Lithium ion irradiation of silicon diodes

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Motivation of the study

- The next generation silicon detectors for future very high luminosity colliders or a possible LHC upgrade scenario will require radiation-hard semiconductor detectors up to fluences of 10^{16} 1-MeV equivalent neutrons/cm^2.

- These high fluences present strong constraints for prototype device testing because long irradiation times are required at the currently available proton irradiation facilities.

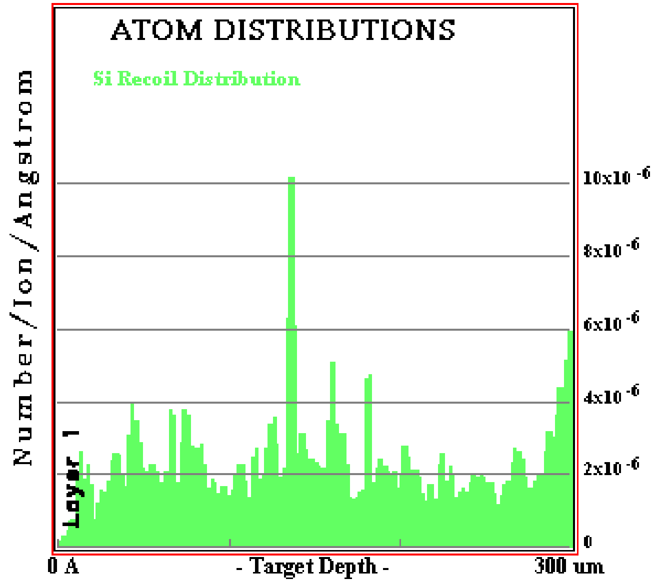
- A possible solution to overcome these time constraints is to irradiate devices with high energetic heavy ions, taking advantage of the large non-ionizing energy-loss (NIEL), which significantly increases with the atomic number of the impinging particles.

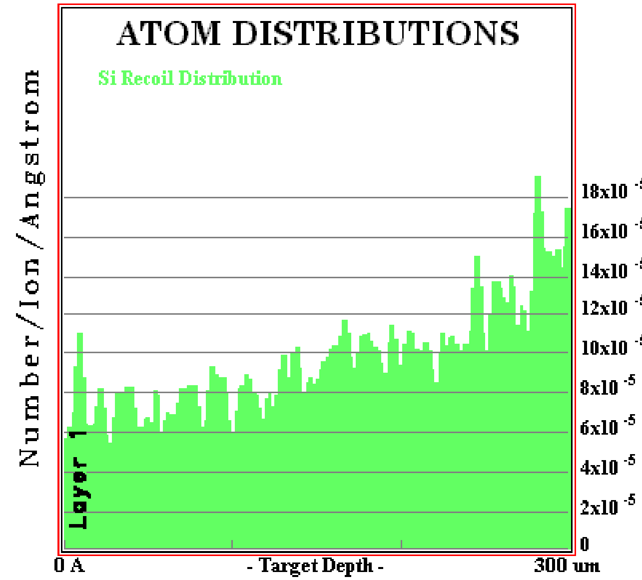
- This study presents the results of the first experiment on detector radiation hardness by making use of high energetic ions heavier than protons.

58 MeV Li ions in silicon

Range:	400 µm
Energy loss in 50 µm:	4.3 MeV
Energy loss in 300 µm:	32.6 MeV
NIEL :	2.003×10^{-4} MeV/cm^2 × mg
Hardness factor 49.1:	27.3 times higher than 27 MeV protons (1.80)
	84.7 times higher than 24 GeV protons (0.58)

Si recoil distribution: 27 MeV protons 58 MeV Li ions





Tested devices

Experiment: part I. Standard and oxygenated float zone silicon diodes

Manufacturer	Substrate	Resistivity (kΩ×cm)	Thickness (µm)	Area (cm^2)	Label
CNM	standard <100>	4	280	0.25	CNM_{STD}
CNM	oxygenated (12h at 1150°C)	4	280	0.25	CNM_{OXY}
ST	standard <100>	2	300	0.25	ST_{STD}
ST	oxygenated (30h at 1200°C)	2	300	0.25	ST_{OXY}

Fluence: up to 5.19×10^{12} Li/cm^2 <==> 1.42 $\times10^{14}$ 27-MeV protons/cm^2. RD48 range

Experiment: part II. Epitaxial silicon diodes

Manufacturer	Substrate	Resistivity (Ω×cm)	Thickness (µm)	Area (cm^2)	Label
CIS	Epitaxial on CZ silicon	50	50	0.25	CIS_{EPI}

Fluence: up to 63.58×10^{12} Li/cm^2 <==>5.38 $\times10^{15}$ 24-GeV protons/cm^2. RD50 range

Irradiation and experimental procedure

- Standard and oxygenated float zone silicon diodes

  -Irradiation in single step with an ion flux of 2.5×10^9 ions/cm$^2\times$s

  -**1 hour** at room temperature after irradiation

  -storing at -20°C

  -1,10,100 kHz C-V and I-V measurements

  -Annealing at 80°C for 4 minutes

  -1,10,100 kHz C-V and I-V measurements

- Epitaxial silicon diodes

  -Irradiation in single step with an ion flux of 2.5×10^9 ions/cm$^2\times$s

  -**1 week** at room temperature

  -storing at -20°C

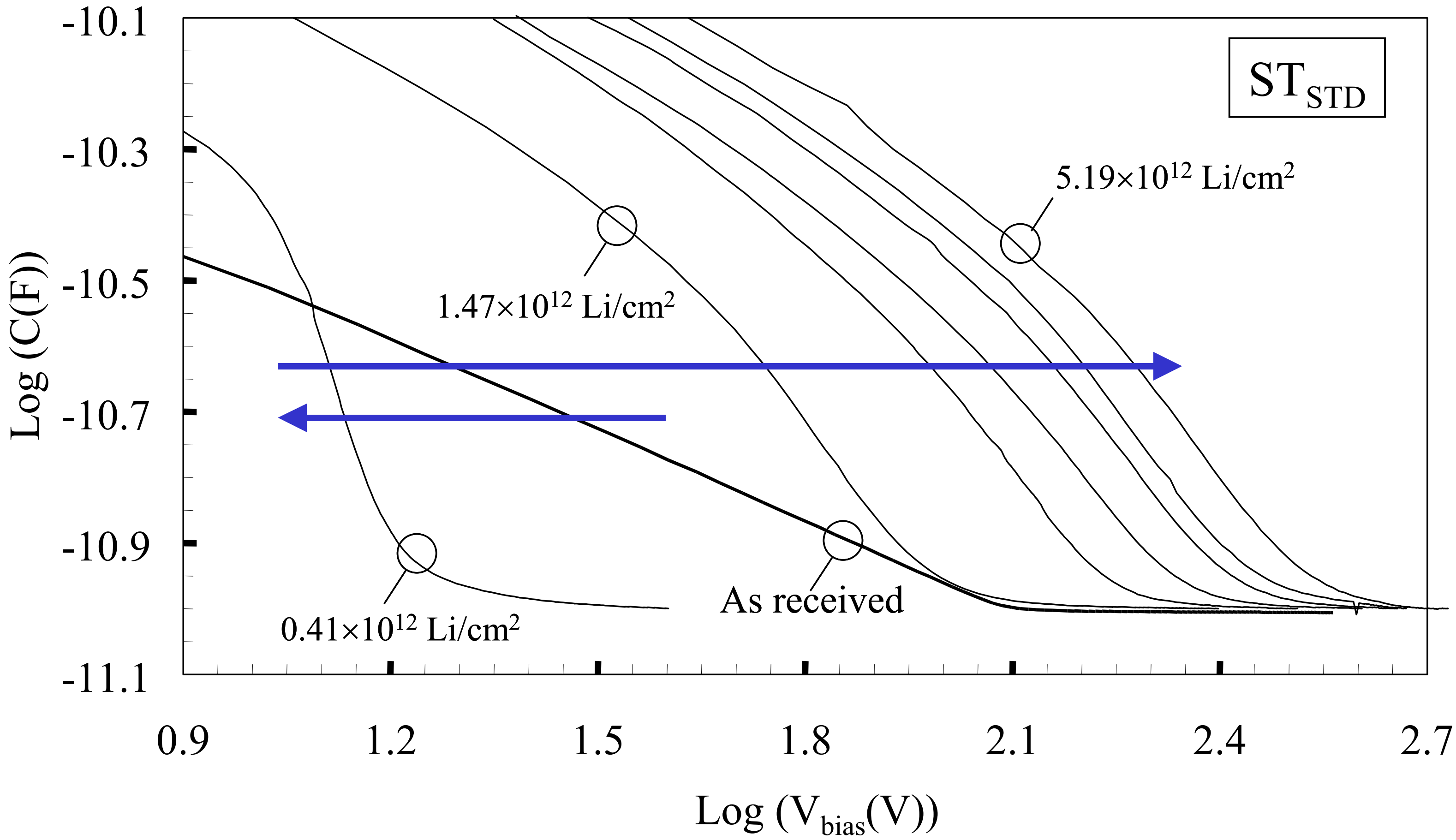
  -1,10,100 kHz C-V and I-V measurements

  -Annealing at 80°C for 4 minutes

  -1,10,100 kHz C-V and I-V measurements

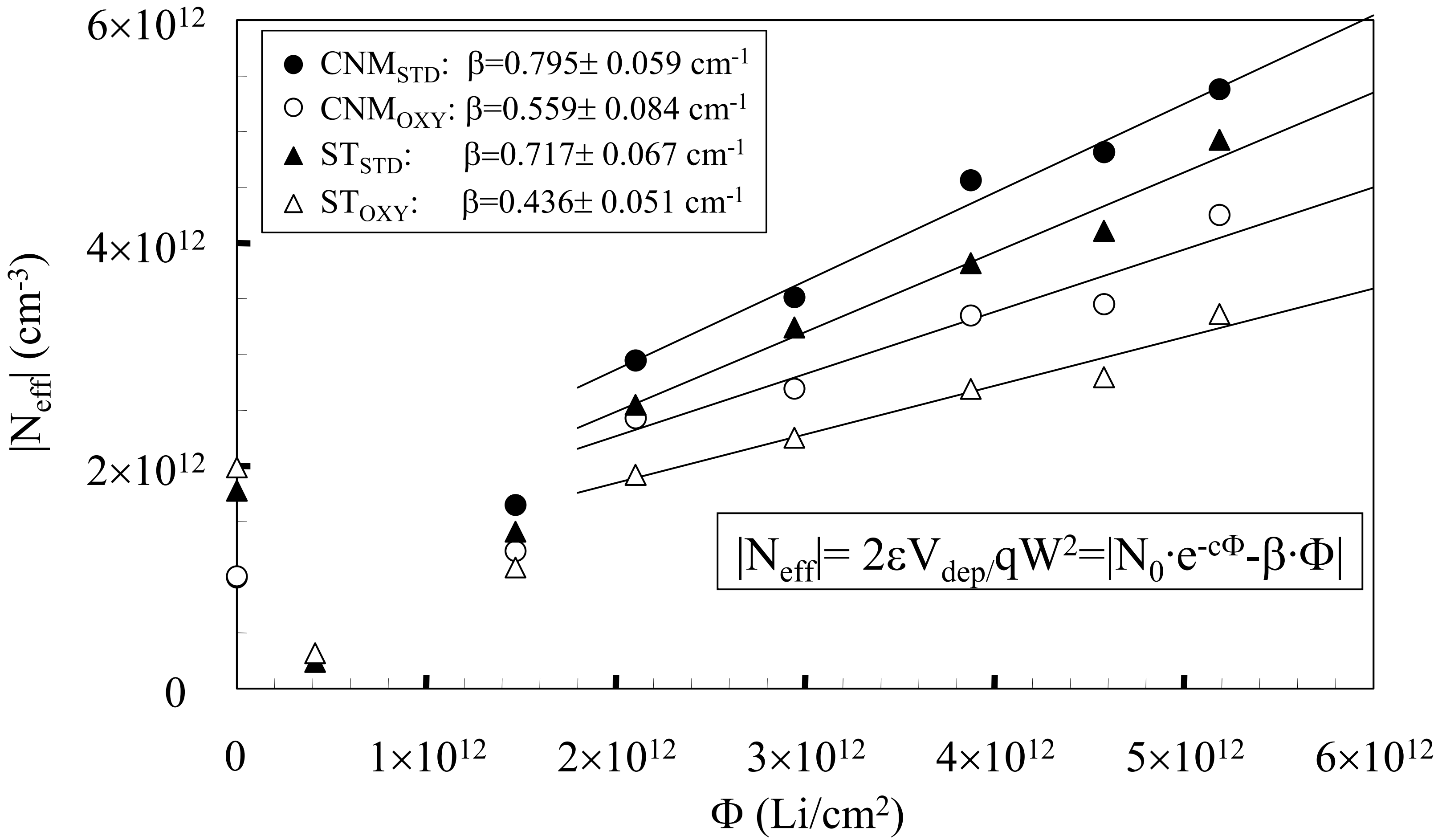
The analysis of the experimental data has been performed
by considering the 10 kHz C-V curves and by scaling the I-V curves at 20°C

Standard and oxygenated FZ diodes: 10 kHz C-V curves after irradiation



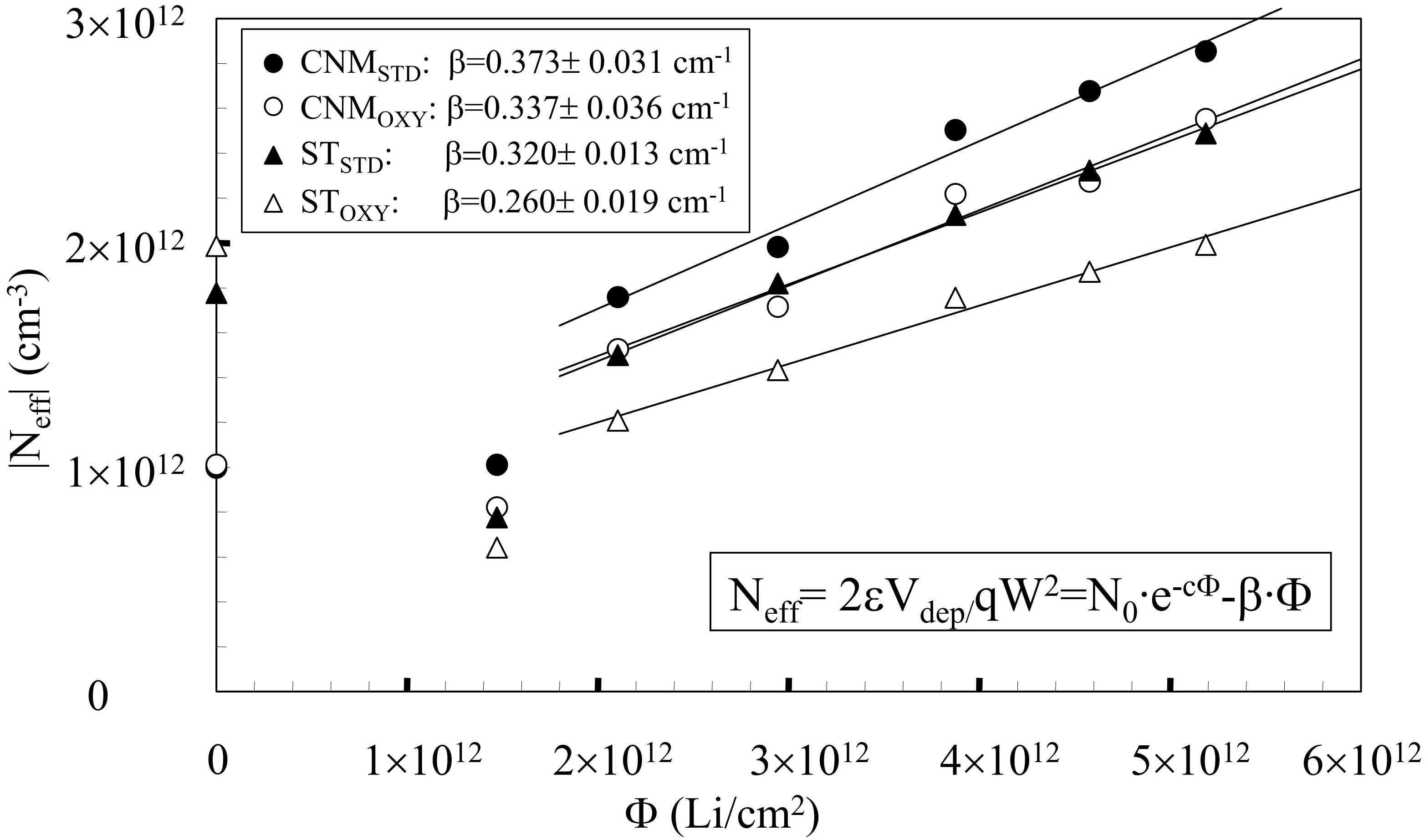
Space charge sign inversion (SCSI) after Li ion irradiation

Standard and oxygenated FZ diodes: N_{eff} after irradiation



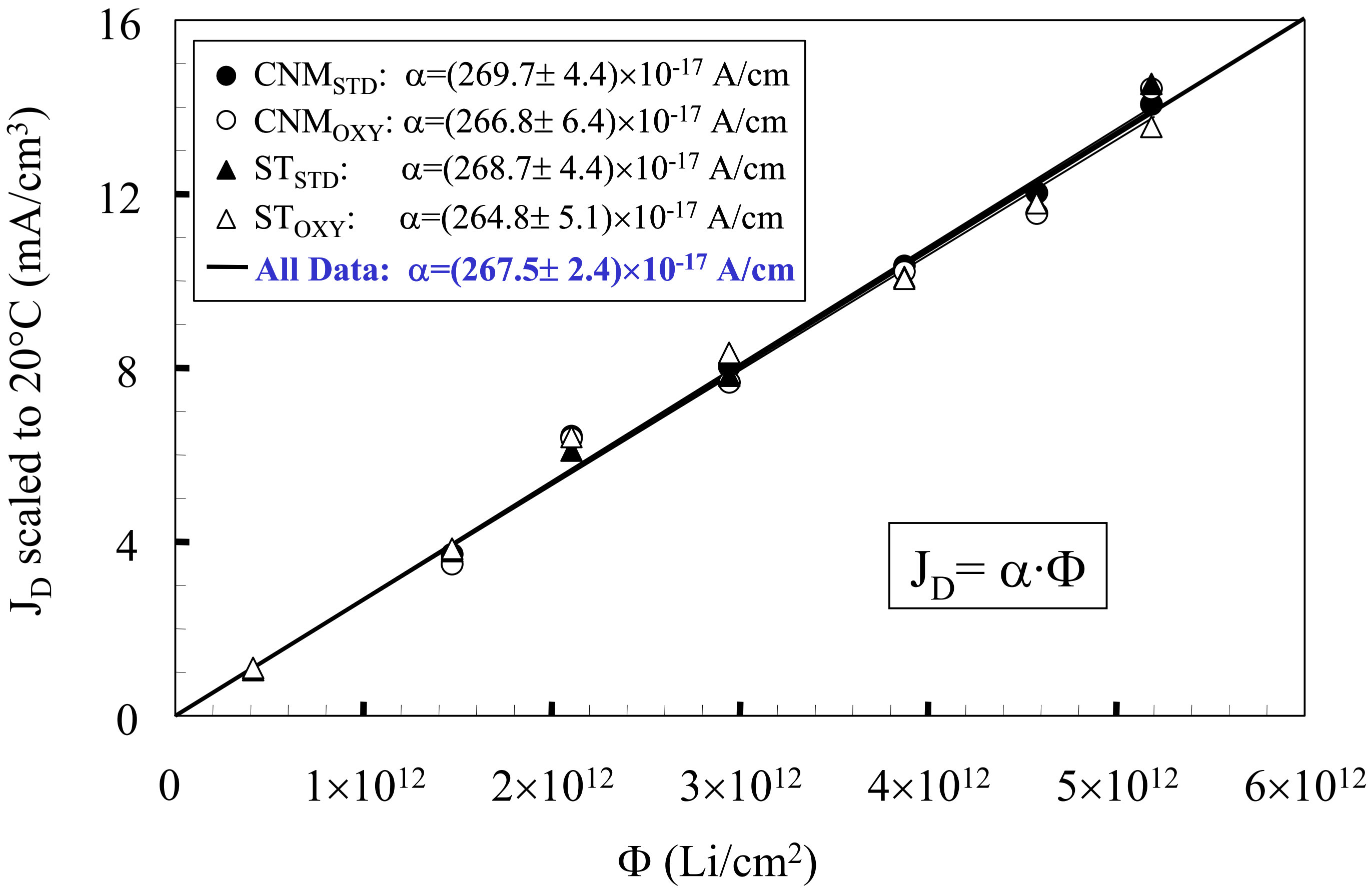
- $|N_{eff}| \propto \beta \cdot \Phi$ after SCSI
- β **is** lower for oxygenated devices
- ST_{OXY}: highest [O] and lowest β

Standard and oxygenated FZ diodes: N_{eff} after 4 min at 80°C



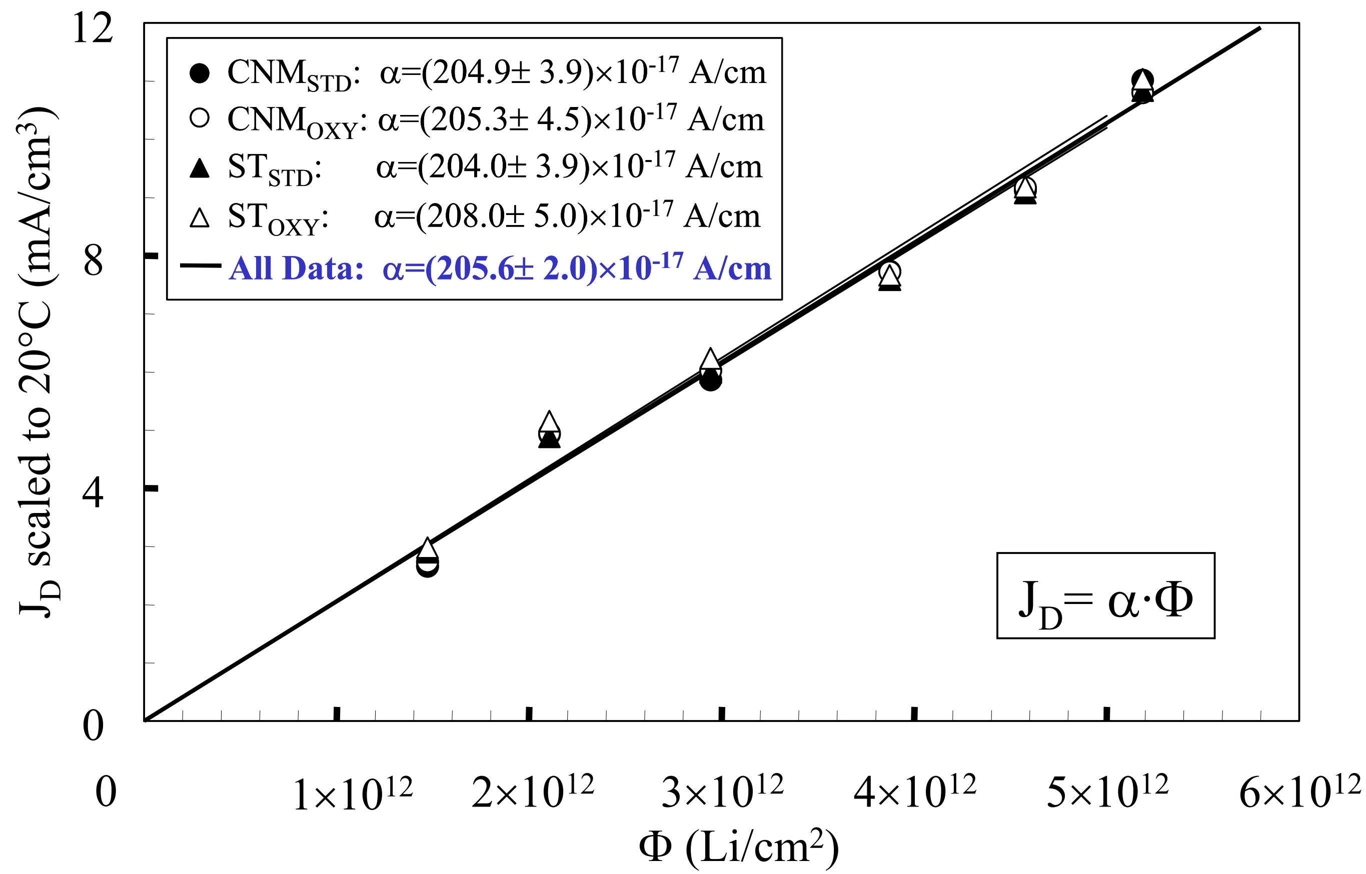
- $|N_{eff}| \propto \beta\cdot\Phi$ after SCSI
- β **is slightly** lower for the oxygenated devices
- ST_{OXY}: highest [O] and lowest β

Standard and oxygenated FZ diodes: J at V_{dep} (J_D) after irradiation



-Linear dependence of J_D on the Li ion fluence
-α is independent from starting material and/or processing

Standard and oxygenated FZ diodes: J at V_{dep} (J_D) after 4 min at 80°C



Experimental hardness factor: **H_{EXP}**= α(58 MeV Li)/α(1 MeV neutrons)=**45.08**

Theoretical hardness factor: **H_{TEO}**= = **49.11**

Difference of the theoretical-experimental values: $(H_{TEO}-H_{EXP})/H_{TEO}$=8.2%

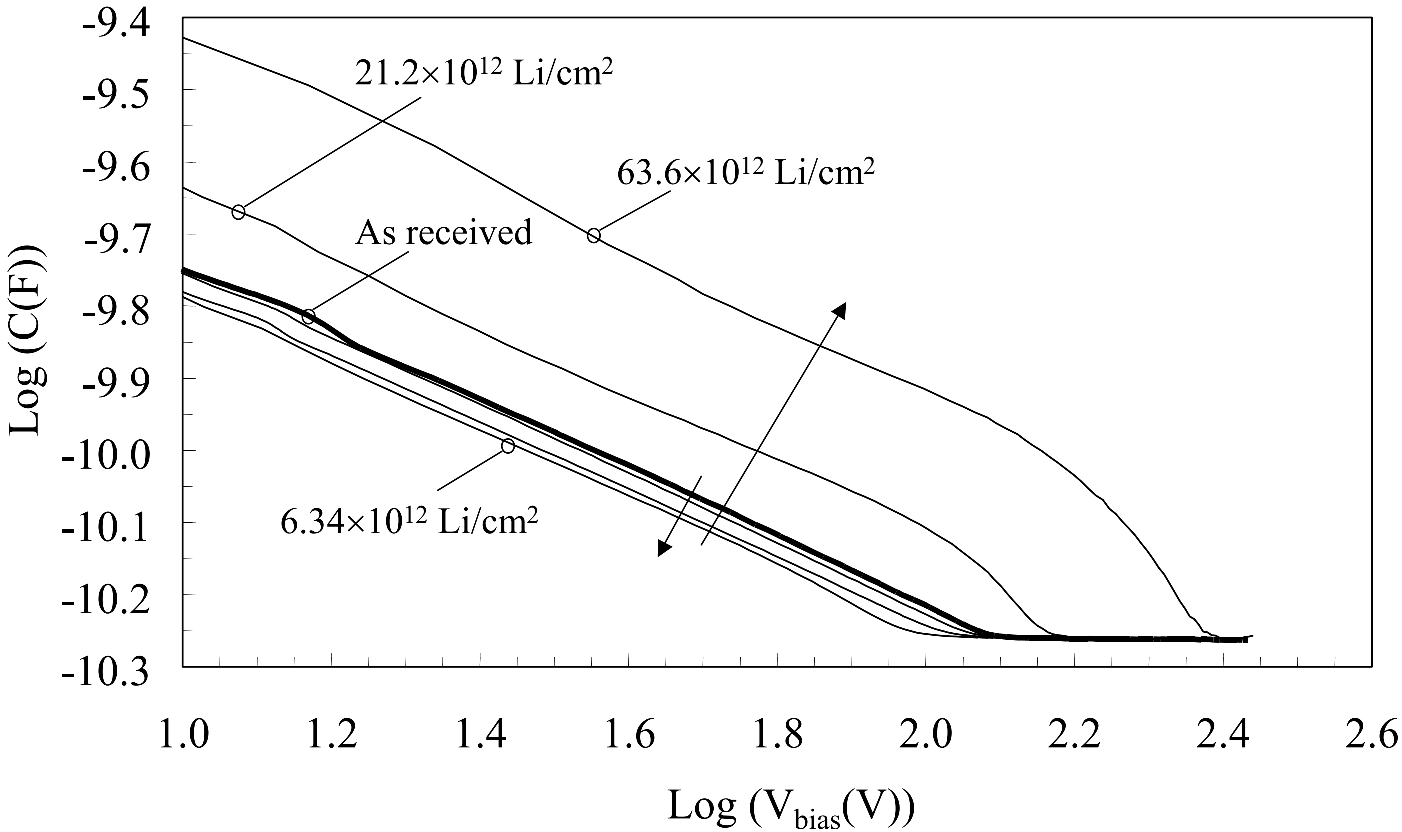
Standard and oxygenated FZ diodes: 27 MeV protons and 58 MeV Li

Diode	$\alpha_{27\ MeV\ protons}$	$\alpha_{58\ MeV\ Li\ ions}$	$\alpha_{58\ MeV\ Li\ ions}/\alpha_{27\ MeV\ protons}$
CNM_{STD}	$(8.48\pm0.06)\times10^{-17}$	$(204.9\pm3.9)\times10^{-17}$	24.2 ± 0.6
CNM_{OXY}	$(8.35\pm0.04)\times10^{-17}$	$(205.3\pm4.5)\times10^{-17}$	24.6 ± 0.7
ST_{STD}	$(8.26\pm0.06)\times10^{-17}$	$(204.0\pm3.9)\times10^{-17}$	24.7 ± 0.6
ST_{OXY}	$(8.12\pm0.14)\times10^{-17}$	$(208.0\pm5.0)\times10^{-17}$	25.6 ± 1.1

Diode	$\beta_{27\ MeV\ protons}$	$\beta_{58\ MeV\ Li\ ions}$	$\beta_{58\ MeV\ Li\ ions}/\beta_{27\ MeV\ protons}$
CNM_{STD}	0.0243 ± 0.0019	0.3735 ± 0.0306	15.4 ± 2.5
CNM_{OXY}	0.0208 ± 0.0024	0.3366 ± 0.0359	16.2 ± 3.6
ST_{STD}	0.0286 ± 0.0030	0.3197 ± 0.0126	11.2 ± 1.6
ST_{OXY}	0.0170 ± 0.0019	0.2599 ± 0.0188	15.3 ± 2.8

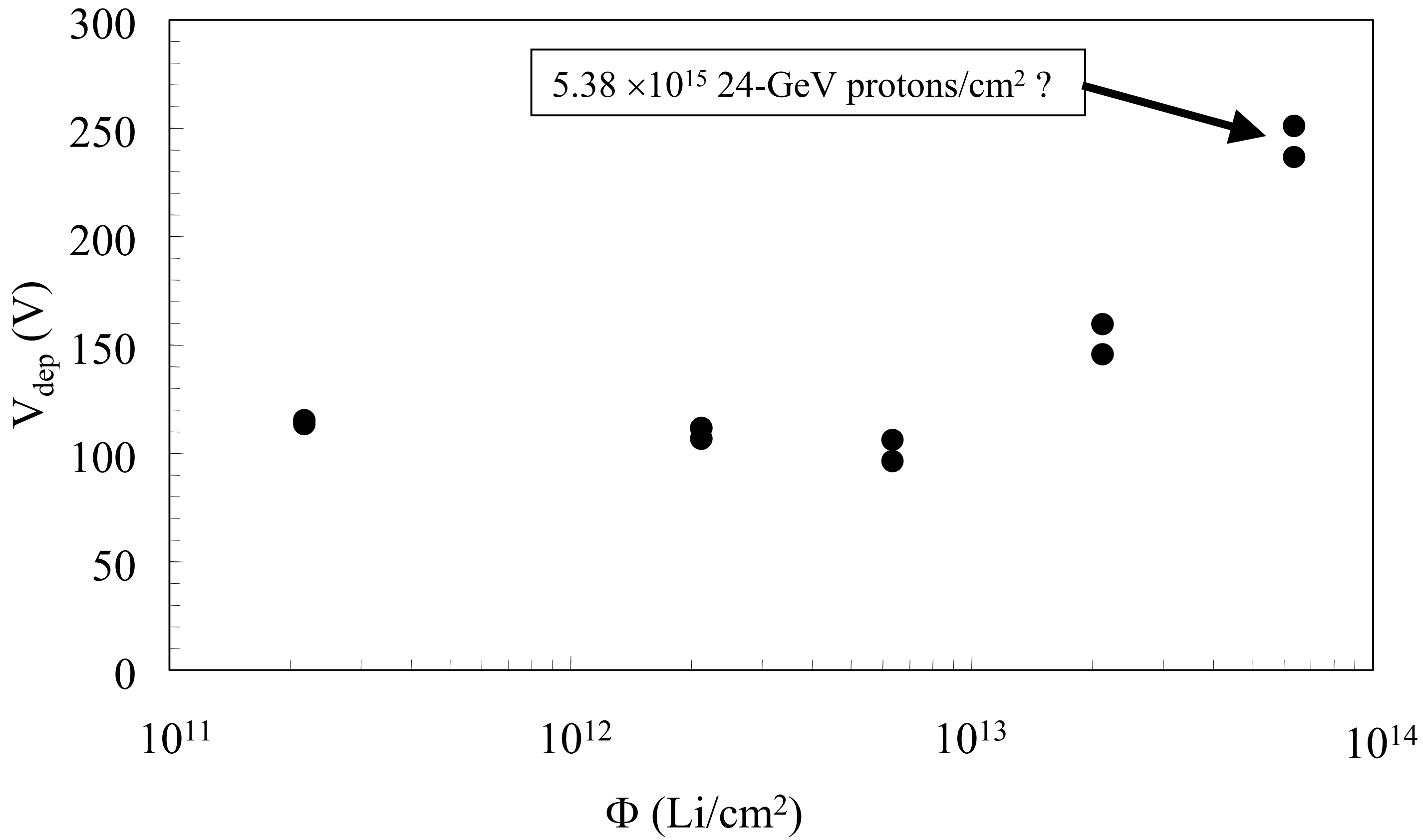
-The ratios of the β and α values for 27 MeV protons and 58 MeV Li ions appear independent on starting material and/or processing

Epitaxial diodes: 10 kHz C-V curves after 4 min at 80°C



V_{dep} slightly decreases for $\Phi \leq 6.34 \times 10^{12}$ Li/cm^2
increases for $\Phi \geq 21.2 \times 10^{12}$ Li/cm^2

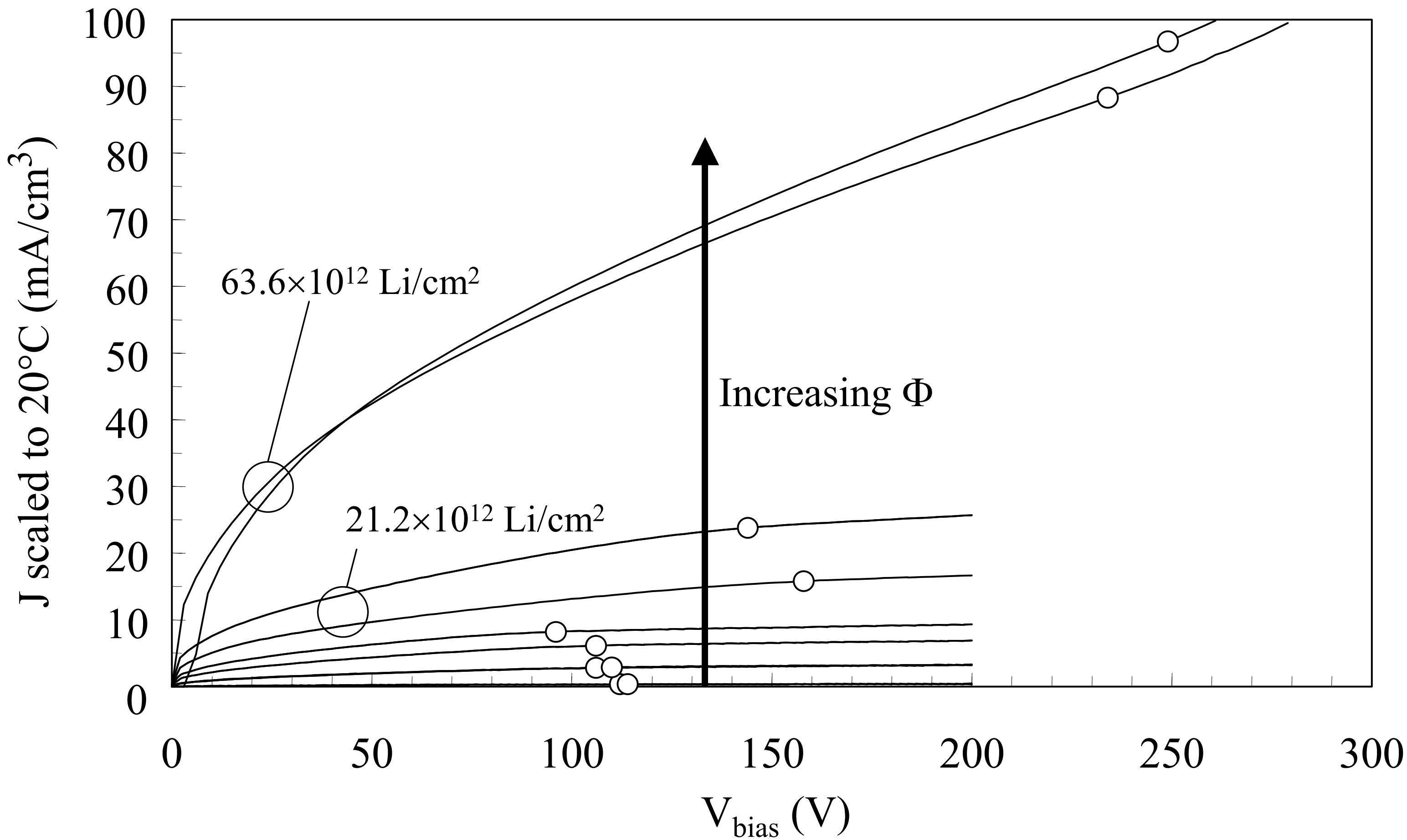
Epitaxial diodes: V_{dep} vs Φ after 4 min at 80°C



-SCSI or positive space charge increase? Under investigation.

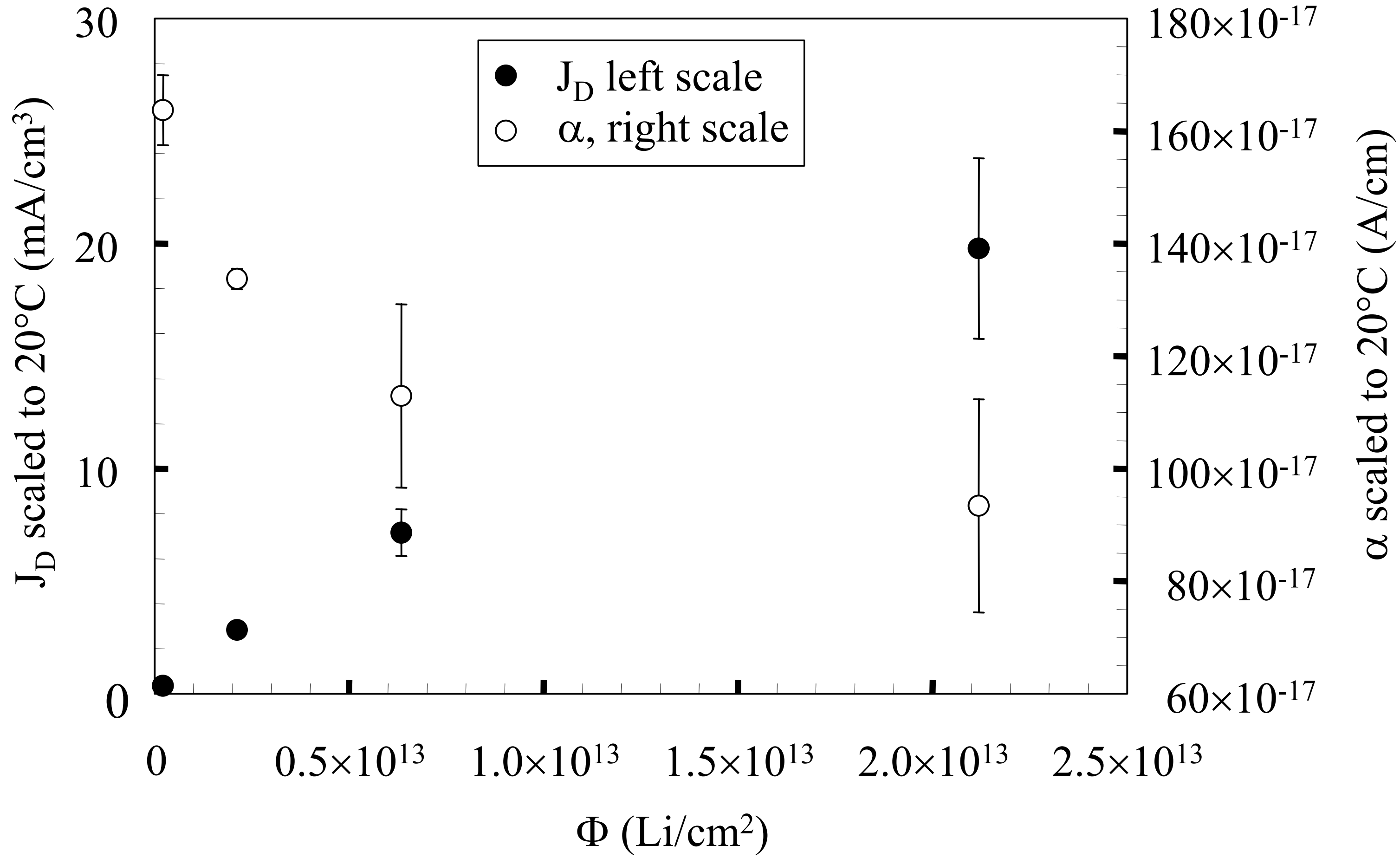
-Quasi-flat V_{dep} behavior ($\Phi \leq 6.34 \times 10^{12}$ Li/cm^2) also confirmed by 24 GeV proton irradiation data from Hamburg group up to 1.3×10^{15} 24-GeV protons/cm^2 (1.54×10^{13} Li/cm^2).

Epitaxial diodes: J-V curves after 4 min at 80°C



-J at full depletion is in the flat part of the J-V curves apart from the highest fluence where a saturation of the J-V curve is not observed

Epitaxial diodes: J at V_{dep} (J_D) and $\alpha=J_D/\Phi$



- J_D presents a sub-linear trend, consequently α decreases.
- α at the lowest fluence ($164\pm6\times10^{-17}$ A/cm) is in agreement within 12% in the NIEL scaling hypothesis with the value measured by the Hamburg group after 24 GeV proton irradiation ($\alpha=(2.20\pm0.15)\times10^{-17}$ A/cm)
- α is lower for epitaxial diodes than for FZ silicon devices (effect already observed by RD48 collaboration).

Conclusions

- 58 MeV Li ion irradiation effects on float zone diodes (RD48 range):
  - very similar to protons:
    - space charge sign inversion;
    - β is lower for oxygenated devices;
    - α is independent on starting material and/or processing;
  - scaling of the irradiation time by a factor ≈45:
    - the experimental hardness factor (45.08) is within 8.2% the values expected from the NIEL scaling hypothesis;
    - the ratio of the β and α parameters for 27 MeV protons and 58 MeV Li ions appear independent on starting material and/or processing;

- 58 MeV Li ion irradiation effects on epitaxial diodes (RD50 range):
  - non-monotonic trend of the V_{dep} variation,
  (the quasi-flat behavior of V_{dep} is in agreement with proton irradiation data);
  - sub-linear trend of the diode current density increase at full depletion,
  (α at the lowest fluence is in agreement with the proton irradiation data).

Radiation hardness by heavy ions: a new research topic!

Future Activity

- Investigation of the V_{dep} and J_D characteristics for long annealing times up to 2048 minutes

- Investigation of the microscopic defects induced by Li ions by DLTS and TSC.

- Investigation of the charge collection efficiency

- Comparison of the degradation induced by 58 MeV Li ions and protons extending the fluence range.

- Irradiation of diodes manufactured on CZ silicon

- ...