High-energy electron irradiation of different silicon materials

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D. Contarato[1], L. Bosisio[2,3], M. Ciacchi[2], G. D'Auria[4],
S. Dittongo[2,3], E. Fretwurst[1], G. Lindström[1]

[1] University of Hamburg, Germany
[2] INFN, Sezione di Trieste, Italy
[3] University of Trieste, Italy
[4] Sincrotrone Trieste S.C.p.A., Trieste, Italy

Outline

- Introduction & motivation
- Devices and experimental conditions
- Experimental results
  - Effective dopant concentration
  - Leakage current
  - Charge collection efficiency
  - Annealing effects
- Comparison with low-energy electrons
- Conclusions

Introduction: why high-energy electrons?

- In last years, many studies on the radiation hardness of silicon detectors (from different substrates) against different particle types (charged hadrons, neutrons and γ rays)
- By contrast, very few contributions devoted to damage induced by high-energy (GeV) electrons, energy range of interest for future linear colliders
- Previous irradiation with 900 MeV electrons, up to $\Phi \sim 4.5 \times 10^{14}$ e/cm^2: bulk type inversion of high-resistivity standard and oxygenated FZ devices. No significant effect of oxygen diffusion up to this fluence.
- New experiment: higher fluences and wider range of substrate materials (standard and oxygenated float-zone, Czochralski and epitaxial silicon)
- Correlation (preliminary) of damage induced by low- (15 MeV) and high- (900 MeV) energy electrons, to be compared also with results from Co-60 irradiation

Tested devices

$p^+/n^-/n^+$ diodes fabricated on different silicon substrates (thickness ~300 µm), provided with a 100 µm wide guard-ring, surronded by floating rings

Standard (FZ) and oxygenated (DOFZ) float-zone devices by ITC-irst (Trento, Italy)

- fabricated on Topsil (111) and (100) substrates, resistivity~10-20 kΩ·cm
- DOFZ: 12 hour oxidation @ 1150°C + 36 hour diffusion in N_2 @ 1150°C, [O]~$1\text{-}3\times10^{17}\ \mathrm{cm}^{-3}$

FZ and DOFZ devices by CiS (Erfurt, Germany)

- fabricated on Wacker (111) substrates, resistivity~3-4 kΩ·cm
- DOFZ: oxygen diffusion in N_2 environment for 72 hours @ 1150°C, [O] ~ $1.2\times10^{17}\ \mathrm{cm}^{-3}$

Czochralski (CZ) devices by CiS

- fabricated on Sumitomo (100) substrates, resistivity~1.2 kΩ·cm, thermal-donor killed (2 hours @ 800°C + fast cooling to RT)

Epitaxial (EPI) devices by CiS

- 50 µm thick epitaxial layer (resistivity~50 Ω·cm) grown by ITME (Warszawa, Poland) on 300 µm thick, low resistivity (~0.01 Ω·cm) Czochralski (111) substrate

Experimental conditions

Irradiations

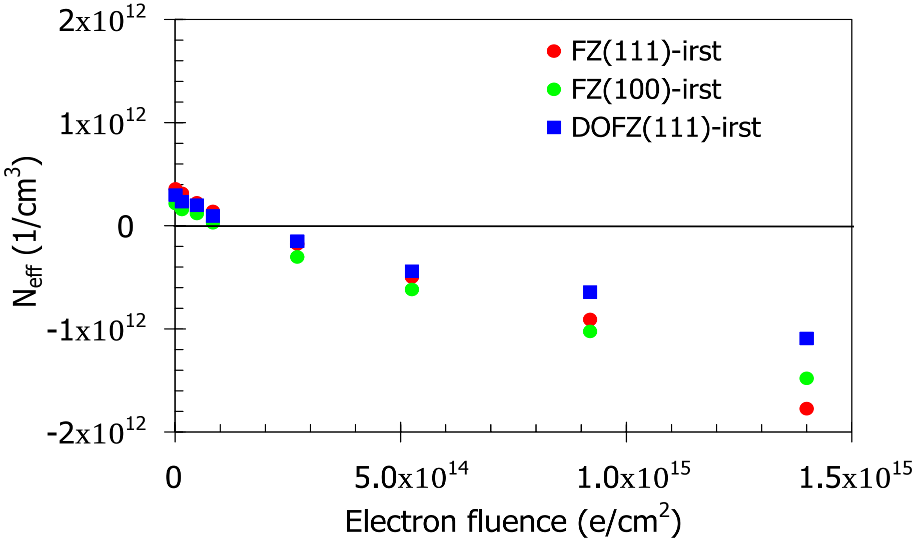
- 900 MeV electron beam of the LINAC injector at Elettra (Trieste, Italy)
- fluence measured by a toroidal coil coaxial with beam
- devices kept unbiased during irradiation, at room temperature (~25^{o}C)

step	Fluence (e/cm^2)
1	$(1.17\pm0.04\pm0.04)x10^{12}$
2	$(1.55\pm0.005\pm0.05)x10^{13}$
3	$(4.86\pm0.03\pm0.17)x10^{13}$
4	$(8.41\pm0.08\pm0.28)x10^{13}$
5	$(2.71\pm0.01\pm0.10)x10^{14}$
6	$(5.25\pm0.02\pm0.18)x10^{14}$
7	$(9.20\pm0.05\pm0.31)x10^{14}$
8	$(1.40\pm0.003\pm0.05)x10^{15}$

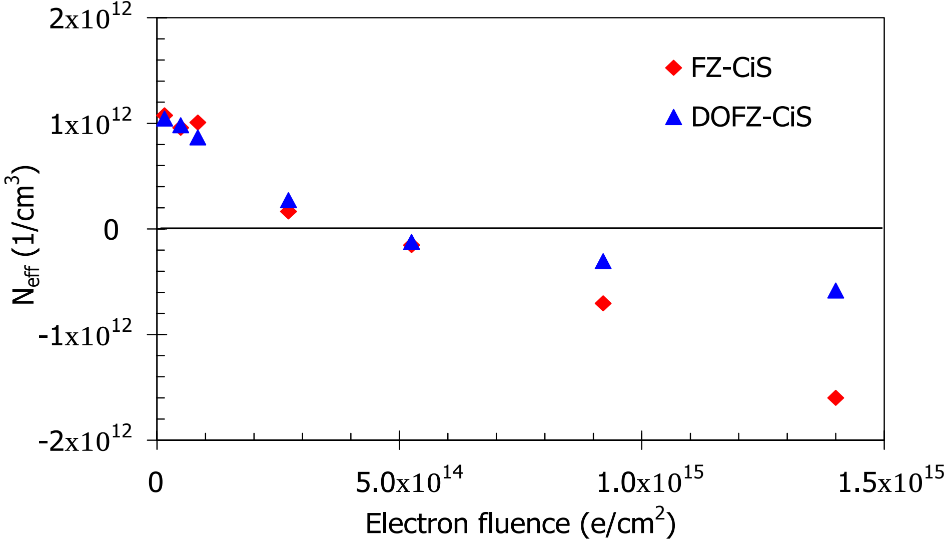
Measurements

- irradiated devices electrically characterized by standard I-V and C-V measurements
- C-V measurements @ 10 kHz
- currents normalized to 20^{o}C
- isothermal annealing cycles up to a few 10000 min @ 80^{o}C on the devices irradiated at the two highest fluences

Effective dopant concentration: FZ and DOFZ



FZ & DOFZ from irst



FZ & DOFZ from CiS

- Measurements performed after annealing for 8 min @ 80°C. Type inversion at:
  $\rightarrow \Phi \sim 1.5\text{x}10^{14}$ e/cm^2 for ITC-irst devices
  $\rightarrow \Phi \sim 3\text{x}10^{14}$ e/cm^2 for CiS devices (higher initial doping)

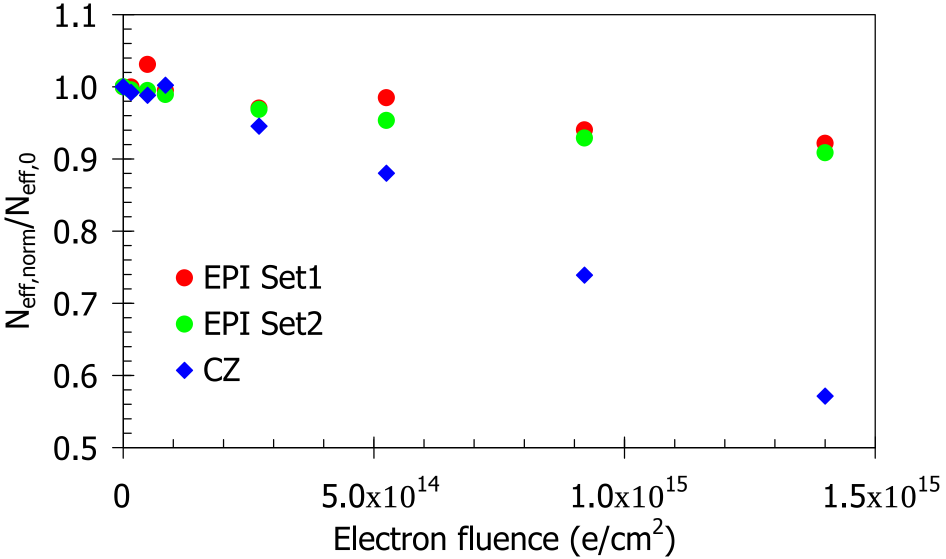
- Post inversion slopes (β values, lower for DOFZ devices)

FZ (IRST) ~ 1.5x10^{-3} cm^{-1}	FZ (CiS) ~ 1.9x10^{-3} cm^{-1}
DOFZ (IRST) ~ 0.9x10^{-3} cm^{-1}	DOFZ (CiS) ~ 0.7x10^{-3} cm^{-1}

- differences between IRST and CiS devices probably due to different starting materials and oxygenation procedures

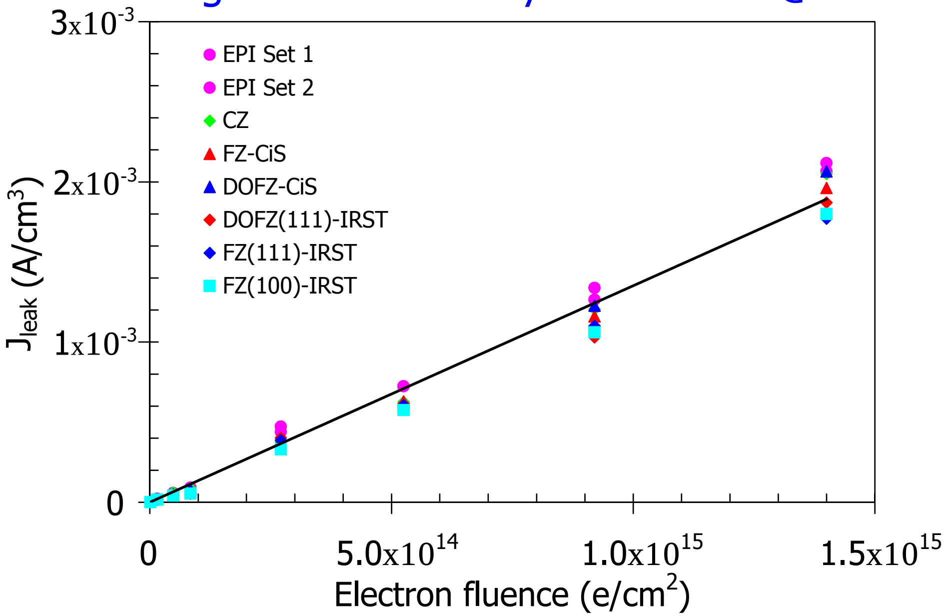
Effective dopant concentration: EPI and CZ

- samples used for various irradiations have non negligibly differing values of N_{eff}. Normalization: $N_{eff,norm}=[N_{eff}(after) - N_{eff}(pre)] + \langle N_{eff}(pre) \rangle$



- type inversion not observed
  - the pre-irradiation N_{eff} is higher than for FZ substrates
  - high oxygen concentration: shallow donors generation
- EPI: small variations of N_{eff} (comparable with measurement uncertainty)
- CZ: trend appears ~linear with fluence (slope~-1.5×10^{-3} cm^{-1}). A simple extrapolation leads to eventual type inversion at $\Phi \sim 3 \times 10^{15}$ e/cm^2

Leakage current and damage constant



Leakage current density after 8 min @ 80°C

- the leakage current density increase does not depend on substrate material (as observed after hadron irradiations)
- estimation of damage constant α from slope of the linear fit:

$$\alpha = 1.35\text{x}10^{-18}\ \text{A/cm}$$

- Theoretical hardness factor (asymptotic value):

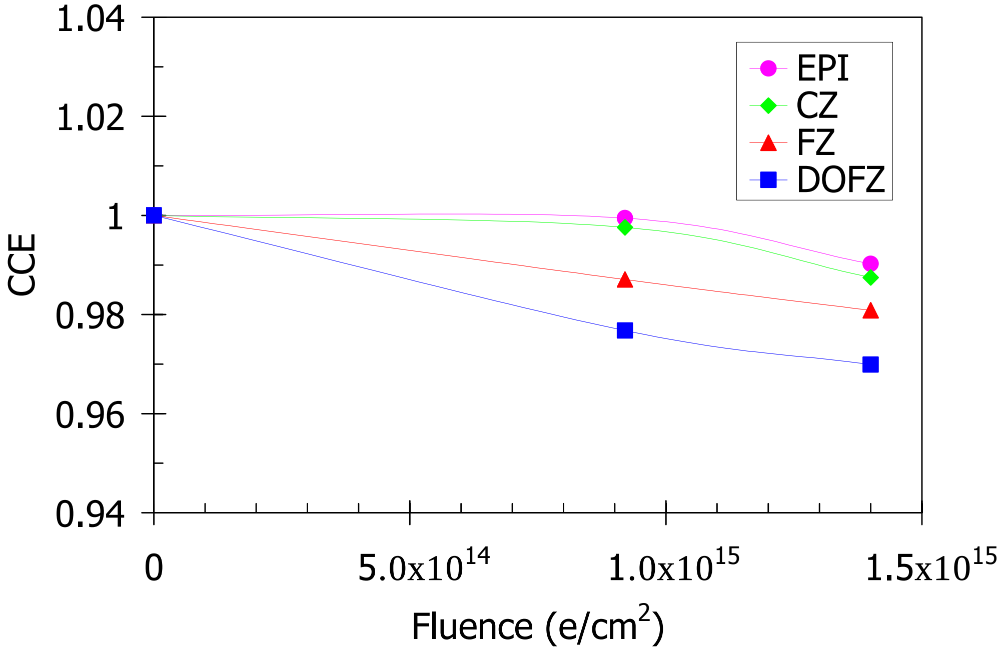
κ_{theo}=NIEL(900 MeV e^-)/NIEL(1 MeV n)= $8.1\text{x}10^{-2}$ [Summers et al., IEEE TNS 40(6), 1993]

- Experimental hardness factor: $\kappa_{exp} = \alpha(900\ \text{MeV}\ e^-)/\alpha(1\ \text{MeV n}) = 3.4\text{x}10^{-2}$

→ $\kappa_{theo}/\kappa_{exp}=2.4$: the NIEL scaling hypothesis seems not adequate when comparing electrons to hadrons

Charge collection efficiency

- measured with the Transient Current Technique (TCT) on samples annealed for 8 minutes @ 80°C (all devices by CiS)
- charge injection from a collimated source of α particles (^{244}Cm)
- bias voltage ≥150 V for EPI devices, ≥300 V for CZ, FZ and DOFZ devices
- CCE defined as the ratio between charge induced in irradiated device and charge induced in non-irradiated device



- The decrease of CCE at the highest fluences is of 1-3%, more pronounced for FZ and DOFZ devices

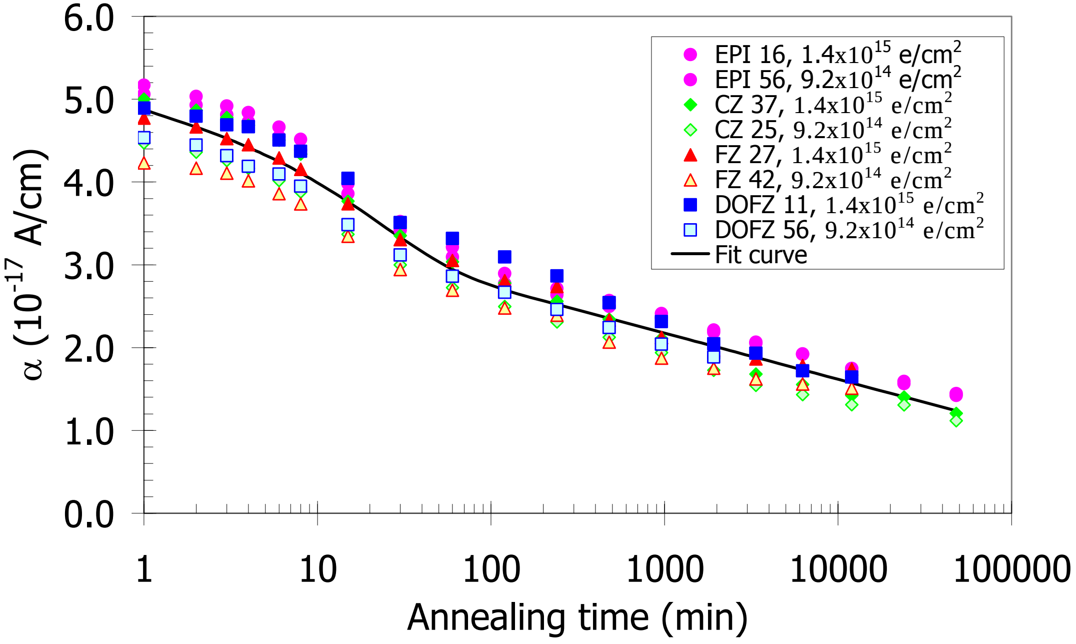
Annealing of the leakage current

- The evolution of the leakage current vs. annealing time is proportional to the time evolution of the damage constant α:

$$\alpha(t) = \frac{J_{leak}(t)}{\Phi_{eq}} = \alpha_I \cdot \exp\left(-\frac{t}{\tau_I}\right) + \alpha_0 - \beta \cdot \ln\left(\frac{t}{\tau_0}\right), \qquad \Phi_{eq} = \kappa \cdot \Phi_{el}$$

Short-term annealing

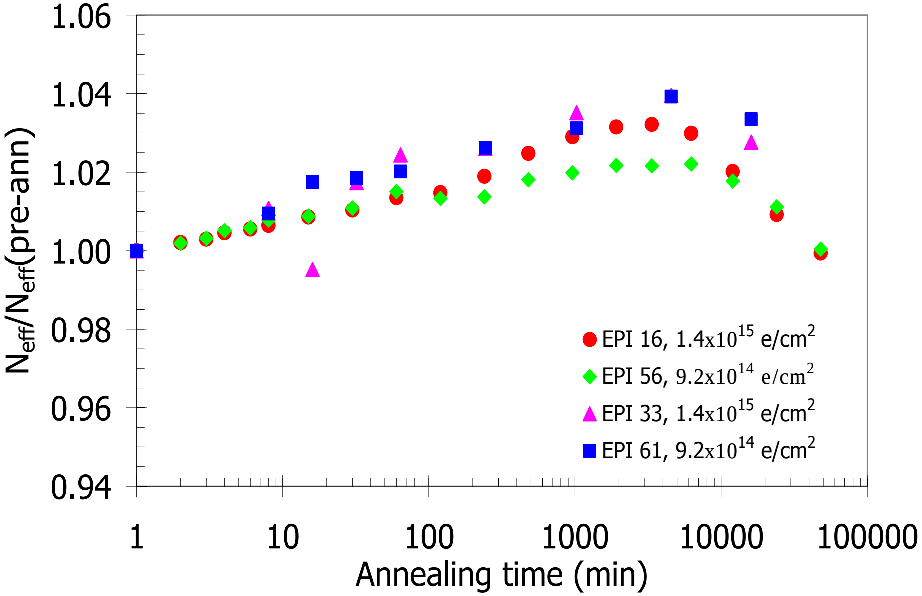
Long-term annealing

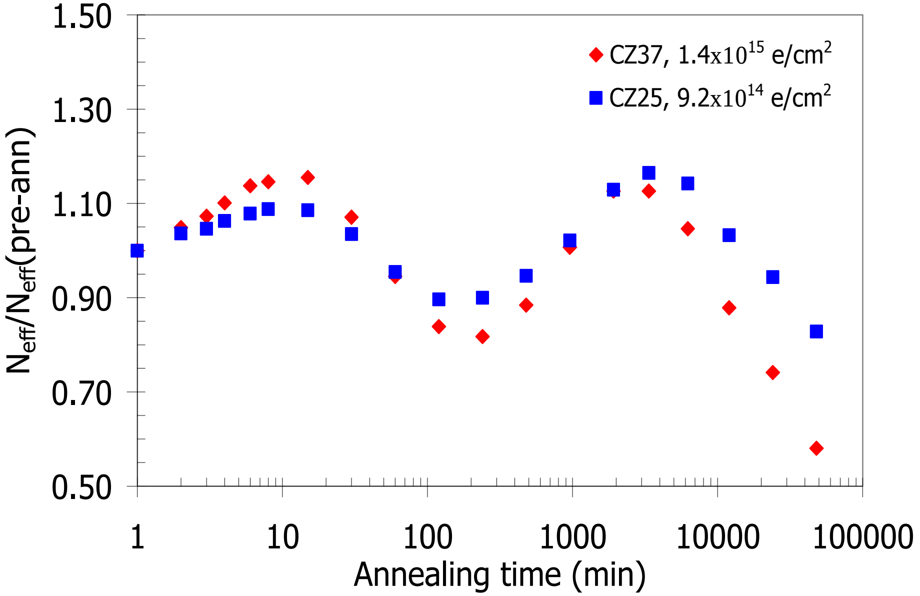


- α_I, τ_I, α_0 and β are free parameters, τ_0=1 min

α_I	$(1.06\pm0.11)\mathrm{x}10^{-17}$ A/cm
τ_I	(23.94 ± 4.59) min
α_0	$(3.85\pm0.11)\mathrm{x}10^{-17}$ A/cm
β	$(2.43\pm0.15)\mathrm{x}10^{-18}$ A/cm

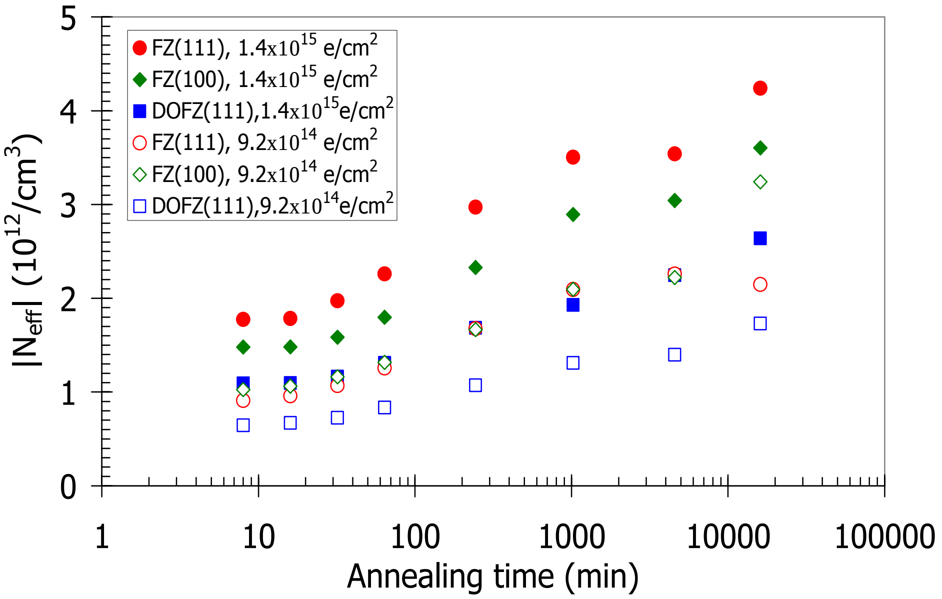
Annealing of N_{eff}: CZ and EPI


EPI devices from CiS

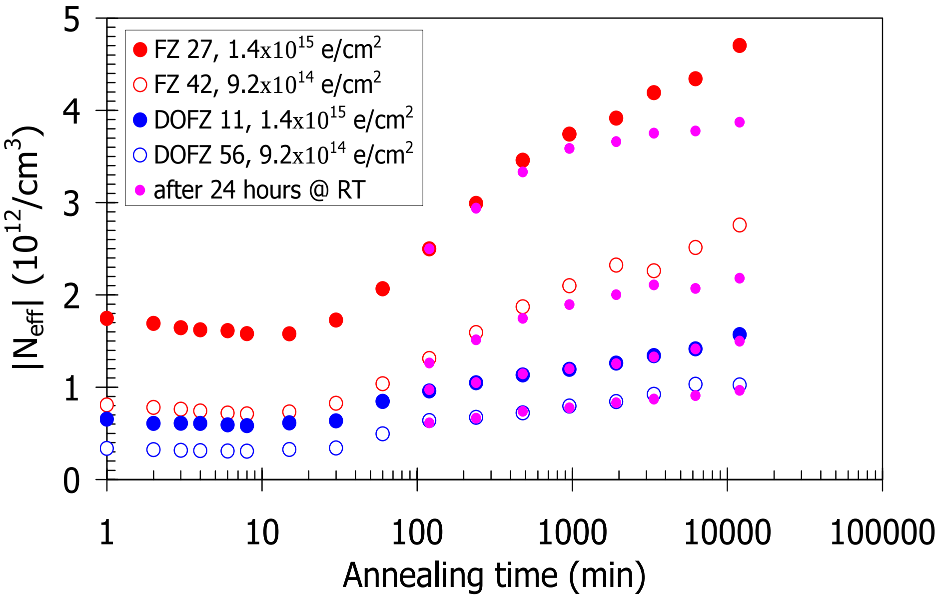

CZ devices from CiS

- EPI devices (non-inverted) show an increase of effective donor concentration with time, then a decreasing trend starts at (very) long annealing times. Variations anyway in the order of a few %.
- CZ devices (non-inverted) show an atypical behavior, observed also after hadron irradiation (see talk E. Fretwurst). Possible reasons... under investigation!

Annealing of N_{eff}: FZ and DOFZ



FZ & DOFZ from irst

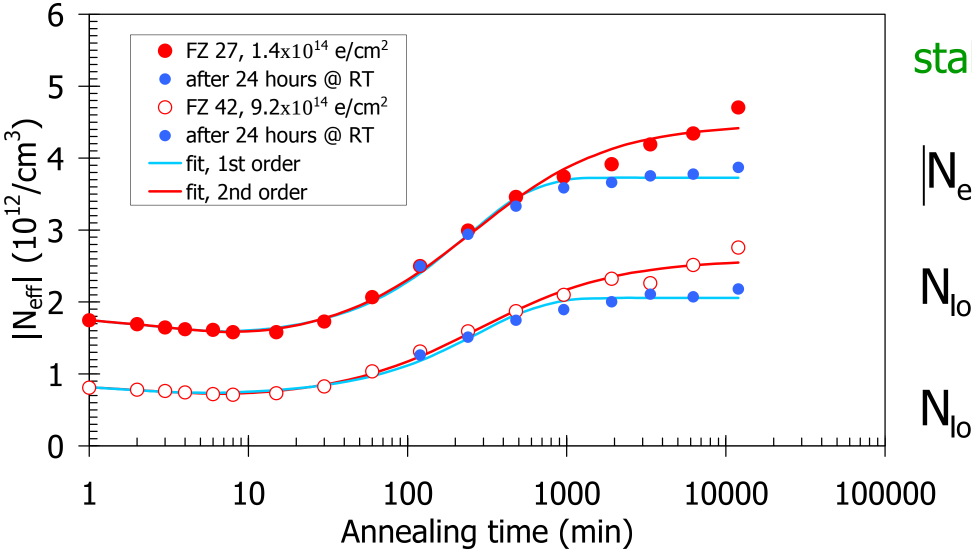


FZ & DOFZ from CiS

- FZ and DOFZ devices (inverted) reach a minimum in the effective acceptor concentration after ~10 minutes (beneficial annealing), followed by an increase (reverse annealing)
- Higher effect in FZ devices, more pronounced for CiS devices
- Measurements performed after 24 hours @ RT (for CiS devices) show bistable damage effect in FZ but not in DOFZ devices

Parametrization of N_{eff} annealing (FZ)

FZ from CiS



stable damage

short-term annealing

$$\left|N_{eff}(t)\right| = N_0 + N_1 \cdot \exp\left(\frac{-t}{\tau_1}\right) + N_{long}(t)$$

$$N_{long,I}(t) = N_2 \cdot \left(1 - \exp(-t/\tau_2)\right)$$

1st order process

$$N_{long,II}(t) = N_3 \cdot \left(1 - \frac{1}{1 + t/\tau_3}\right)$$

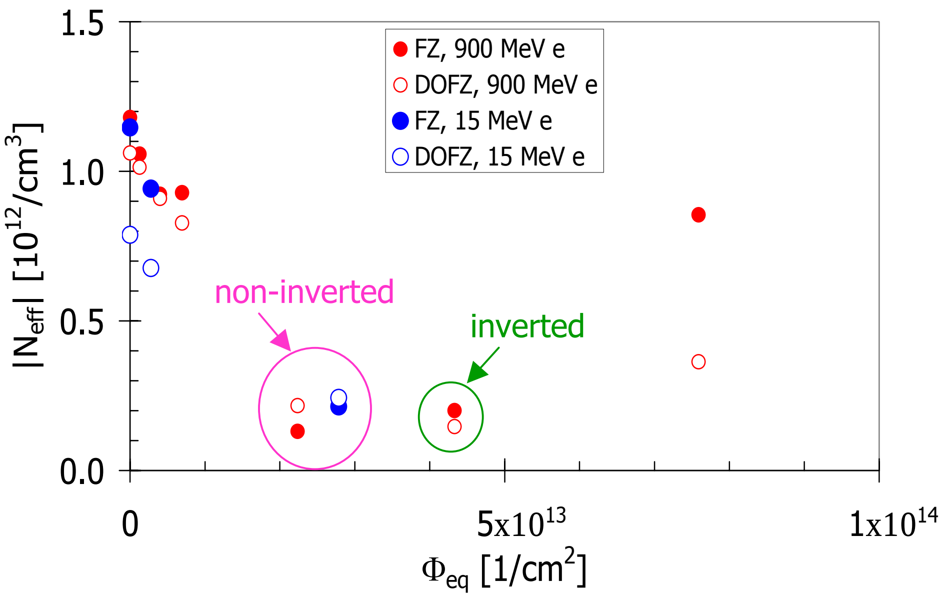
2nd order process

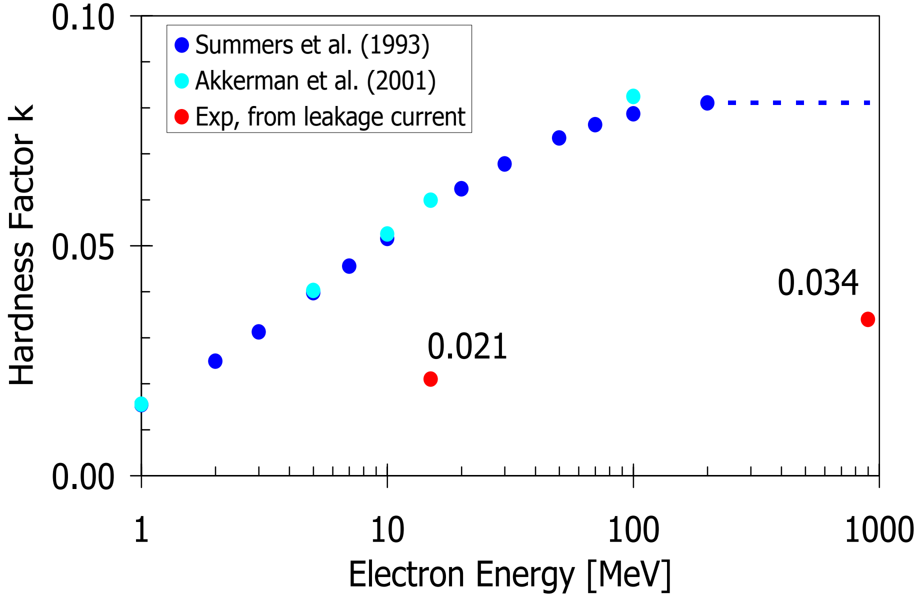
Φ_{el} [1/cm³]	N_0 [10^{12}/cm³]	N_1 [10^{12}/cm³]	τ_1 [min]	N_2 [10^{12}/cm³]	τ_2 [min]	N_3 [10^{12}/cm³]	τ_3 [min]
9.2·10^{14}	0.70±0.04	0.19±0.21	1.8±2.8	1.35±0.05	274±32		
9.2 ·10^{14}	0.66±0.07	0.21±0.18	2.7±4.1			1.93±0.08	280±49
1.4 ·10^{15}	1.5±0.06	0.34±0.15	2.8±2.3	2.23±0.07	232±20		
1.4 ·10^{15}	1.45±0.11	0.37 ±0.19	3.6±3.8			3.02±0.11	254±40

- Data from measurements soon after annealing well described by 2nd order process, while data measured after 24 hours (@ RT) are better described by 1st order process

- Stable damage component estimation consistent with results after 15 MeV e^- and 23 GeV p^+ irradiations

Comparison with 15 MeV electrons





- Irradiation performed in Stockholm on FZ and DOFZ devices from CiS; two fluences only available
- Type inversion not observed (checked with field profile after TCT measurements). Fluences too small?
- Annealing of N_{eff}: estimation of stable damage component is consistent
- Next step: correlation with results from Co-60 irradiation

Conclusions

- Effective dopant concentration N_{eff}:
  - → FZ and DOFZ substrates: type inversion observed; beneficial effect of oxygen diffusion. Standard parametrization for annealing behavior
  - → EPI and CZ substrates: type inversion not observed (to be checked at higher fluences for CZ). Annealing behavior: small effect for EPI, significant but atypical for CZ

- Leakage current: no difference is observed among different materials, as after hadron irradiation. Standard parametrization for annealing behavior

- CCE: very small reduction (1-3%) observed at the highest fluence

- Preliminary comparison with other irradiations of the same substrates gives consistent results