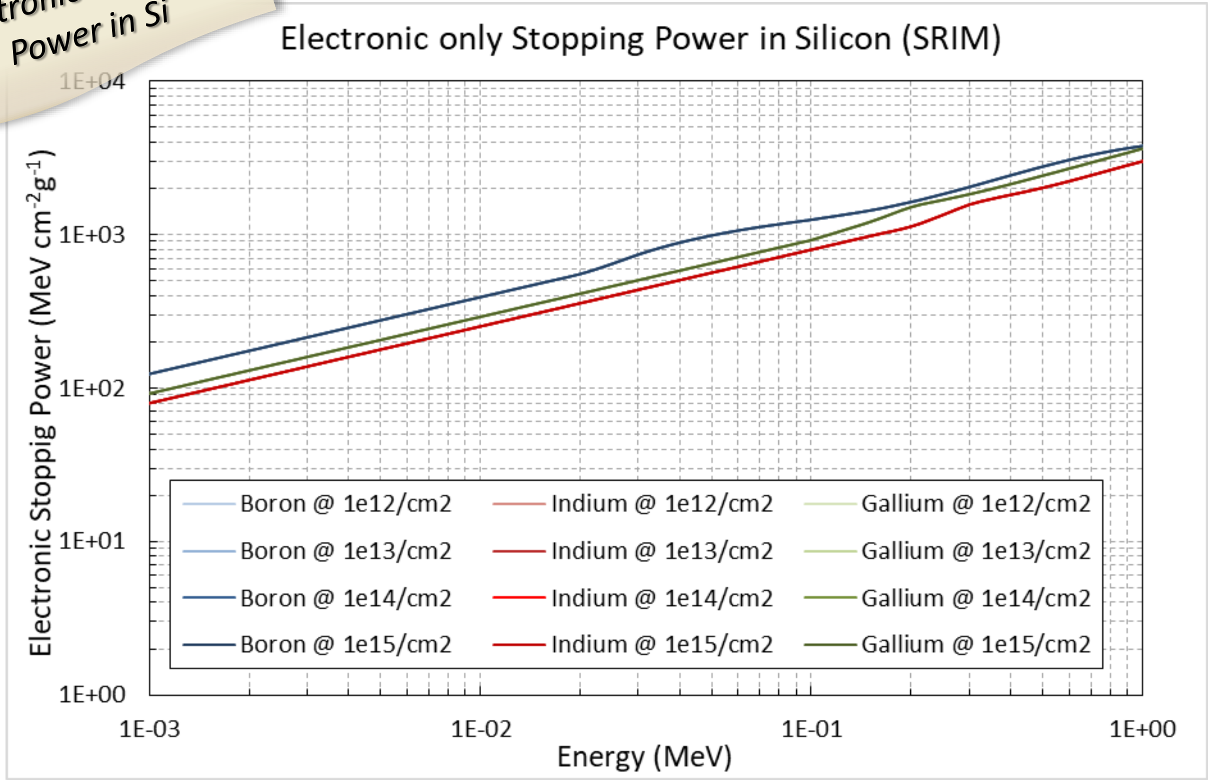


Implantation energy ↔ **Stopping Power**

*High energy regime*
**electronic stopping power (ionization)**

*Low energy regime*
**nuclear stopping power (elastic scattering)**

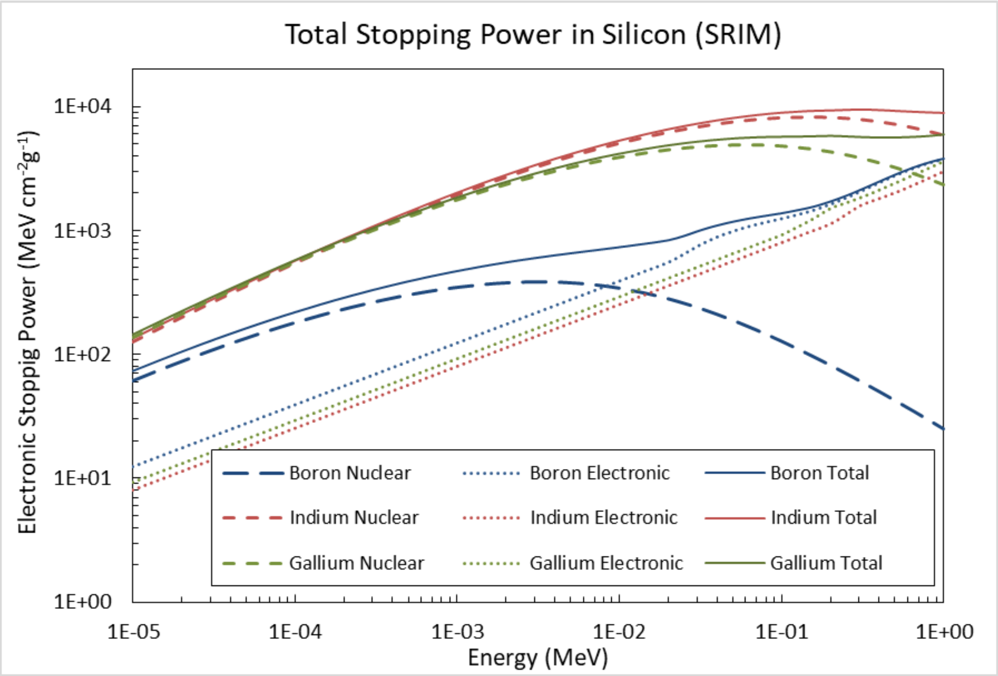
Electronic Stopping Power in Si



Electronic stopping power (ionization) consistency

- ✓ Varies with incident particle dose
- ✓ Typical doses in range of $10^{12}$ $cm^{-2}$ – $10^{15}$ $cm^{-2}$
- ✓ Simulate with:
  - Real time implementation of SRIM (2013 version)
  - Implantation in pure $^{14}Si$
  - No delta-ray assumption
  - Four different implantation doses tested ($10^{12}$, $10^{13}$, $10^{14}$, $10^{15}$)
  - Energy range 1 keV – 1MeV
- ✓ No variation for any of the three implants in the dose rate of interest

# •Implantation Parameters – Energy 2



| Element | Energy | At. Mass |
|---|---|---|
| Ga | ~200 keV | 69 |
| B | ~ 50 keV | 11 |
| In | ~ 310 keV | 114 |

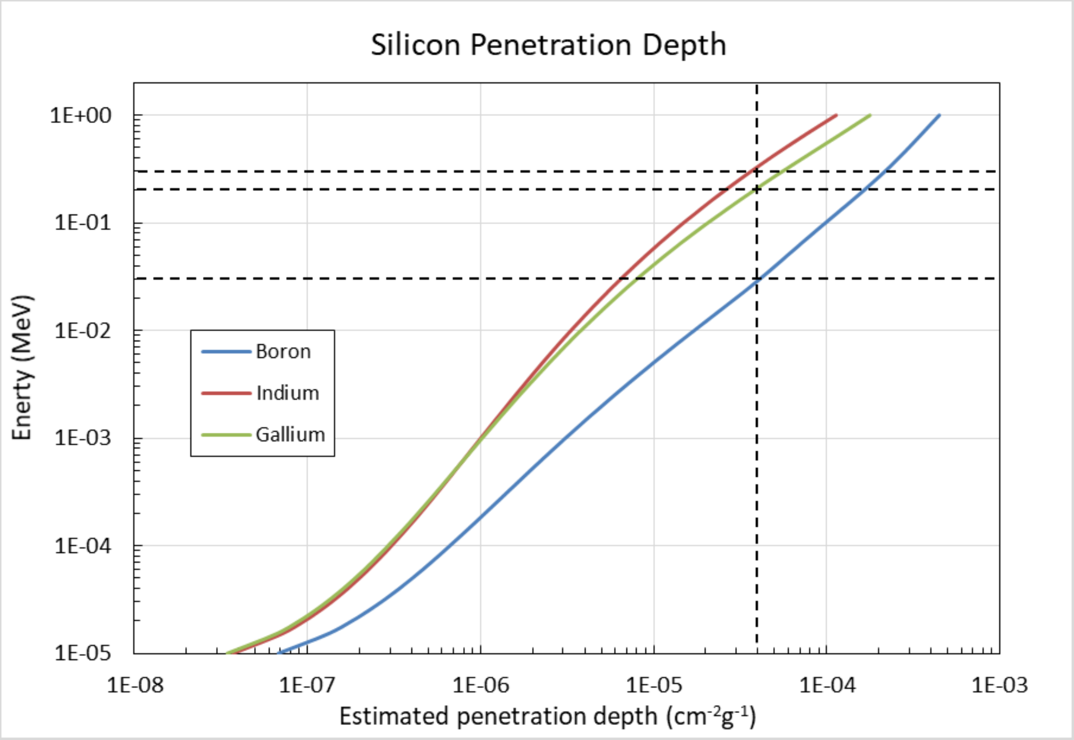
Assuming a Gallium implantation energy of 195 keV, same penetration depth:

**$E_{In}$≈340 keV and $E_B$ ≈ 40 keV**

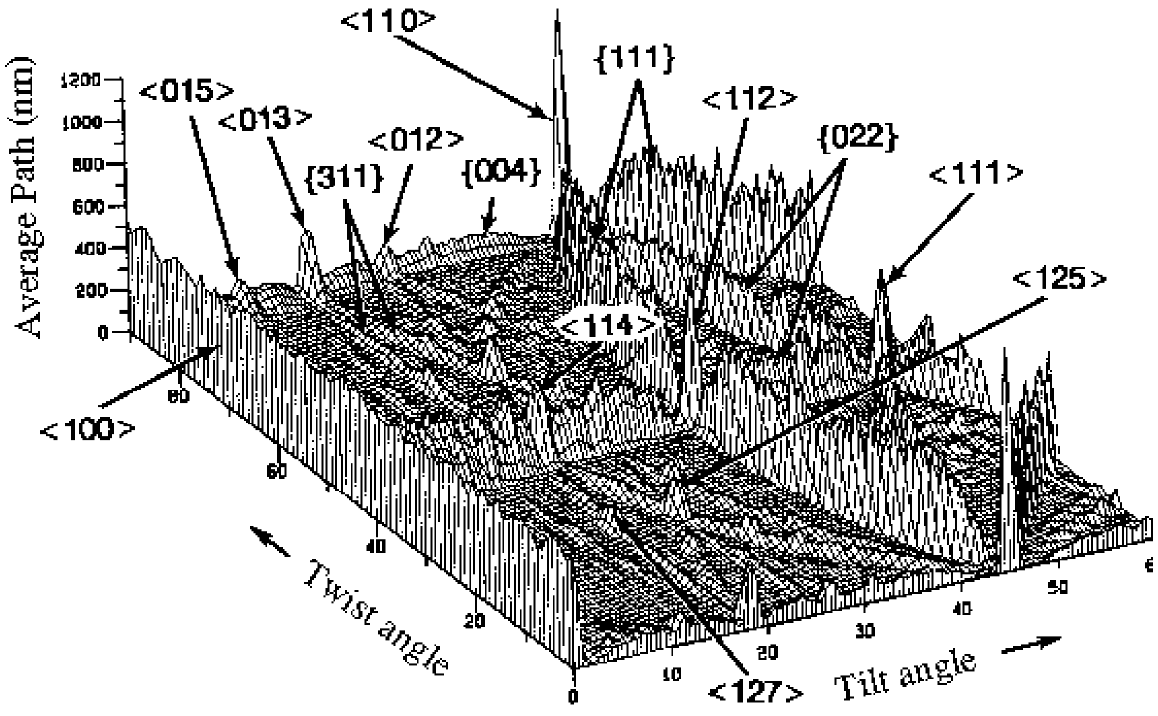
Total penetration depth:

$$\Delta x = \int_0^{E_0} \frac{1}{S(E)} \partial E$$

- SRIM 2013 version: http://www.sr-niel.org
- Linear energy loss approximation (directional)
- Assume complete absorption of energy loss within material
- Ziegler, Biersack and Littmark model ("ZBL" stopping model)
- No relativistic approximations (Bremsstrahlung)



# •Implantation parameters – Tilt Angle

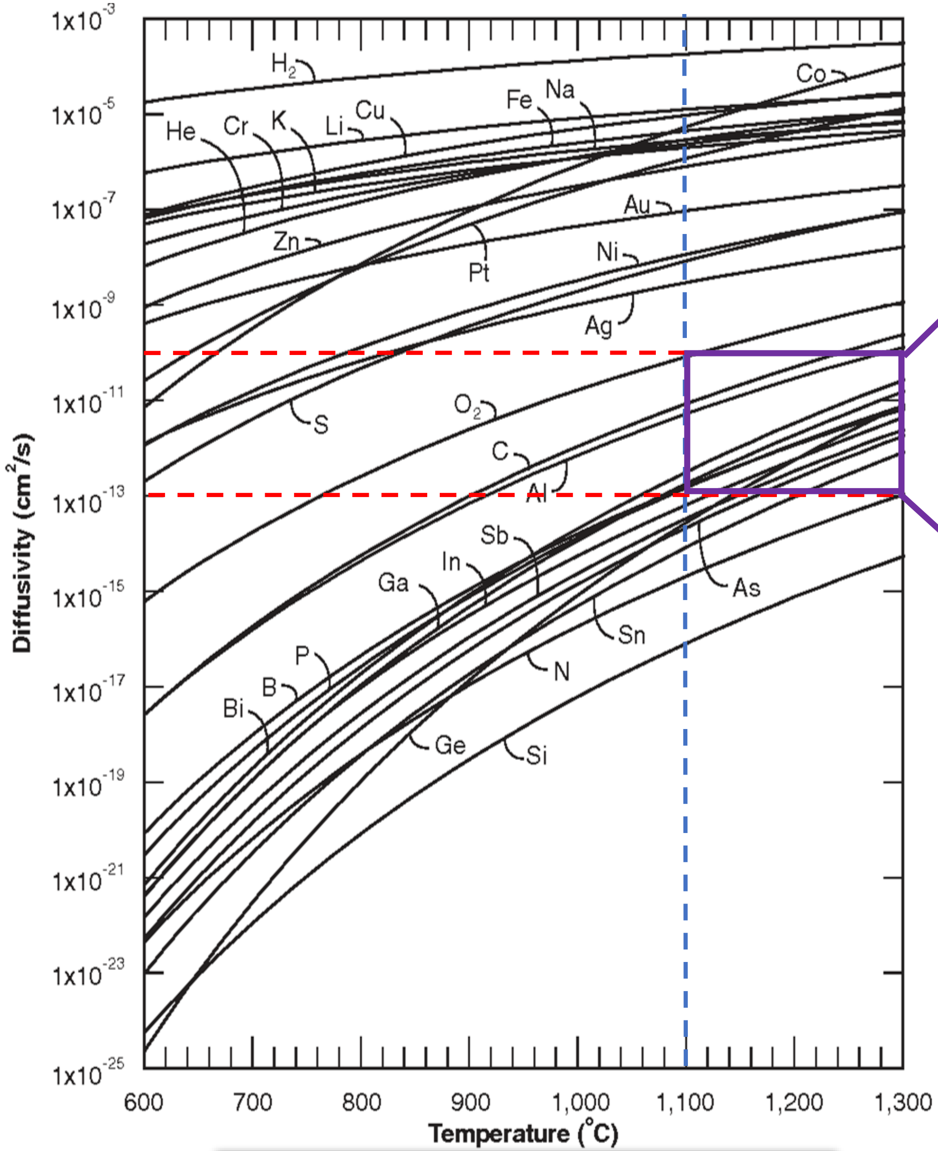


Implantation angle definition

- ✓ Large Variation of implant path with respect to angle
- ✓ Tunneling in directions paralleled to crystallographic planes
- ✓ Assuming a standard <100> Si wafer:
  - 7° tilt angle
  - 30° rotation angle
  - First quadrant of path diagram
  - Safe distance form any tunneling peaks
- ✓ Parameters also suitable for <111> crystals
- ✓ Additional protection provided by ~ 10-20 nm screen oxide

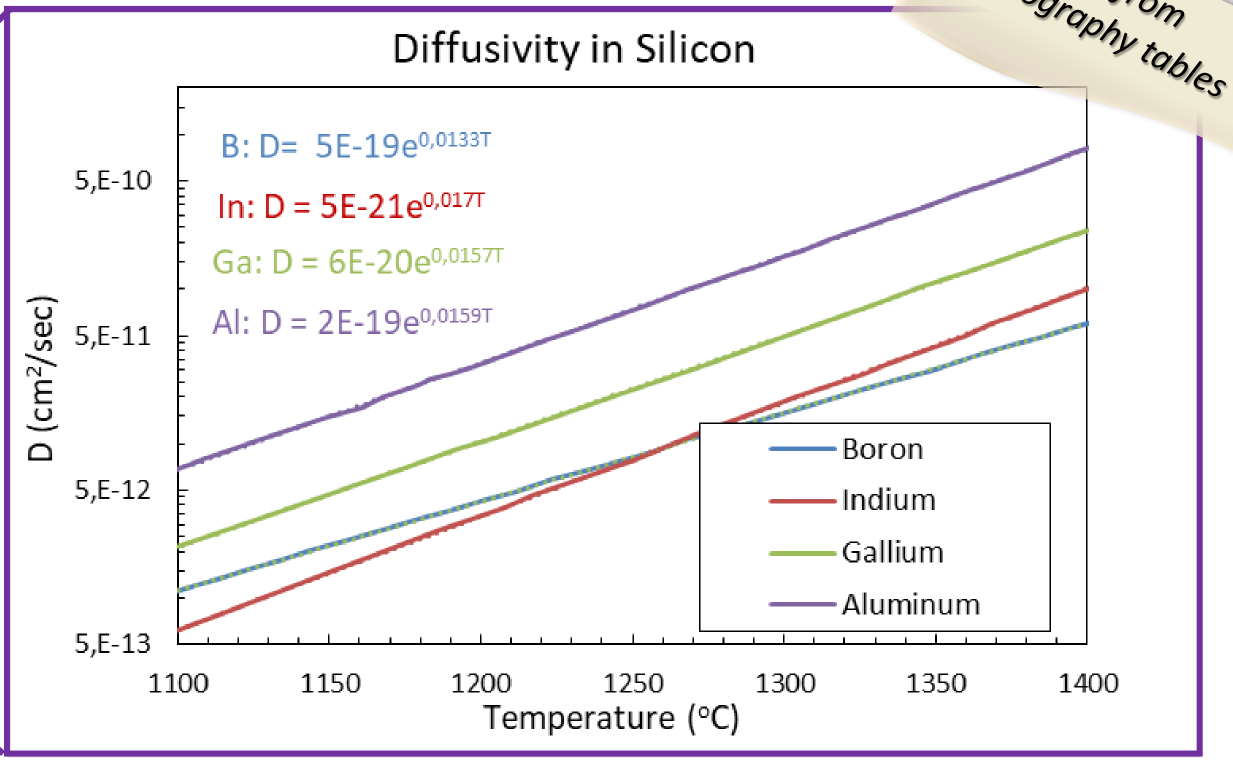
- Expected average projection rates in silicon:(in <100> with 7° tilt and 30° rotation)
  - ✓ Boron (@100keV): 0.2994 μm

# •Diffusion parameters



“Diffusion in Silicon”, Scotten W. Jones (link)

Data from bibliography tables



- ✓ Range of interest 1100 °C < T < 1400 °C
- ✓ Exponential behavior of diffusivity in range of interest

$$D = a \times e^{b \times T}$$

- ✓ Exponential fit approximation applied for Ga, B and In
- ✓ Hard stop at T > 1400 °C due to Si fusion temperature (1414 °C)

# •Preliminary parametrization

**"Standard Candle" process**

| Element | Temperature | Diffusivity | Eq. Time |
|---|---|---|---|
| **Ga** | **1100 °C** | **1,90E-12** | **180** |
| In | 1100 °C | 6,61E-13 | 517 |
| B | 1100 °C | 1,13E-12 | 303 |

| Element | Temperature | Diffusivity | Eq. Time |
|---|---|---|---|
| Ga | 1200 °C | 9,13E-12 | 37 |
| In | 1200 °C | 3,62E-12 | 94 |
| B | 1200 °C | 4,27E-12 | 80 |

| Element | Temperature | Diffusivity | Eq. Time |
|---|---|---|---|
| Ga | 1150 °C | 4,16E-12 | 82 |
| In | 1150 °C | 1,55E-12 | 221 |
| B | 1150 °C | 2,20E-12 | 156 |

- ➢ "Standard" Ga process diffusion of 180 min @ 1100 °C
- ➢ Establish diffusion scenarios for each dopant to achieve relevant diffusion pattern

***Parameters***

***Diffusion temperature***

- ✓ $T_{max}$ < 1400 °C
- ✓ $T_{min}$ > 1100 °C
- ✓ Same temperature for all implants (process uniformity)

***Diffusion Time***

- ✓ $t_{max}$ < 210 min (3.5h)
- ✓ $t_{min}$ > 60 min (1h)

**Using fit parameters for diffusion coefficients and assuming literary dependence of diffusion time**

- @ 1100 °C, Indium diffusion impractical (~8.5 h diffusion time)
- @ 1200 °C, Gallium diffusion time to short to account for stabilization steps (~ 0.5 h)
- @ 1150 °C, criteria are fulfilled for all cases

# •TCAD Processes Simulation

General parameters

Boron:

- Energy: 40 – 60 keV with 5 keV steps
- Annealing temp.: 1150 °C
- Annealing time: 120 – 170 min with 10 min steps
- Dose: $5\times10^{13}$cm$^{-2}$ - $5\times10^{14}$cm$^{-2}$ with x10 geometrical steps

Indium:

- Energy: 300 – 350 keV with 10 keV steps
- Annealing temp.: 1150 °C
- Annealing time: 200 – 250 min with 10 min steps
- Dose: $5\times10^{13}$cm$^{-2}$ - $5\times10^{14}$cm$^{-2}$ with x10 geometrical steps

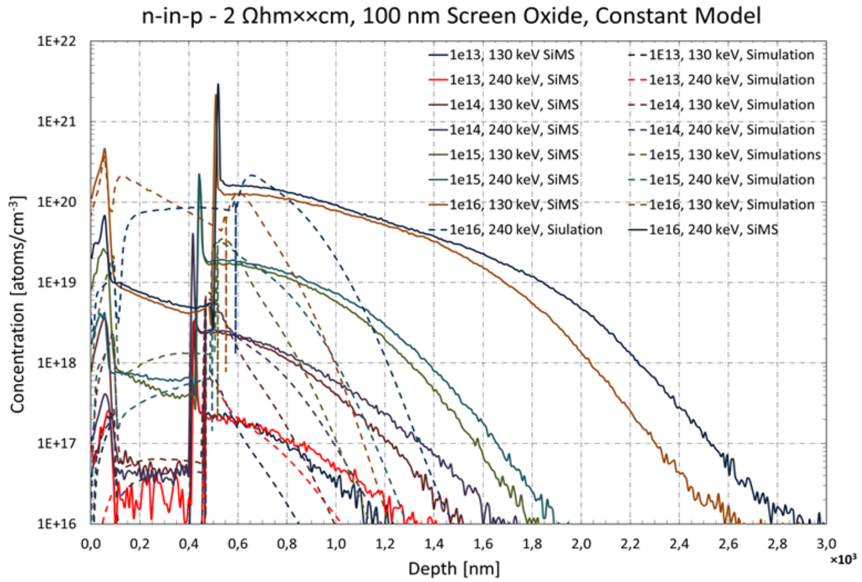
Gallium:

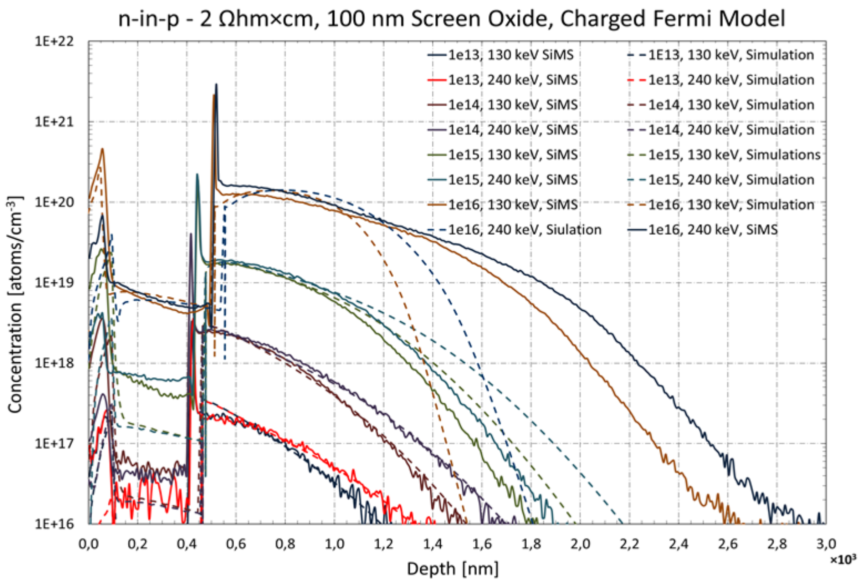
- Energy: 180 – 220 keV with 10 keV steps
- Annealing temp.: 1150 °C
- Annealing time: 60 – 100 min with 10 min steps
- Dose: $5\times10^{13}$cm$^{-2}$ - $5\times10^{14}$cm$^{-2}$ with x10 geometrical steps

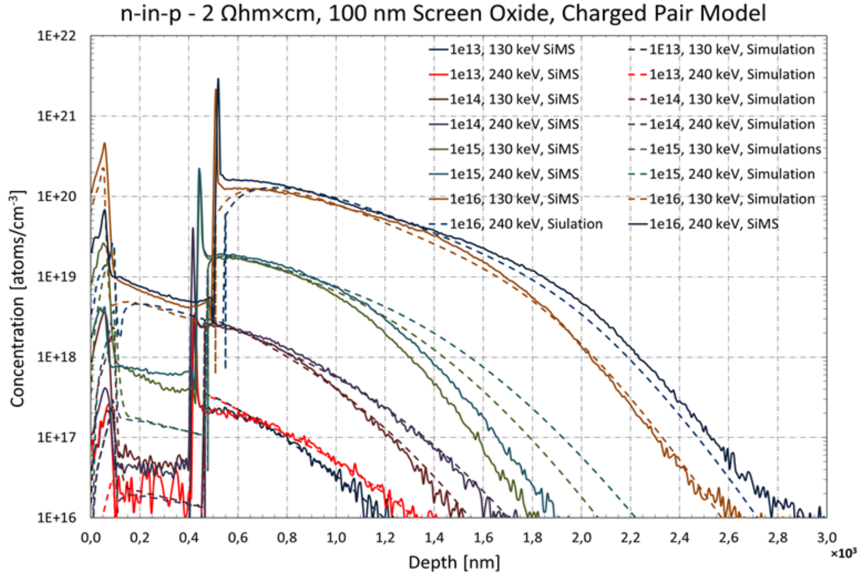
- ➢ Cz High Resistivity Si substrate
  - ➢ <100> orientation (dicing, radiation hardness)
  - ➢ Resistivity >4kΩhm*cm
  - ➢ P concentration of $10^{12}$ atoms/cm$^3$
  - ➢ Active thickness 50 μm
- ➢ Native oxide: 1.9 nm
- ➢ Screen Oxide: 50 nm (deposited)
- ➢ MC implantation:
  - ✓ 1000 tracks
  - ✓ Max track splits 4, splints per element 2
  - ✓ CristalTRIM algorithm
  - ✓ Clock seed randomization
  - ✓ Optimization error: ± $10^{15}$ atoms/cm$^3$
  - ✓ Full cascade BCA damage (binary collision approx.,)
- ➢ Diffusion Mode: Charged Pair
- ➢ Activation: Only thermal (no oxidation)
- ➢ Synopsys info
  - ✓ Version 2019.12 with Advanced Calibration
  - ✓ MGOALS meshing algorithm

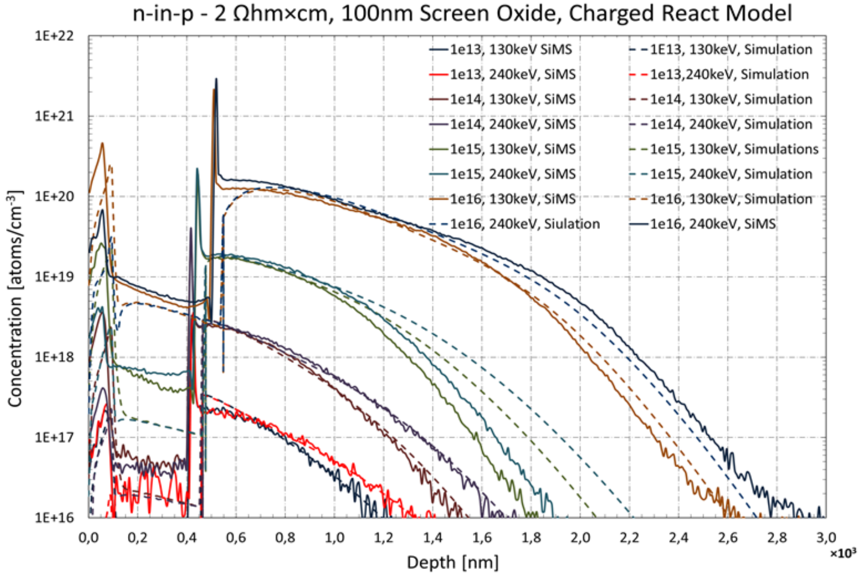
# •Diffusion Model Comparison

Gkougkousis V., 10th Trento Workshop Talk, February 2015: link


n-in-p - 2 Ωhm××cm, 100 nm Screen Oxide, Constant Model


n-in-p - 2 Ωhm×cm, 100 nm Screen Oxide, Charged Fermi Model


n-in-p - 2 Ωhm×cm, 100 nm Screen Oxide, Charged Pair Model


n-in-p - 2 Ωhm×cm, 100nm Screen Oxide, Charged React Model

- ✓ Different diffusion models tested
- ✓ Simulations compared with SiMS on n-in-p samples
- ✓ Constant model only good for very low doses < 1e13 cm$^{-2}$
- ✓ Charged Fermi model successfully describes dopant behavior up to doses of 1e15/cm$^{2}$
- ✓ Pair model, taking into account binary interactions, covers the entire dose range up to 1e16 /cm$^{2}$
- ✓ Charged versions of the models take into account ion charge (not relevant here)
- ✓ React models should be used when chemical reactions are expected

# •Simulation parameter space

| Boron | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Screen Oxide** | 40 nm | | | 50 nm | | | | 60 nm | | |
| **Implantation dose** | 5e13 cm$^{-2}$ | 6e13 cm$^{-2}$ | 7e13 cm$^{-2}$ | 8e13 cm$^{-2}$ | 9e13 cm$^{-2}$ | 1e14 cm$^{-2}$ | 2e14 cm$^{-2}$ | 3e14 cm$^{-2}$ | 4e14 cm$^{-2}$ | 5e14 cm$^{-2}$ |
| **Implantation energy** | 40 keV | | 45 keV | | 50 keV | | 55 keV | | 60 keV | |
| **Diffusion Time** | 120 min | | 130 min | | 140 min | | 150 min | | 160 min | |

| Gallium | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Screen Oxide** | 40 nm | | | 50 nm | | | | 60 nm | | |
| **Implantation dose** | 5e13 cm$^{-2}$ | 6e13 cm$^{-2}$ | 7e13 cm$^{-2}$ | 8e13 cm$^{-2}$ | 9e13 cm$^{-2}$ | 1e14 cm$^{-2}$ | 2e14 cm$^{-2}$ | 3e14 cm$^{-2}$ | 4e14 cm$^{-2}$ | 5e14 cm$^{-2}$ |
| **Implantation energy** | 180 keV | | 190 keV | | 200 keV | | 210 keV | | 220 keV | |
| **Diffusion Time** | 60 min | | 70 min | | 80 min | | 90 min | | 100 min | |

| Indium | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Screen Oxide** | 40 nm | | | 50 nm | | | | 60 nm | | |
| **Implantation dose** | 5e13 cm$^{-2}$ | 6e13 cm$^{-2}$ | 7e13 cm$^{-2}$ | 8e13 cm$^{-2}$ | 9e13 cm$^{-2}$ | 1e14 cm$^{-2}$ | 2e14 cm$^{-2}$ | 3e14 cm$^{-2}$ | 4e14 cm$^{-2}$ | 5e14 cm$^{-2}$ |
| **Implantation energy** | 300 keV | | 310 keV | | 320 keV | 330 keV | | 340 keV | | 350 keV |
| **Diffusion Time** | 200 min | | 210 min | | 220 min | 230 min | | 240 min | | 250 min |

| | ***Screen oxide layer thickness*** | | ***Implantation energy*** | | ***Implantation dose*** | | ***Diffusion time*** | | ***Total Scenarios*** |
|---|---|---|---|---|---|---|---|---|---|
| ***Boron :*** | ***3*** | ***X*** | ***5*** | ***X*** | ***10*** | ***X*** | ***5*** | **=** | ***750*** |
| ***Gallium :*** | ***3*** | ***X*** | ***5*** | ***X*** | ***10*** | ***X*** | ***5*** | **=** | ***750*** |
| ***Indium :*** | ***3*** | ***X*** | ***6*** | ***X*** | ***10*** | ***X*** | ***6*** | **=** | ***1080*** |

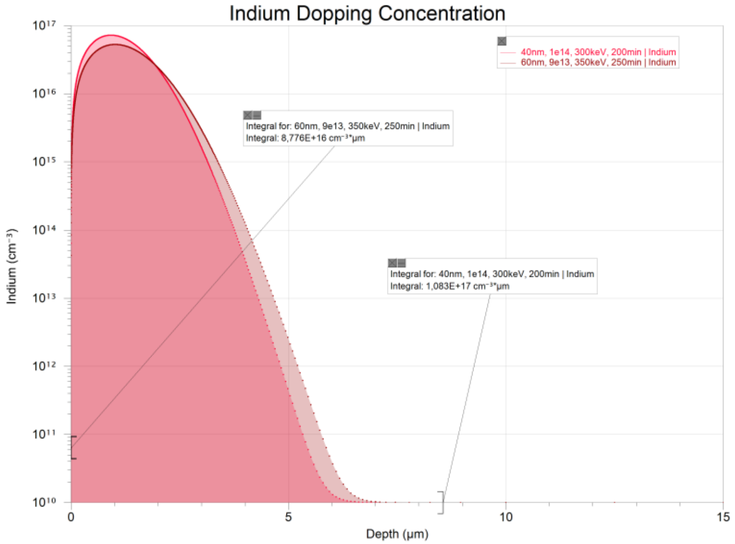
***~ Total of 2580 nodes***

15 day simulation time @ 16 cores

# •Parameters of merit

## *Dose Integral*

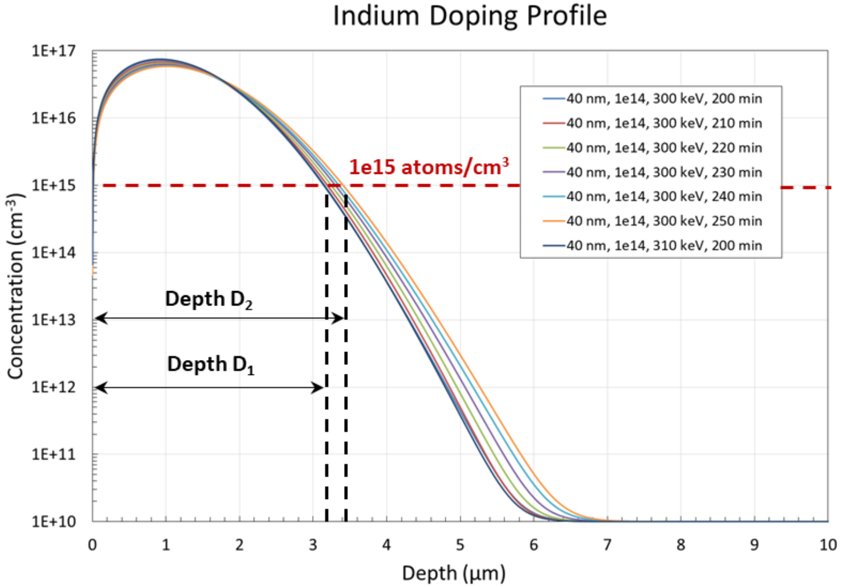
$$D_{Tot} = \int_{Si} N_{act.}(x)dx$$



- ✓ Integrated implant within silicon up to substrate boarder
- ✓ Oxide region not taken into consideration
- ✓ Only active implant considered

## *Precision Depth*

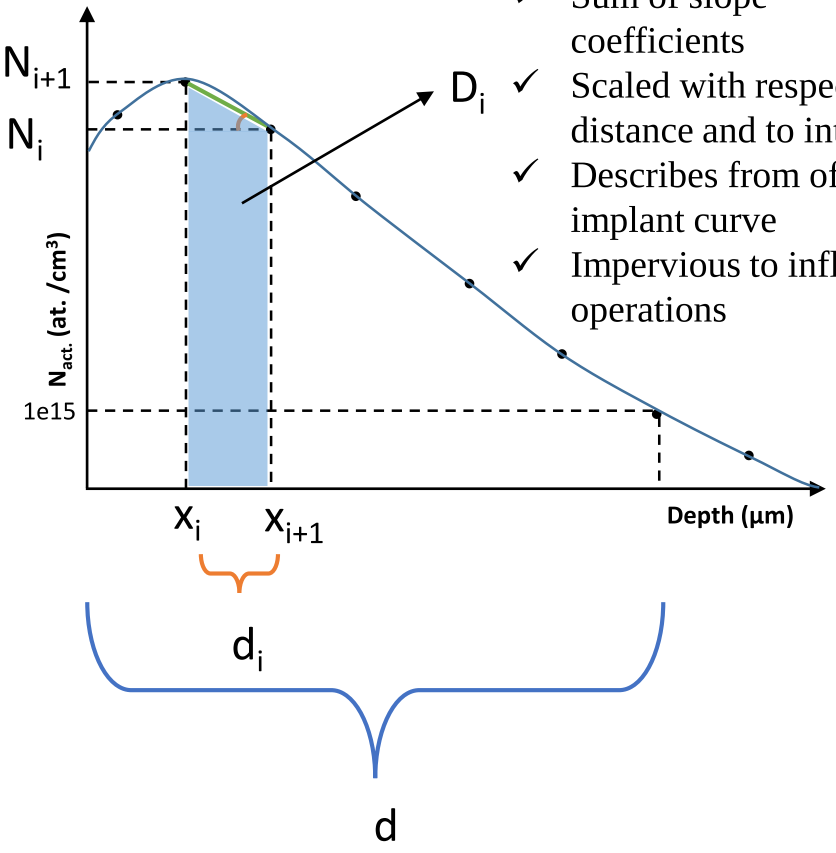
$$d = x|_{N_{act.}=1e15}$$



- ✓ Depth for witch an active concentration of 1e15 atoms/cm$^3$ is reached
- ✓ Relevant for SiMS process verifications
- ✓ Considered as implant depth

## *Form Factor*

$$F = \sum_{Si} \left|\frac{N_{i+1} - N_i}{x_{i+1} - x_i}\right| \times \frac{x_{i+1} - x_i}{d} \times \frac{\int_i^{i+1} N_{act.}(x)dx}{D_{Tot}}$$



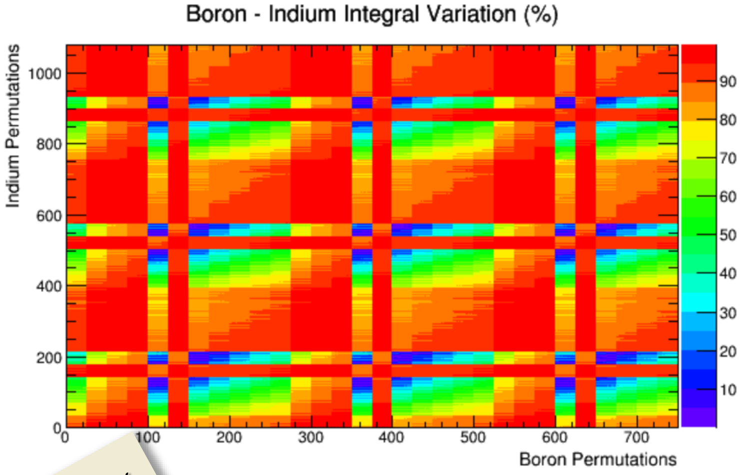
- ✓ Sum of slope coefficients
- ✓ Scaled with respect top distance and to integral
- ✓ Describes from of implant curve
- ✓ Impervious to inflation operations

# •Boron – Indium Minimization

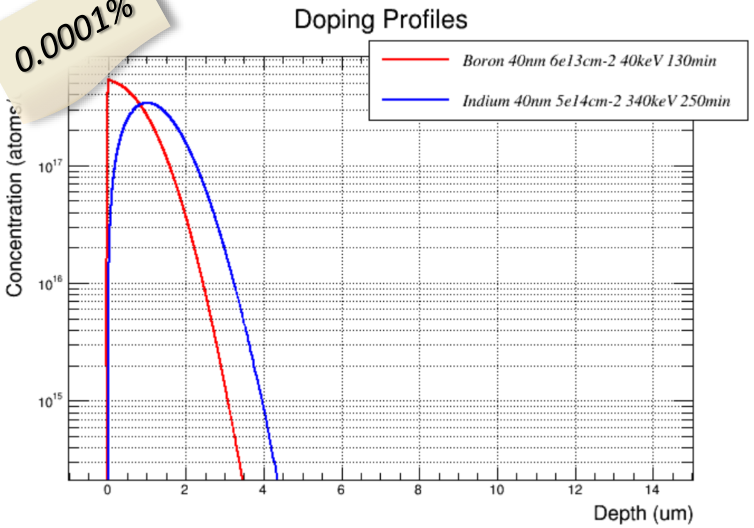
**~ Minimization across 750 x 1080 ≈ 0,8M scenarios**

## Dose Integral

$$VAR(D_{Tot.}) = \frac{\left|D^{In}_{Tot} - D^{B}_{Tot}\right|}{D^{B}_{Tot}} \times 100$$

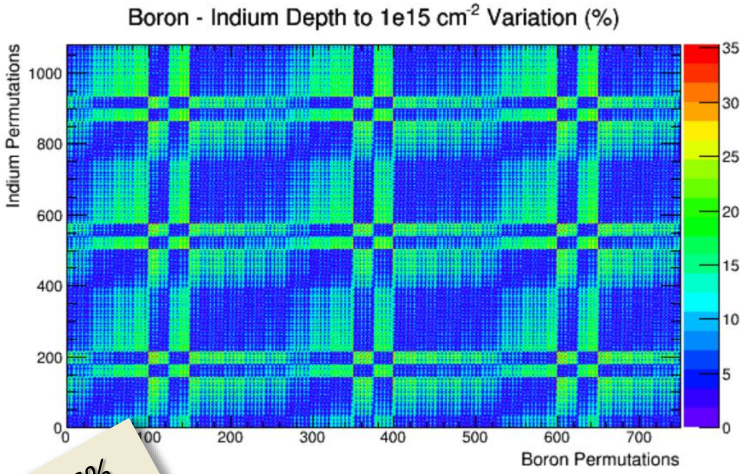


0.0001%

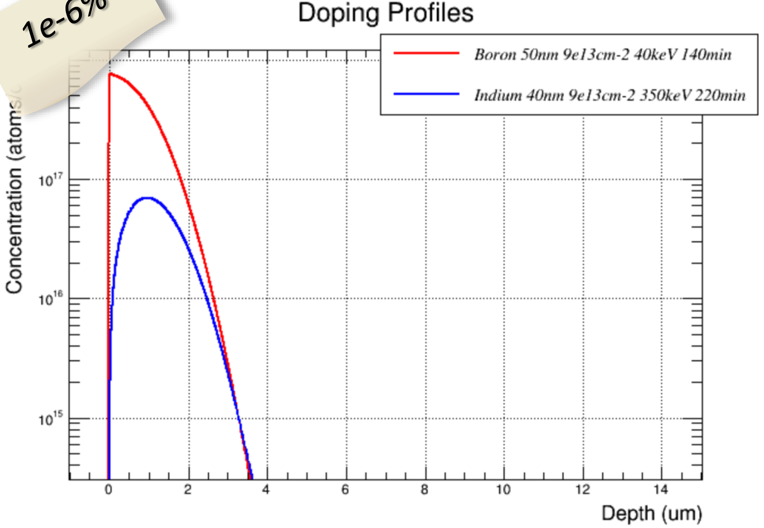


## Precision Depth

$$VAR(d) = \frac{\left|d^{In} - d^{B}\right|}{d^{B}} \times 100$$

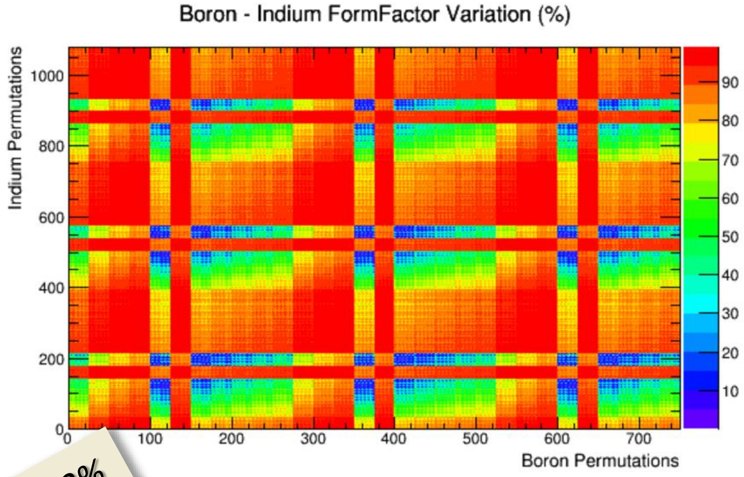


1e-6%

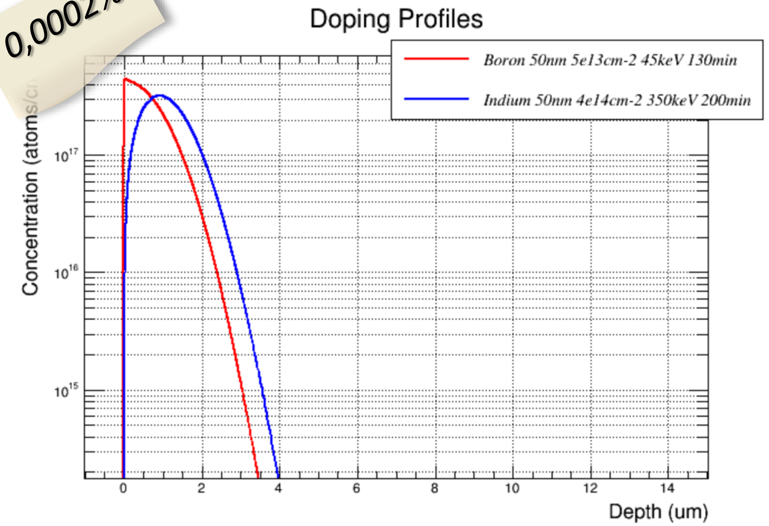


## Form Factor

$$VAR(F) = \frac{\left|F^{In} - F^{B}\right|}{F^{B}} \times 100$$



0,0002%



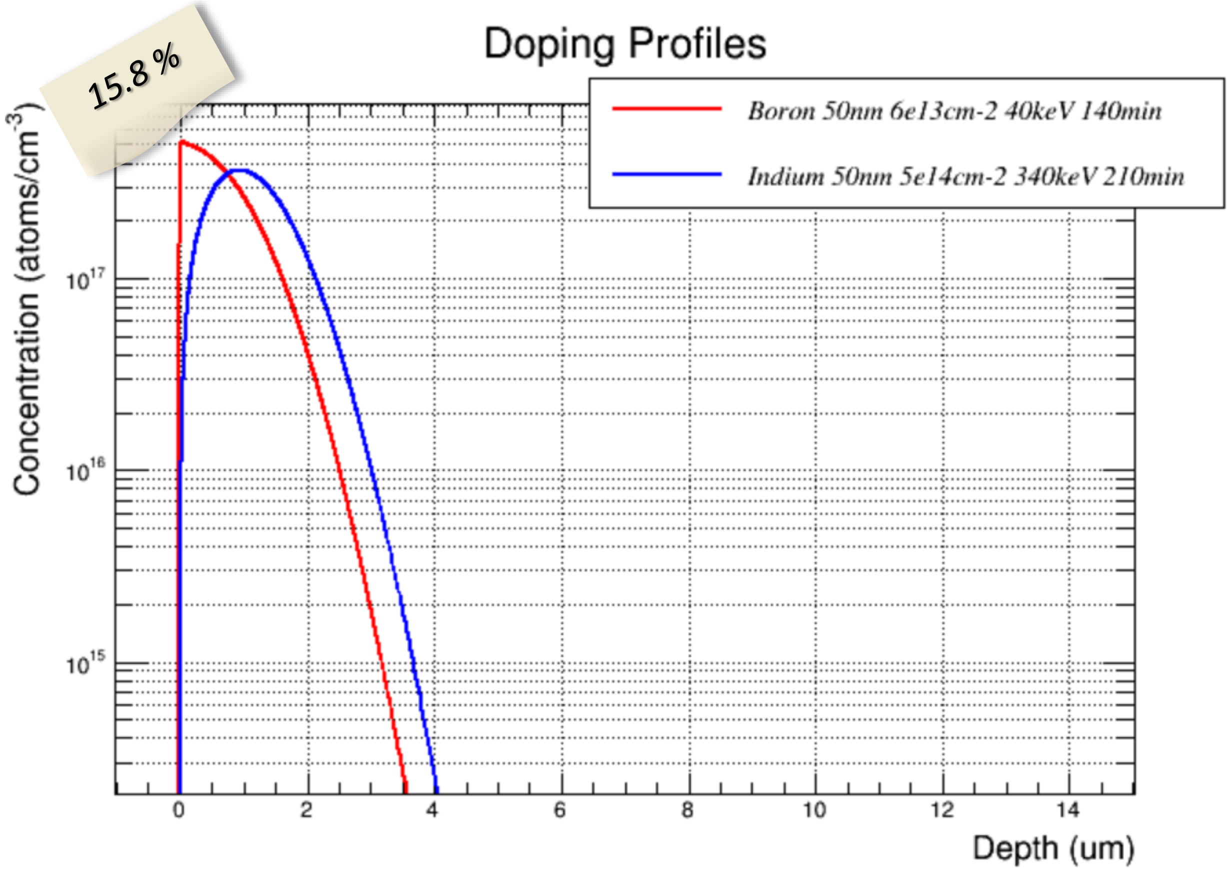
# •Boron – Indium minimization

- ✓ Combine all three variables to a single and construct the combined variance:

$$VAR_{Tot} = VAR(D_{Tot.}) + VAR(d) + VAR(F)$$

- ✓ Best overall solution minimizes the total variance:

**Boron, 50 nm screen oxide, 6e13 cm$^{-2}$ at 40 keV with 140 min diffusion time**
**Indium, 50nm screen oxide 5e14 cm$^{-2}$ at 340 keV with 210 min diffusion time**

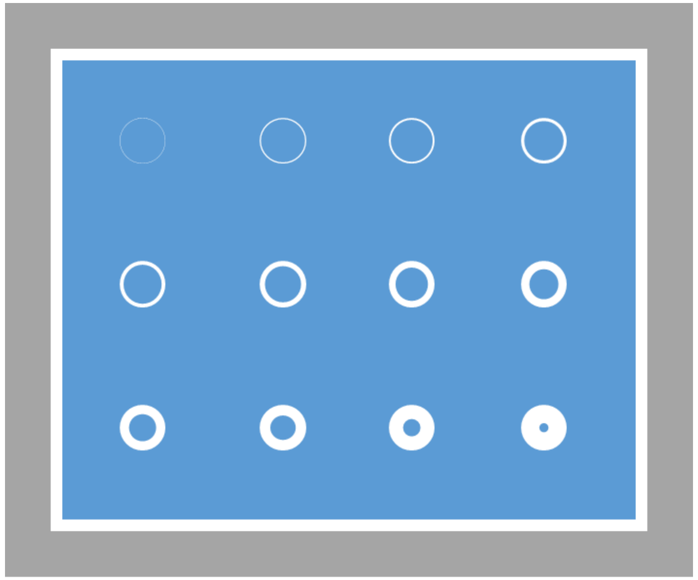


**But there is an inconsistency at the beginning……**
**What about:**
- **Oxide growth for diffusion??**

**Lets optimize further with the producer**

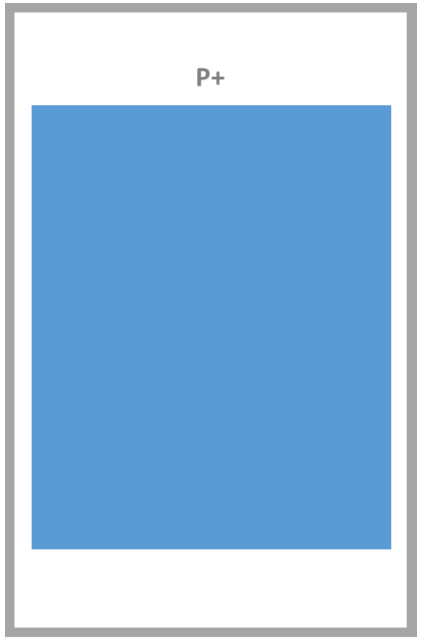
# •Active implant testing

*TLM mask*



**Scale 1:0.05**

*SiMS Mask*



**Scale 1:0.08**

▨ AlSi
▨ Passivation Open
▨ Die edge region

- ➢ Variable implant ring widths
- ➢ Die size: 5 x 6 mm
- ➢ Die edge region: 400 µm
- ➢ Dicing gap: To be determined

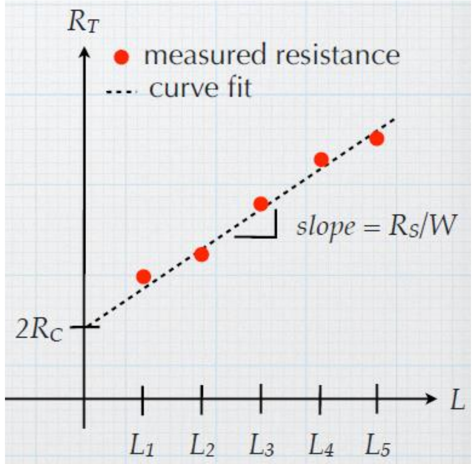
- ➢ Die size: 6,5 x 10 mm
- ➢ Die edge region: 150 µm
- ➢ Dicing gap: To be determined

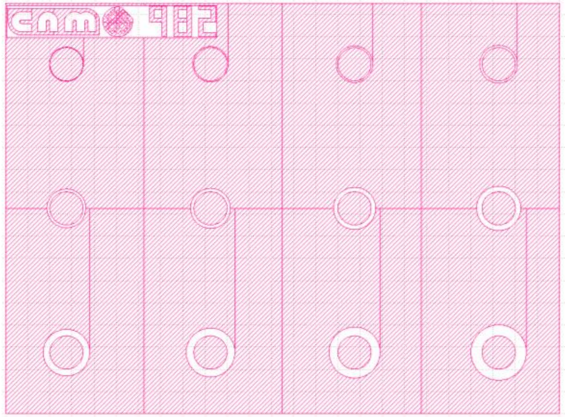
*TLM Method (Transition line Resistance)*

- Measure conductivity of uniform implant
- Determine percentage of active implant
- Perform after different irradiation levels
- Compare between boron, Indium, Aluminum

$$R_T = 2R_m + 2R_c + R_{semi}$$

$$R_T = \underbrace{2R_m}_{\text{Ignored}} + 2R_c + R_S\frac{W}{L}$$





# •Additional Ideas and next steps

What About ……

- Carbon co-implantation in B, Ga, and In test wafers
- Lithium co-implantation ONLY on p-implant layers
    - Lithium is n-type but in low doses should not impact p layer
    - Proven to improve radiation hardness of solar cells after 1MeV neutron irradiation
    - Lowers annealing temperature when implanted in substrate
    - Defect engineering at low temperatures E. Oliviero et Al. (link)
    - Original Solar cell study Weinberg et Al. (link)

Next steps

- Optimization of best parameter combination
- RD50 project in submission
    - CERN, CNM implicated, other welcome ☺
    - Include SiMS measurements for the engineering stage

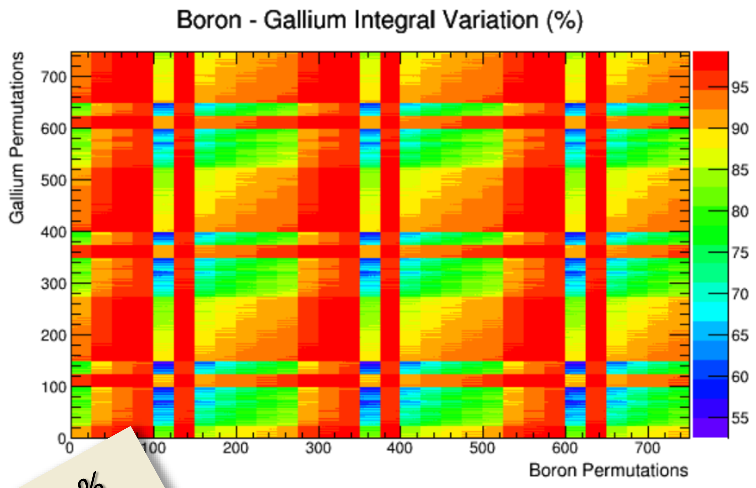
# •BackUp

# •Boron – Gallium Minimization

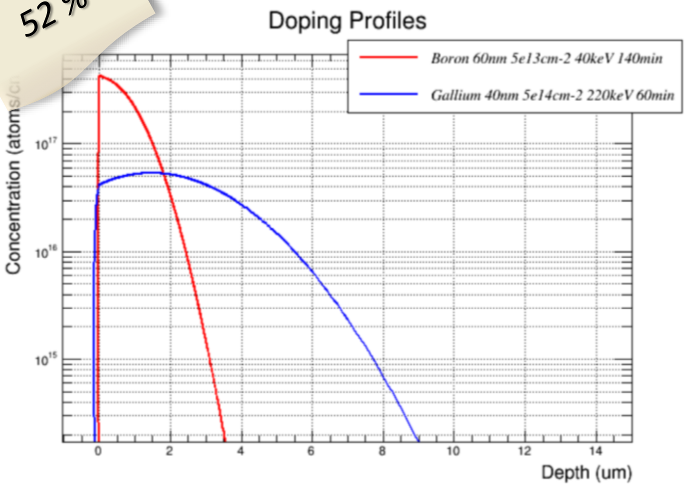
**~ Minimization across 750 x 750 ≈ 0,6M scenarios**

## Dose Integral

$$VAR(D_{Tot.}) = \left|\frac{D_{Tot}^{In} - D_{Tot}^{B}}{D_{Tot}^{B}}\right| \times 100$$

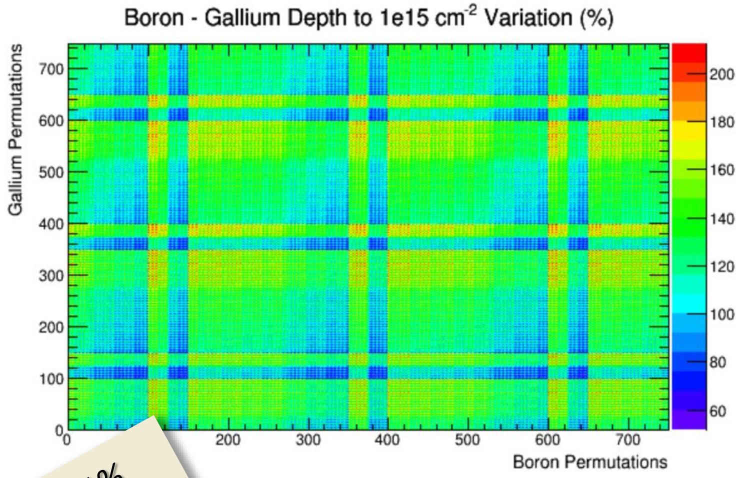

Boron - Gallium Integral Variation (%)

52 %

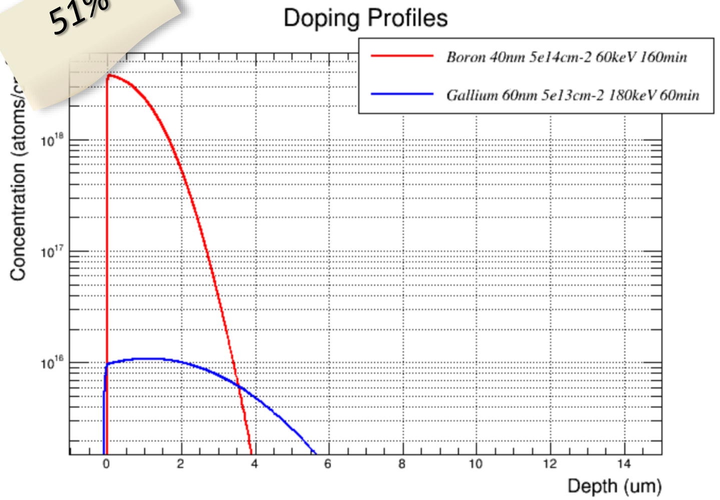

Doping Profiles

## Precision Depth

$$VAR(d) = \left|\frac{d^{In} - d^{B}}{d^{B}}\right| \times 100$$

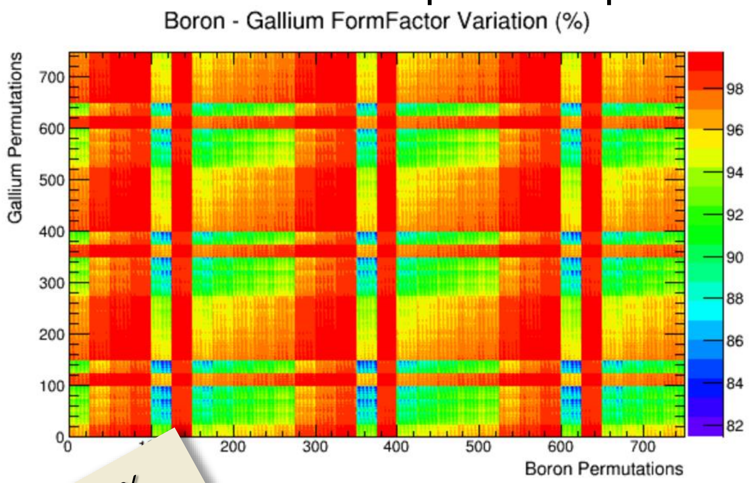

Boron - Gallium Depth to 1e15 cm$^{-2}$ Variation (%)

51%

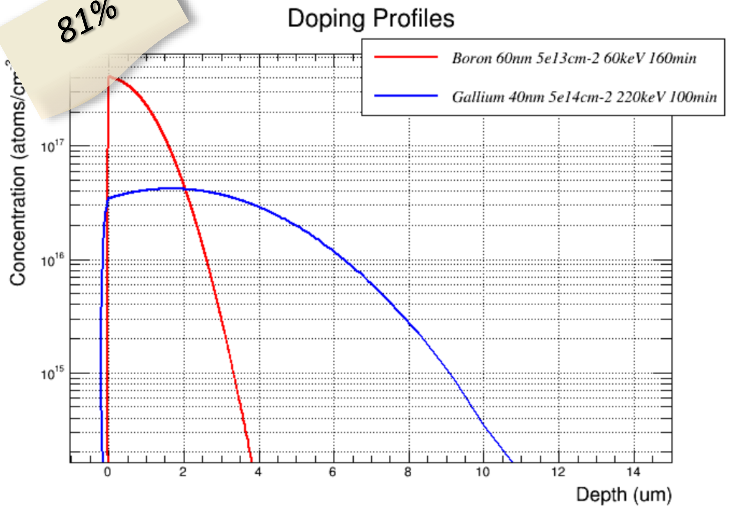

Doping Profiles

## Form Factor

$$VAR(F) = \left|\frac{F^{In} - F^{B}}{F^{B}}\right| \times 100$$


Boron - Gallium FormFactor Variation (%)

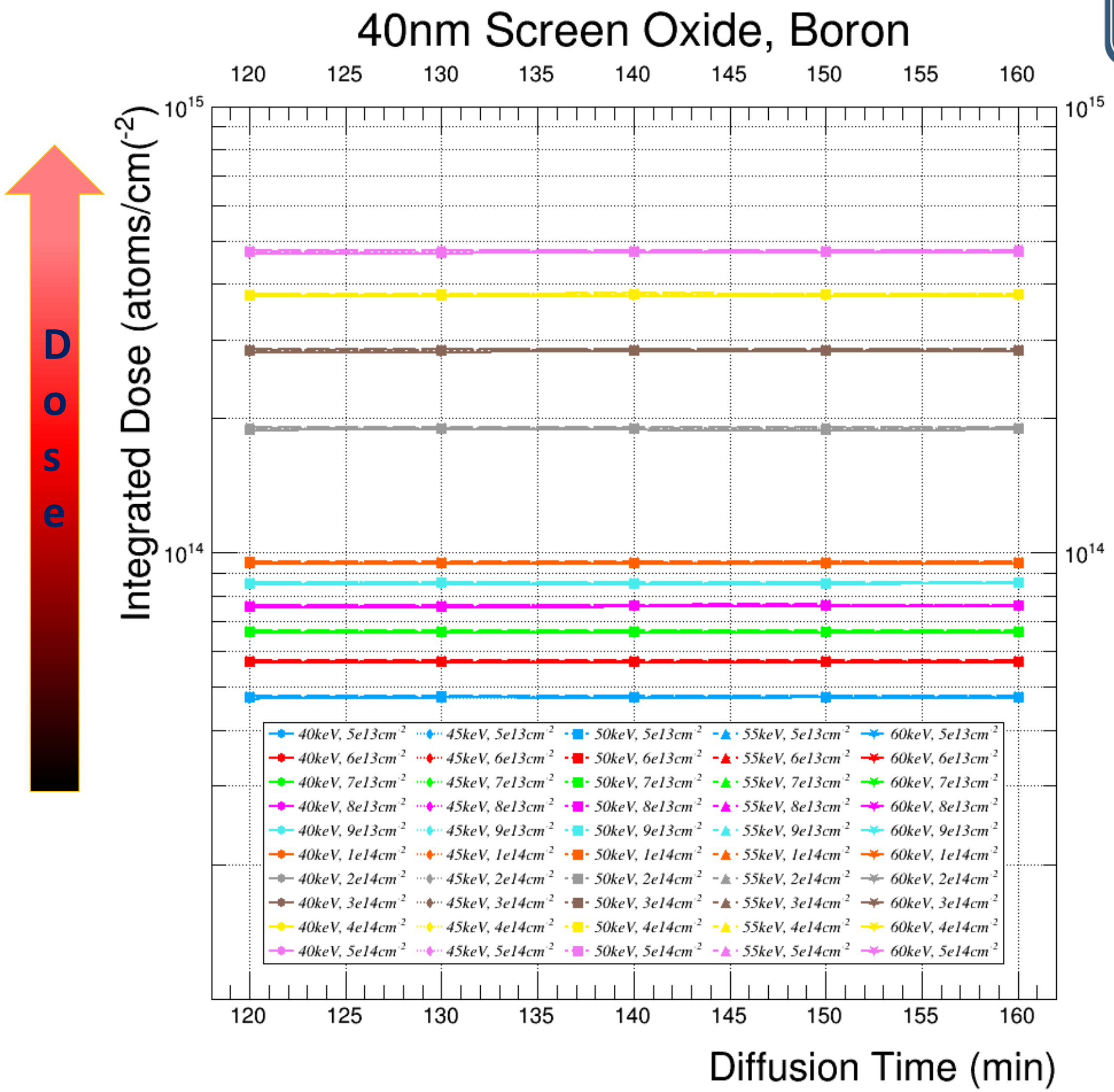
81%

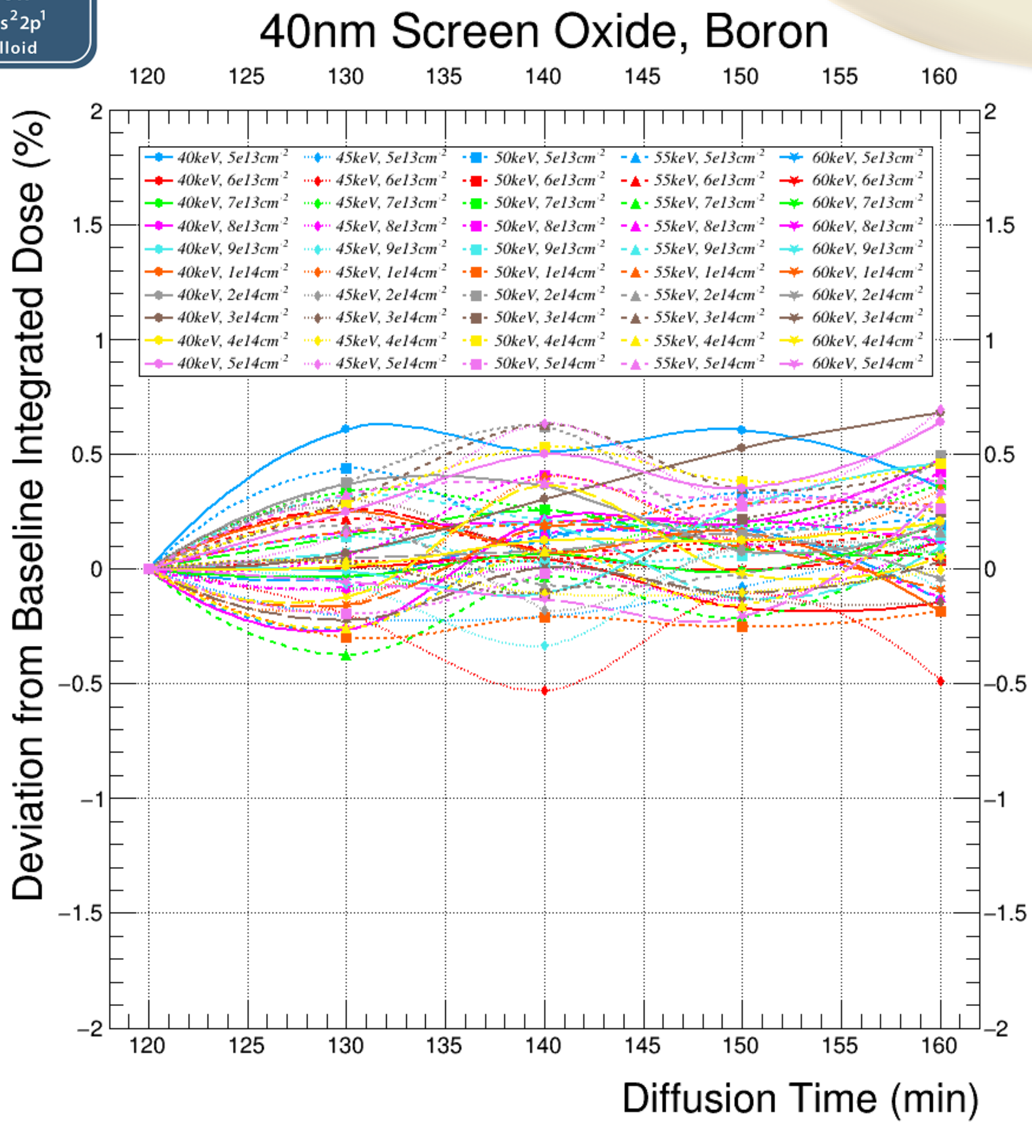

Doping Profiles

# •Dose integral – Diffusion time Impact

5 10.811
**B**
Boron
[He] $2s^2 2p^1$
Metalloid

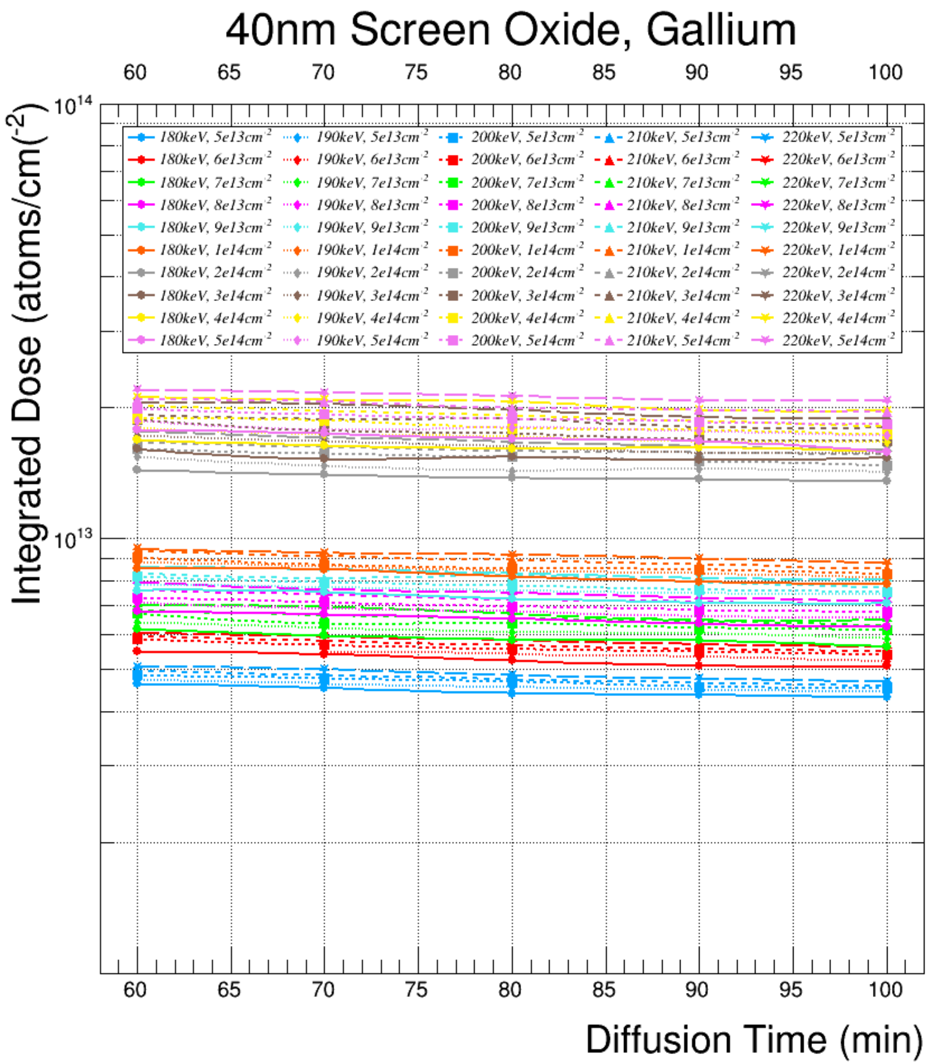
~ ± 0,5 % Effect

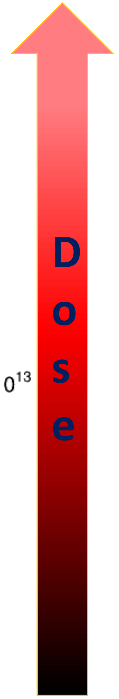


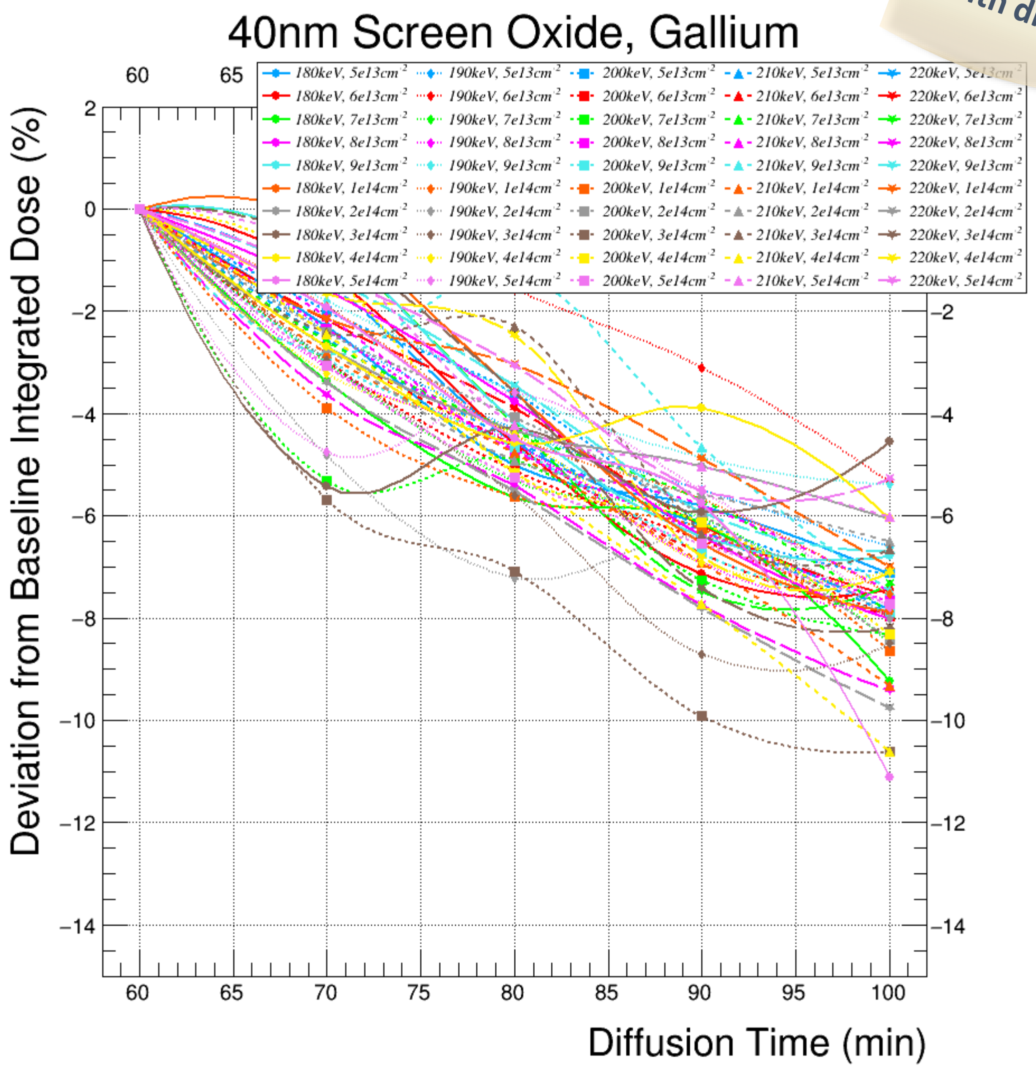


# •Dose integral – Diffusion time Impact

31 69.723
**Ga**
Gallium
[Ar] $3d^{10}4s^24p^1$
Post-Transition Metal





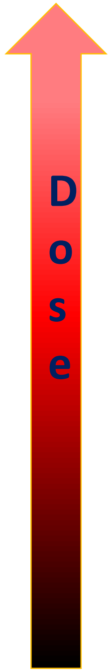


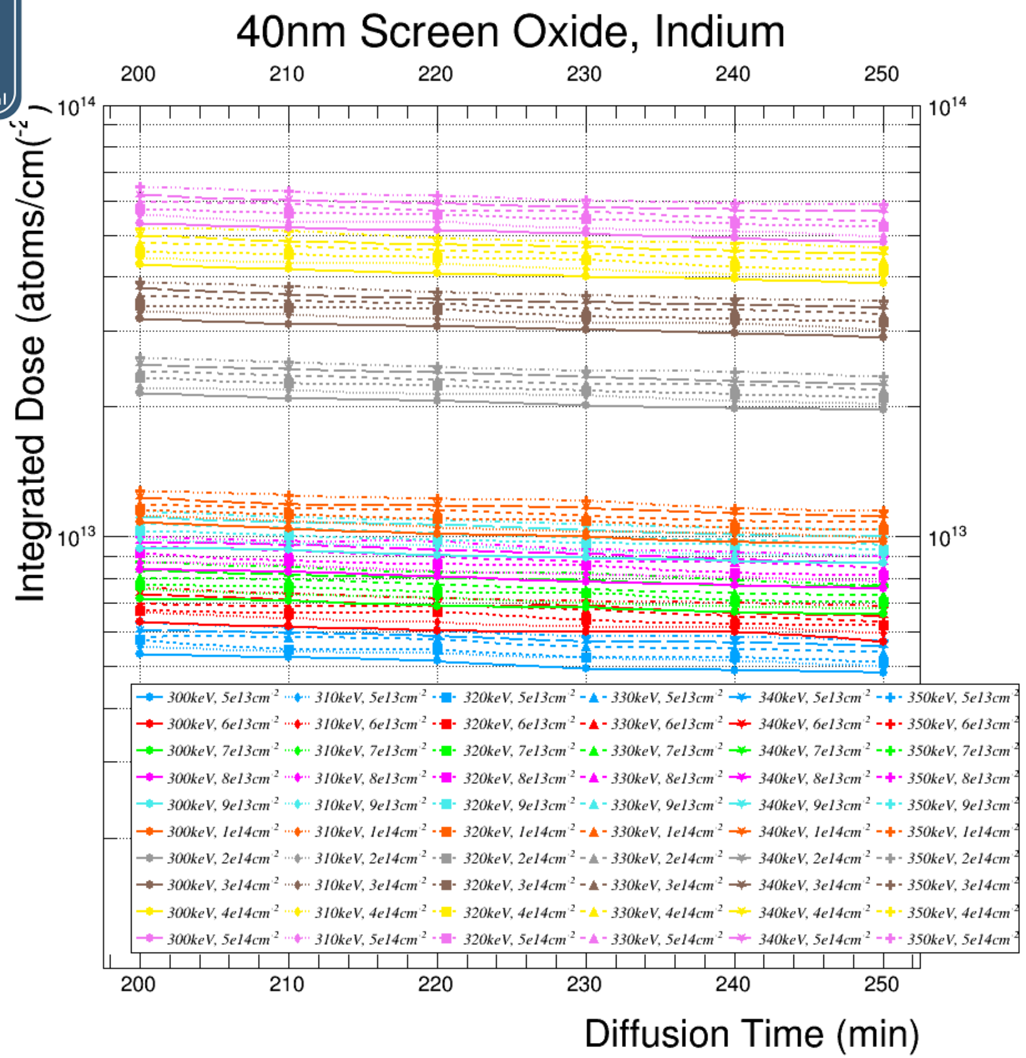
Up to 12 % reduction with diffusion itme

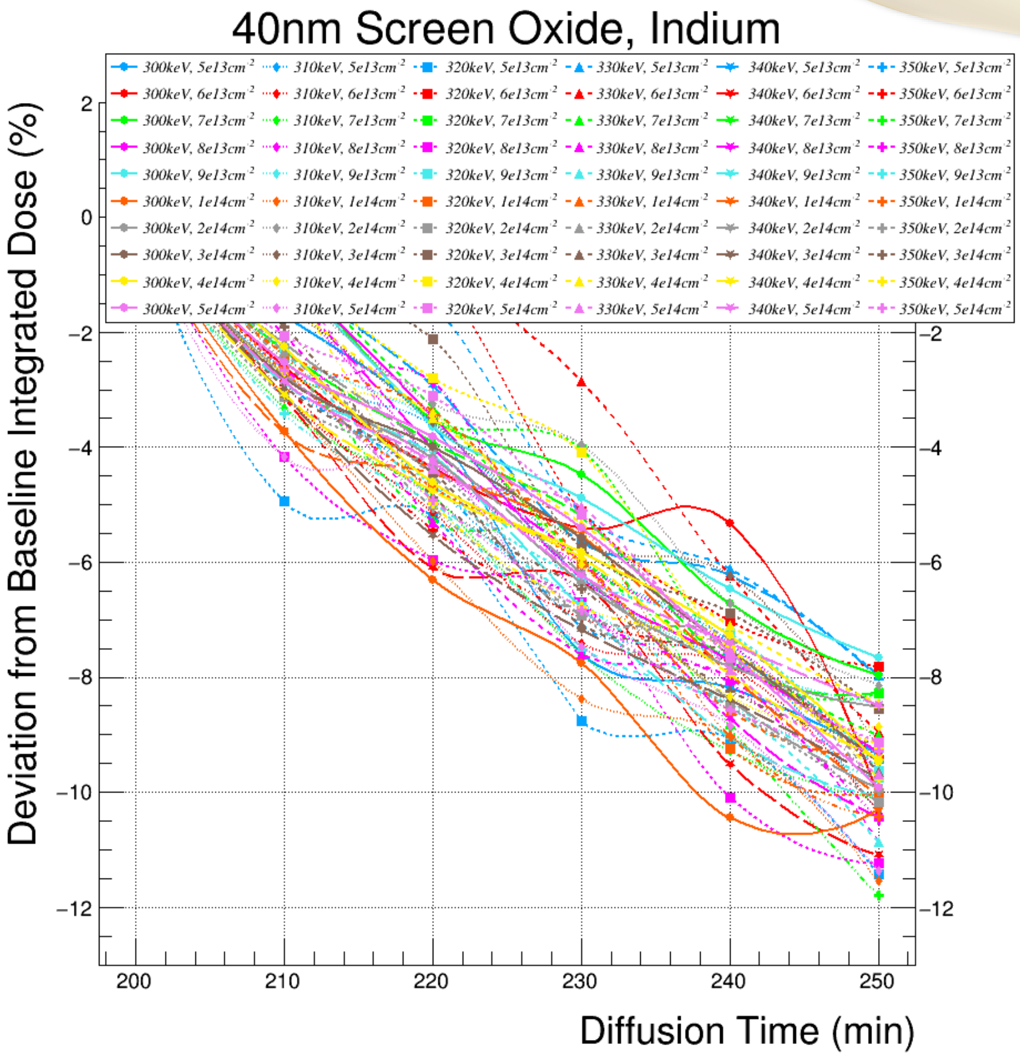
E. L. Gkougkousis

# •Dose integral – Diffusion time Impact

49 114.818
**In**
Indium
[Kr] 4d$^{10}$5s$^2$5p$^1$
Post-Transition Metal







~10% decrease with diff. time