Comparison of neutron damage in thin FZ, MCz and epitaxial silicon detectors

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Motivation

- **Findings from RD48:**
  Neutron damage is independent on Si material type (n- or p-type, oxygen concentration). These results were found for mainly 300 µm thick Si-devices

- **From RD50:**
  Thin n-type epi-Si (25 and 50 µm, 50 Ω·cm) show no type inversion after neutron damage

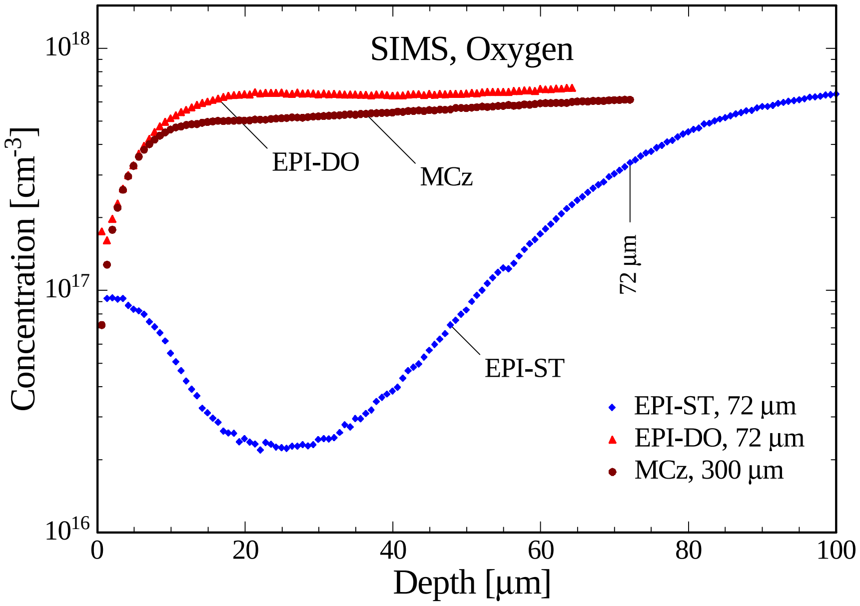
- **Questions:**
  - Is the fluence dependence of the full depletion voltage or the effective doping concentration for thin Si-detectors in general different compared to thick (300 µm) devices?
  - Which impurities play a major role (P, B, O, others)?

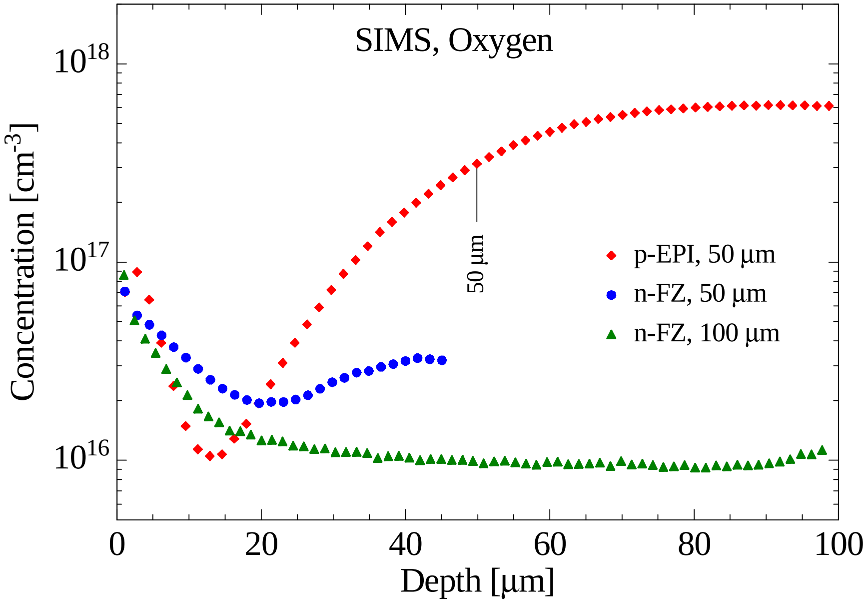
Material under investigation

Material	**Cond. type**	**Orientation**	$N_{eff,0}$ [10^{13} cm^{-3}]	**d [µm]**
N-EPI-ST(1)	**N**	**<111>**	**2.6**	**72**
N-EPI-DO(2)	**N**	**<111>**	**2.6**	**72**
P-EPI-ST	**P**	**<111>**	**-9.0**	**50**
FZ-50(3)	**N**	**<100>**	**3.3**	**50**
FZ-100	**N**	**<100>**	**1.4**	**100**
MCz-IP(4)	**N**	**<100>**	**0.48**	**100**
MCZ-DI(5)	**N**	**<100>**	**0.77**	**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)*
(5) *Rear side P diffused after thinning (CiS)*

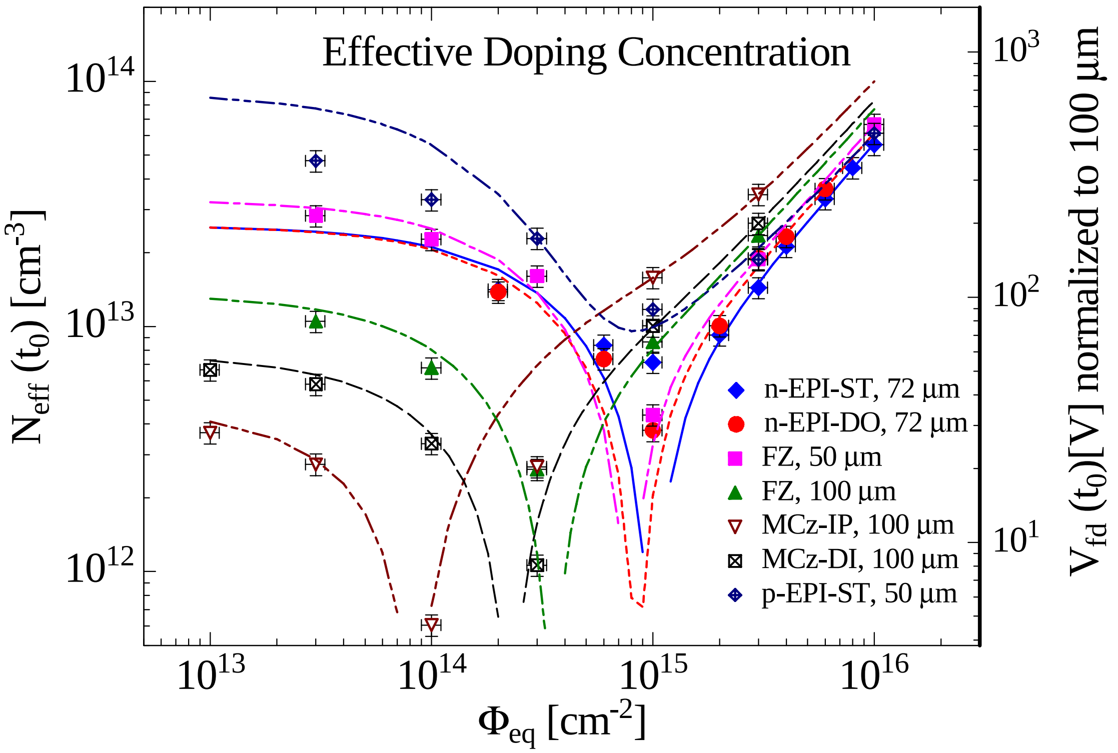
Oxygen depth profiles





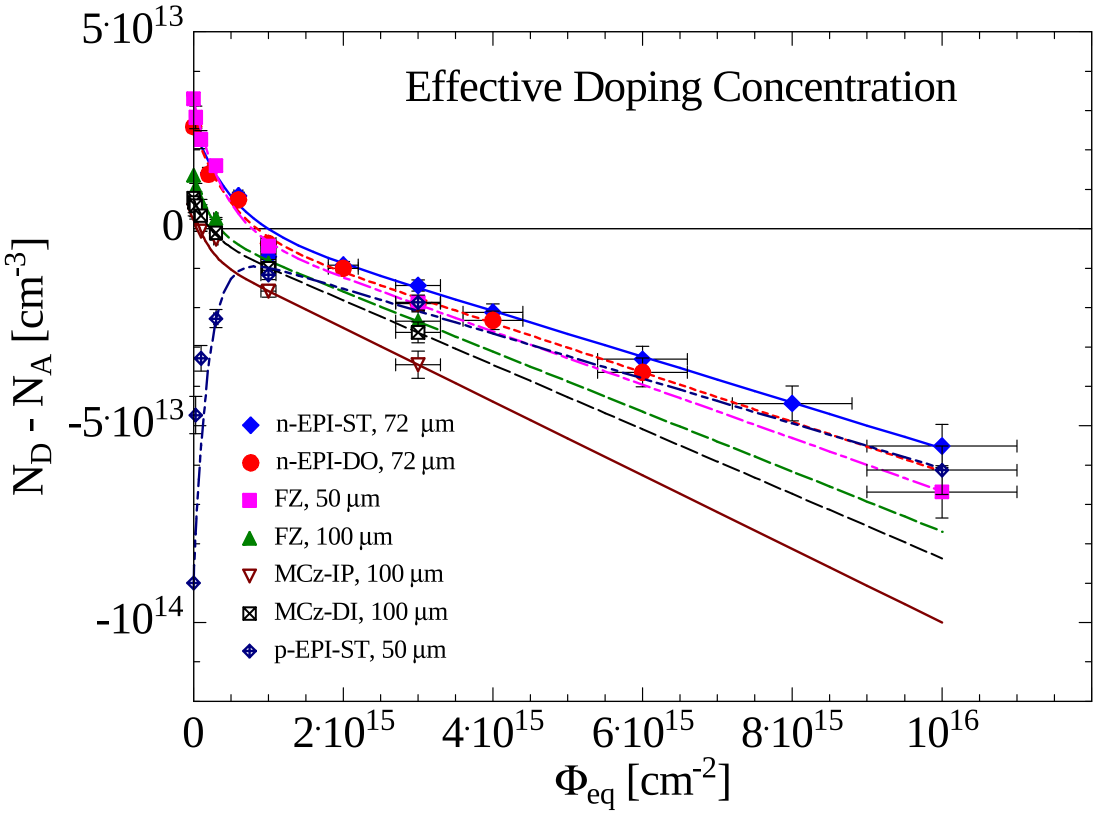
- **EPI-ST: [O] inhomogeneous,**
  <[O]> = 9.3 10^{16} cm^{-3}
- **EPI-DO: [O] homogeneous, except surface**
  <[O]> = 6.0 10^{17} cm^{-3}
- **MCz: [O] homogeneous, except surface**
  <[O]> = 5.2 10^{17} cm^{-3}
- **P-type EPI: [O] inhomogeneous**
  <[O]> = 1.0 10^{17} cm^{-3}
- **FZ 50 µm: inhomogeneous**
  <[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



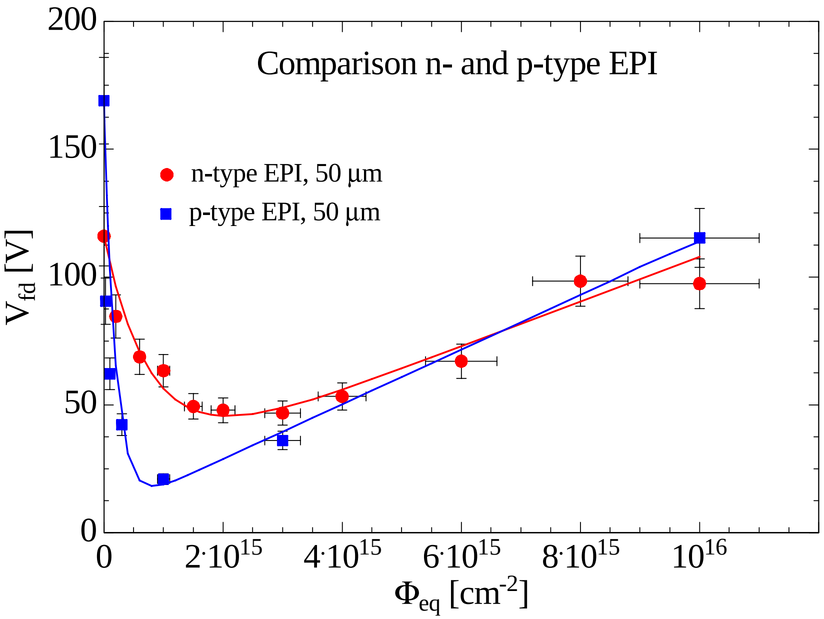
- **Space charge sign inversion (SCSI) for all n-type materials, p-type EPI always negative space charge**
- **Fluence for SCSI depends on primary donor concentration (P and TD concentration, compare MCz-DI with TD and MCz-IP without TD)**
- **Development of N_{eff} for n-type and p-type material seems to be dominated by doping (P or B) removal and introduction of negative space charge although a creation of donors has to be taken into account (see I. Pintilie)**

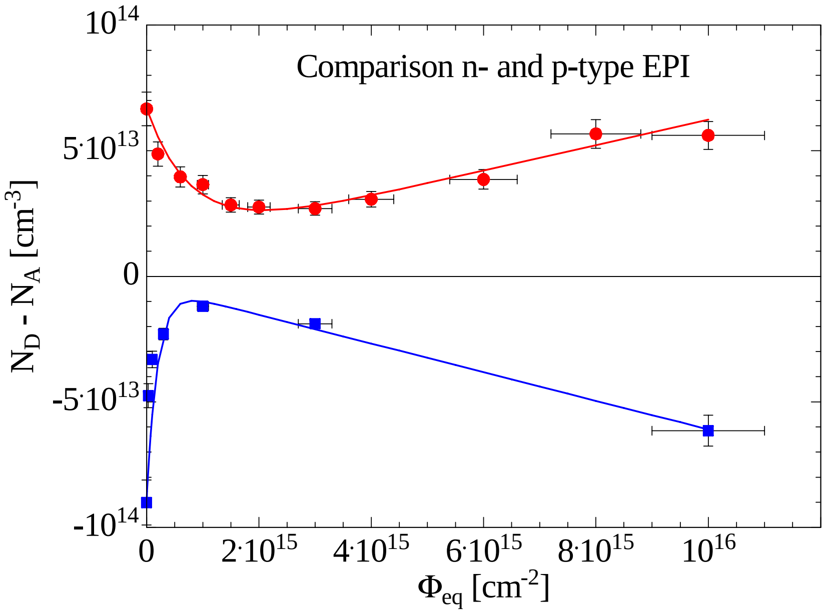
Effective space charge concentration



- **Former studies on 50 Ωcm n-type EPI-devices revealed no SCSI contrary to these different n-type materials**
- **Space charge of p-type EPI stays negative**
- **The introduction of negative space charge is lower for low resistivity material (EPI and FZ) compared to the higher resistivity MCz material**

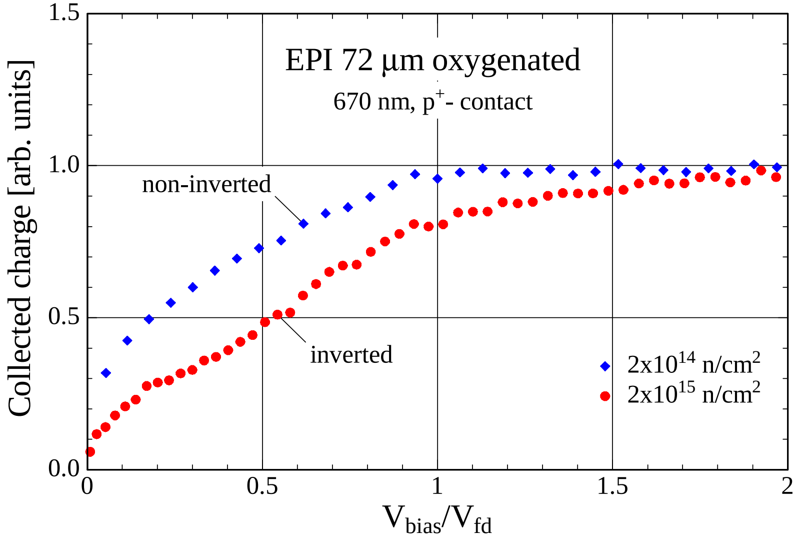
Comparison 50 µm n- and p-type EPI

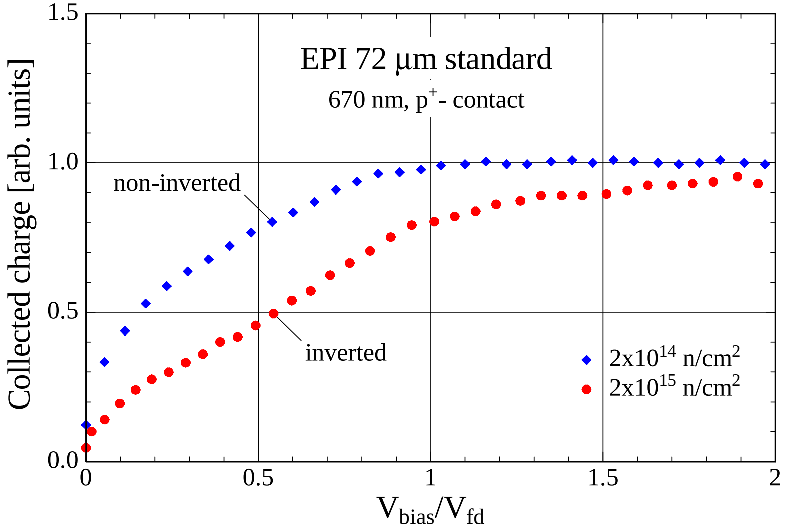




- **N-type EPI: Donor (P) removal in low fluence range, dominant donor generation (BD) in high fluence range**
- **P-type EPI: Fast acceptor (B) removal in low fluence range, dominant acceptor generation in high fluence range**

Space Charge Sign in 72 µm n-EPI-devices

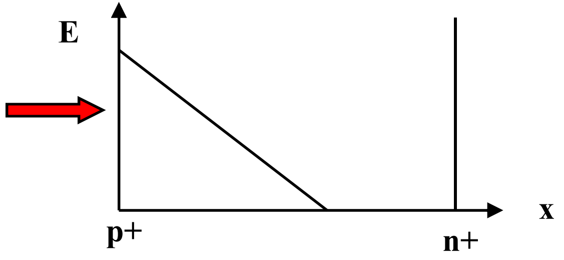




Illumination of p+-contact with 670 nm laser light (absorption length at RT about 3 µm):

No SCSI:

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

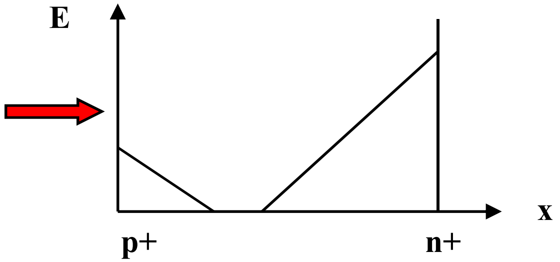


SCSI (two E-field regions):

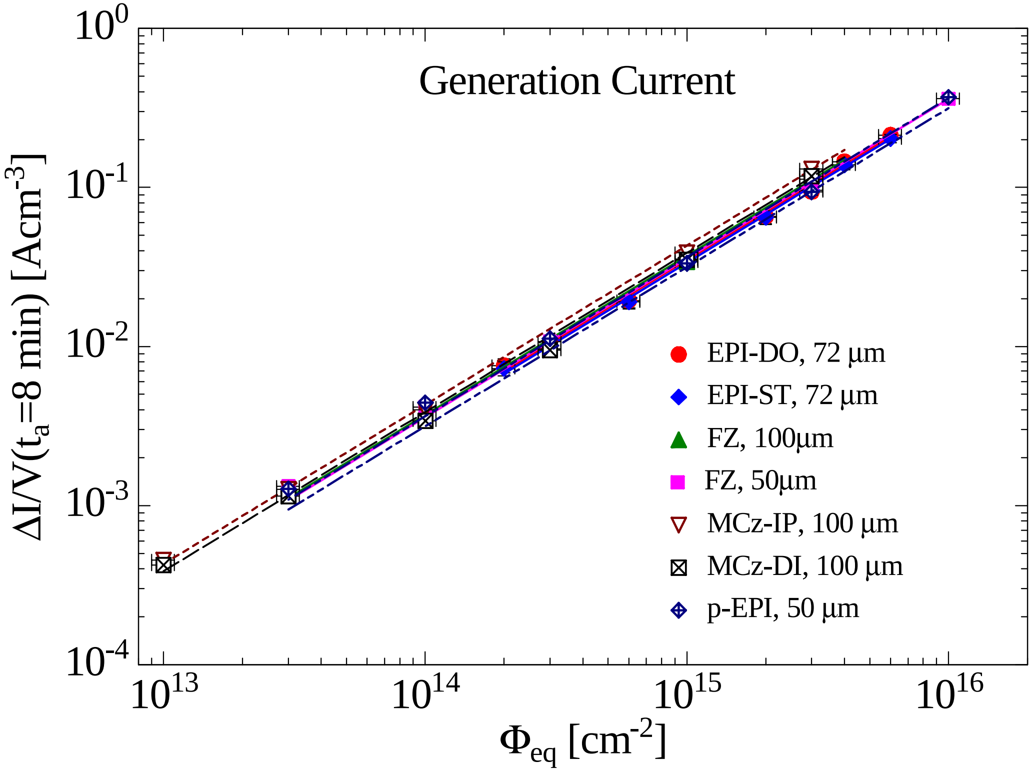
Increase of collected charge with „normalized“ bias voltage in two stages

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

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



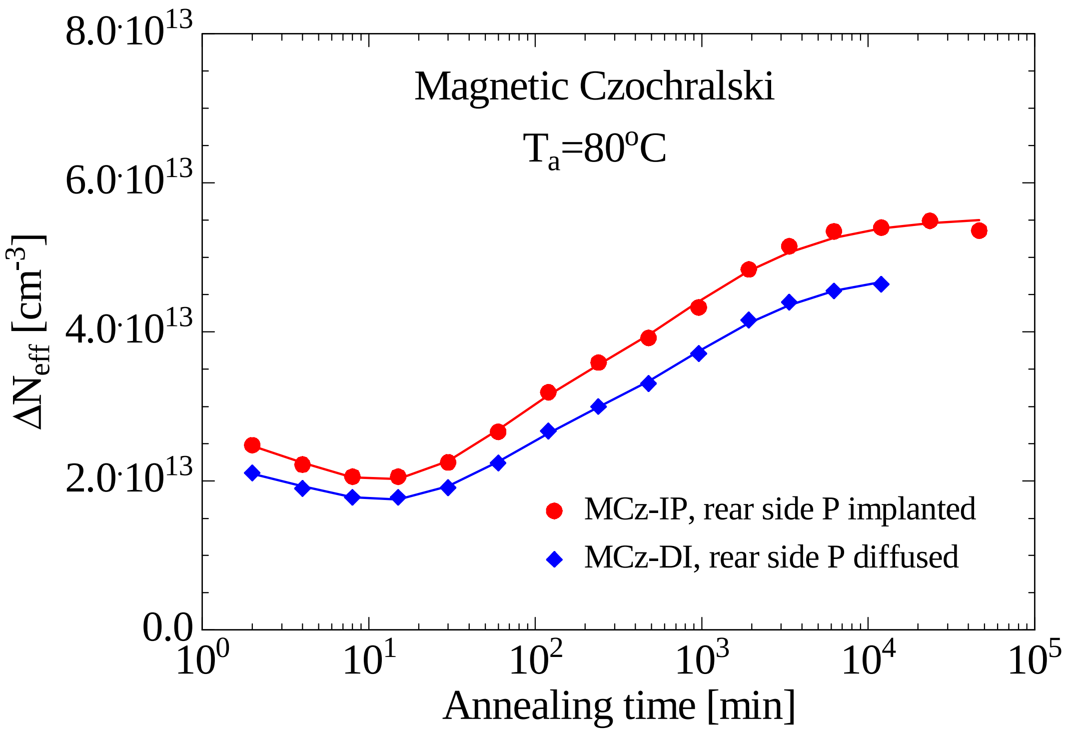
Generation current increase



Generation current increase after annealing for 8 min at 80°C:

- **Almost linear increase between 10^{13} cm^{-2} up to 10^{16} cm^{-2} damage parameter α varies between 3.4 10^{-17} and 4.0 10^{-17} A/cm**
- **Nearly independent on material type**

Annealing of ΔN_{eff} at 80 °C



$$\Delta N_{eff}(\Phi,t) = N_a(\Phi,t) + N_C(F) + N_Y(\Phi,t)$$

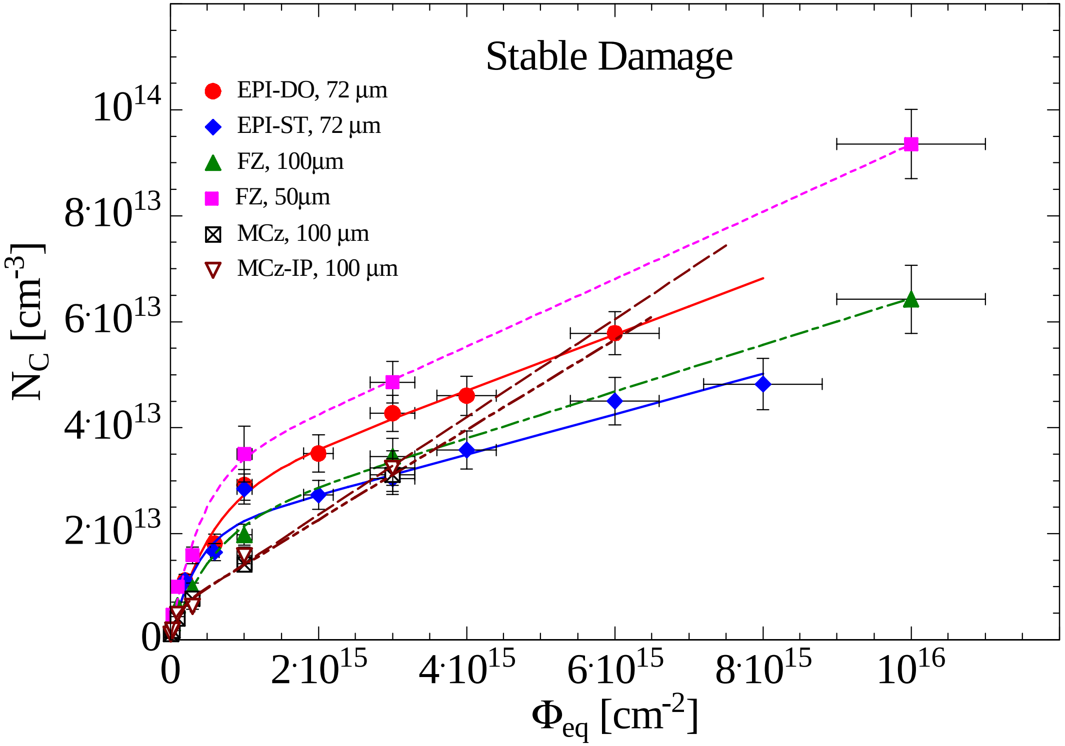
with

$$N_Y(\Phi,t) = N_{Y,1}(\Phi,t) + N_{Y,2}(\Phi,t)$$

- **Typical annealing behavior:**
  short term annealingN_a
  + stable component N_C
  + reverse annealing N_Y

  reverse annealing best described by 2 components: 1. order + 2. order process
- **Difference between MCz-IP (rear side P implanted) and MCz-DI (rear side P diffused) due to process induced TD's in MCz-DI**
- **TD's are stable at 80°C**

Stable damage component N_C



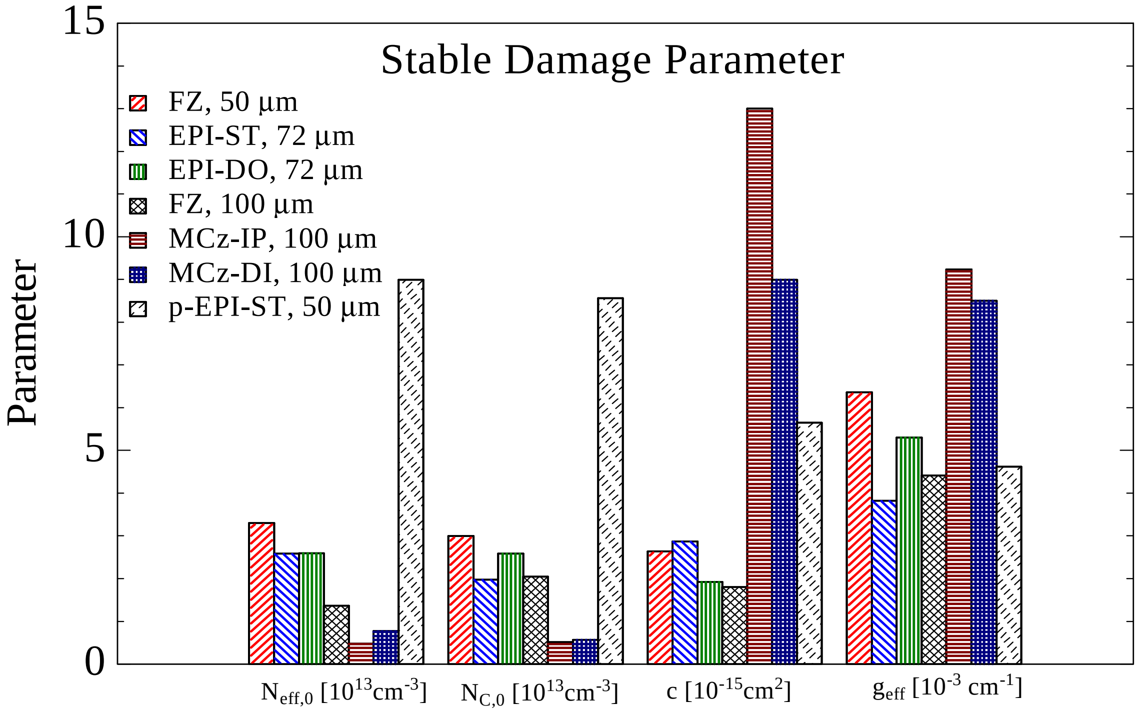
$$N_C(\Phi) = N_{C,0}\cdot\{1-\exp(c\cdot\Phi)\} + g_C\cdot\Phi$$

- **Similarities:**
  - in high fluence range N_C linear in Φ for all materials (g_C term)
  - g_C is nearly the same for low resistivity material

- **Differences:**
  - the offset ($N_{C,0}$) seems to be correlated with the primary doping
  - the introduction rate g_C for the MCz material is larger compared to all other materials

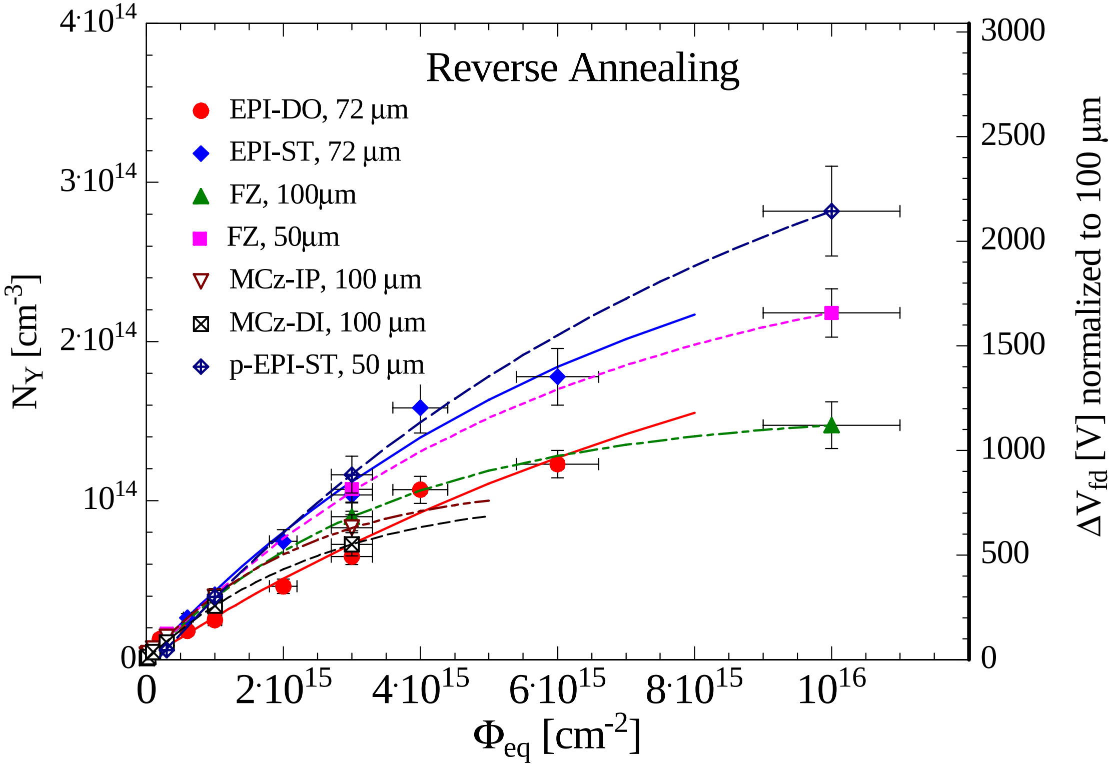
Donor or acceptor removal + introduction of charged acceptors and donors

Stable damage parameter



- **Doping removal $N_{C,0}$ correlates with primary doping concentration $N_{eff,0}$**
  $N_{C,0} \approx N_{eff,0}$
- **Removal parameter c depends on $N_{C,0}$ resp. $N_{eff,0}$.**
  The “removal rate” $c \times N_{C,0}$ is nearly constant
  $(5.6 \pm 1.5)\ 10^{-2}$ cm^{-1}
  for n-type material.
  For p-type the value is:
  $48 \cdot 10^{-2}$ cm^{-1}
- **Introduction rate g_{eff} (=g_C) for high doping:**
  $(4.9 \pm 1.0) \cdot 10^{-3}$ cm^{-1}
  For low doping (MCz)
  $(8.9 \pm 0.5) \cdot 10^{-3}$ cm^{-1}

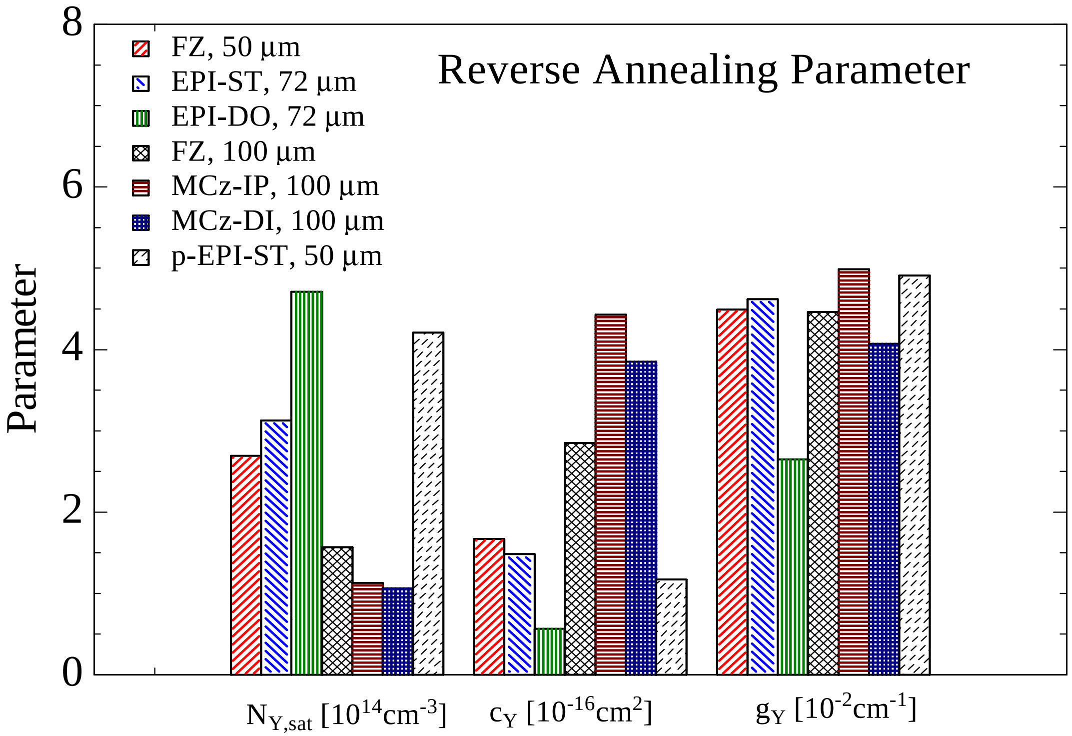
Reverse annealing amplitude N_Y



- **Saturation:**
  Saturating development holds for all materials
- **Oxygen effect?**
  A dependence of N_Y on the oxygen concentration can so far not be stated, e.g. FZ 100 µm material has extremely low [O] and a very low N_Y at 10^{16} cm^{-2}
- **Introduction rate g_Y:**
  see next page

$$N_Y(\Phi) = N_{Y,S} \cdot \{1 - \exp(-c_Y \cdot \Phi)\}$$

Reverse annealing parameter



- **Saturation amplitude $N_{Y,sat}$:**
  strong variation between different materials

- **Rate parameter c_Y:**
  also strong variation between different materials but seems to be anti-correlated with $N_{Y,sat}$

  ⇓

- **Introduction rate g_Y:**
  defined by

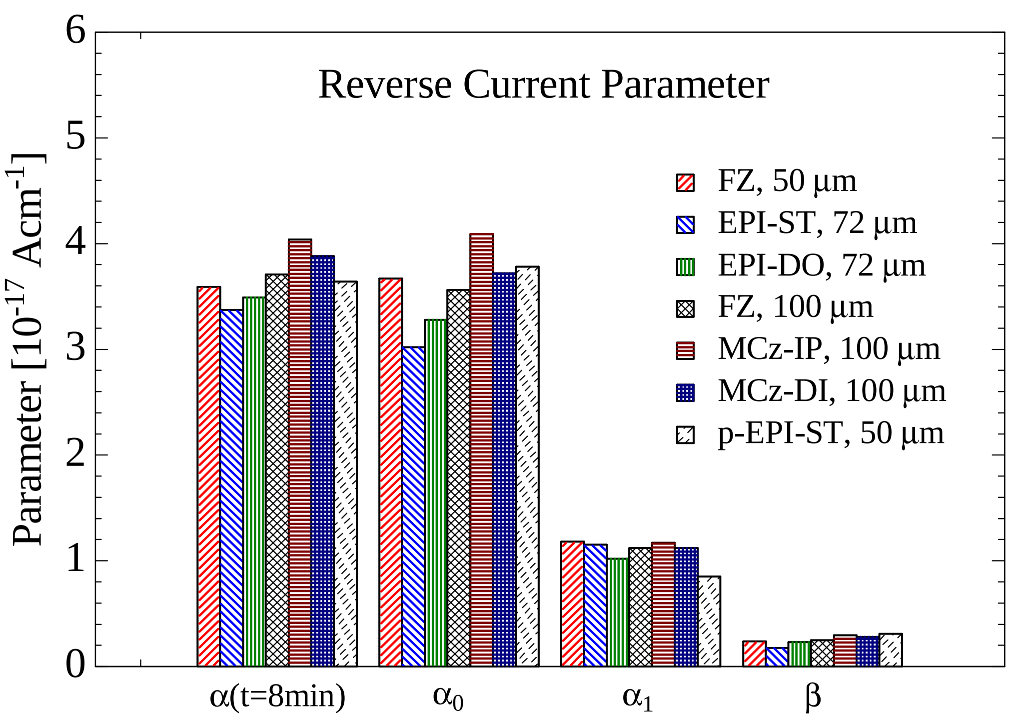
  $$g_Y = c_Y \cdot N_{Y,sat}$$

  excluding EPI-DO

  $$\langle g_Y \rangle = (4.6 \pm 0.3)\cdot 10^{-2}\ \mathrm{cm}^{-1}$$

  EPI-DO: $g_Y = 2.7\cdot 10^{-2}$ cm^{-1}

Reverse current annealing parameter



- **All parameters are independent of the material type.**

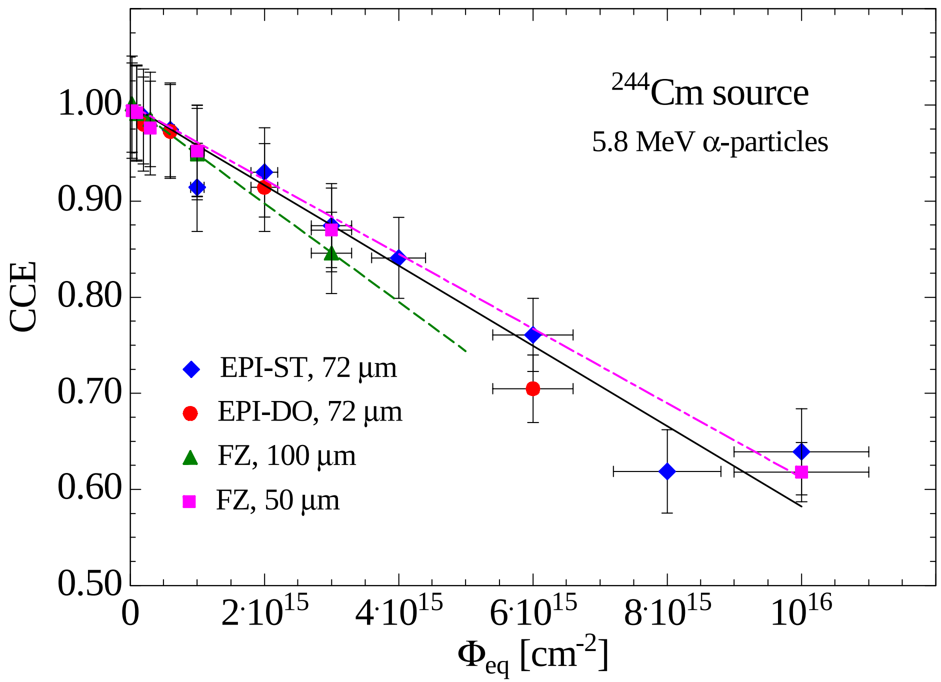
  This holds also for the p-type EPI material

- **The generation current is dominated by intrinsic defects like vacancy clusters**

$$\alpha(t)=\alpha_1\cdot\exp(-t/\tau_I)+\alpha_0-\beta\cdot\ln(t/t_0)$$

	this work	*M. Moll*
α(t=8min) [10^{-17}A/cm]	3.7 ± 0.2	4.01
α_0 [10^{-17}A/cm]	3.6 ± 0.3	4.2
α_1 [10^{-17}A/cm]	1.1 ± 0.1	1.1
β [10^{-17}A/cm]	0.25 ± 0.05	0.28
τ [min]	14.8 ± 3.1	9

Charge Collection Efficiency



^{244}Cm α-source, E_α = 5.8 MeV

Collected charge measured by TCT voltage scan
Integration time window 10 ns

Collected charge taken at about 2 x full depletion voltage

Estimate of damage parameter β_α from linear fits

$$\langle\beta_\alpha\rangle = (4.5 \pm 0.6)\cdot10^{-17}\ \mathrm{cm}^2$$

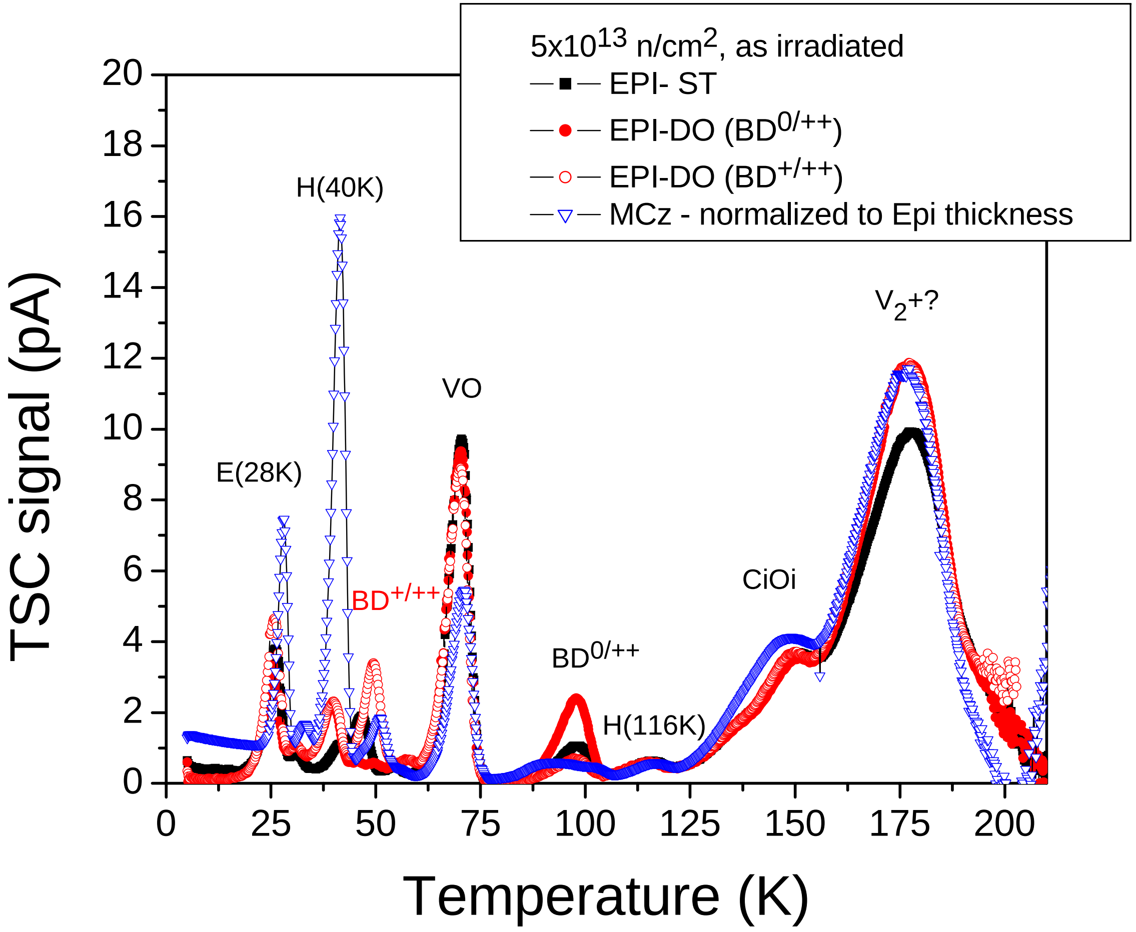
Trapping is independent on material type

Conclusions

Comparison of thin Si-detectors processed on different materials (n- and p-type EPI, FZ and MCz) after neutron irradiation shows:

- **Neff development dominated by doping removal (P,B; low fluence) and introduction of negative space charge (acceptors)**
- **Oxygen effect not seen**
- **SCSI observed for all n-type materials contrary to former results on 50 Ωcm/50 µm EPI-material**
- **No SCSI for p-type EPI**
- **Introduction of shallow donors (BD) could be detected via TSC in n-type EPI and MCz (see I. Pintilie) but the introduction rate is too small for an overcompensation of the induced negative space charge**
- **Reverse current increase independent on material type**
- **No difference is seen in the charge collection properties of n-type EPI and FZ materials**

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