Detectors and electronics for Super-LHC:
IRRADIATION RESULTS

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OUTLINE

The presented results are from experiments performed by:

-SMART Collaboration (Bari, Firenze, Pisa, Padova, Perugia, Trieste, Trento)
(V. Khomenkov, A. Litovchenko, A. Candelori)

-Department of Information Engineering (**DEI**), University of Padova
(A. Paccagnella, A. Cester, S. Gerardin)

Measurements are in progress ... some new results after the Trento RD50 Meeting

1) Nuclear reactor irradiation in Lubjana (V. Cindro):

-**Epitaxial** n-type detectors (**SMART**)

-**Pre-irradiated** n-type detectors (**Kiev, IRST, Padova**)

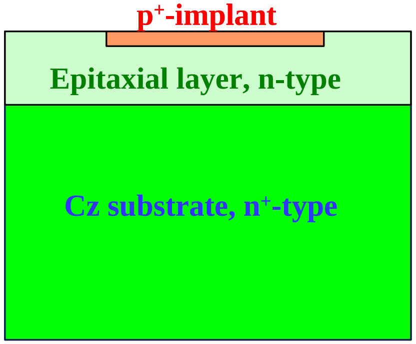
2) 24 GeV proton irradiation at CERN (M. Glaser, M. Moll, F. Ravotti):

-**Epitaxial** n-type detectors (**SMART**)

-**FZ thinned** n-type detectors (**SMART**)

- **0.13 μm CMOS** technology (**DEI**)

DETECTORS



-**Epitaxial** detectors:

Epitaxial layer: n-type, 50 μm thick, ρ= 50 Ω·cm, grown by ITME on CZ substrate

Detector processing: IRST.

-**Pre-irradiated** detectors:

Substrate: FZ, n-type, 300 μm thick, ρ= 3-4 kΩ·cm.

Pre-irradiation: irradiation by fast nuclear reactor neutrons up to $\approx 10^{16}$ n/cm^2; maximum annealing temperature: 850 ºC; total annealing time with RT≤T≤ 850 ºC: 2 hours.

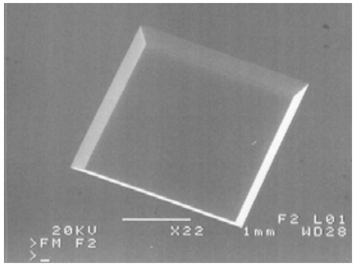
Detector processing: IRST.

-**FZ thinned** detectors:

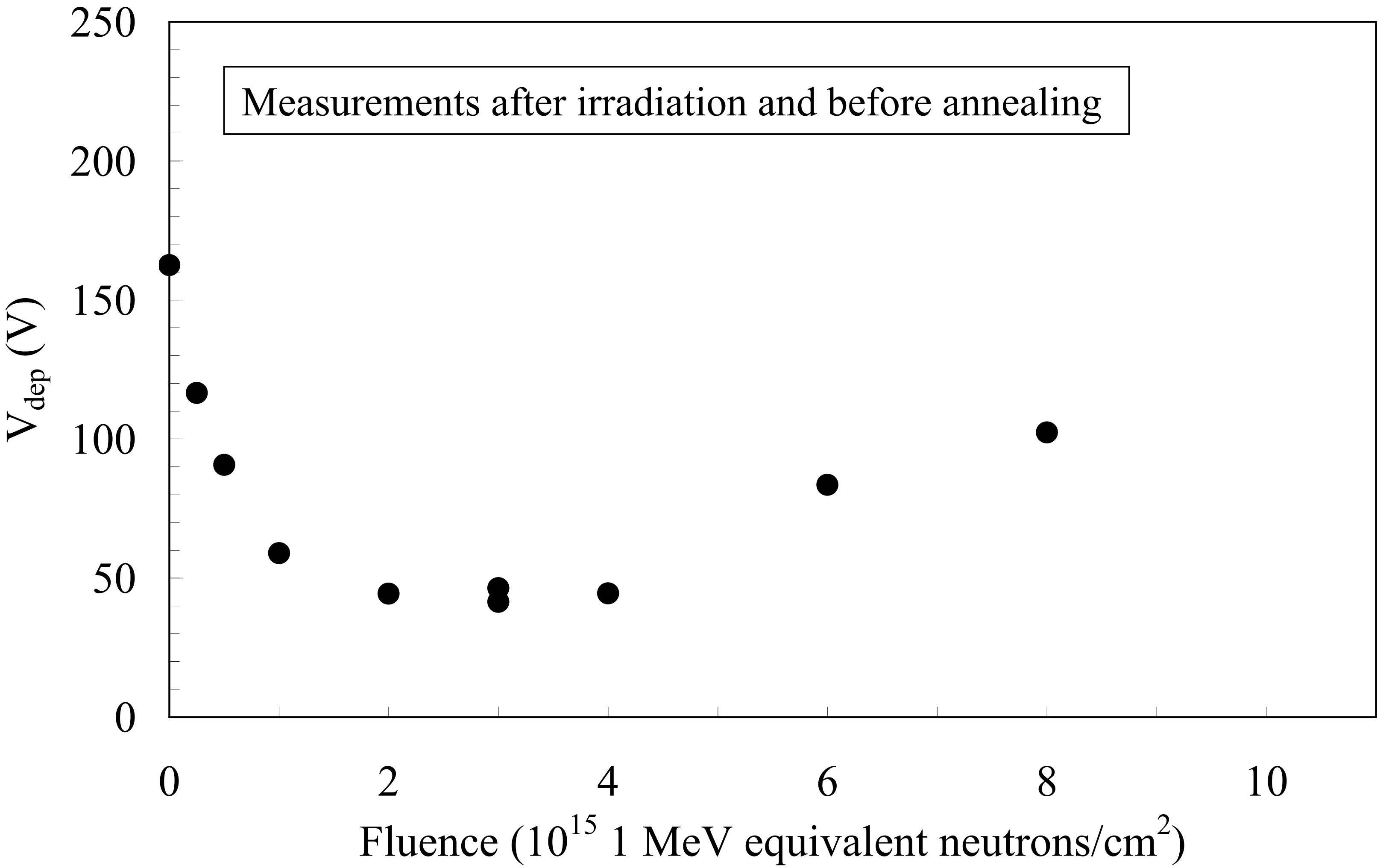
Substrate: FZ, n-type, 300 μm thick, ρ= 6 kΩ·cm.

Thinning: down to 50-100 μm by Tetra Methyl Ammonium Hydroxide (TMAH) etching from backside: IRST.

Detector processing: IRST.

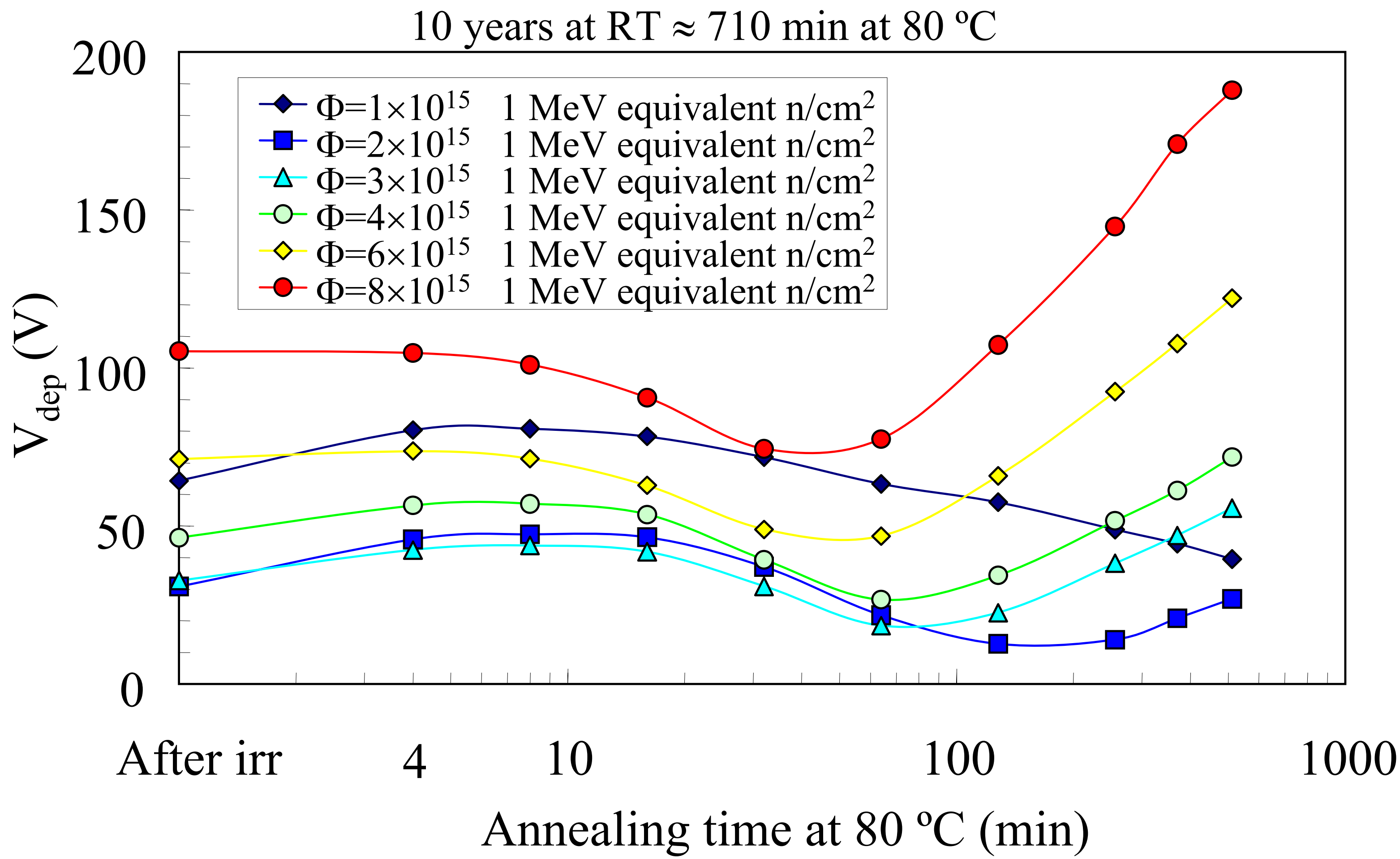


Epitaxial n-type 50 μm thick detectors: neutron irradiation



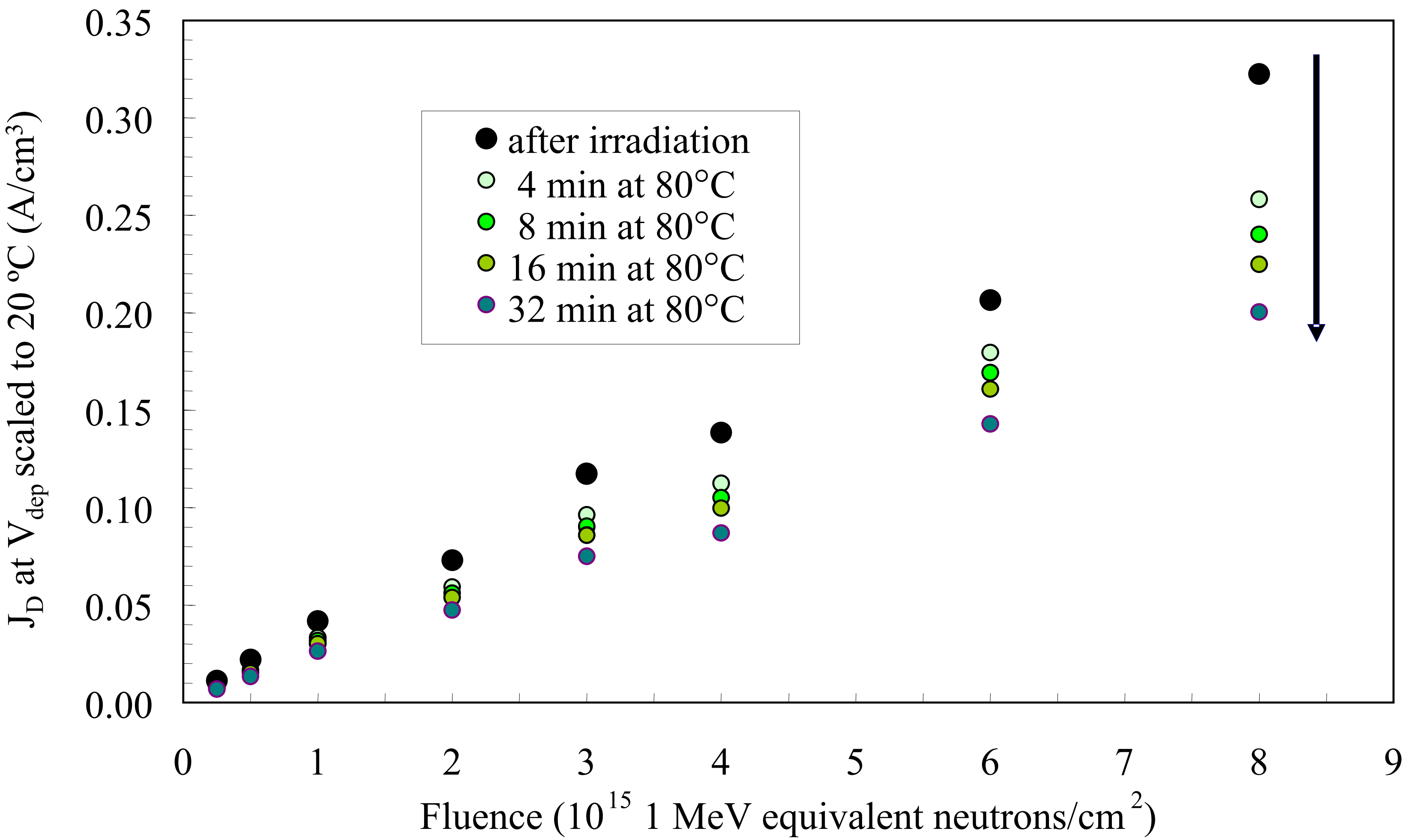
- The minimum of $V_{dep} \approx 40\text{-}50$ V is reached at $2\text{-}4 \times 10^{15}$ n/cm^2.
- $V_{dep} < V_{dep,0}$ at the maximum fluence (8×10^{15} n/cm^2).

Epitaxial n-type 50 μm thick detectors: neutron irradiation



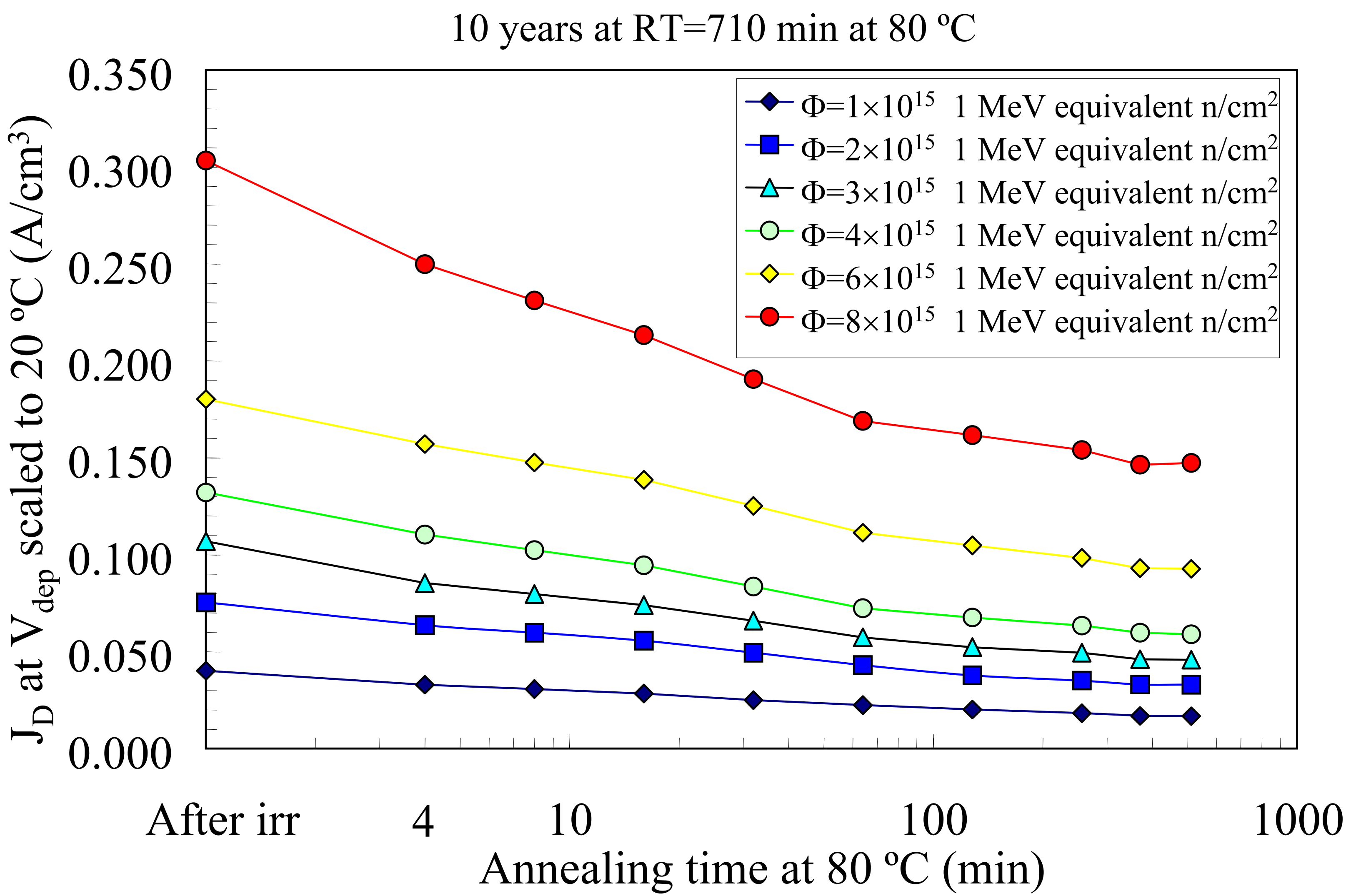
- Initial V_{dep} increase as a function of the annealing time: less evidence by increasing Φ.
- Low Φ. V_{dep} ↑, ↓, no SCSI during long-term annealing.
- Medium Φ. V_{dep} ↑, ↓, ↑, SCSI during long-term annealing.
- High Φ. V_{dep} ↑ less evident, ↓, ↑: already SCSI after irradiation or SCSI during long-term annealing?

Epitaxial n-type 50 μm thick detectors: neutron irradiation



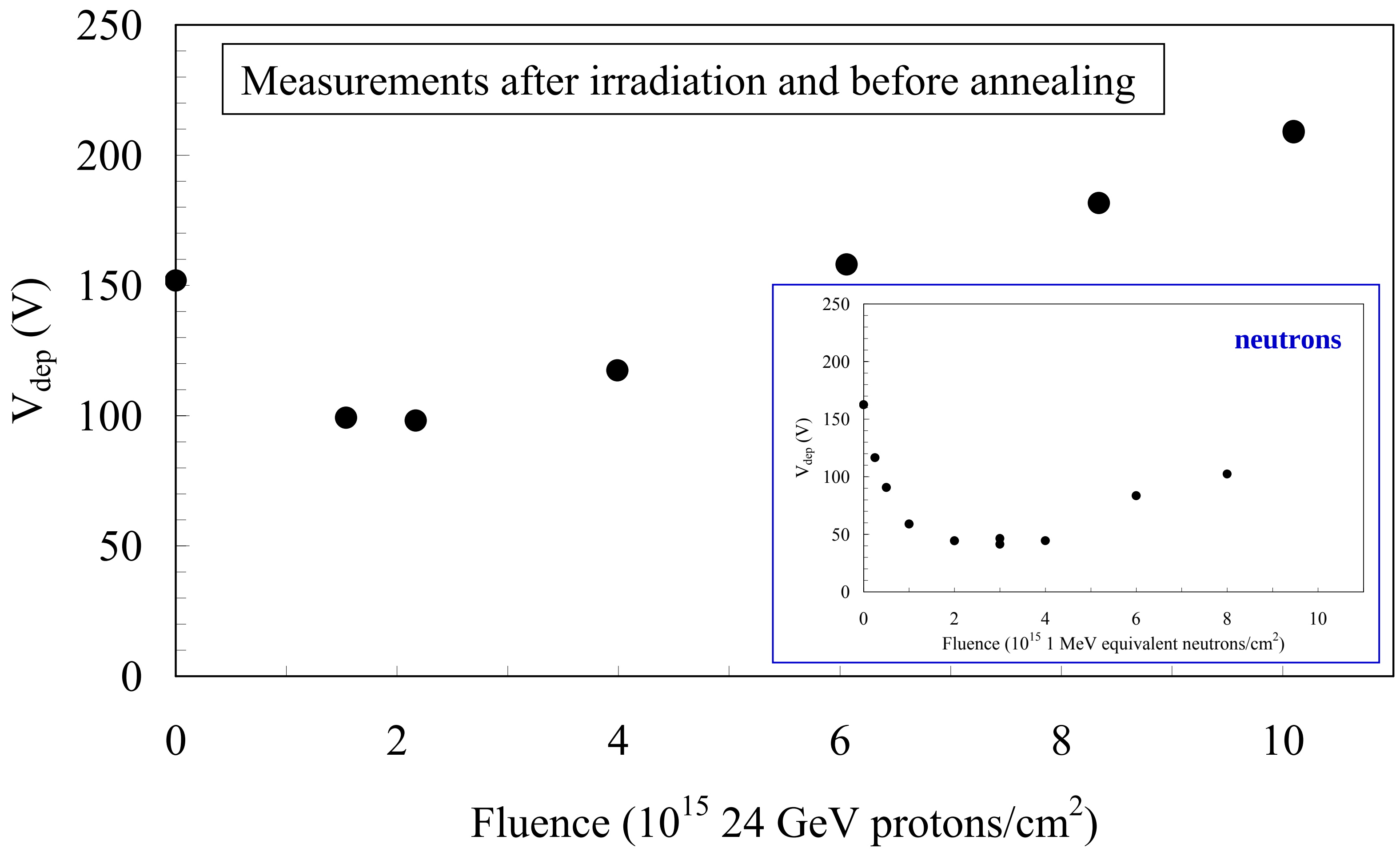
- J_D linearly increases with fluence.
- J_D decreases with annealing time at 80 °C.

Epitaxial n-type 50 μm thick detectors: neutron irradiation



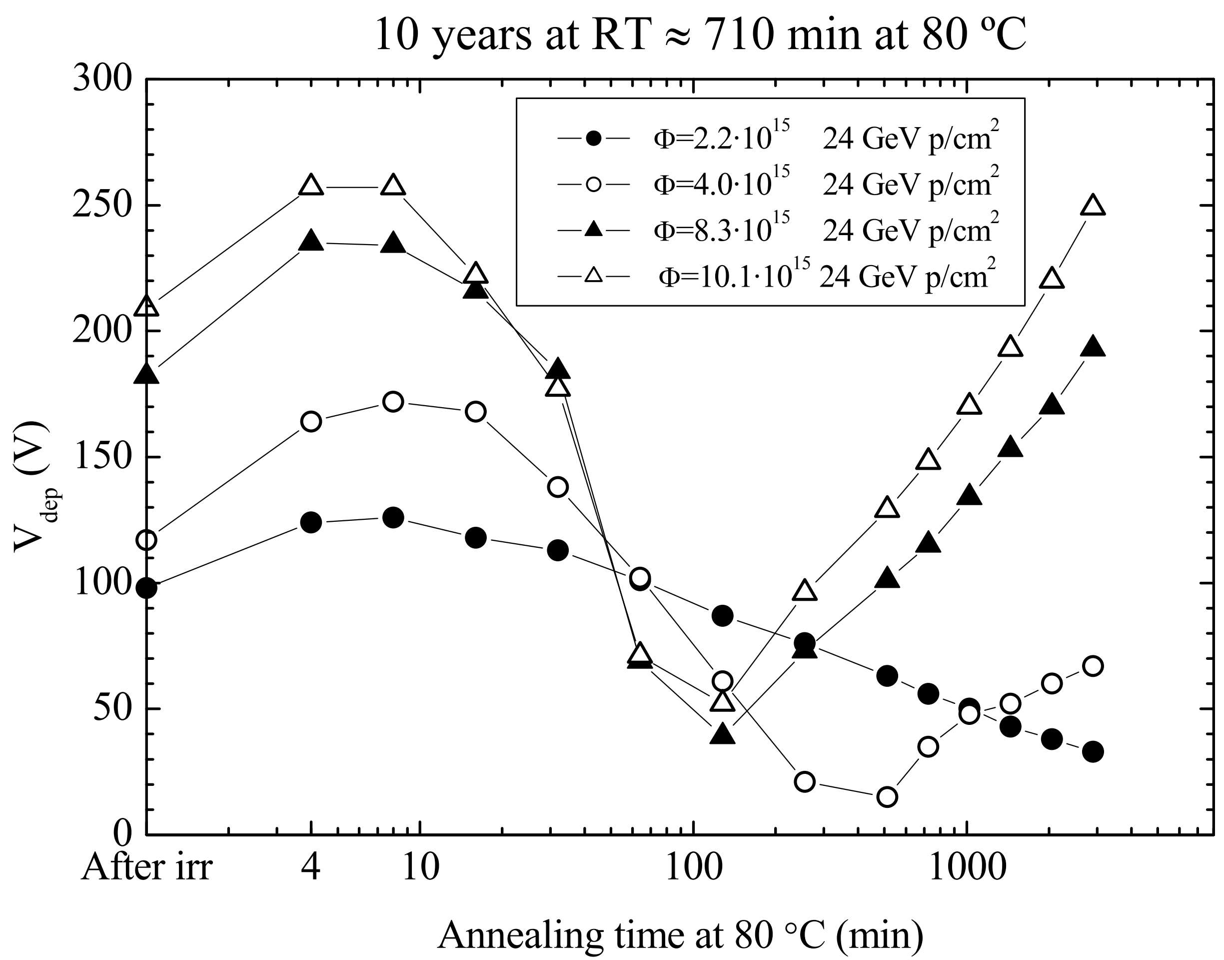
- J_D decreases with annealing time at 80 °C.

Epitaxial n-type 50 μm thick detectors: proton irradiation



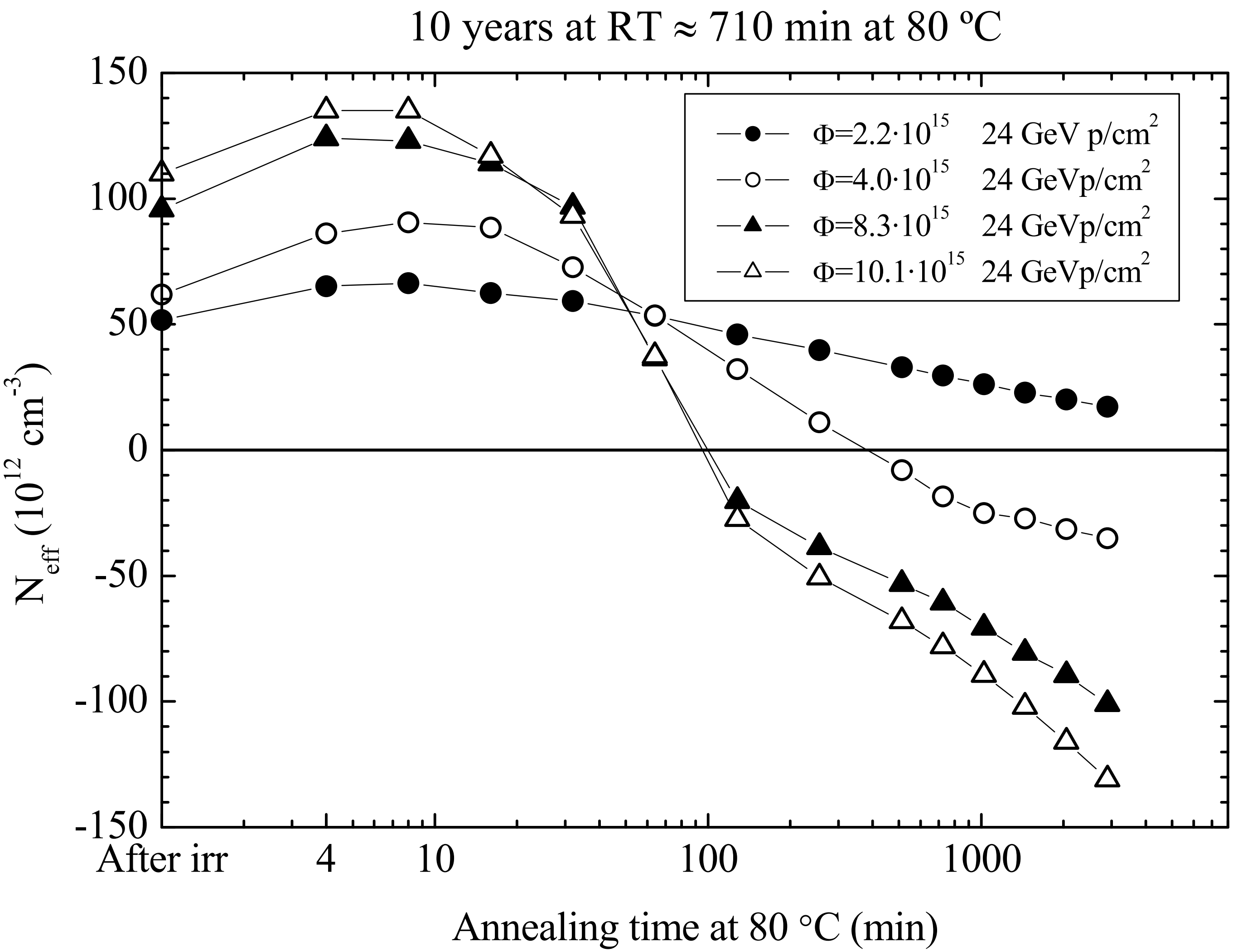
- The minimum of V_{dep} for protons (90-100 V) is higher than for neutrons (40-50 V).
- $V_{dep} > V_{dep,0}$ at the maximum irradiation fluence (10^{16} p/cm^2).
- Radiation effects induced by neutrons and protons are different.

Epitaxial n-type 50 μm thick detectors: proton irradiation



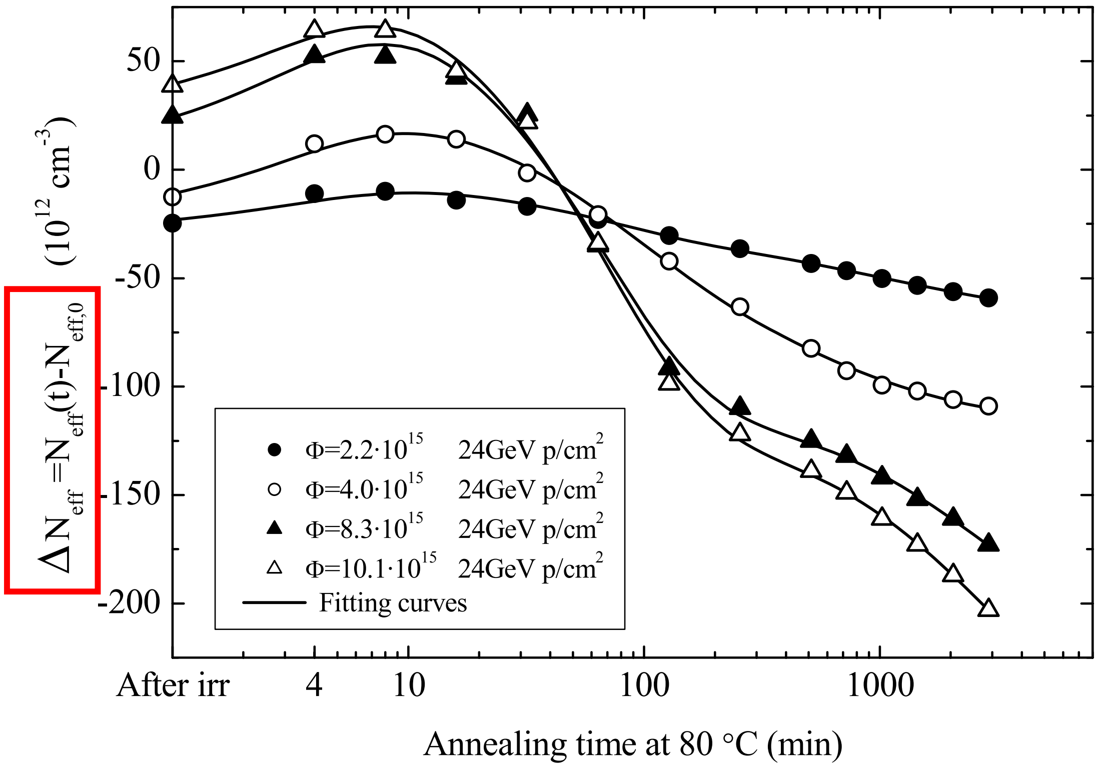
- V_{dep} decreases for annealing times at 80 °C higher than 8 minutes.
- If this effect is due to deep acceptor generation, devices are before SCSI after irradiation.
- For devices irradiated at **low fluences** V_{dep} ↑, ↓: **no SCSI during long-term annealing**;
- For devices irradiated at **high fluences** V_{dep} ↑, ↓, ↑: **SCSI during long-term annealing**.
- **Radiation effects induced by neutrons and protons are different.**

Epitaxial n-type 50 μm thick detectors: proton irradiation



N_{eff} as a function of the annealing time, assuming that the V_{dep} increase, at high annealing times and for devices irradiated at high fluences, is due to SCSI.

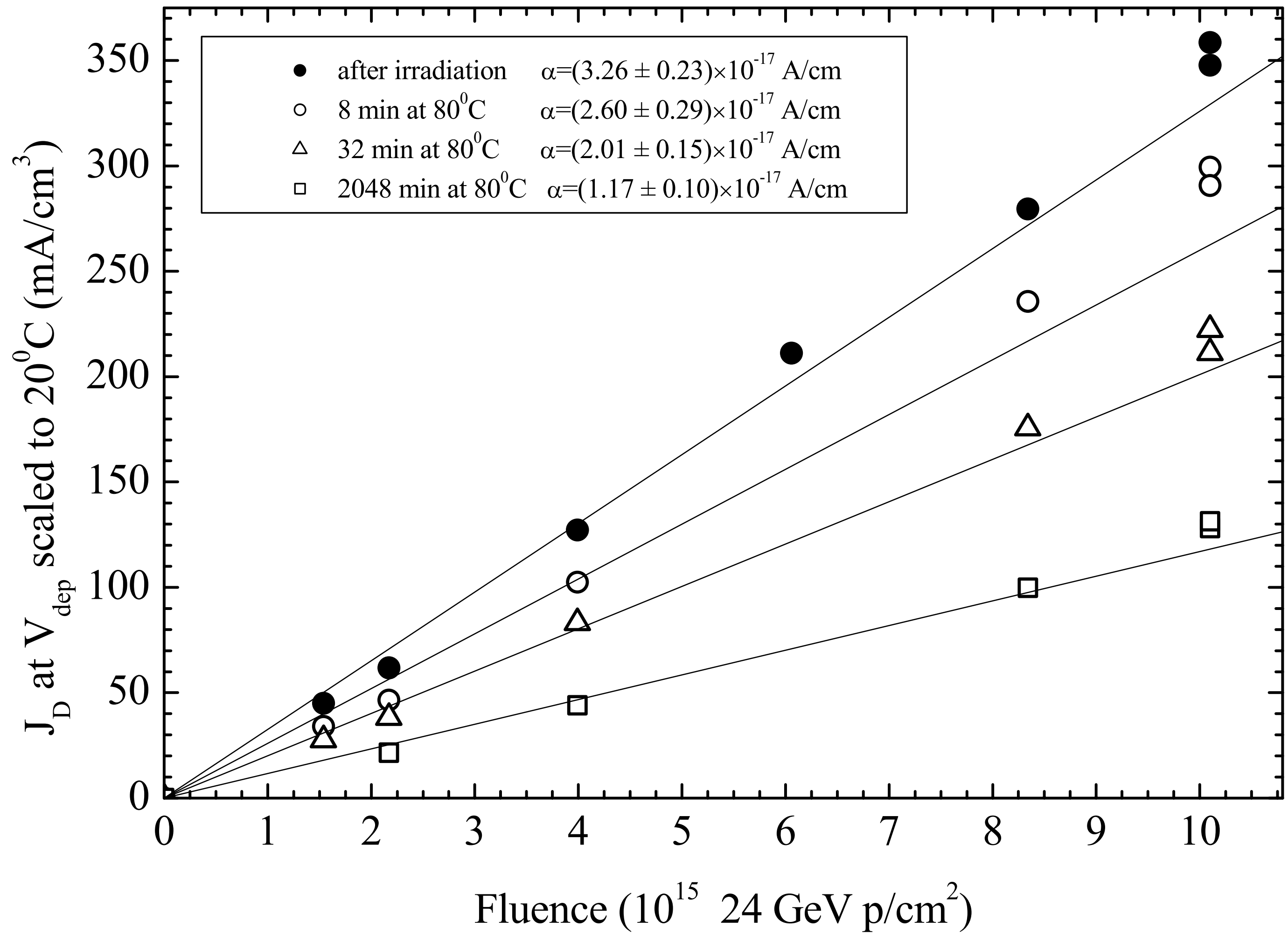
Epitaxial n-type 50 μm thick detectors: proton irradiation



$$\Delta N_{eff} = N_{eff}(t) - N_{eff,0} = -N_0 - N_1 \times \exp(-t/\tau_1) - N_2 \times (1-\exp(-t/\tau_2)) - N_3 \times (1 - 1/(1+t/\tau_3))$$

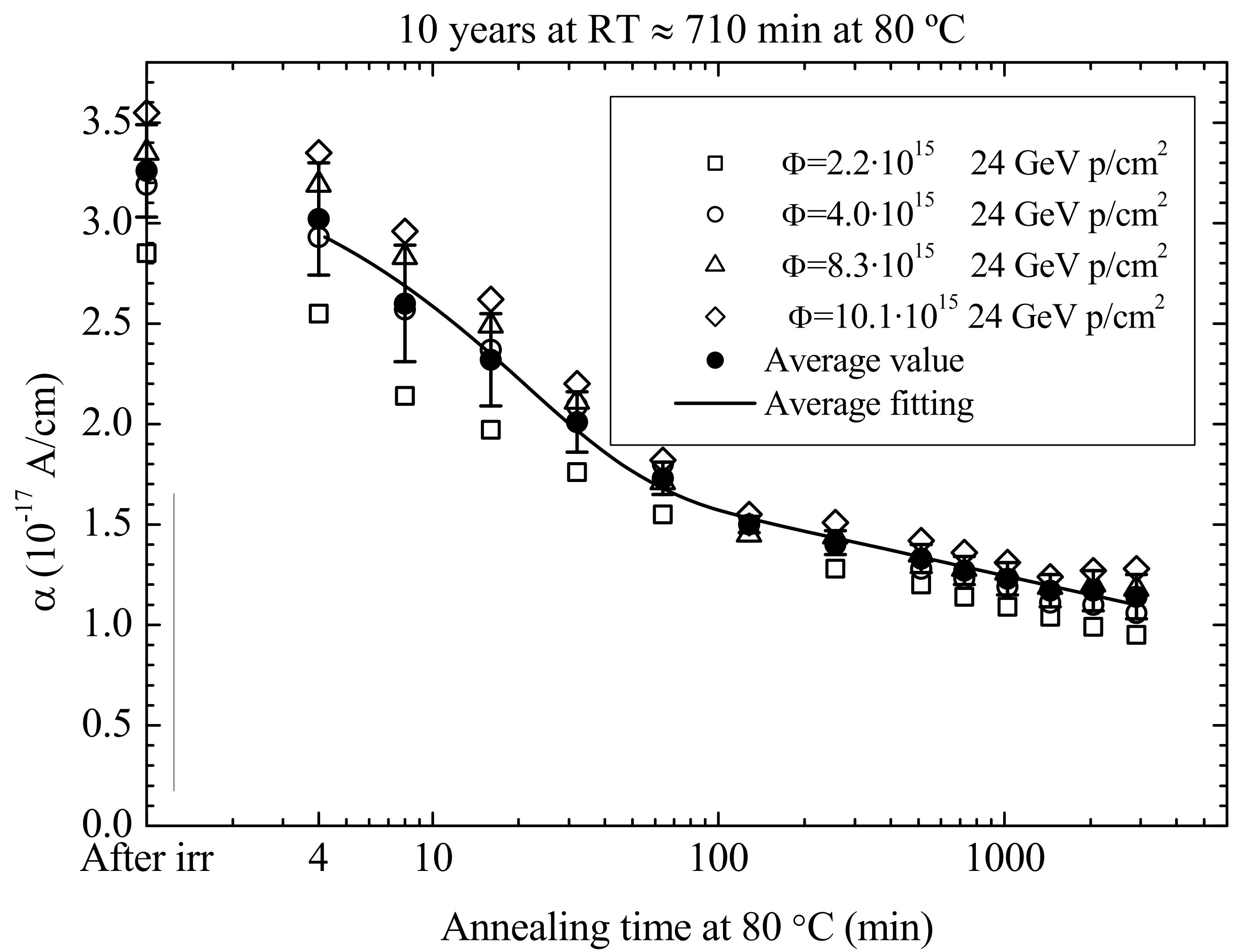
	Φ (10^{15} 24 GeV p/cm^2) 2.17	3.99	8.34	10.1
N_0 (10^{13} cm^{-3})	**0.4 ± 0.4**	**-3.3 ± 0.5**	**-9.5 ± 0.6**	**-10.3 ± 0.6**
N_1 (10^{13} cm^{-3})	**1.9 ± 0.6**	**4.4 ± 0.6**	**7.2 ± 0.7**	**6.5 ± 0.7**
τ_1 (min)	**5.0 ± 0.7**			
N_2 (10^{13} cm^{-3})	**2.6 ± 0.9**	**5.7 ± 2.1**	**20.2 ± 0.8**	**22.0 ± 0.7**
τ_2 (min)	**65 ± 4**			
N_3 (10^{13} cm^{-3})	**3.9 ± 0.8**	**9.5 ± 1.5**	**13.8 ± 3.9**	**18.9 ± 3.6**
τ_3 (10^3 min)	**1.0 ± 1.0**	**0.3 ± 0.2**	**3.1 ± 1.9**	**2.9 ± 1.2**

Epitaxial n-type 50 μm thick detectors: proton irradiation



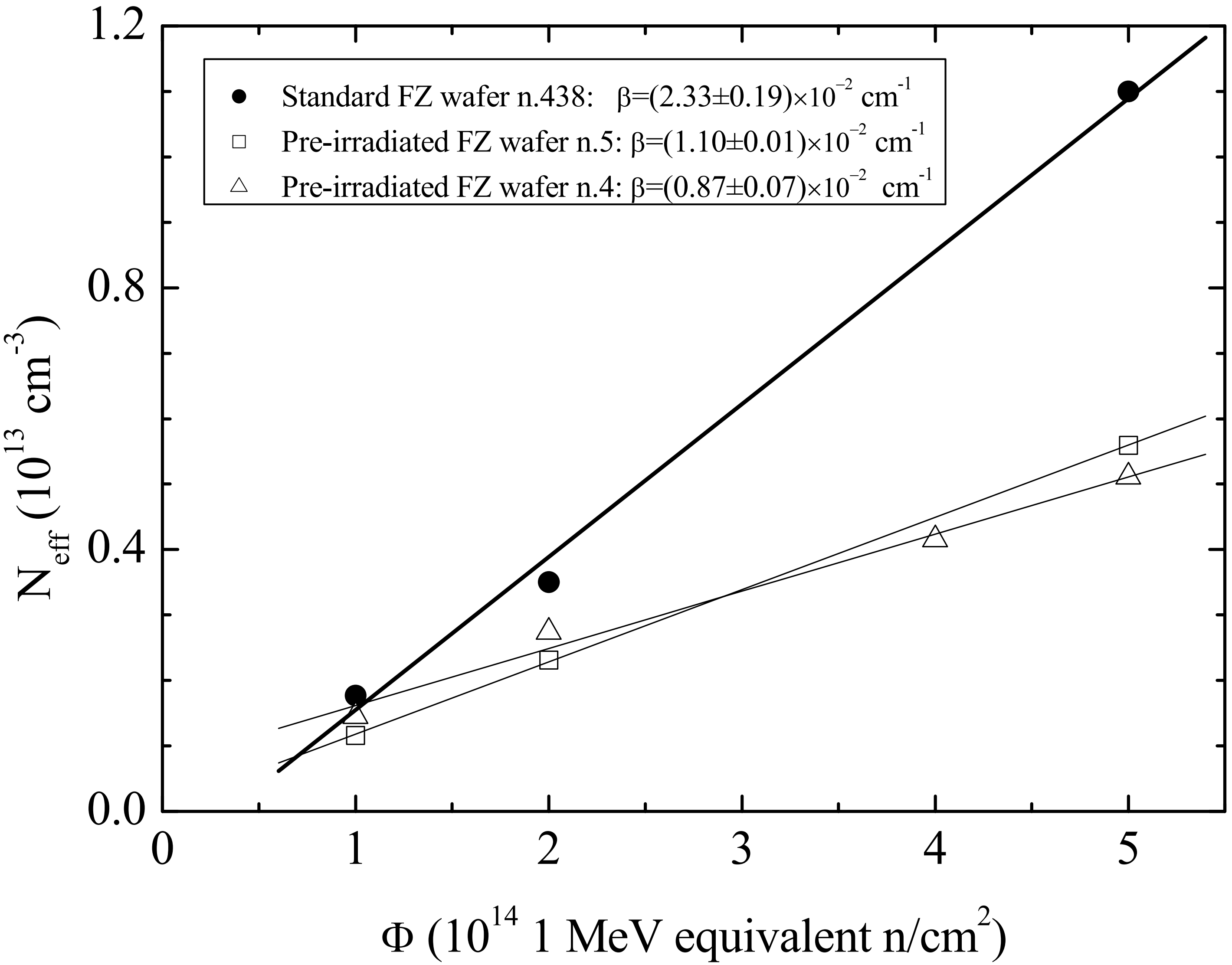
- J_D linearly increases with fluence.
- Average $\alpha = J_D/\Phi$ value after **8 min at 80 ºC** is (**2.60±029)×10^{-17} A/cm**, **in agreement within 10%** with the value measured by Hamburg group for epitaxial diodes (2.43 ×10^{-17} A/cm).

Epitaxial n-type 50 μm thick detectors: proton irradiation



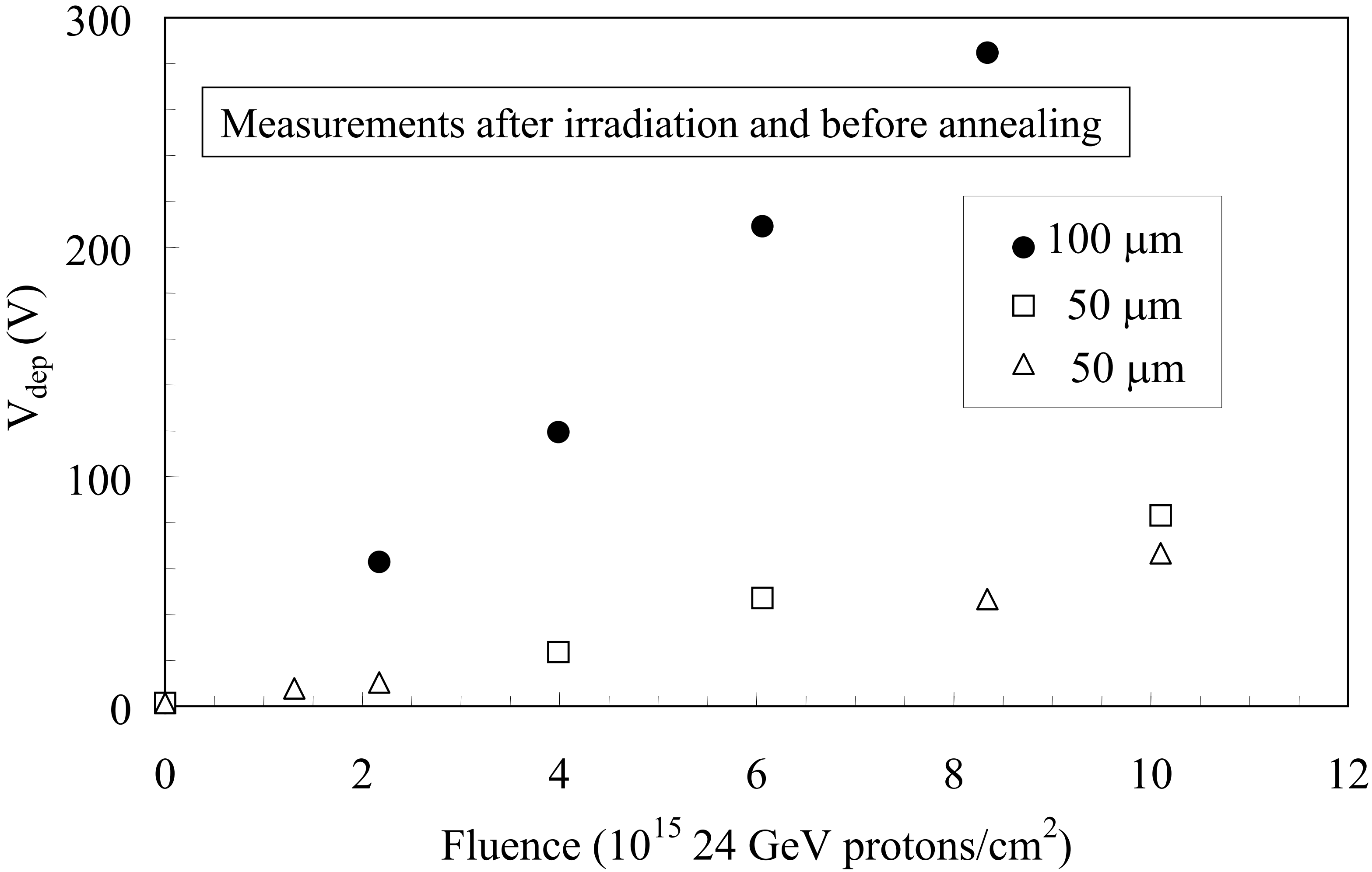
$$\alpha(t) = \alpha_0 + \alpha_1 \times \exp\left(-t/\tau_1\right) + \alpha_2 \times \ln\left(t/\tau_2\right)$$

Pre-irradiated n-type detectors: neutron irradiation



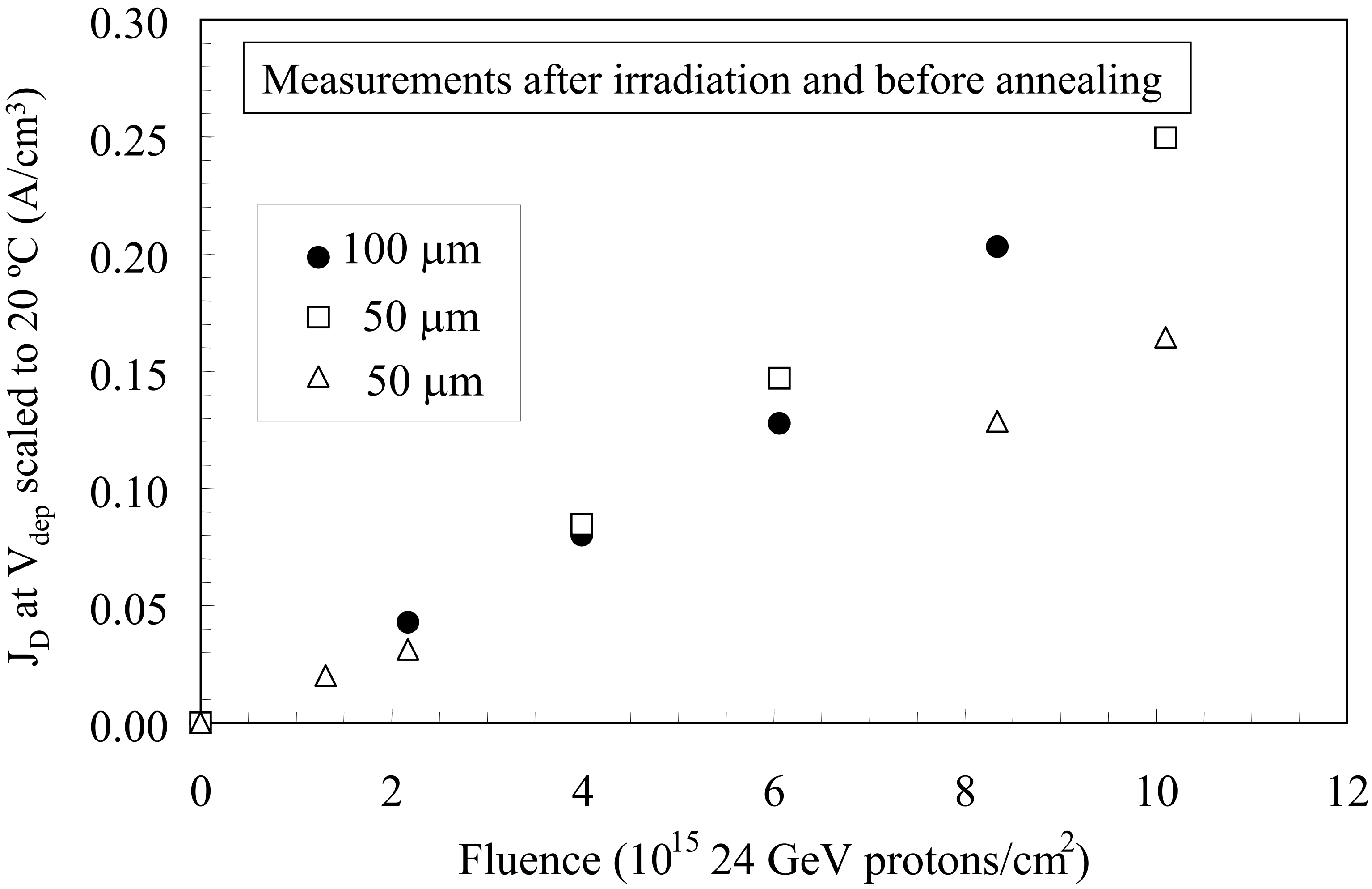
The deep acceptor introduction rate β is lower for pre-irradiated than standard FZ devices.

FZ thinned n-type detectors: proton irradiation



Device thinning limits the V_{dep} increase after irradiation:
- $V_{dep} \approx 290$ V for 100 µm thick detectors at 8×10^{15} p/cm^2;
- $V_{dep} \approx 70$ V for 50 µm thick detectors at 10^{16} p/cm^2.

FZ thinned n-type detectors: proton irradiation

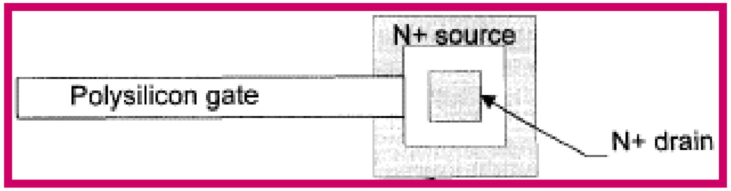


- J_D linearly increases with fluence, independently on the thickness (some data dispersion is present).

ELECTRONICS

-**Electronics for LHC** (10 Mrad(Si) and 10^{15} fast hadrons/cm^2):

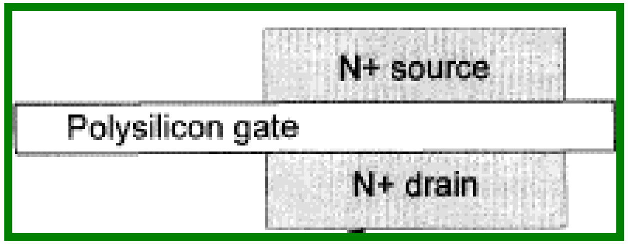
- **0.25 μm CMOS** technology from **IBM**;
- **5.5 nm** oxide thickness;
- radiation hardened by design: **enclosed geometry** transistors.



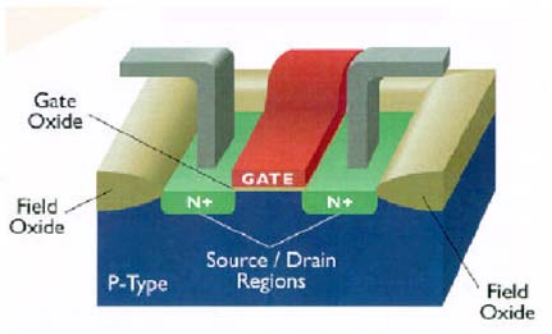
The 0.25 μm CMOS technology will not be probably any more available for Super-LHC

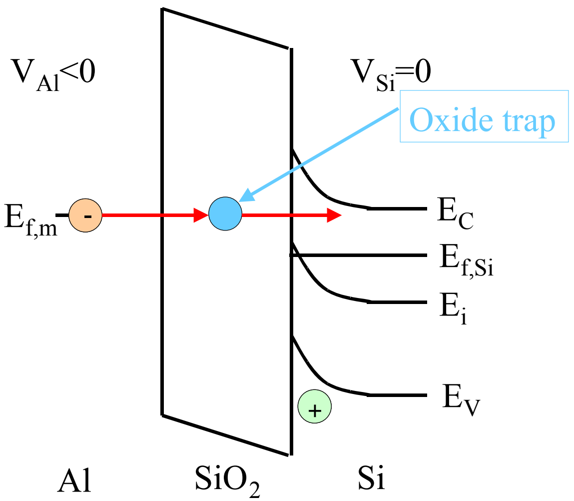
-**Electronics for Super-LHC** (100 Mrad(Si) and 10^{16} fast hadrons/cm^2): following the scaling down of the commercial CMOS technologies?

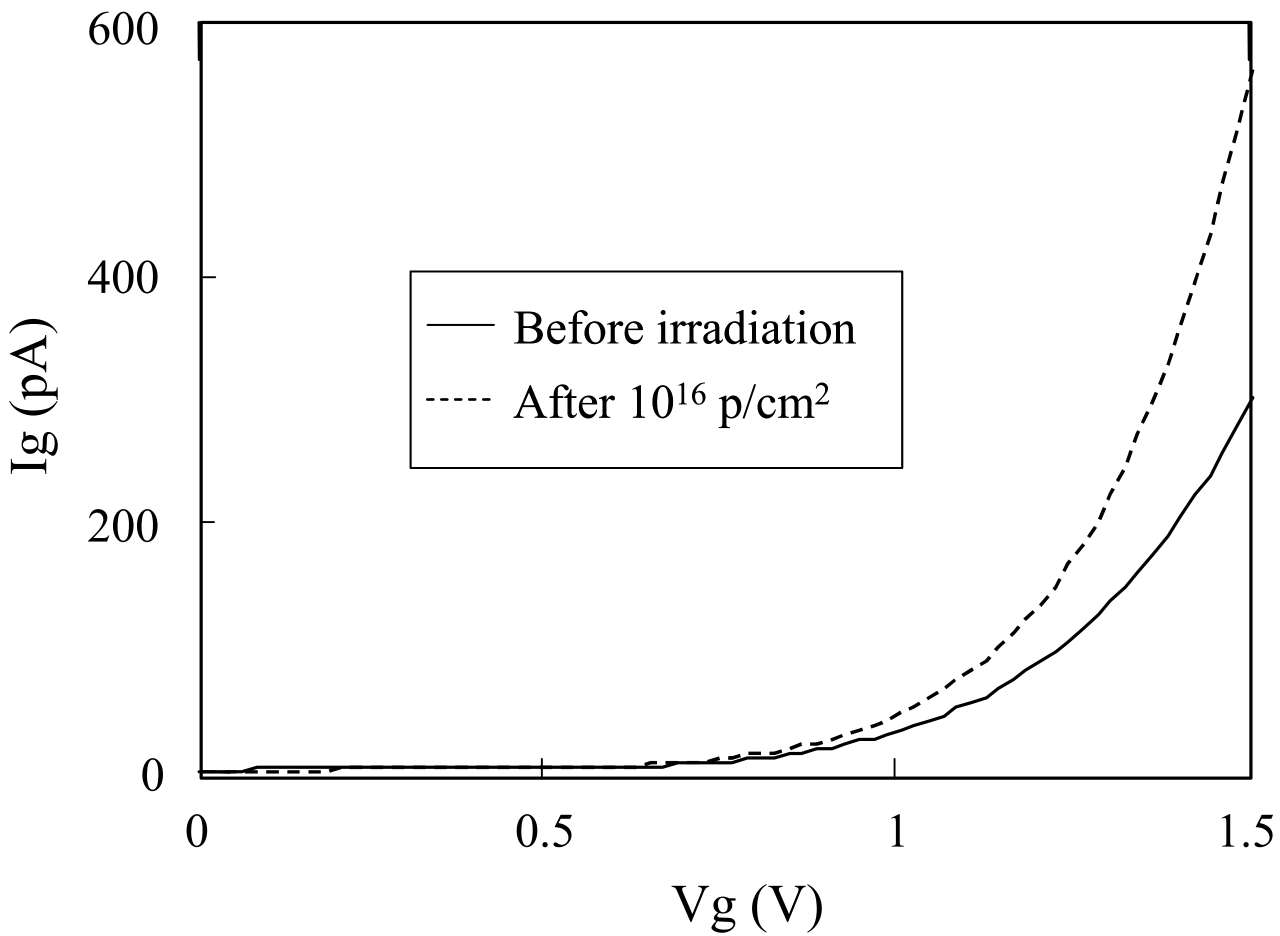
- **0.13 μm** minimum channel length;
- **2.5 nm** oxide thickness;
- no radiation hardened by process;
- no radiation hardened by design (i.e., no enclosed geometry);
- from **ST-Microelectronics**.



0.13 μm CMOS technology: proton irradiation

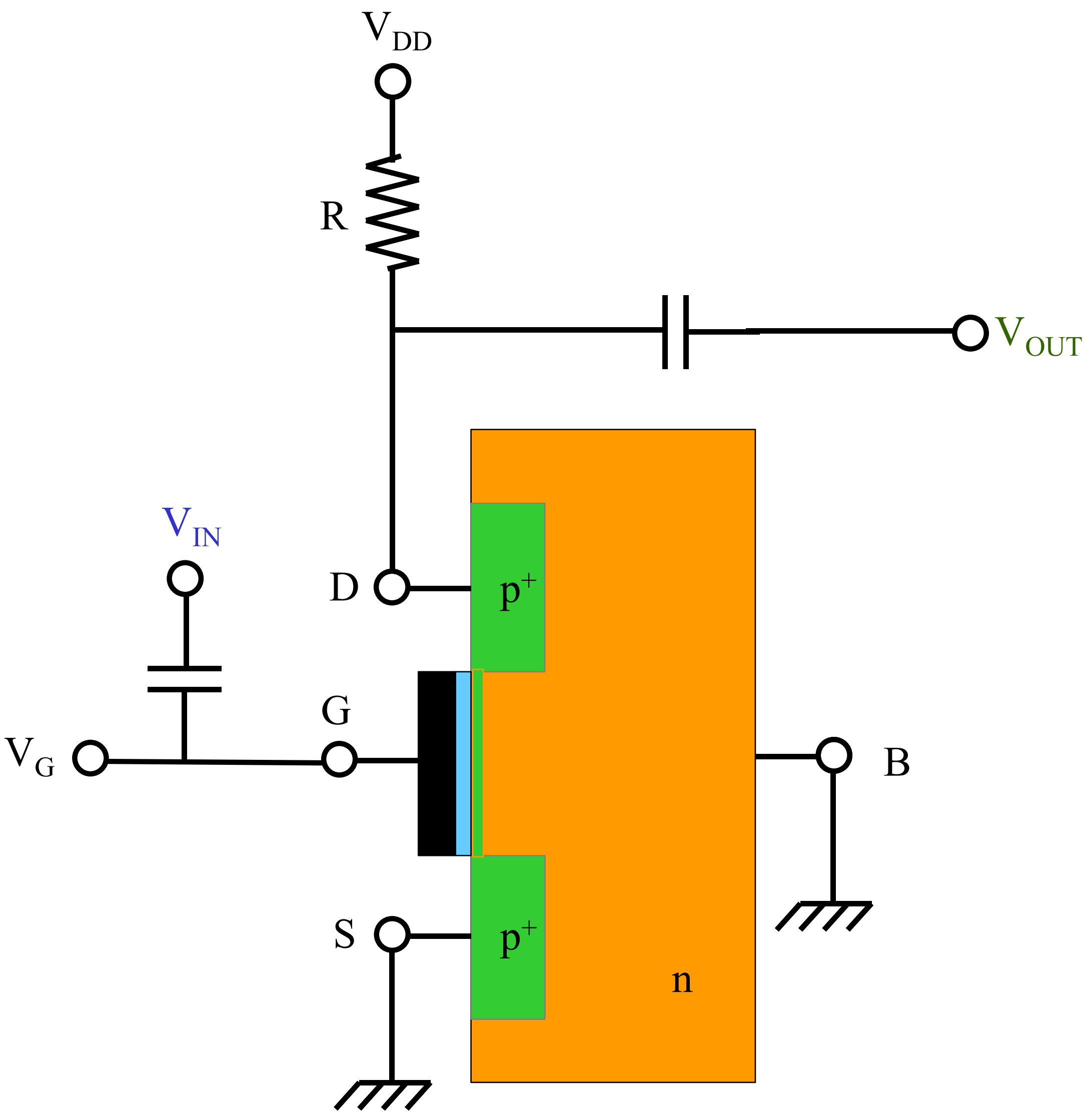






- The gate leakage current is almost doubled at $\Phi = 10^{16}$ 24 GeV p/cm^2.
- This is due to defect generation in the gate oxide: RILC (already observed after γ-ray, X-ray and ion irradiation).

The MOSFET as an amplifier



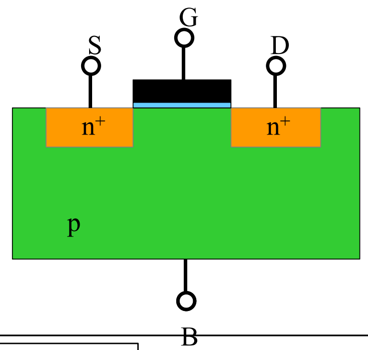
$$V_{OUT} = V_{IN} \times g_M \times R$$

$$g_M = \Delta I_{DS} / \Delta V_{GS}$$

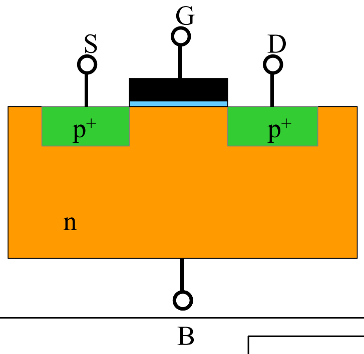
Trans-conductance

0.13 μm CMOS technology: proton irradiation

n-channel MOSFET

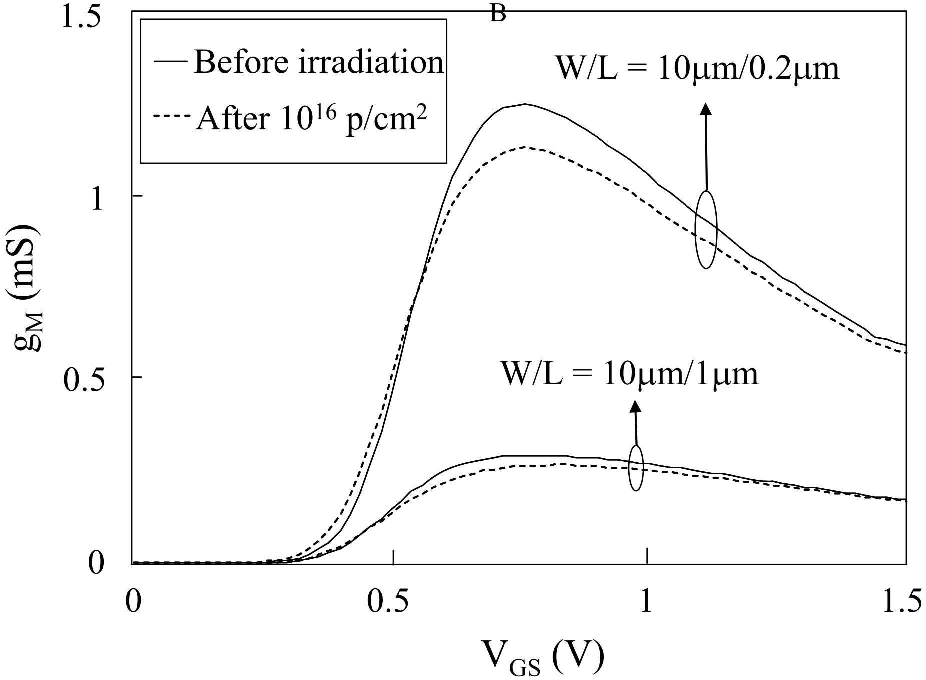


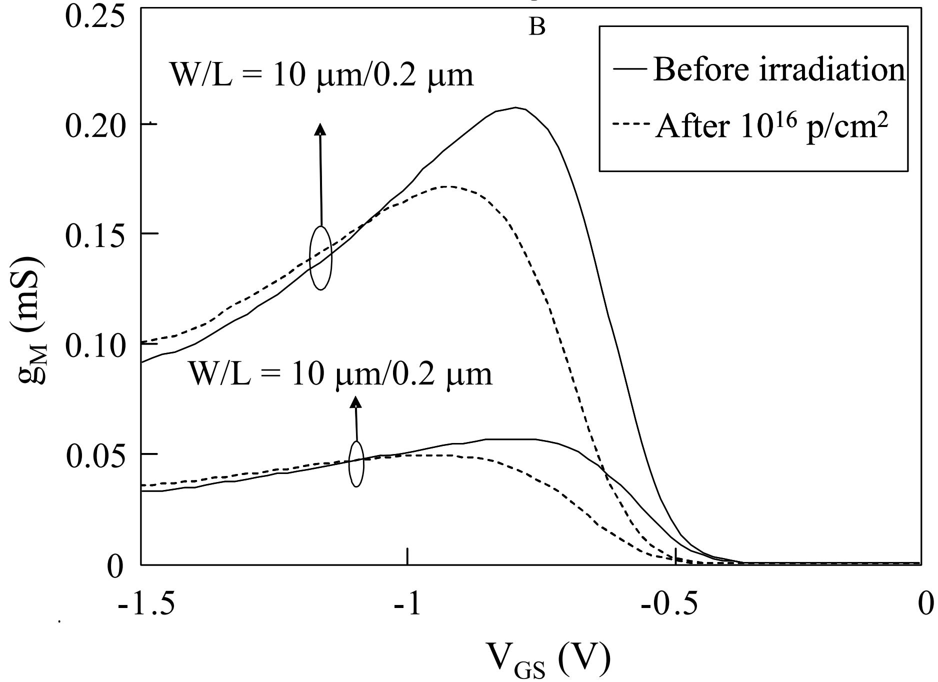
p-channel MOSFET



$g_M = \Delta I_{DS} / \Delta V_{GS}$

Trans-conductance



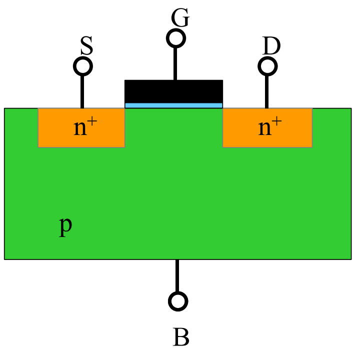


- g_M peak decrease 15%.
- g_M peak shift negligible.

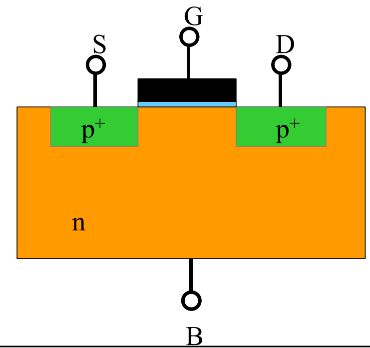
- g_M peak decrease higher than in n-MOSFET.
- g_M peak shift of 200 mV.

0.13 μm CMOS technology: proton irradiation

n-channel MOSFET

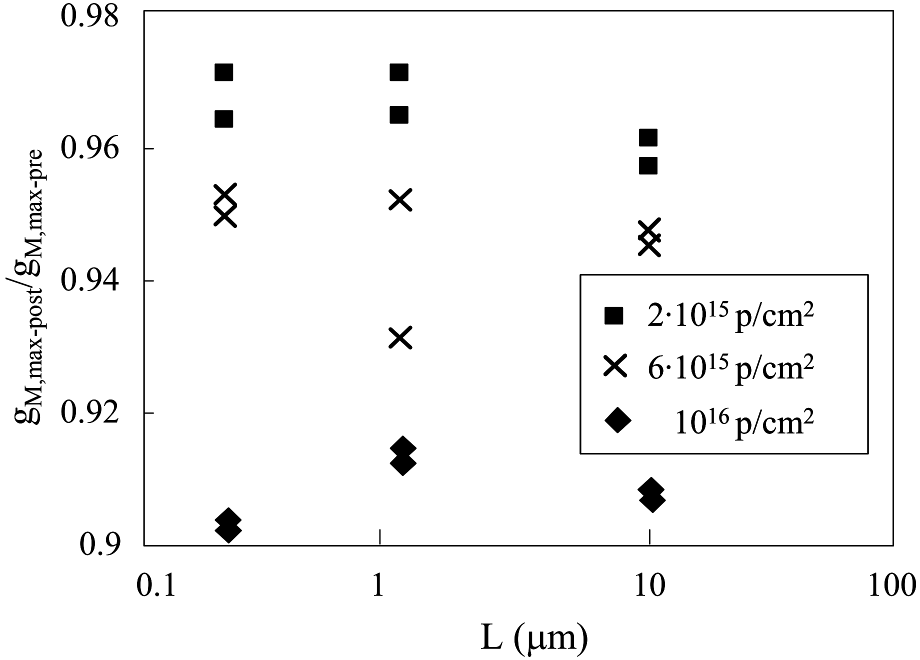


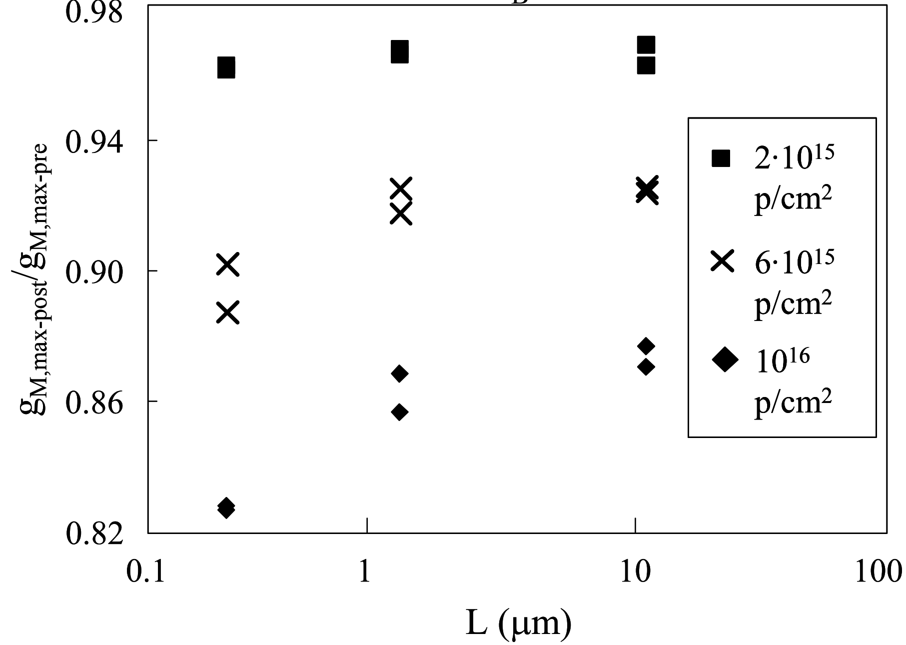
p-channel MOSFET



$g_M = \Delta I_{DS} / \Delta V_{GS}$

Trans-conductance

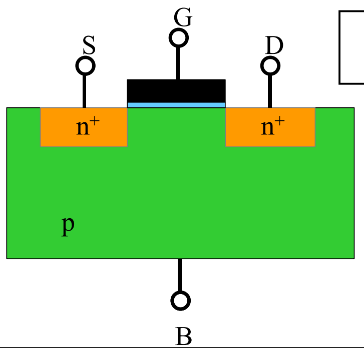




- The g_M peak degradation increases with fluence.

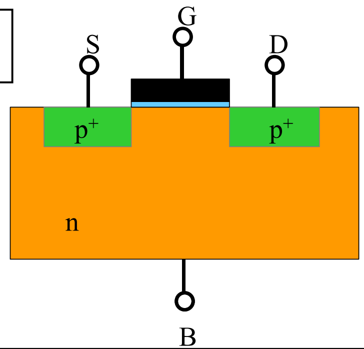
0.13 μm CMOS Technology: proton irradiation

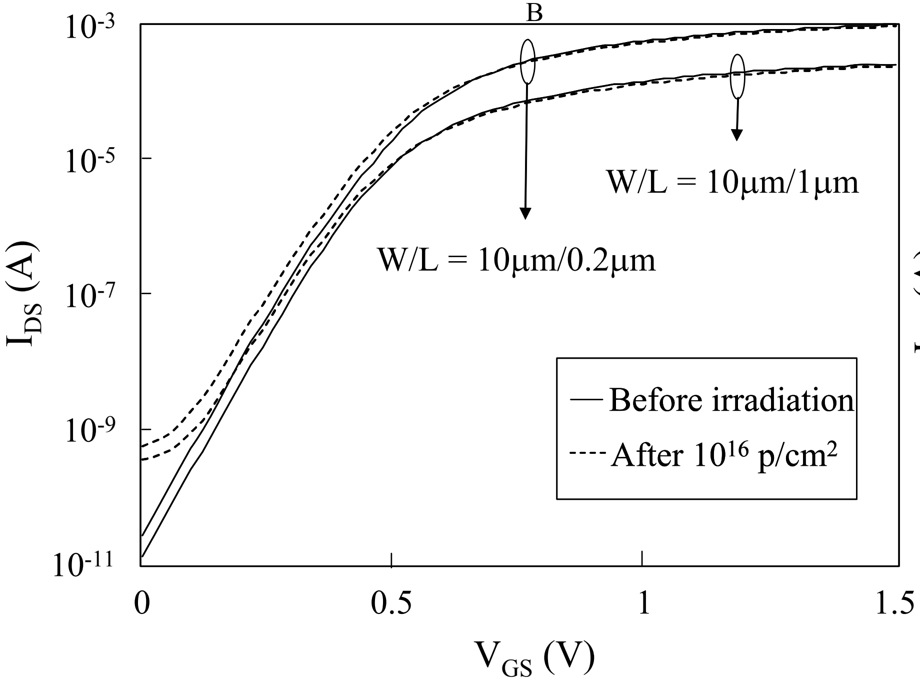
n-channel MOSFET

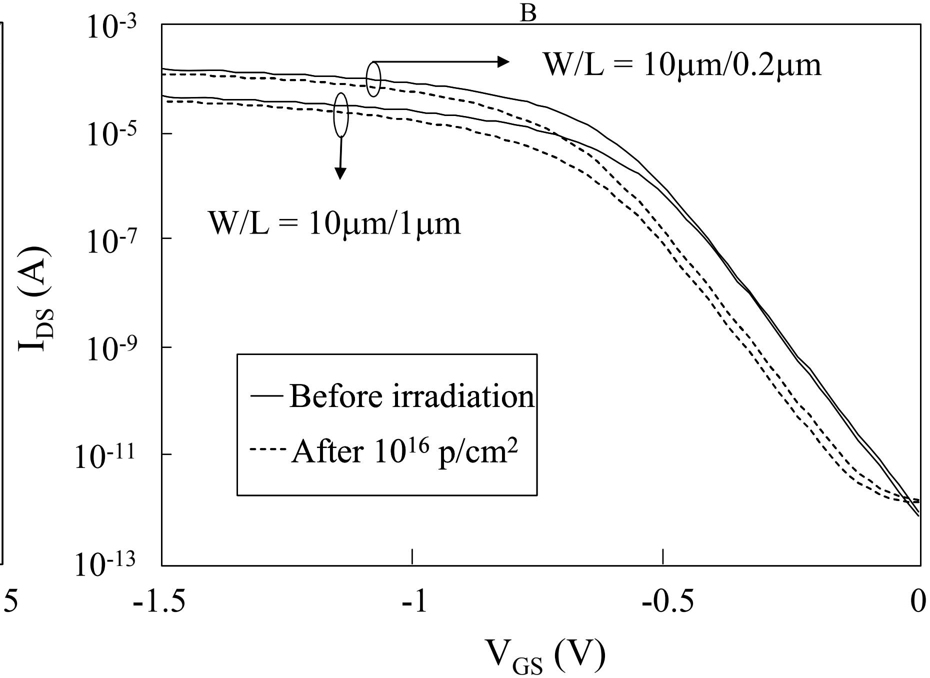


$$S = \ln 10 \times (\Delta V_{GS} / \Delta(\ln(I_{DS})))$$

p-channel MOSFET







- Subthreshold swing change negligible
- Subthreshold shift lower than in p-MOSFET

- Subthreshold swing change negligible
- Subthreshold shift higher than in n-MOSFET

Conclusion

-Epitaxial detectors

- V_{dep} vs Φ: **V_{dep} minimum lower for neutrons** than protons.
- V_{dep} vs annealing time for **24 GeV protons**:
  SCSI can **not** be **reached** during **proton irradiation**.
  SCSI can be **reached** during **annealing** at 80 ºC.
- V_{dep} vs annealing time for **nuclear reactor neutrons**:
  SCSI can be reached during neutron irradiation?
  SCSI can be **reached** during **annealing** at 80 ºC.

-Pre-irradiated detectors

- The deep acceptor introduction rate **β** is **lower by a factor 2-3** for pre-irradiated **than standard FZ** devices **irradiated** by **neutrons.**

-TMAH-thinned detectors

- **Device thinning limits** the **V_{dep} increase** after irradiation:
  $V_{dep}\approx 290$ V for 100 μm thick detectors at 8×10^{15} 24 GeV p/cm^2.
  $V_{dep}\approx 70$ V for 50 μm thick detectors at 10^{16} 24 GeV p/cm^2.

- 0.13 μm CMOS technology

- The degradation has been evaluated up to 10^{16} 24 GeV p/cm^2 on MOSFET test structures.