First results on 24 GeV/c proton irradiated thin silicon detectors

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Motivation

- **Thin detectors**

  Advantage:

  lower depletion voltage ($V_{fd} \propto d^2$), full depletion at large Φ possible

  lower leakage current ($I_{rev} \propto d$), lower noise contribution, lower power dissipation

  smaller collection time ($t_c \propto d$), less charge carrier trapping

  Draw back:

  smaller signal for mips (signal $\propto$ d)

  larger capacitance (Cdet $\propto$ 1/d), larger electronic noise

  → find an optimal thickness

- **Questions:**

  - depend the damage effects on the device thickness?

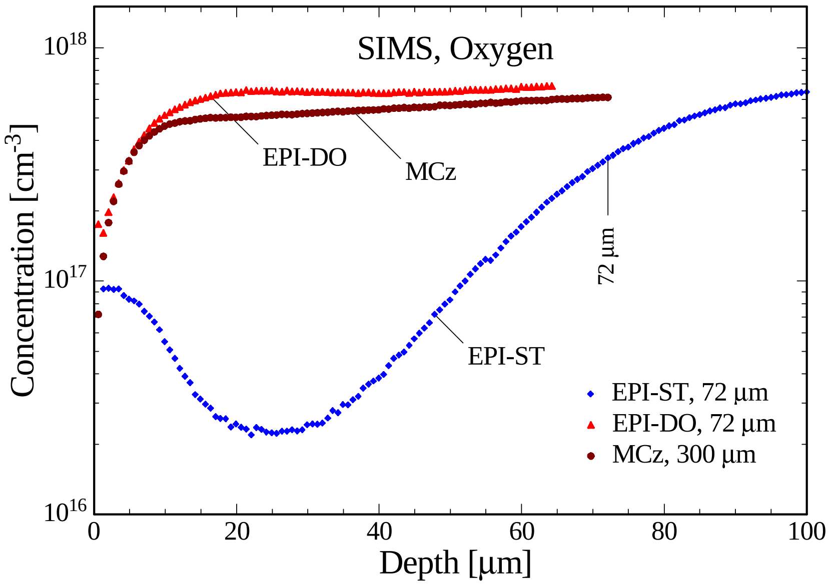
  - which impurities play a major role in the damage (P, O, C, H, others)?

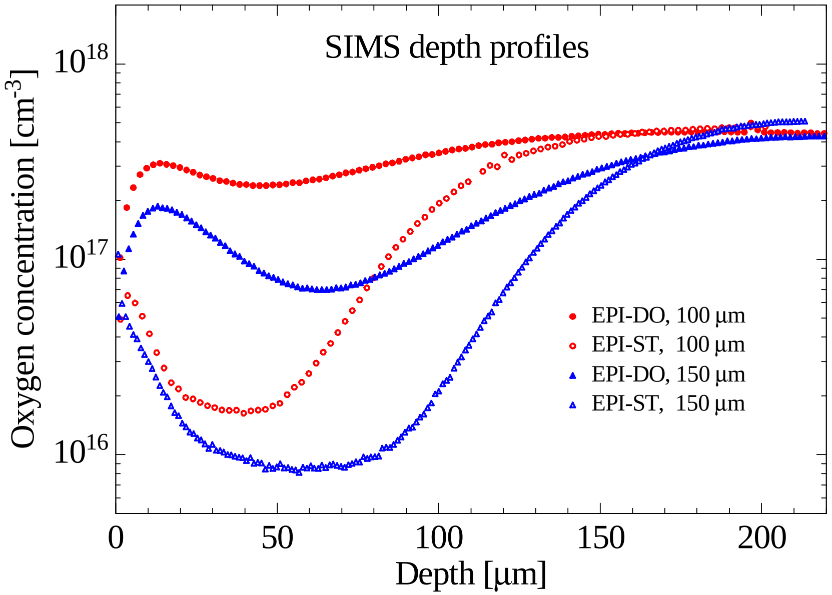
Material under investigation

Material	Cond. type	Orientation	$N_{eff,0}$ [10^{13} cm^{-3}]	d [µm]
EPI-ST(1)	N	<111>	2.6	72
EPI-DO(2)	N	<111>	2.6	72
EPI-ST(1)	N	<100>	1.5/0.88	100/150
EPI-DO(2)	N	<100>	1.3/0.80	100/150
FZ-50(3)	N	<100>	3.3	50
FZ-100	N	<100>	1.4	100
MCz-IP(4)	N	<100>	0.42	100

(1) *Standard detector process (CiS)*
(2) *Oxygen enriched, diffusion for 24 h at 1100°C (CiS)*
(3) *Produced in wafer bonding technology (MPI)*
(4) *Rear side P implanted after thinning (CiS)*

Oxygen depth profiles

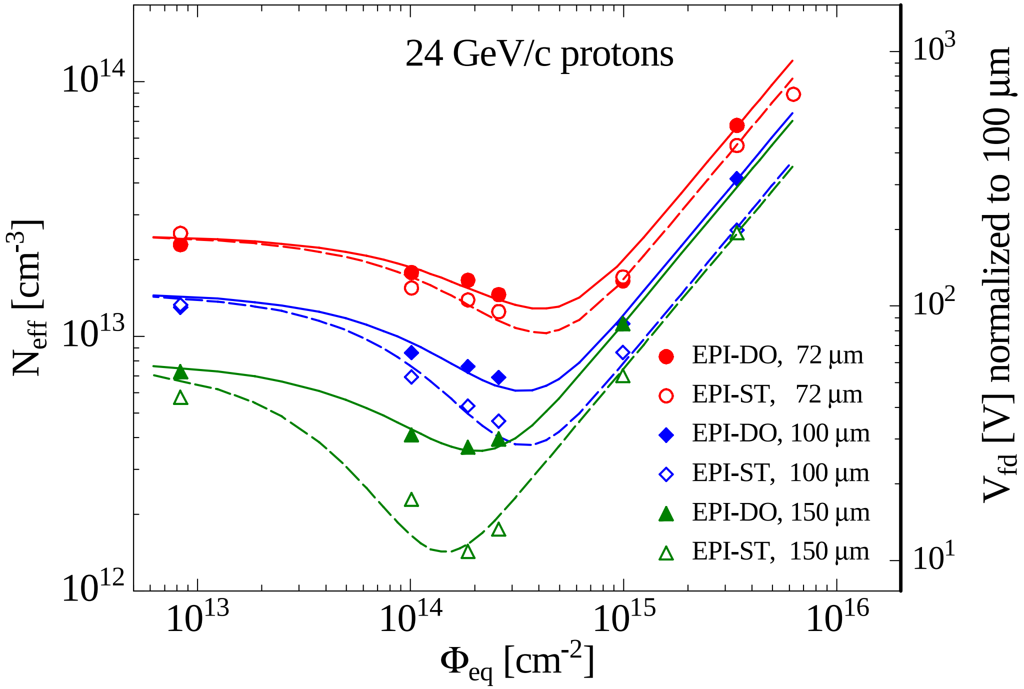




- **EPI-ST, 72 µm: [O] inhomogeneous, <[O]> = 9.3 10^{16} cm^{-3}**
- **EPI-DO, 72 µm: [O] homogeneous, except surface, <[O]> = 6.0 10^{17} cm^{-3}**
- **MCz: [O] homogeneous, except surface <[O]> = 5.2 10^{17} cm^{-3}**

- **EPI-ST, 100/150 µm: [O] inhomogeneous, <[O]> = 5.4 10^{16} / 4.5 10^{16} cm^{-3}**
- **EPI-DO, 100/150 µm: [O] more homogeneous, <[O]> = 2.8 10^{17} / 1.4 10^{17} cm^{-3}**
- **FZ 50 µm: inhomogeneous <[O]> = 3.0 10^{16} cm^{-3}**
- **FZ 100 µm: homogeneous, except surface <[O]> = 1.4 10^{16} cm^{-3}**

Development of N_{eff} resp. V_{fd} normalized to 100 µm
EPI



$$N_{eff}(\Phi) = N_{eff,0} \cdot \exp(-c \cdot \Phi) + \beta \cdot \Phi$$

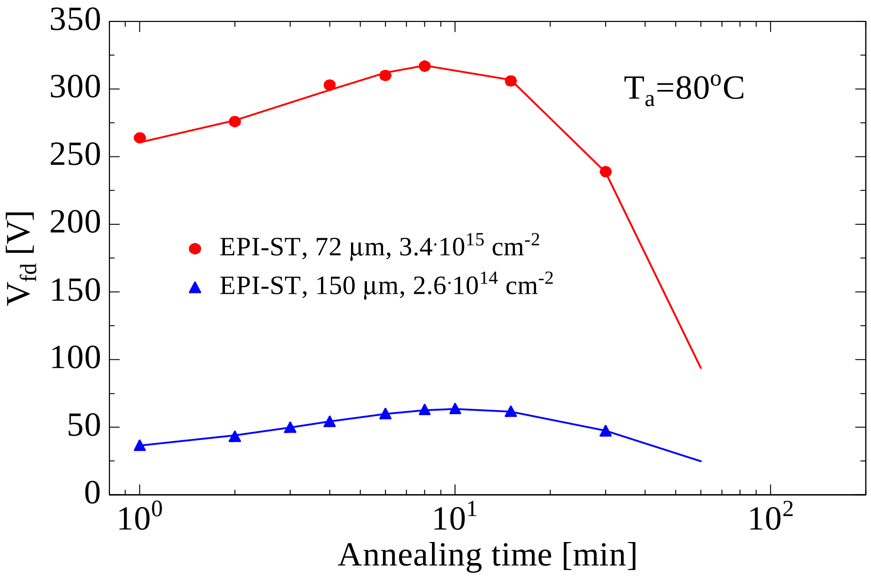
$\beta > 0$, dominant donor generation

$\beta < 0$, dominant acceptor generation

- **Low fluence range:**
  Donor removal, depends on $N_{eff,0}$, Minimum in $N_{eff}(\Phi)$ shifts to larger Φ for higher doping
- **High fluence range:**
  EPI-DO and -ST:
  $\beta(72) > \beta(100) \approx \beta(150)$ → initial doping?
  and
  β(EPI-DO) > β(EPI-ST) → oxygen effect?
- **$\beta > 0$ or < 0 ?:**
  i.e.
  dominant donor or acceptor creation?
  or
  no type inversion or type inversion?
- **Statement:**

  NO TYPE INVERSION, $\beta > 0$

Annealing of V_{fd} at 80 °C
EPI diodes



- **Typical annealing behavior of non-inverted diodes:**

  → V_{fd} increase, short term annealing

  → $V_{fd,max}$ (at $t_a \approx$ 8 min), stable damage

  → V_{fd} decrease, long term annealing

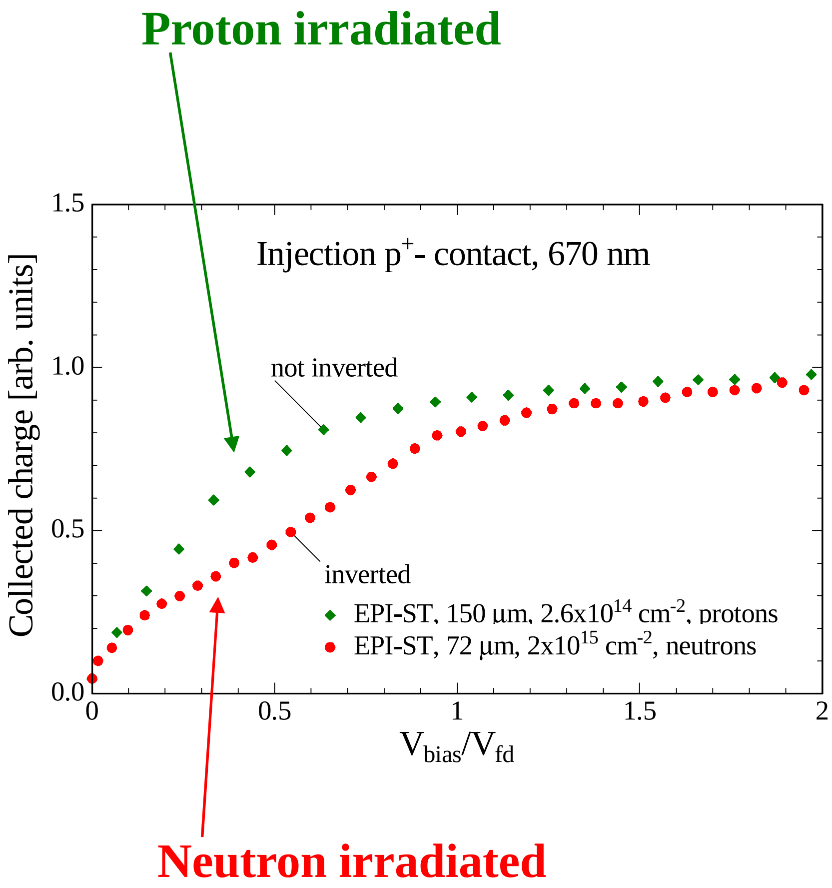
$$V_{fd}(\Phi,t) = V_C(\Phi) \pm V_a(\Phi,t) \pm V_Y(\Phi,t)$$

→ stable damage ± short term ± long term annealing

→ + sign if inverted

→ – sign if not inverted

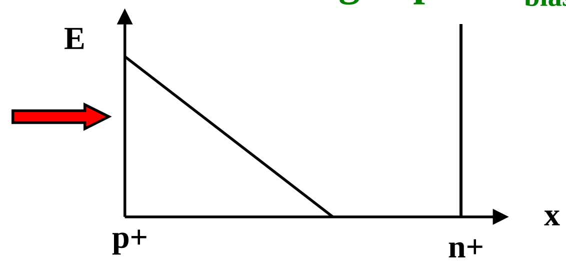
Space Charge Sign in EPI-devices



Illumination of p+-contact with 670 nm laser light (absorption length at RT about 3 µm):

<u>No SCSI:</u>

Smooth increase of collected charge with „normalized“ bias voltage up to $V_{bias}/V_{fd} = 1$

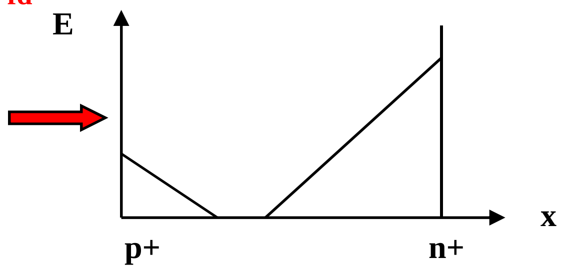


<u>SCSI (two E-field regions):</u>

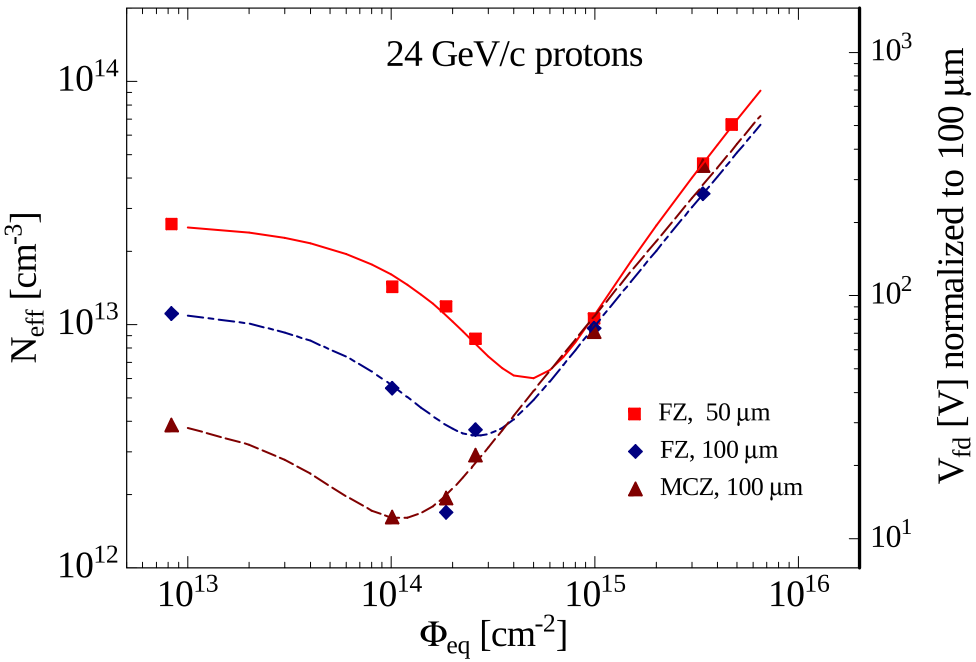
Increase of collected charge with „normalized“ bias voltage in two stages

V_{bias}/V_{fd} = 0 – 0.5: small „saturating“ increase

V_{bias}/V_{fd} = 0.5 – 1: linear increase



Development of N_{eff} resp. V_{fd} normalized to 100 µm
FZ and MCz



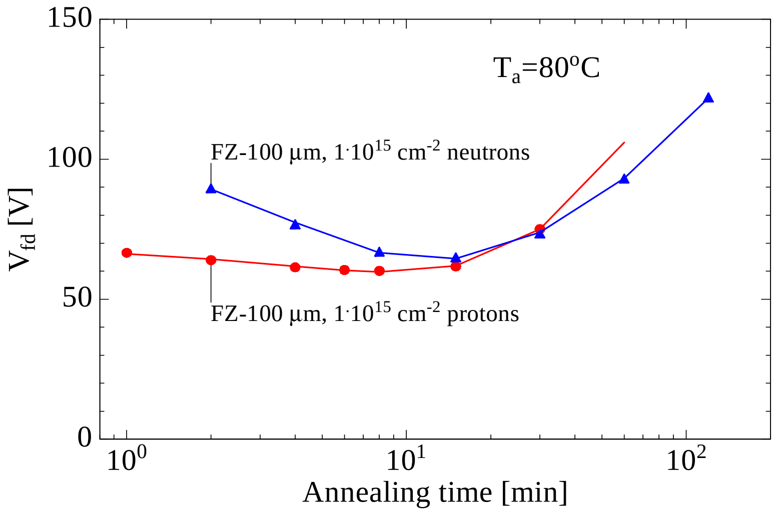
- **Low fluence range:**
  Donor removal, depends on $N_{eff,0}$, Minimum in $N_{eff}(\Phi)$ shifts to larger Φ for higher doping
- **High fluence range:**
  β(FZ-50) ≈ β(MCz-100) > β(FZ-100)
- ***β* > 0 or < 0 ?:**

  Expected:

  FZ-50, FZ-100 → β < 0, inversion, low [O]

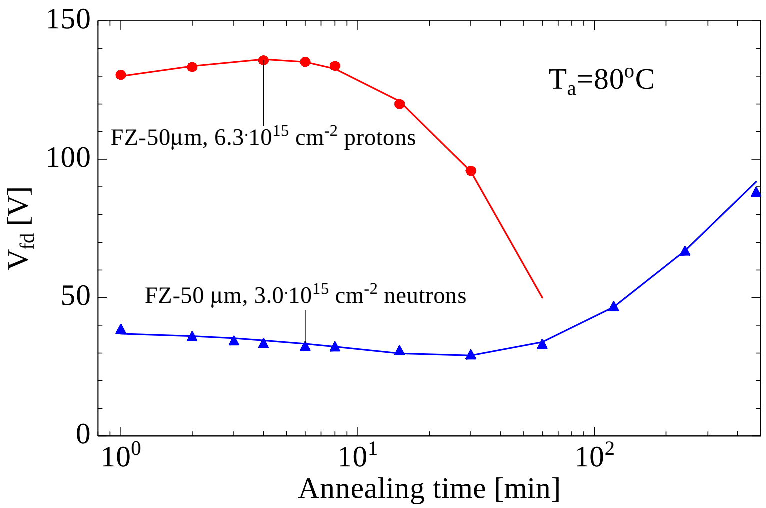
  MCz-100 → β > 0, no inversion, high [O]

Annealing of V_{fd} at 80 °C
FZ diodes



- **Annealing behavior of FZ-100 µm:**
  Inverted diode
  V_{fd} decrease (short term component)
  $V_{fd,min}$ (stable component)
  V_{fd} increase (long term component)

  for protons and neutrons

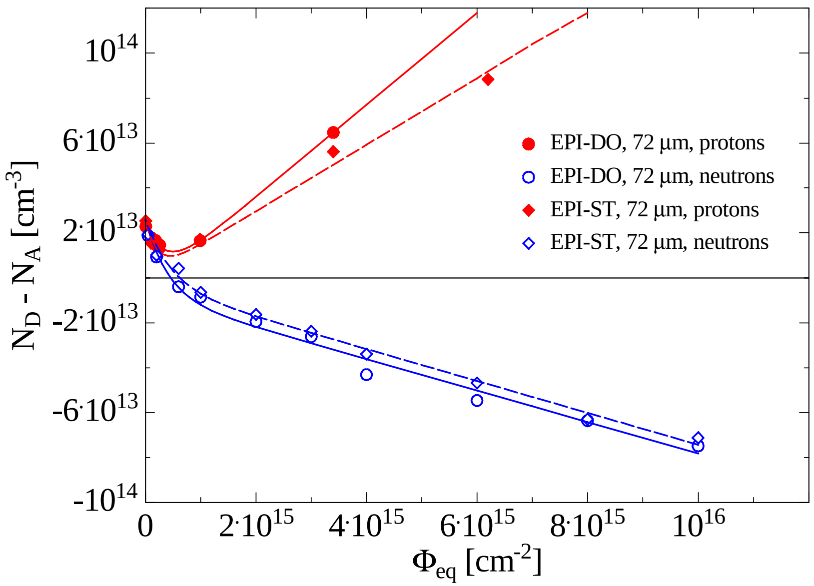


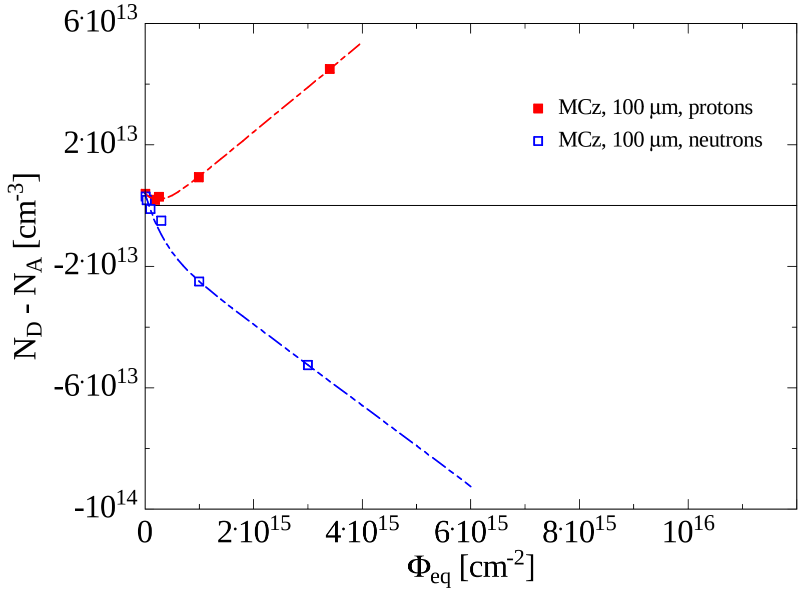
- **Annealing behavior of FZ-50 µm:**

  Big surprise:
  after proton damage no inversion

  after neutron damage inversion

Comparison protons versus neutrons
EPI-72 µm, MCz-100 µm

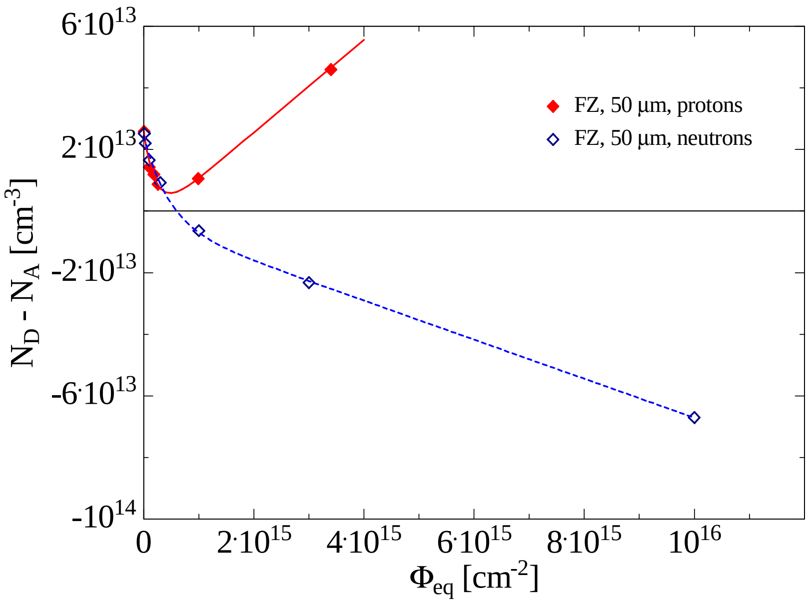


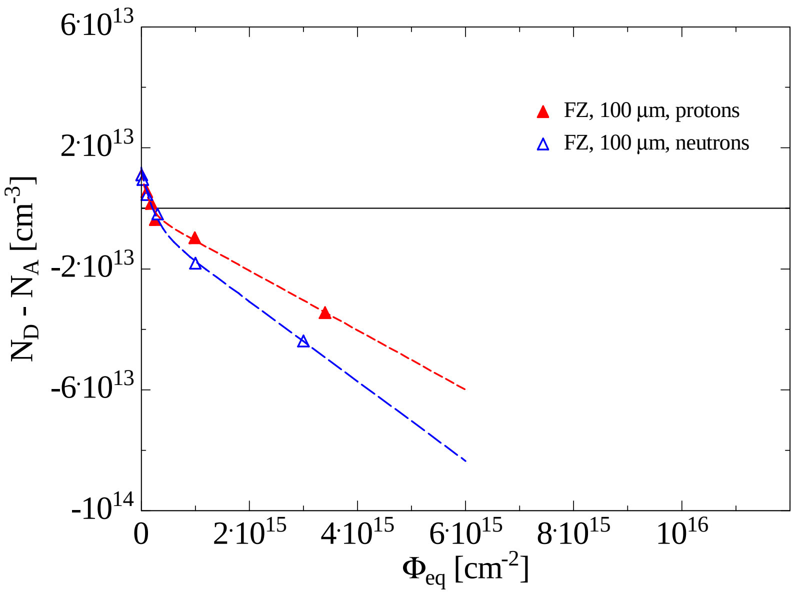


- **EPI-devices (here 72 µm) reveal no SCSI after proton damage contrary to neutron damage**
- **Same behavior holds for thin MCz-diodes**
- **$\beta > 0$ (dominant donor creation) for protons (more point defects than clusters)**
- **$\beta < 0$ (dominant acceptor creation) for neutrons (more clusters than point defects)**

Comparison protons versus neutrons

FZ-50 µm, FZ-100 µm





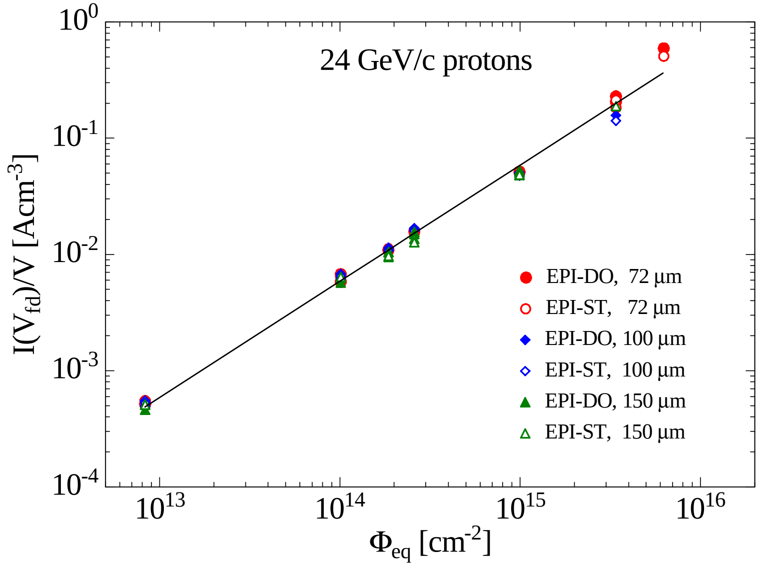
FZ-50 µm:

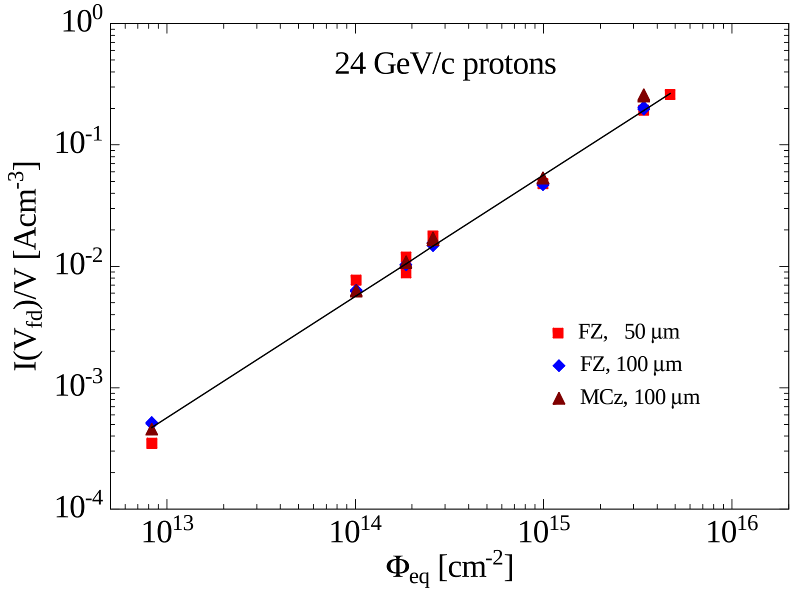
- **$\beta > 0$ for protons (dominant donor creation)**
- **$\beta < 0$ for neutrons (dominant acceptor creation)**

FZ-100 µm:

- **$\beta < 0$ for protons and neutrons (dominant acceptor creation)**

Generation current increase



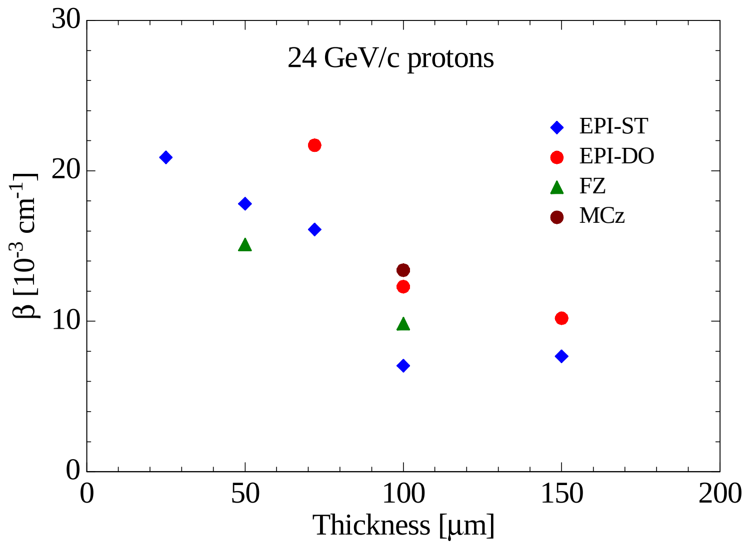


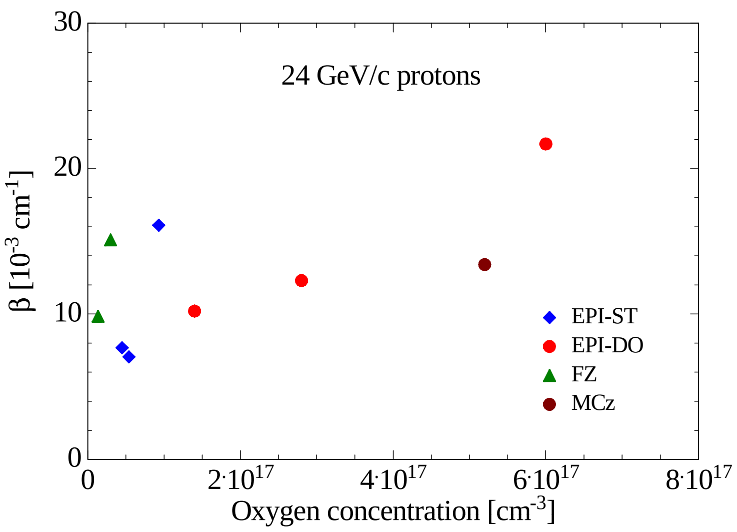
Generation current increase for 24 GeV/c protons (as irradiated):

- **Almost linear increase between 10^{13} cm^{-2} up to $6 \cdot 10^{15}$ cm^{-2} damage parameter α varies between $5 \cdot 10^{-17}$ and $6 \cdot 10^{-17}$ A/cm**
- **Independent on material type and device thickness**

β-parameter for 24 GeV/c protons

Preliminary results





- **β versus device thickness**

  Trend:
  β decreases with increasing thickness,
  but
  β(EPI-DO) > β(EPI-ST)

  → oxygen effect ?

- **β versus oxygen concentration**

  Trend:
  β increases with increasing [O],
  but
  β for EPI-ST(72 µm) and FZ(50 µm)
  outside the trend

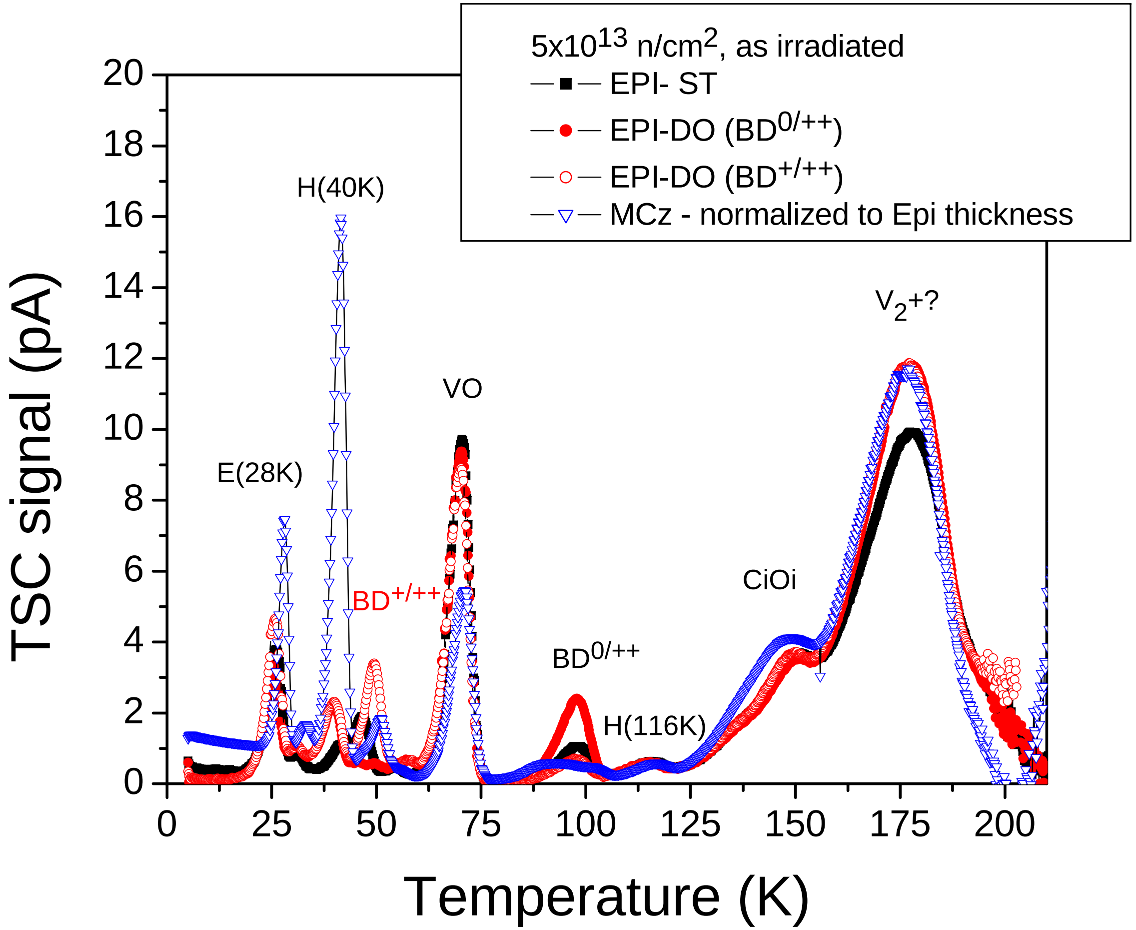
> **➢ Microscopic studies needed**

Conclusions

Comparison of thin Si-detectors processed on different materials (n-type EPI, FZ and MCz) after 24 GeV/c proton irradiation shows:

- **N_{eff} development dominated by donor removal (P, low fluence) and introduction of positive space charge (β > 0, donors, high fluence) except FZ-100 µm**
- **Surprise: no SCSI for FZ-50 µm after proton damage contrary to neutron damage although [O] much smaller compared to EPI or MCz material**
- **Inversion/no inversion demonstrated by annealing of V_{fd} or 670 nm TCT**
- **Reverse current increase independent on material type and device thickness**
- **β-value correlation?**
  Device thickness: trend visible but possibly indirect effect more likely
  Oxygen concentration: trend visible mainly for EPI-DO and MCz, EPI-ST and FZ partly outside the trend possibly due to strong inhomogeneity in [O]

TSC Studies on Neutron Irradiated Devices



Main defects:

- **V_2, clustered**
- **C_iO_i**
- **VO**
- **Bistable donor:**
  $BD^{(0/++)}$
  $BD^{(+/++)}$ first time observed
- **Several shallow hole and electron traps** (H(40K), E(28K))

Main differences:

- **BD(+/++) only in EPI-DO?**
- **BD(0/++) dominant in EPI-DO, but also detected in EPI-ST and MCz**
- **[VO] identical in EPI-DO and EPI-ST, lower in MCz**