SMART

INFN Istituto Nazionale di Fisica Nucleare

SMART Detector Project:
recent results from the SMART experiment

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*on behalf of the SMART Collaboration **

(*) INFN Bari, Firenze, Perugia, Pisa;
External collaborators: INFN Padova , ITC-IRST Trento
V. Eremin, E. Verbitskaya, Ioffe Institute, St. Petersburg

- ✓ *Comparison between CV measurements and TCT analysis on n-type MCz samples irradiated with 26 MeV protons*
- ✓ *Studies on 150 μm thick epi-diodes irradiated with neutrons and 26 MeV protons*
- ✓ *Status of the next SMART production*
- ✓ *Conclusions*

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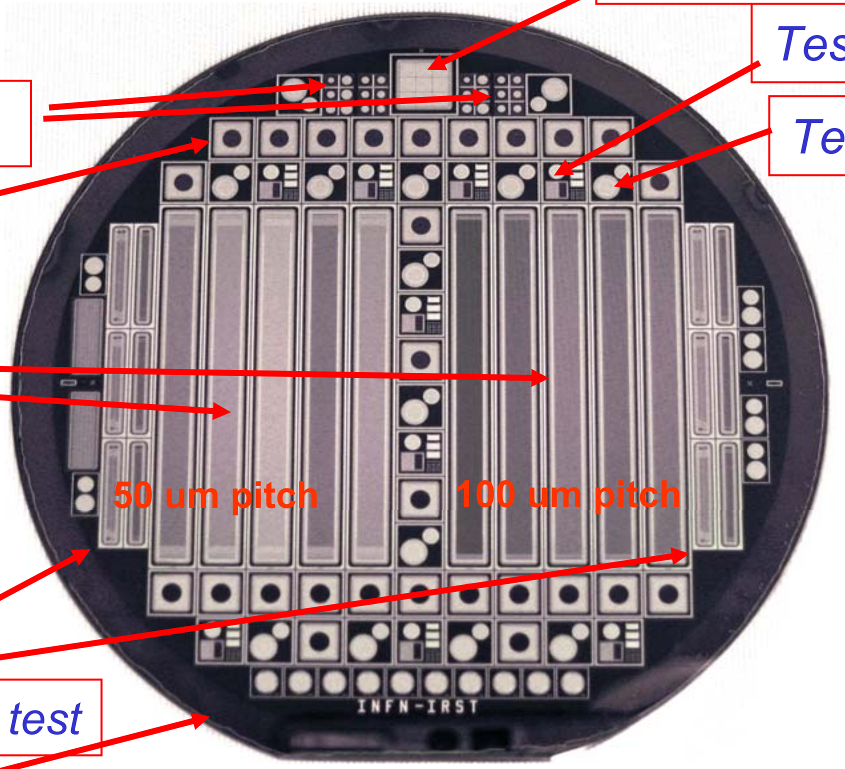
SMART: Wafer layout

1st p-type MCz microstrip detectors



Pad detector

Test2

Test1

Edge structures

Square MG-diodes

Micro-strip detectors

Inter strip Capacitance test

Round MG-diodes

RUN I p-on-n

22 wafers

Fz, MCz, Cz, Epi

RUN II n-on-p

24 wafers Fz, MCz

two p-spray doses:

3E12 & 5E12 cm^{-2}

- ✓ **RD50 common wafers procurement**
- ✓ **Wafer Layout designed by SMART collaboration**
- ✓ **Masks and process by ITC-IRST (Trento)**

Irradiations

April 2006

Irradiation with reactor neutrons in Ljubljana

12 fluences: 5.0x10^{13} 8.5x10^{15} 1-MeV n/cm^2

27 mini-sensors, 11 test structure (capts),100 diodes

60 % n-type, 40 % p-type, Fz, MCz, Epi

Thanks to V.Cindro and G.Kramberger

Set up for the irradiation @ JSI(Ljubljana)

June 2006

Irradiation with 26 MeV protons at the

Cyclotron of the Forschungszentrum Karlsruhe

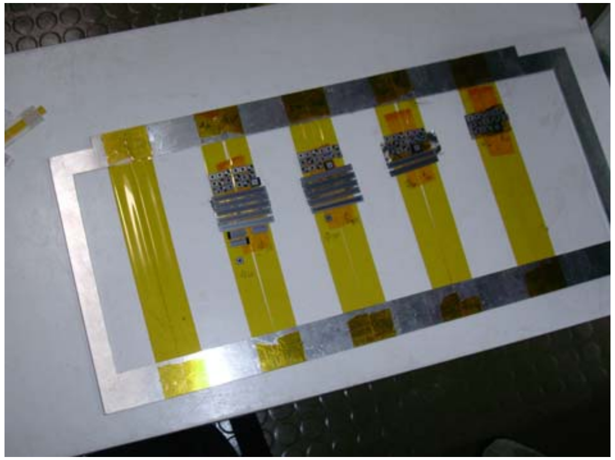
***10 fluences:** 1.2x10^{14} - 6x10^{15} 1-MeV n/cm^2*

20 mini-sensors, 8 test structure(capts), 100 diodes

60 % n-type, 40 % p-type, Fz, MCz, Epi

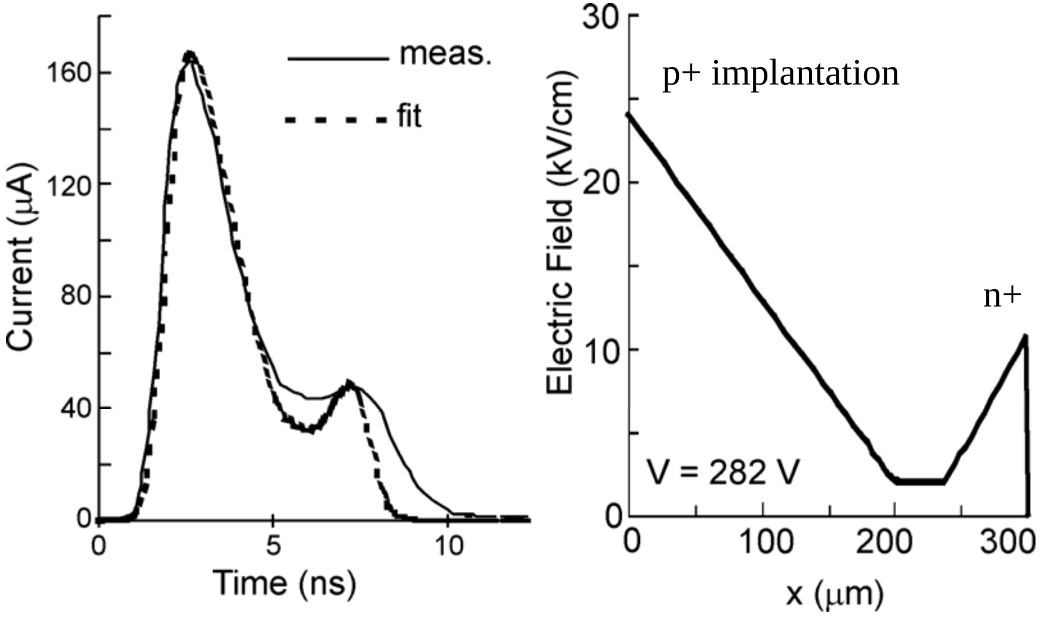
Thanks to A. Furgeri

Set up for the irradiation @ FZK(Karlsruhe)



SMART Previous TCT measurements on SMART MCz samples: 24 GeV/c protons

M. Scaringella et al., NIM A



Detector # 20, proton irradiated, Fp = 2.17e15 cm-2; τ = 6 ns

SMART Samples

•*Double junction effect has been observed starting from $\Phi=3\times10^{14}$ n/cm^2*

•*At the fluence $\Phi=1.3\times10^{15}$ n/cm^2 the dominant junction is still on the p^+ side*

Electric field distribution is extracted with a fit, taking into account the charge trapping:

- *E(x) highly non-uniform in heavily irradiated detectors (electrons and hole trapping due to DLs)*
- *Three regions of heavily irradiated detector structure are considered*
- *Reverse current flow induces the electric field Eb into the neutral base*

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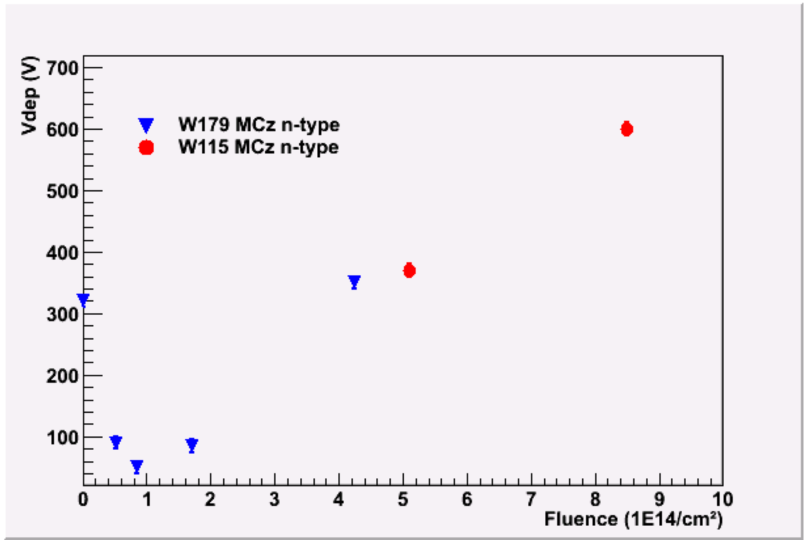
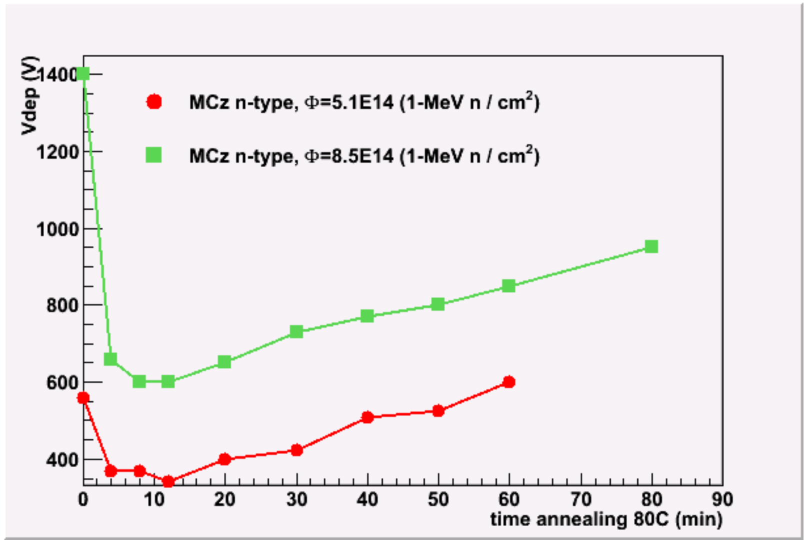
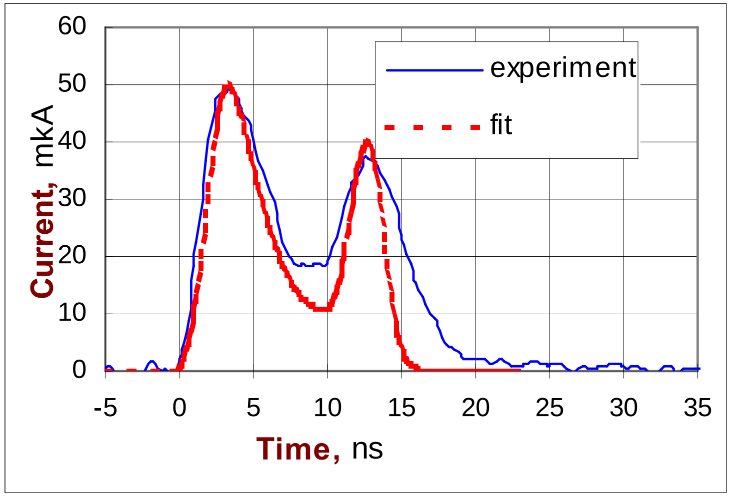
Previous TCT measurements on SMART MCz samples: neutrons

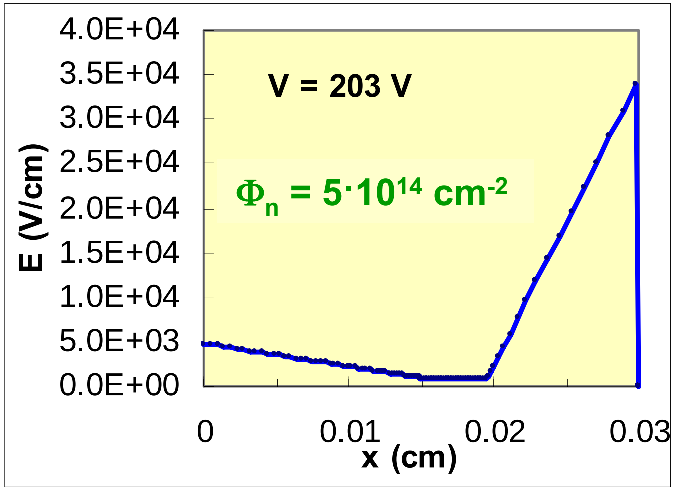
V vs Φ: MCz neutron irradiation



Annealing study







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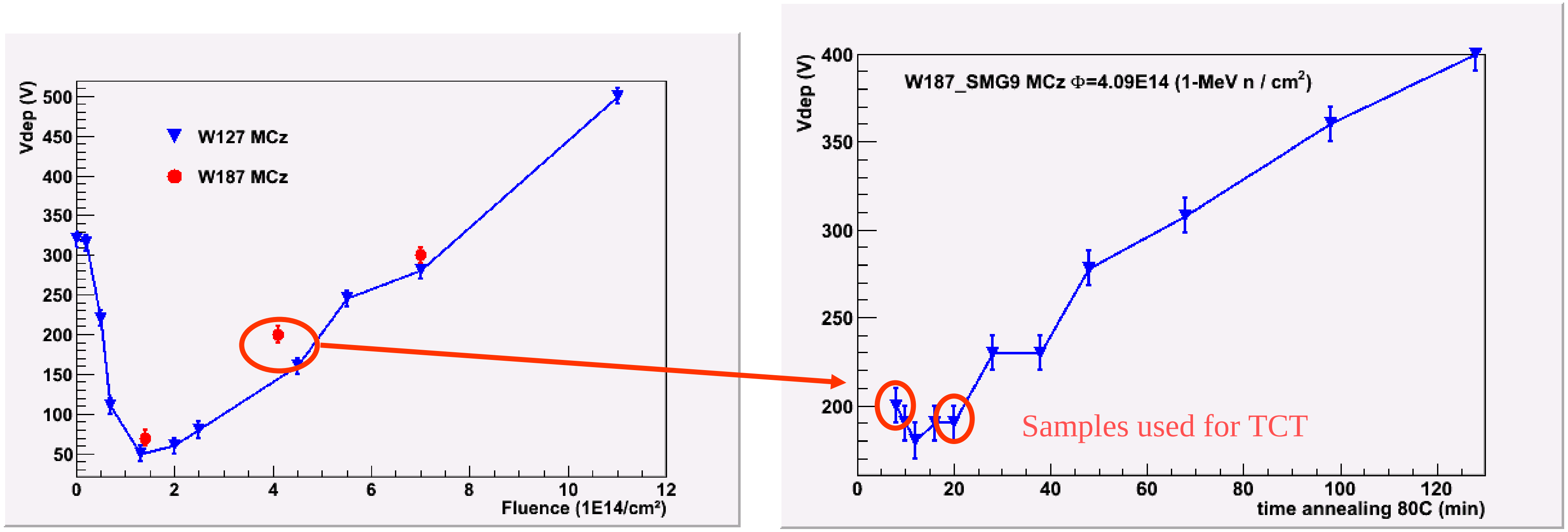
26 MeV proton irradiation: CV measurements

The annealing behaviour observed in the CV measurements of n-t is typical of inverted material after $\Phi_4 > 1E14\ cm^{-2}$



Samples used for TCT

✓ *Minimum of V_{dep} vs Φ well above 0V around $\Phi = 1 \times 10^{14}$ n eq. cm^{-2}, as in the case of the neutrons irradiation*

✓ *Annealing study of the MCz sample irradiated at $\Phi = 4.1 \times 10^{14}$ and measured with TCT: SCSI behaviour*

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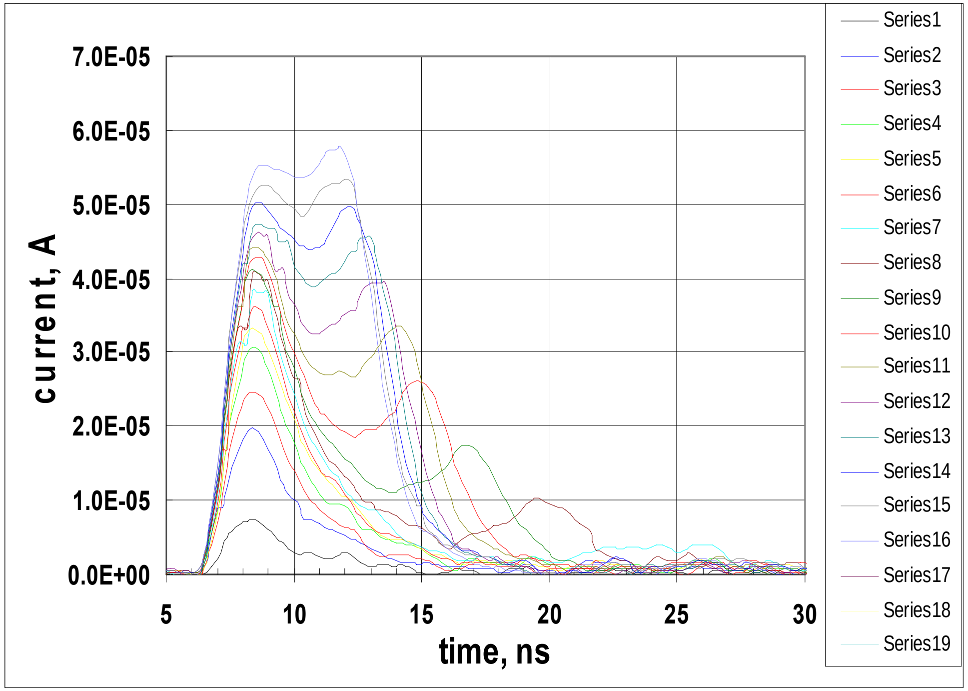
TCT data for silicon MCZ irradiated with 26 MeV protons

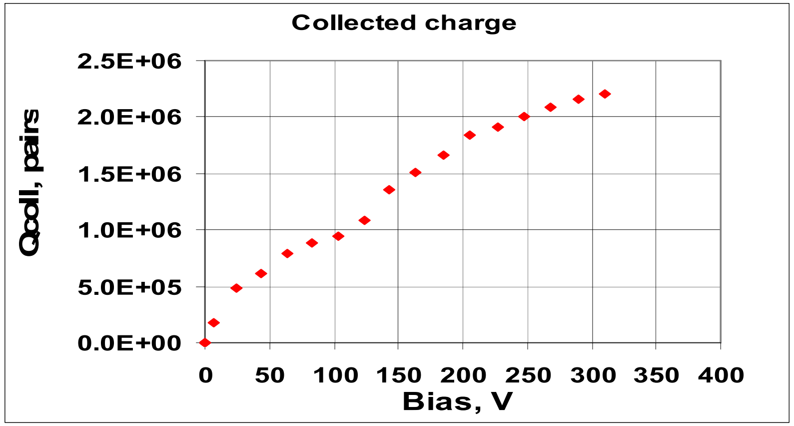
Laser injection from the p+ side: electron collection

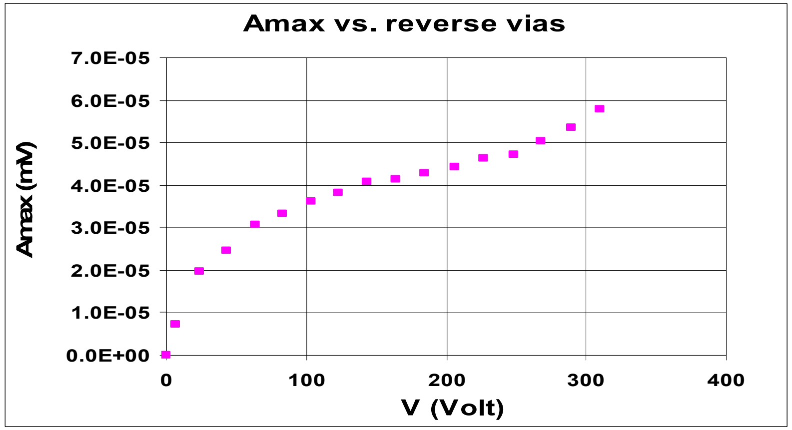
Detector W187-SMG-9
MCZ, 300um
Proton irradiated: 26 MeV, Feq = 4.2 E14 cm-2
Beneficial Annealing

Operational parameters:
T = 293K

Extracted values
*Vfd = **180V***







V. Eremin, RD50, October 06

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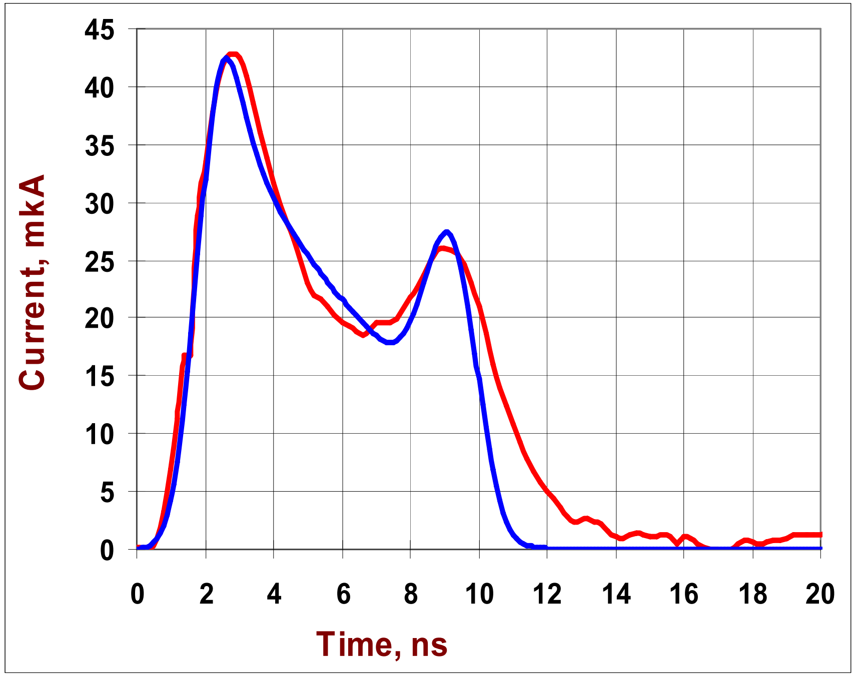
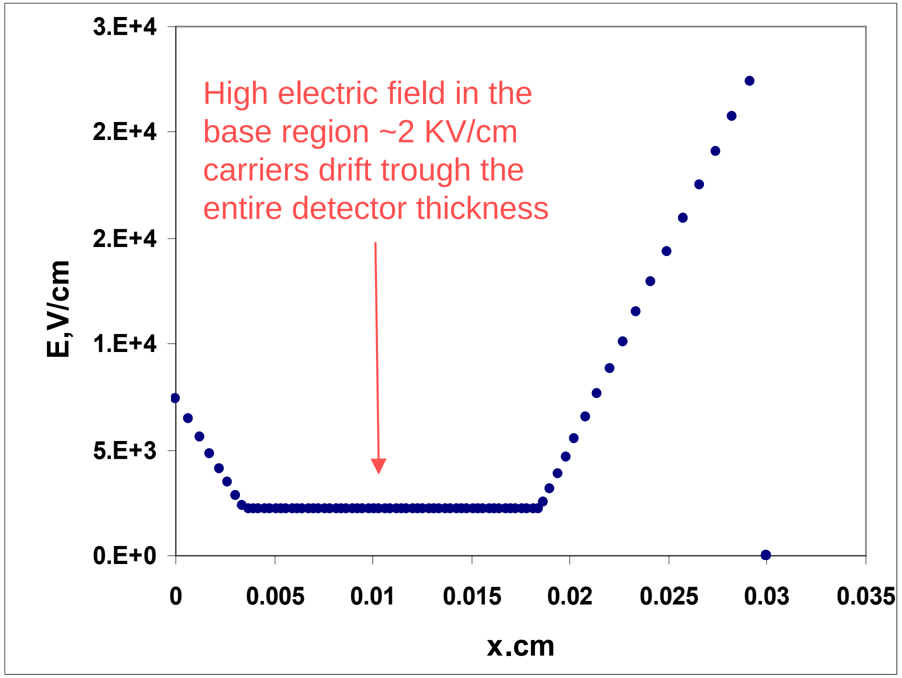
E(x) reconstruction for silicon MCZ as irradiated detector

Detector W187-SMG-9
MCZ, 300um
Proton irradiated: 26 MeV, Feq = 4.2 E14 cm-2
Beneficial annealing

Operational parameters:
V = 184 V
T = 293K

Extracted values
Tau tr = 6 ns
*Vfd = **180V***





High electric field in the base region ~2 KV/cm carriers drift trough the entire detector thickness

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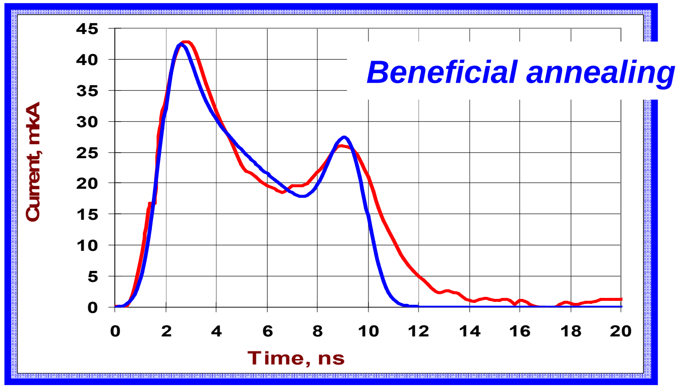
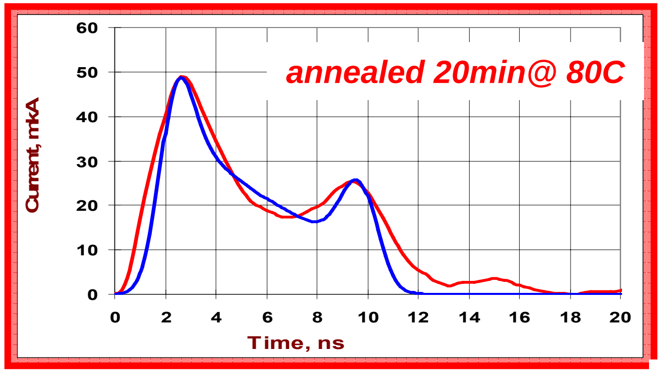
Annealing effect in silicon MCZ detectors

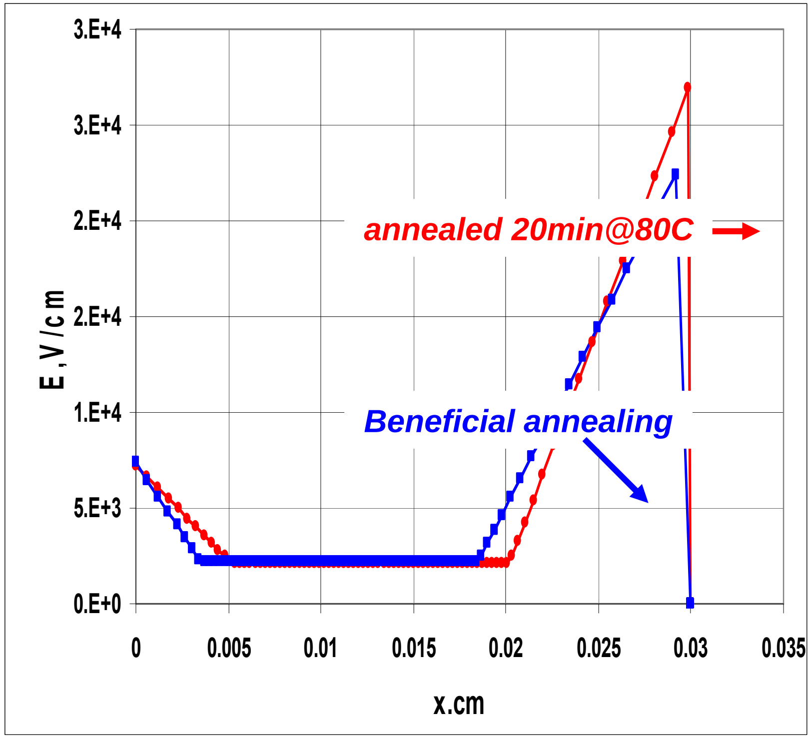
MCZ, 300um
Proton irradiated: 26 MeV, 4.2 E14 cm-2
W187-SMG-9: beneficial annealing
W187-SMG-2: annealed 20min@ 80 C

Operational parameters:
V = 184 V
T = 293K

Extracted values
Tau tr = 6 ns
Vfd = ***180V***







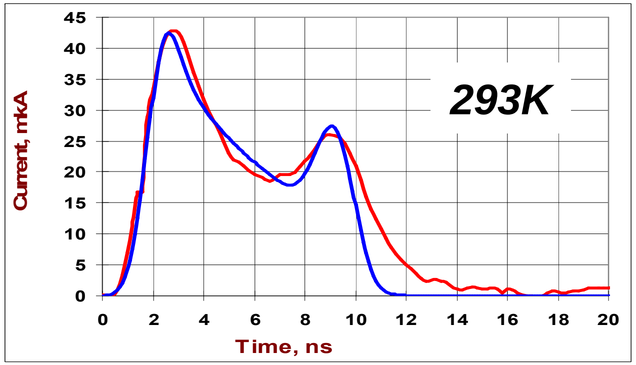
The long term annealing leads to an increase of the electric field at n+ contact and a reduction at p+ contact. The electric field in the base region is insensitive to the annealing.

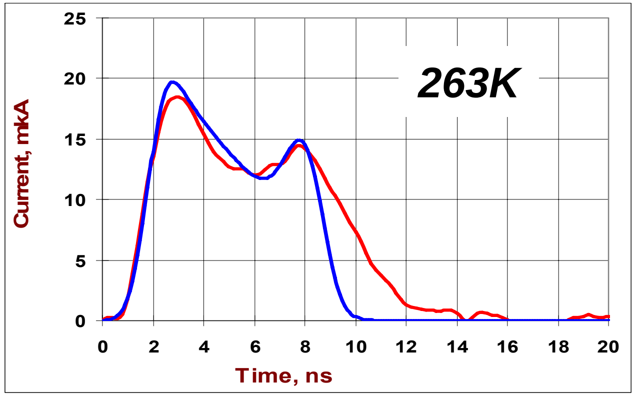
Effect of MCZ detectors cooling

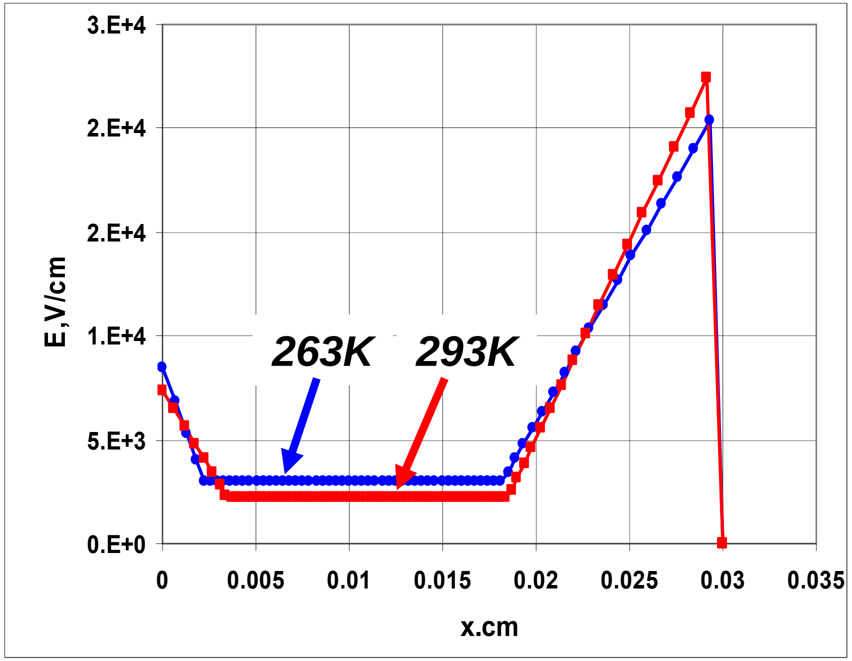
Detector W187-SMG-9
MCZ, 300um
Proton irradiated: 26 MeV, Feg = 4.2 E14 cm-2
Beneficial Annealing

Operational parameters:
V = 184 V

Extracted values
Tau tr = 6 ns
*Vfd = **180V***







The detector cooling redistributes the electric field with a trend towards a better uniformity:
the electric field at the detector contacts decreases and the field in the neutral base increases

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g_c values : comparison between n-type Fz and MCz

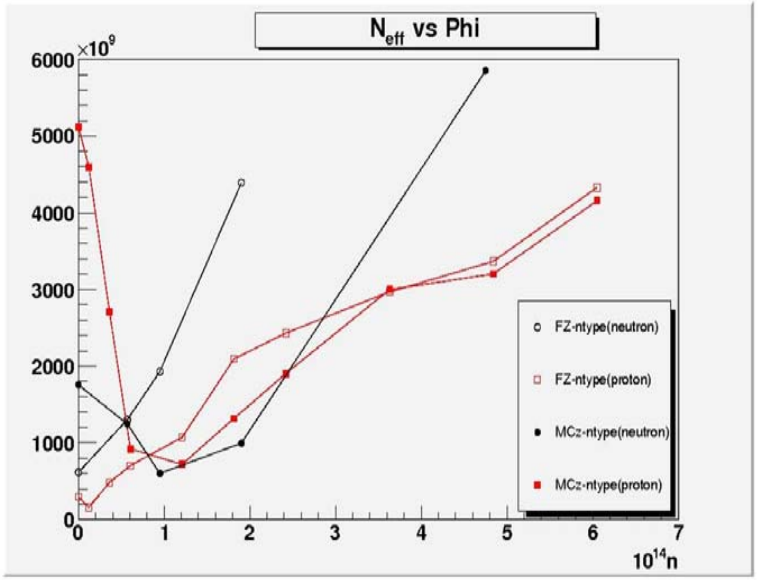
$$N_{eff} = N_{CO} \cdot \left(1 - \exp\left(-c \cdot \Phi_{eq}\right)\right) + g_C \cdot \Phi_{eq}$$

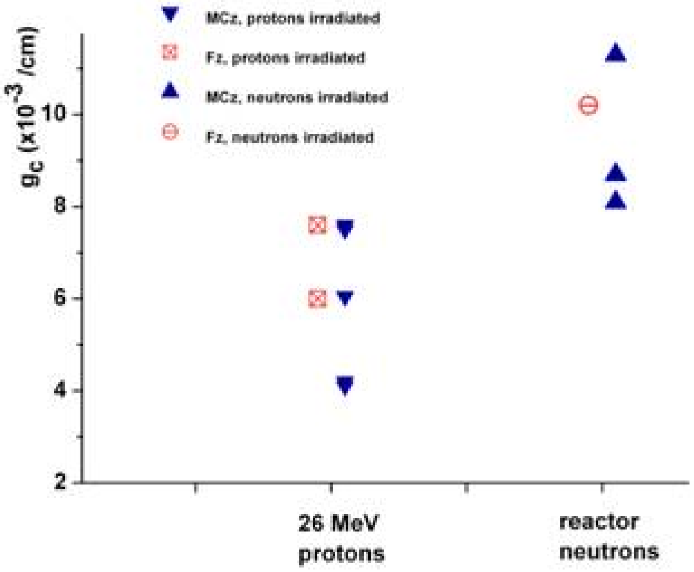
	26 MeV protons (10^{-2} /cm)	**Reactor neutrons (10^{-2} /cm)**
Fz n-type	**0.68±0.08**	**1.02±0.1**
MCz n-type	**0.59±0.17**	**0.94±0.13**

✓The SMART Fz samples show a rather low g_c value in comparison with literature:

g_c for CMS structures=1.2-1.5*10^{-2}/cm

✓Large spread among MCz wafers, probably due to different processes (Aluminum sintering, TDkilling...)





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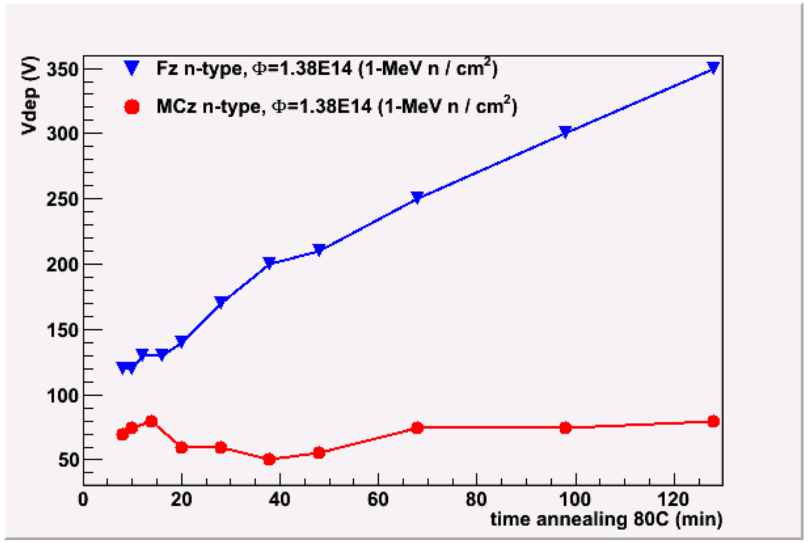
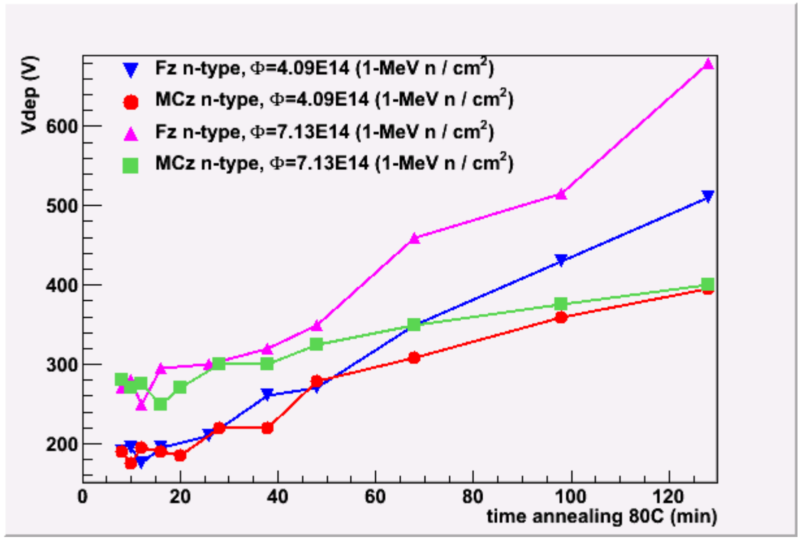
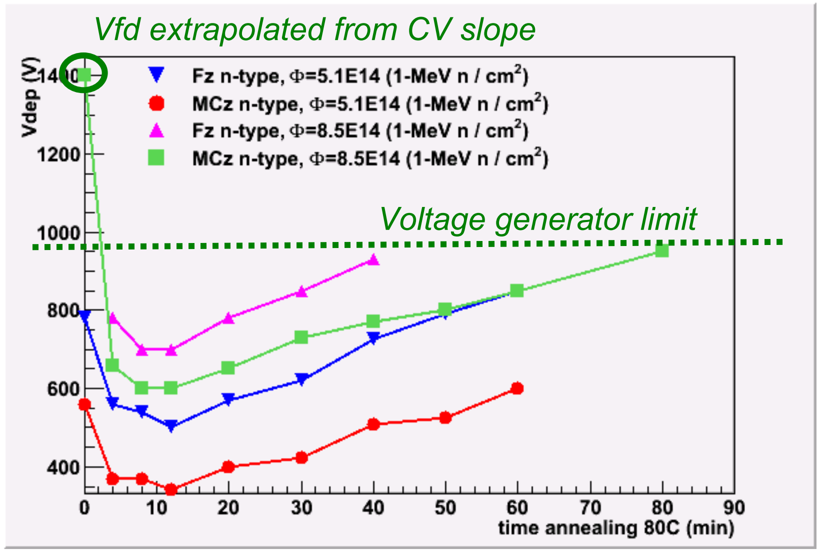
Studies on the reverse annealing of MCz

n-type material irradiated with 26 MeV protons





n-type material irradiated with reactor neutrons



Vfd extrapolated from CV slope

Voltage generator limit

In the case of the neutron irradiation is more problematic to follow the annealing behaviour of the diodes: the Vfd reaches the instrumentation upper voltage limit at lower annealing times

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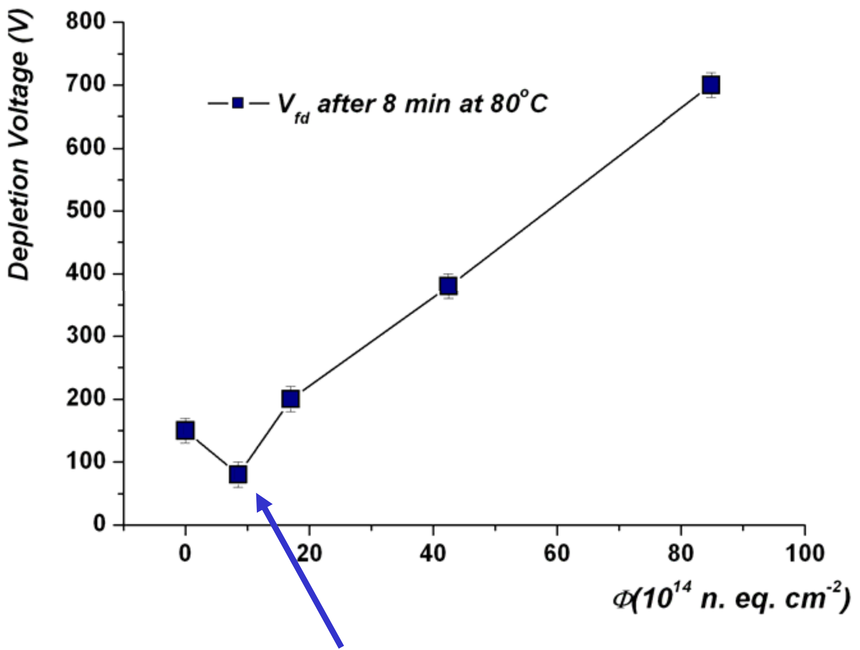
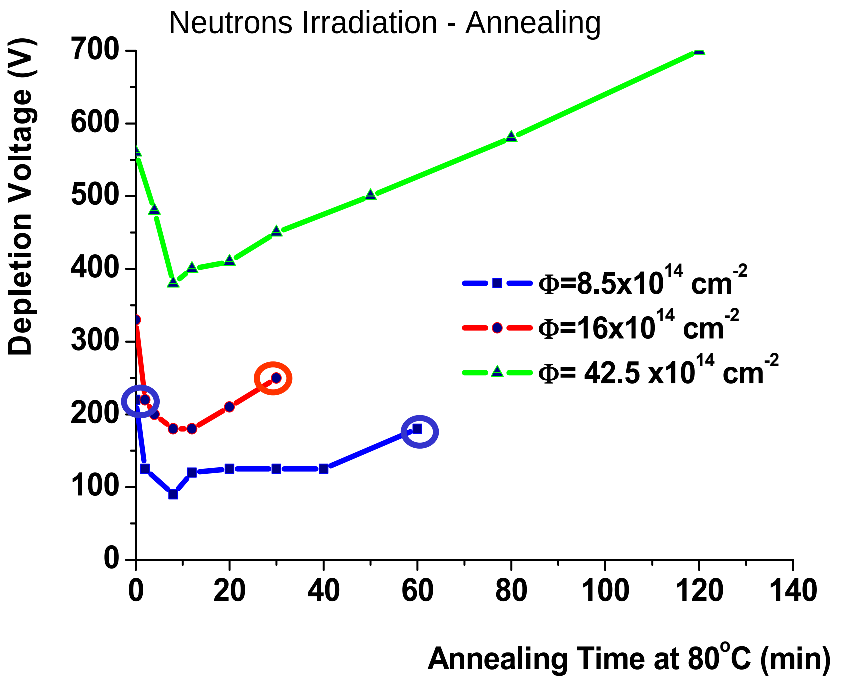
Neutron irradiation of the 150 μm thick epitaxial samples

Epi bulk resistivity: ρ=500 Ω.cm

Irradiation with reactor neutrons in Lubiana

○ *Epi samples analysed with TCT in Ioffe-St Petersburg:*





The fluence points below 10×10^{14} n.eq.cm^{-2} are missing. From the measurements in Padova on equivalent diodes from the same irradiation the minimum is around 2×10^{14} n.eq.cm^{-2}

TCT measurements have confirmed the "inversion" observed with CV curves even at the lowest fluence and without annealing

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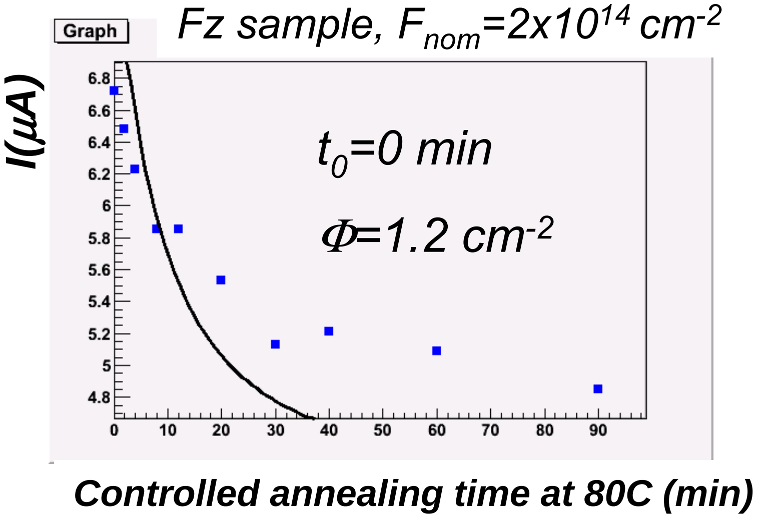
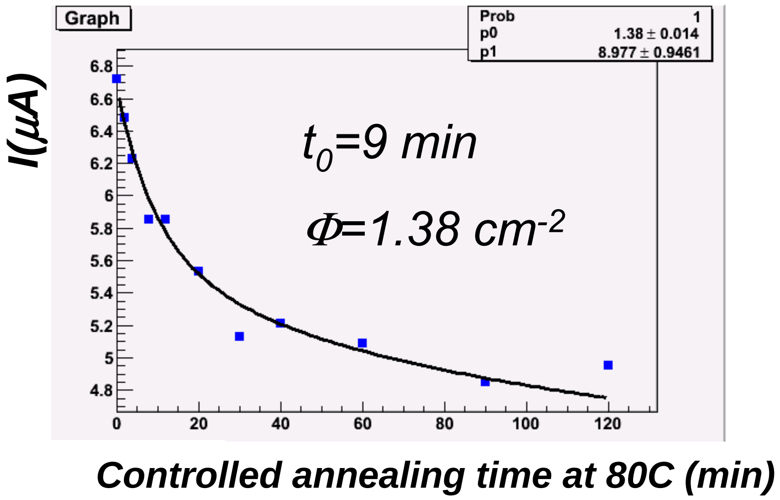
Determination of fluence and annealing time for the 26MeV p irradiation

✓We have observed that the scaling of Vfd and current as a function of the annealing time was not consistent with the expected behaviour

✓The discrepancy could be explained by a long additional annealing time before our controlled annealing --> Confirmed by A. Furgeri: the samples got warmed up during irradiation due to the high beam intensity

$$I=V^*\Phi^*(1.13.\exp(-(t+t_o)/9.)+4.23-0.28(\log(t+t_o)))$$





✓The additional annealing time t_o has been extracted with a fit to the current annealing and expressed in minutes at 80C:

✓Δt=8-11 minutes at 80°C for all the fluences and materials

✓At the same time we have also derived the correction factor for the fluence with respect to the nominal value: 0.68-0.71

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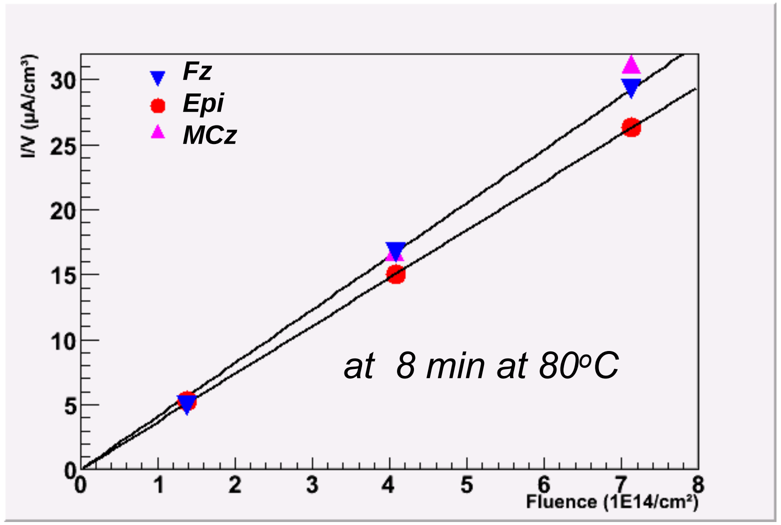
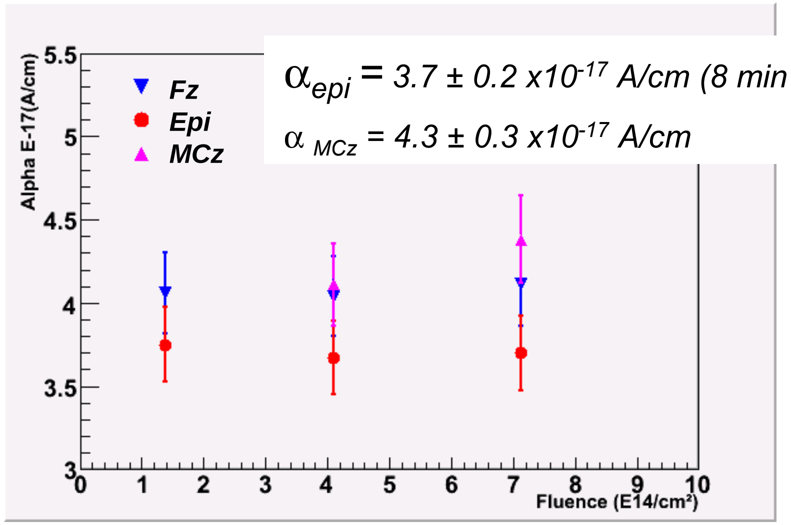
Determination of the alpha parameter for the epitaxial samples

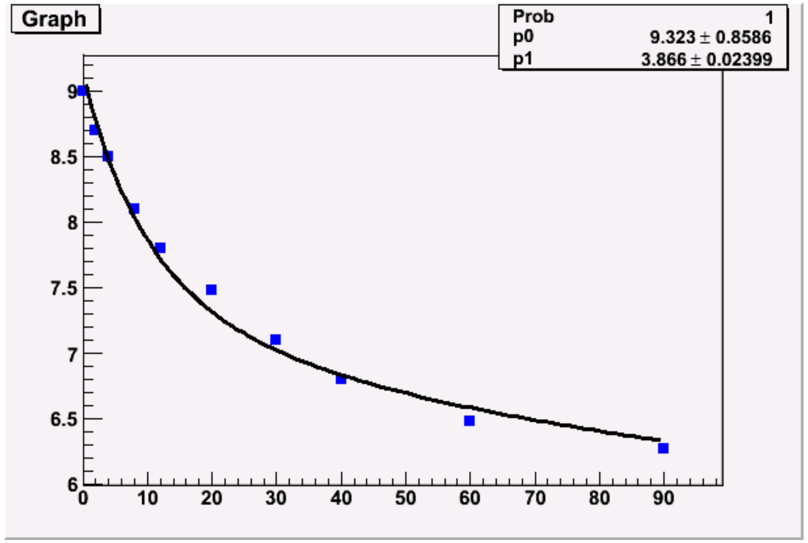
The fluence extracted from the Fz samples has been used in the calculation of the alpha parameter for the epitaxial and the MCz samples:





α_{epi} = 3.7 ± 0.2 $\times 10^{-17}$ A/cm (8 min at 80°C)

α_{MCz} = 4.3 ± 0.3 $\times 10^{-17}$ A/cm



Fit of different parameters of the alpha function with the epitaxial sample at Φ=4.1cm^{-2}

$$I=V*\Phi*(1.13\exp(-(t+8.5)/\tau_I)+\alpha_0-0.28(\log(t+8.5)))$$

✓ additional annealing time as extracted from Fz: t_0=8.5 min at 80°C

✓ τ_I = 9 min

✓ α_0 = 3.87x 10^{-17} A/cm (4.23 for Fz)

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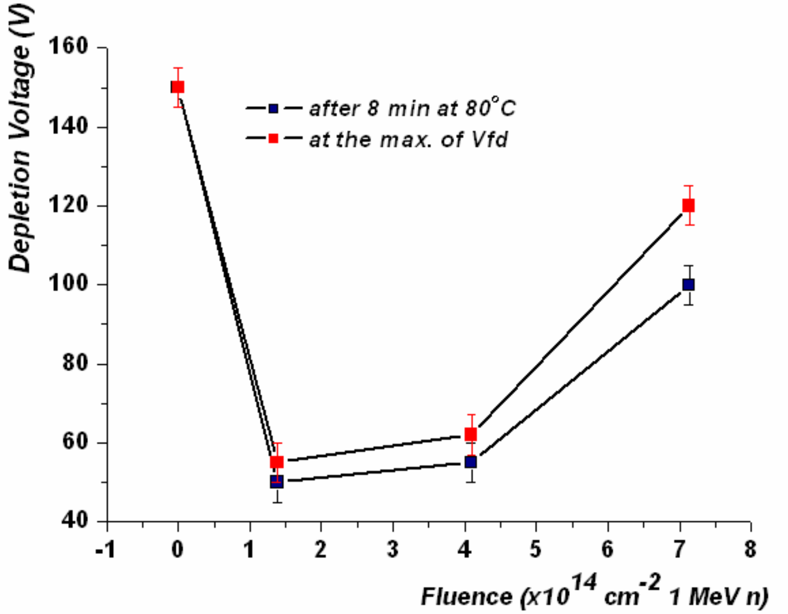
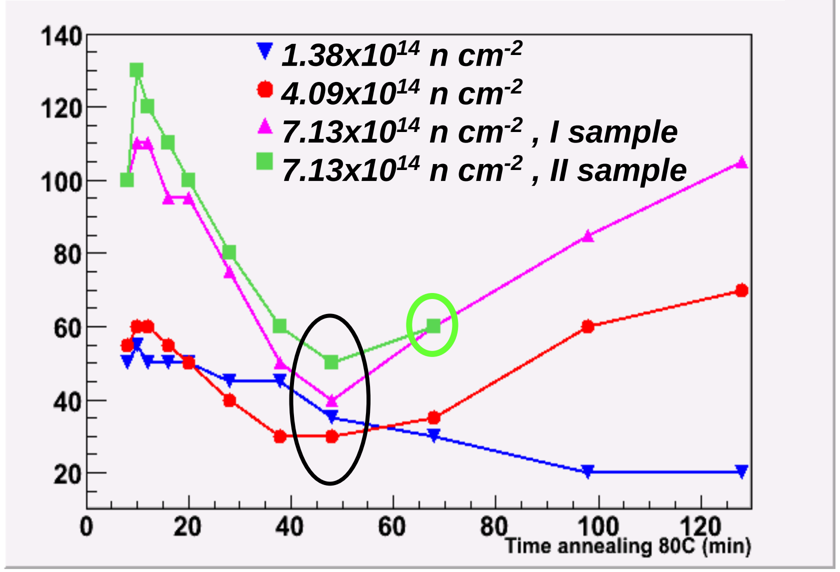
Annealing studies of epitaxial devices irradiated with 26 MeV protons





✓ *The annealing time and the received fluences have been corrected following the procedure explained in the previous two slides*

✓ *The annealing curves suggest that the SCSI takes place around 50 minutes at 80°C except for the lower fluence*

○ *Epi samples analysed with TCT in Ioffe-St Petersburg: the measurements confirm the "inversion"*

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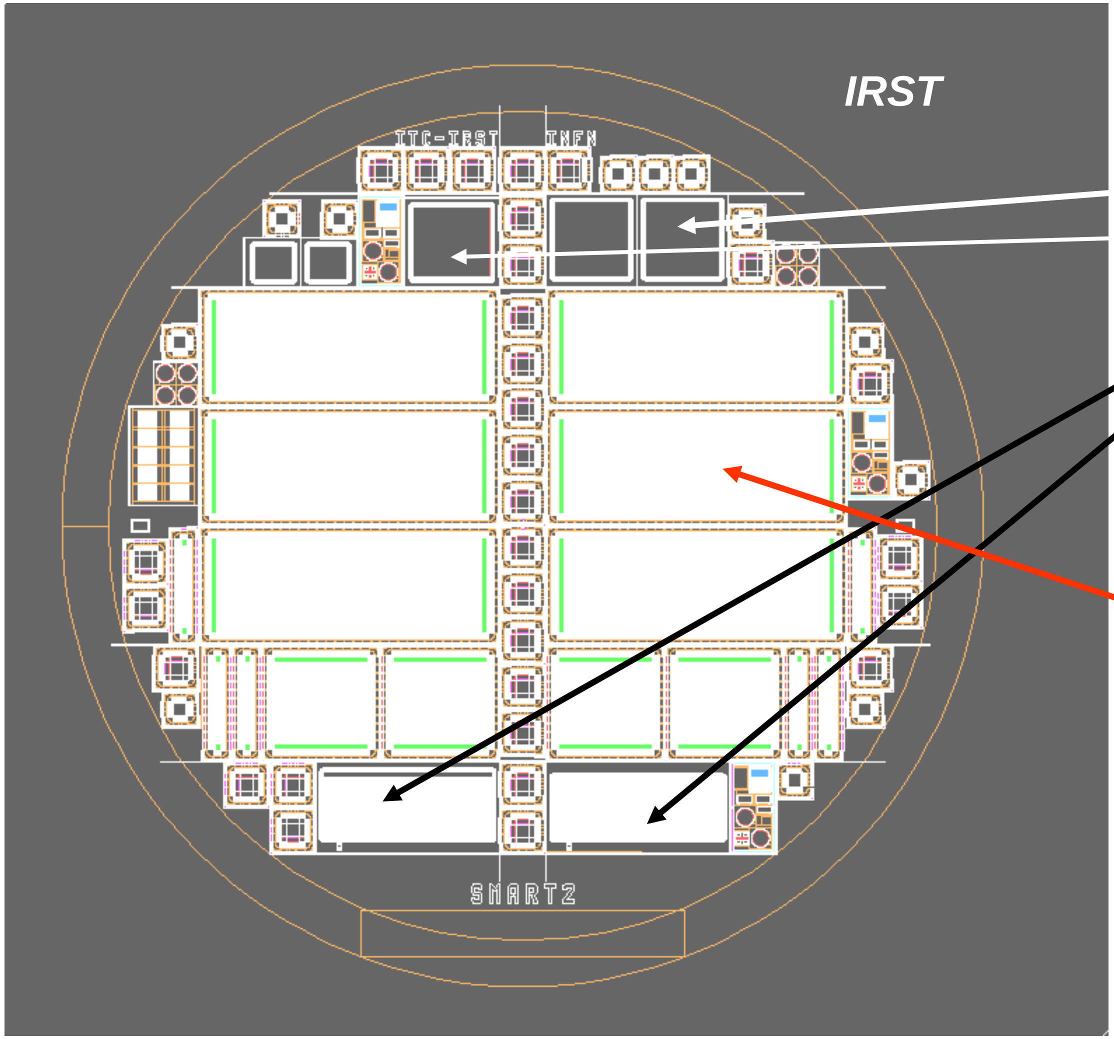
Details of the second SMART wafer layout

4-inch process on p-type material



Small prototype of
1) CMS pixel
2) Atlas Pixel
3) Macro-pixel

“full size” detector
Mini-strip CMS/Atlas

Wafers ordered:
MCz, Epitaxial, FZ Si
with standard specs

SMART

Details of layout: Pixel

Design provided by T. Rohe (PSI)

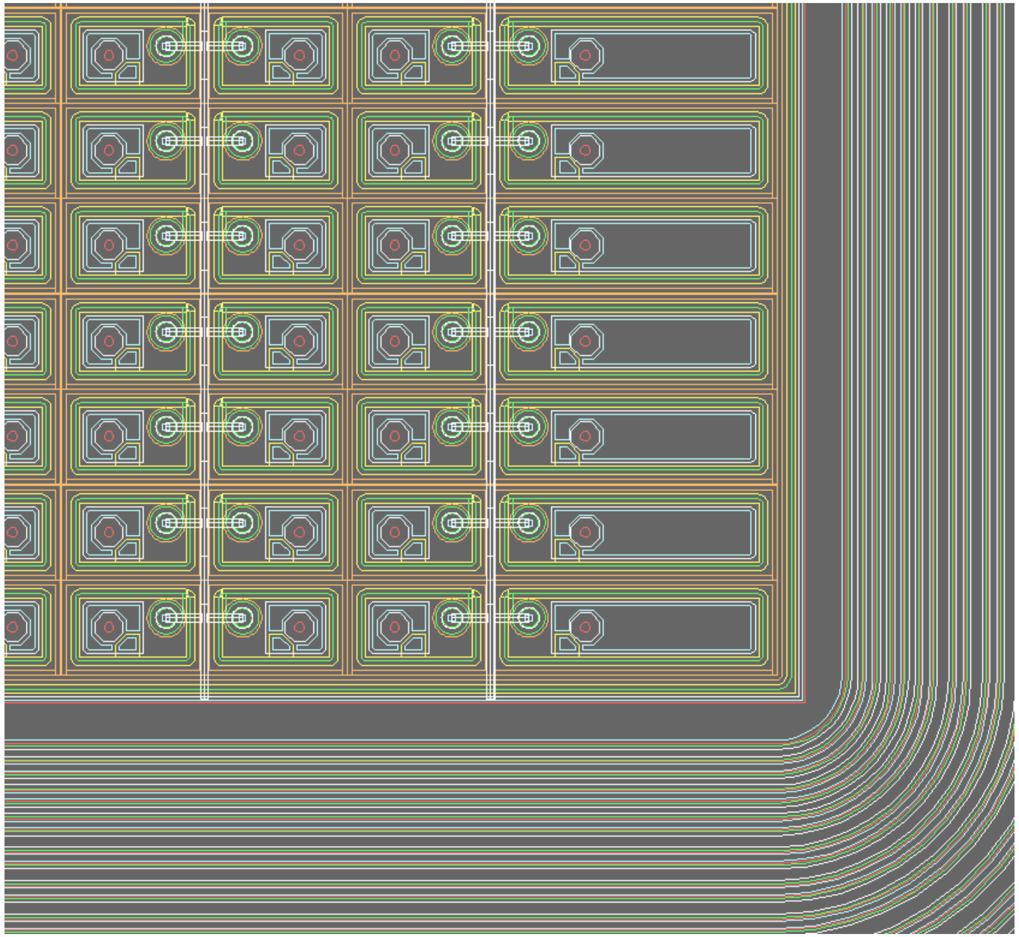
-*Pixel CMS like on p-type bulk*

-*Dimension as present CMS tracker devices (100 X 150 μm^2)*

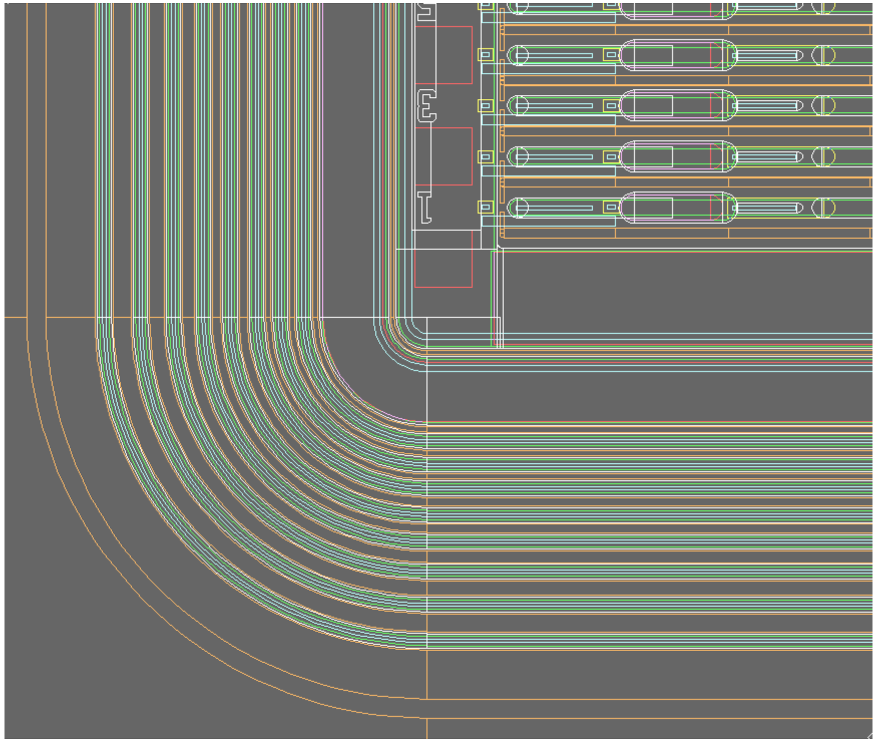
-*CMS-like (expensive) bump bonding*

-*Small size (1 chip size) : can be read-out with standard pixel electronics provided by PSI colleagues*

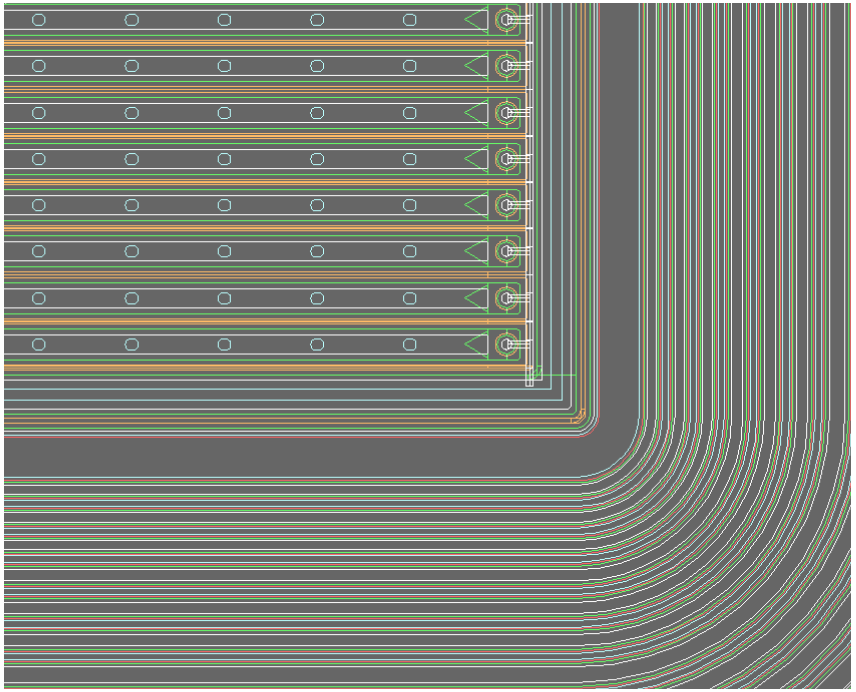
-*SS processing : n^+ on p-type*



Details of layout: mini-strip & macro-pixel



- ✓Macro-pixel : 50 micron pitch
- ✓2 cm long
- ✓Commercial bump bonding and connection routed as strip detectors (double metal technique)



- ✓Mini-strip : 80/100 micron pitch
- ✓3 cm long
- ✓ different implementations of the p-stop and p-spray techniques

(p-stop width ranges from 5 to 25μm)

Conclusions for MCz devices (I)

1. The current response of MCz devices can be explained in the framework of double peak electric field distribution model

2. A difference in the electric field distribution is observed after irradiations with neutrons, 24 GeV and 26 MeV protons:

- 24 GeV protons: up to a fluence of $\Phi=1.3\times10^{15}$ n/cm^2 the dominant junction is still on the p+ side
- Neutrons: at $\Phi=5\times10^{14}$ n/cm^2 are "type inverted" (dominant junction on the back side)
- 26 MeV protons: at $\Phi=4.2\times10^{14}$ n/cm^2 are "type inverted"

3. The long term annealing leads to an increase of the electric field at n+ contact and to a reduction at p+ contact
4. The detector cooling redistributes the electric field with a trend towards a better uniformity:
   the electric field at the detector contacts decreases and the field in the neutral base increases

Conclusions (II)

1. The current damage parameter α for the 150 μm thick epitaxial samples irradiated with 26 MeV protons has been measured to be 3.7± 0.2 $\times 10^{-17}$ A/cm (8 min at 80°C), about 10% lower than the corresponding Fz value

2. From the annealing curves of the Epi diodes irradiated with 26 MeV protons up to a fluence of 7×10^{14} n. eq. cm^{-2} a type inversion takes place only after an annealing of 50 minutes at 80°C → type inversion confirmed by TCT measurements

3. From the annealing curves of the Epi diodes irradiated with neutrons starting from a fluence of 8.5×10^{14} n. eq. cm^{-2} the material is type inverted from the lowest fluence and at low annealing times → confirmed by the TCT measurements

4. The mask design of the next SMART production of p-type material (Fz, MCz, epi) is ready , only waiting for Fz p-type wafers

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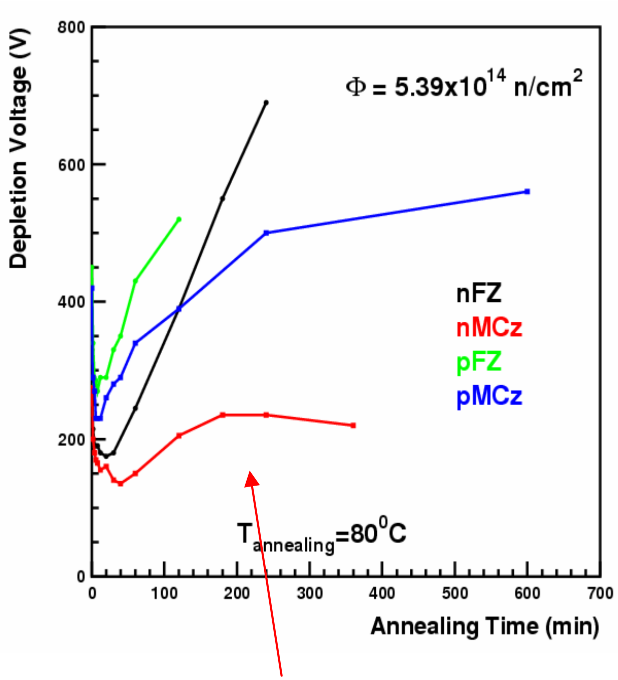
Annealing @ 80^{0}C

PROTON IRRADIATION



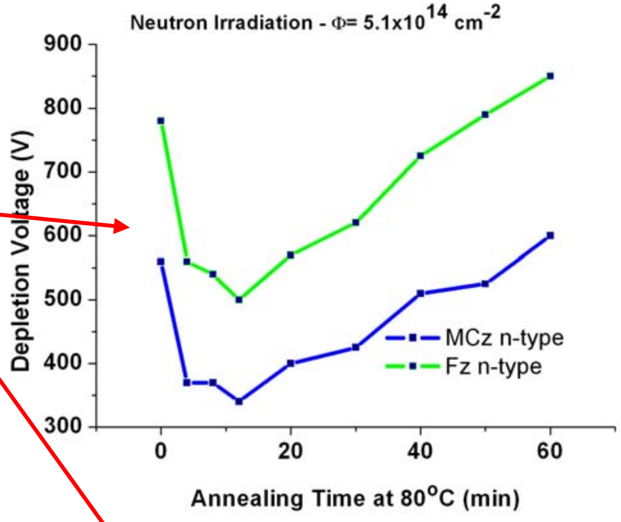
Saturation effect for MCz Si (n & p) beyond 200 minutes at 80 °C

(see also next slide)

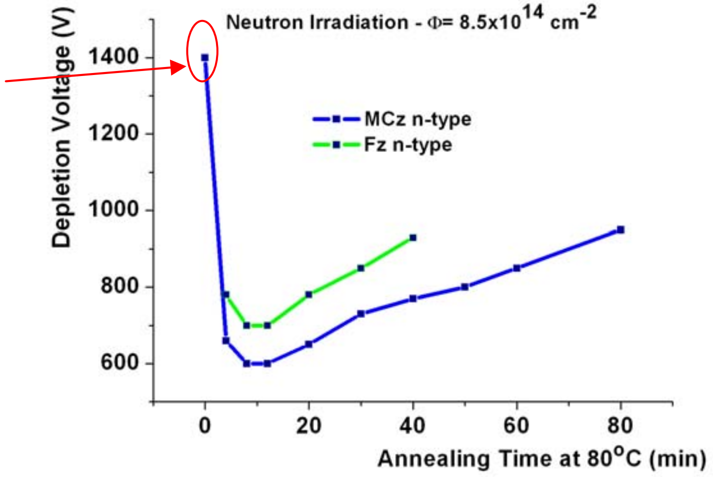
NEUTRON IRRADIATION

Up to 60 min at 80° C

Fz and MCz show the same behavior.



extrapolated



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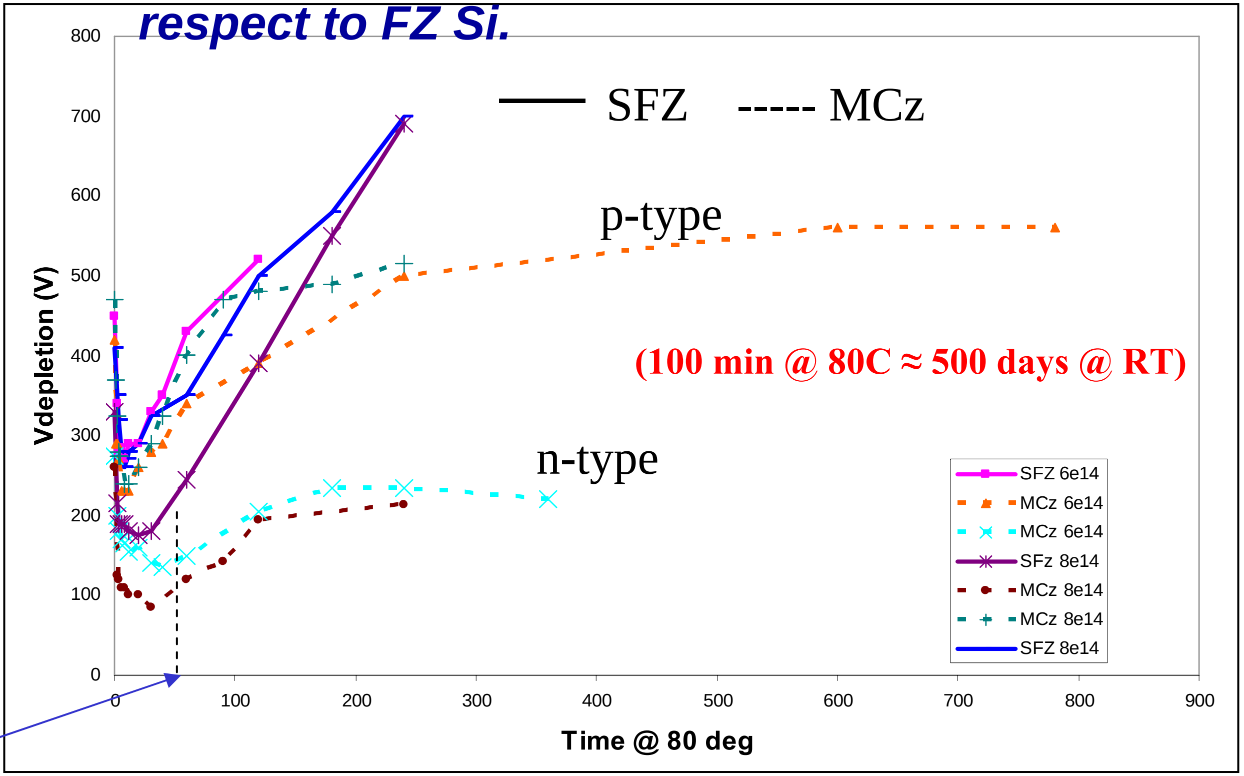
Reverse annealing @ high temperature

Comparison of SFZ and MCz (n- and p-type) @ 80°C:

Effect of reverse annealing significantly reduced in MCz Si after irradiation with 26MeV and 24GeV/c protons up to $2x10^{15}$ n_{eq} cm^{-2} with respect to FZ Si.

Clear saturation for MCz Si (n or p) beyond 200 minutes at 80 °C

Saturation more effective for n-type



SFZ ----- MCz

p-type

n-type

(100 min @ 80C ≈ 500 days @ RT)

`250 days@20°C`

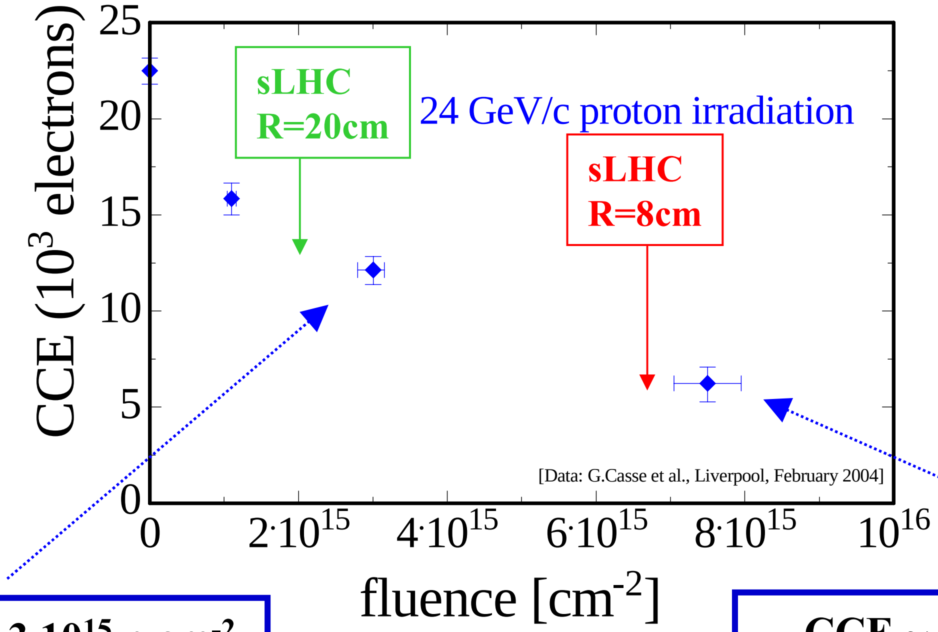
The reduced reverse annealing growth would simplify damage recovery in experimental operational conditions

SMART

n-in-p microstrip detectors

n-in-p: - no type inversion → high electric field stays on structured side
- collection of electrons → less trapping

- *Miniature n-in-p microstrip detectors (280μm)*
- *Detectors read-out with LHC speed (40MHz) chip (SCT128A)*
- *Material: standard (SFZ) and oxygenated (DOFZ) p-type FZ*
- *Irradiation:*



G. Casse et al.,
NIMA535(2004) 362

At the highest fluence
Q~6500e at V_{bias}=900V

CCE ~ 60% after 3 10^{15} p cm^{-2}
at 900V(standard p-type)

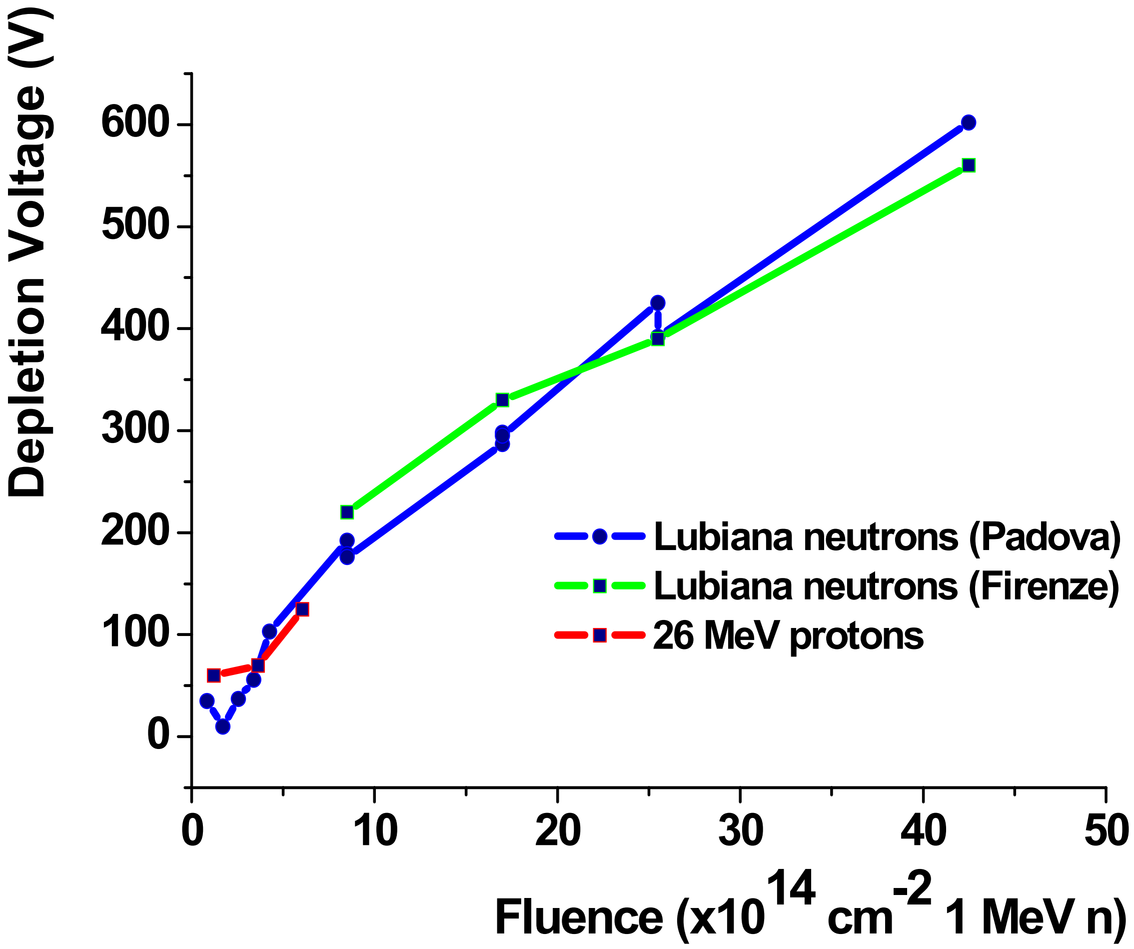
CCE ~ 30% after 7.5 10^{15} p cm^{-2}
900V (oxygenated p-type)

Epitaxial 150 µm

- **Strong increase of the depletion voltage with fluence**

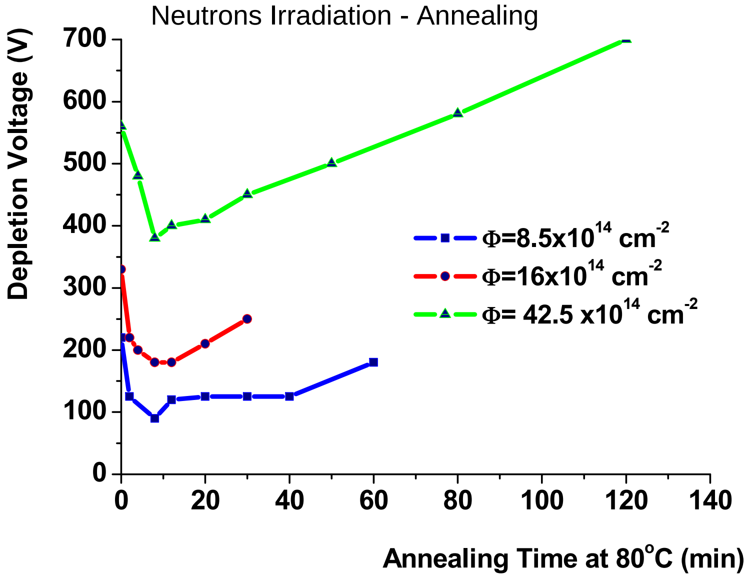
- **V_{fd} at the minimum is above 0 V: inversion or double junction effect?**

(see next slides)



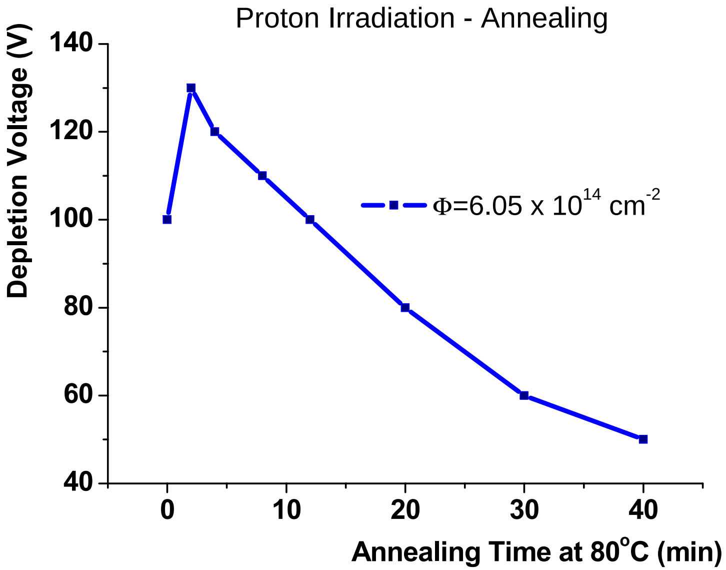
SMART

Epitaxial diodes: Annealing



Neutron irradiation: "inverted-like" behaviour

SCSI?



Proton irradiation: "not inverted-like" behaviour