Studies of bulk damage induced in different silicon materials by 900 MeV electron irradiation

S. Dittongo[1,2], L. Bosisio[1,2], D. Contarato[3], G. D'Auria[4], E.Fretwurst[5], J. Härkönen[6], G. Lindström[5], E. Tuovinen[6]

[1] Dipartimento di Fisica, Universita' di Trieste, Italy
[2] INFN, Sezione di Trieste, Italy
[3] DESY, Hamburg, Germany
[4] Sincrotrone Trieste S.C.p.A., Trieste, Italy
[5] Institut für Experimentalphysik, Universität Hamburg, Germany
[6] Helsinki Institute of Physics, Helsinki, Finland

Overview

- Introduction: why high-energy electrons?
- Irradiation:
  - irradiated devices
  - experimental conditions
- Experimental results:
  - Effective dopant concentration
  - Reverse leakage current, damage constant α
  - Isothermal annealing effects
- Conclusions

Why high-energy electrons?

- In the last years, much effort devoted to study
  - the radiation hardness of silicon detectors against different particle types (charged hadrons, neutrons and γ rays)
  - the improvements achievable by using different silicon substrates
- By contrast, very few contributions devoted to damage induced by high-energy (GeV) electrons
- In previous irradiations, we demonstrated the effectiveness of 900 MeV electrons in creating bulk damage
- In this work we extend these investigations to a wider sample of silicon materials (standard and oxygenated float-zone, magnetic and non-magnetic Czochralski, epitaxial silicon) and by reaching very high fluence levels (6×10^{15} e/cm^2)

Tested devices

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

material	substrate	processed by	resistivity	[O]
FZ & DOFZ	Wacker (111) n-type	CiS (Erfurt, Germany)	3-4 kΩ· cm	$1.2x10^{17}$ cm^{-3} (DOFZ)
FZ & DOFZ	Wacker (111) n-type	Helsinki Institute of Physics	1.2 kΩ·cm	not measured
CZ	Sumitomo (100) n-type	CiS	1.2 kΩ· cm	$8x10^{17}$ cm^{-3}
Magnetic CZ	Okmetic (100) n-type	Helsinki	1.0 kΩ· cm	$5\text{-}9x10^{17}$ cm^{-3}
Magnetic CZ	Okmetic (100) p-type	Helsinki	1.8 kΩ· cm	$5\text{-}9x10^{17}$ cm^{-3}
EPI	ITME CZ (111) n-type	CiS	50 Ω·cm	$9x10^{16}$ cm^{-3}

Experimental conditions

Irradiations

- performed with the 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°C)

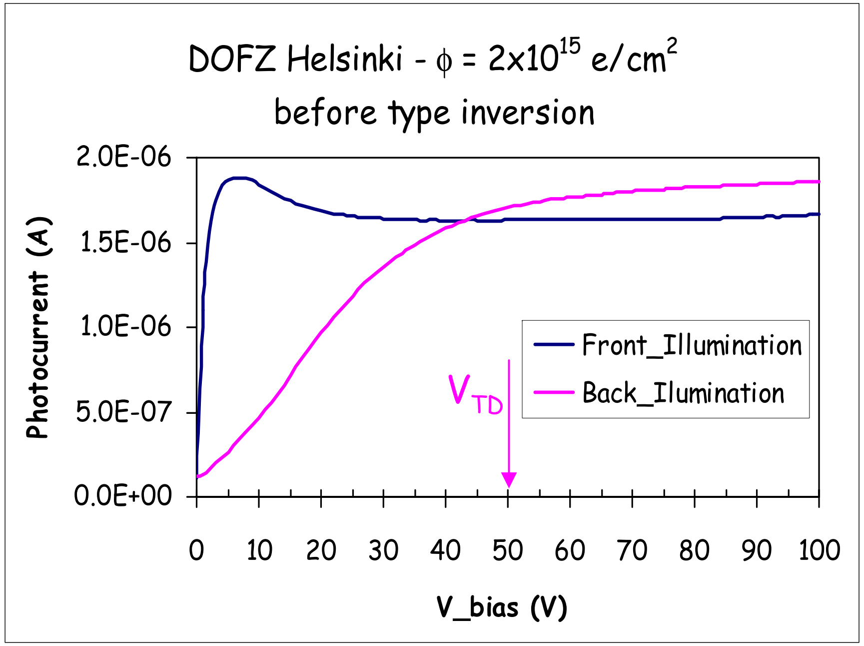
step	Fluence (e/cm^2)
1	(1.06±0.01±0.04)x10^{15}
2	(1.97±0.01±0.08)x10^{15}
3	(4.16±0.05±0.17)x10^{15}
4	(4.97±0.05±0.20)x10^{15}
5	(6.11±0.02±0.25)x10^{15}

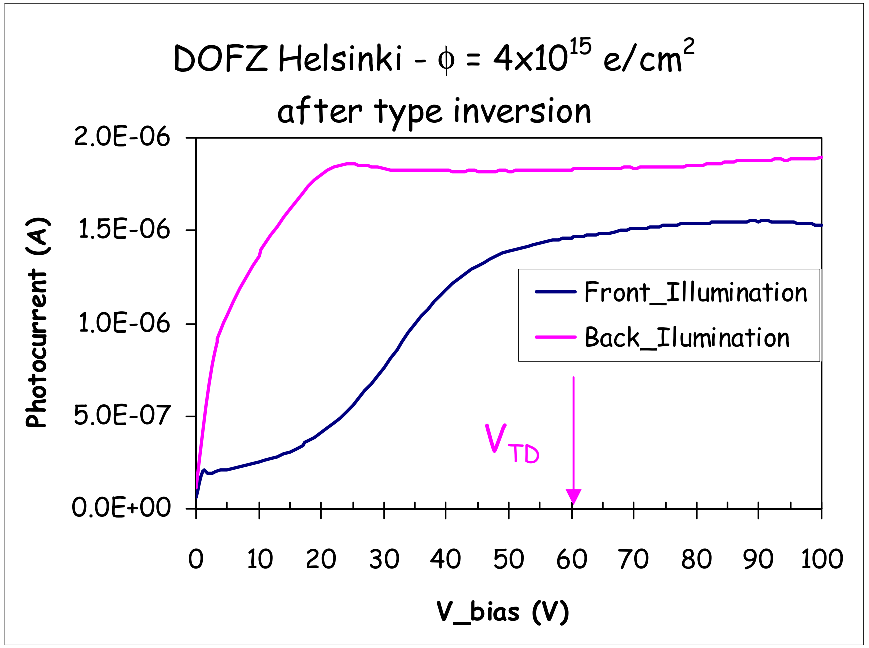
Measurements

- devices electrically characterized by reverse I-V and C-V measurements, performed ~1 day after irradiation
- C-V measurements @ 10 kHz
- currents normalized to 20°C
- isothermal annealing cycles up to 16 hours @ 80°C

Photocurrent vs. bias voltage
a quick and simple method to check for type inversion

- the diode is illuminated on the front or back side by the (dimmed) microscope light
- the I-V curve in the dark is subtracted from the I-V curve with light, to obtain the photogenerated current vs. bias voltage
- comparing the voltage dependence of the photocurrent for the two situations (front and back illumunation) helps in determining whether the substrate is inverted

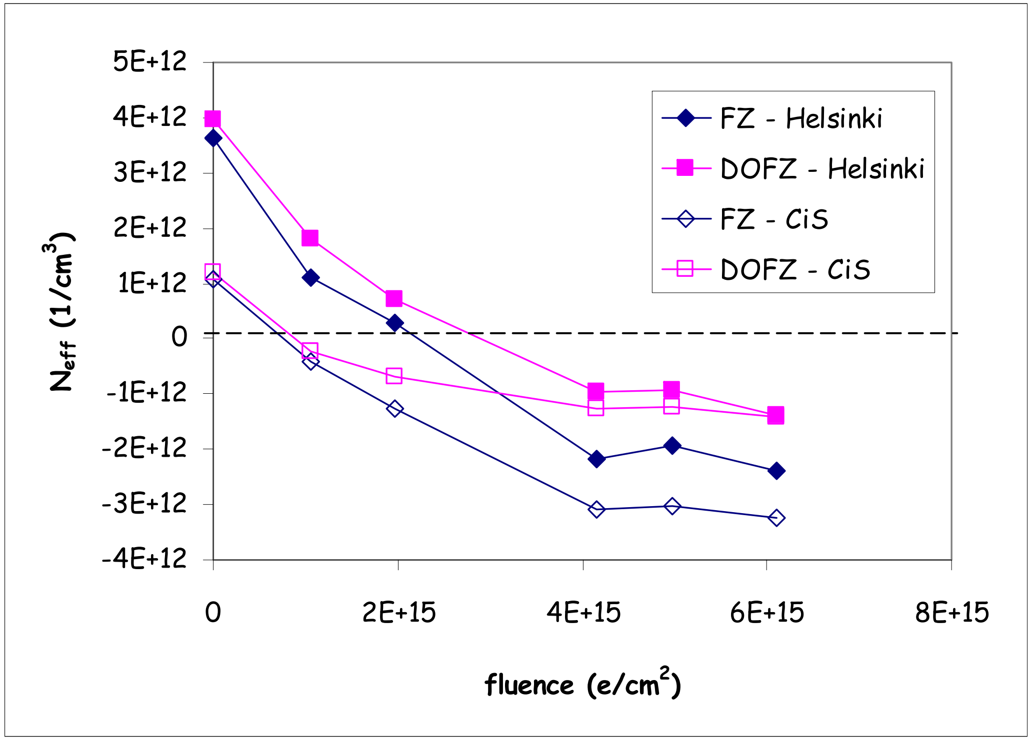




Effective dopant concentration: FZ & DOFZ

type inversion occurs at:

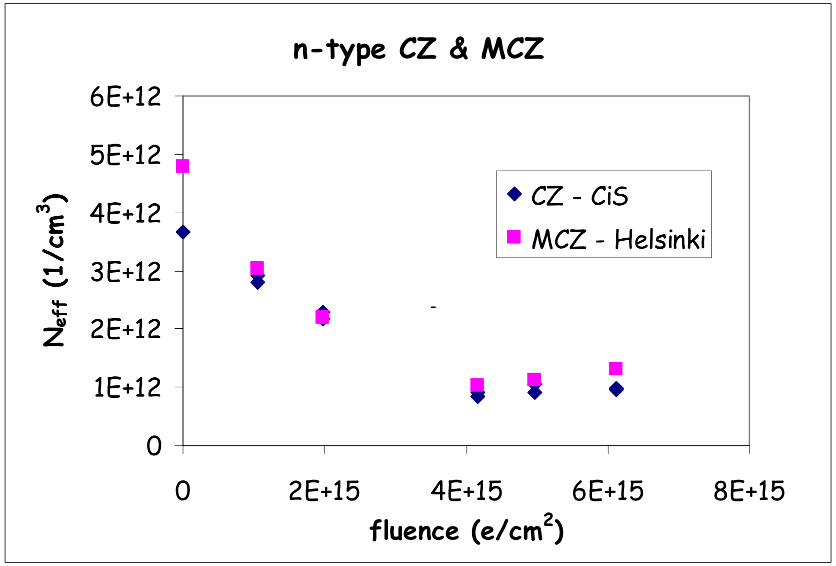
- $\phi \sim 5\times10^{14}$ e/cm^2 for CiS devices (from previous irradiations)
- $\phi \sim 3\times10^{15}$ e/cm^2 for Helsinki devices (higher initial doping)



post-inversion behaviour

- lower N_{eff} variations for DOFZ devices
- N_{eff}(Helsinki devices) ~ 70-80% N_{eff}(CiS devices)
- differences between Helsinki and CiS diodes likely due to different starting materials and oxygenation procedures (CiS: oxygen diffusion performed in N_2 environment for 72 hours @1150°C; Helsinki: 8 hour oxidation in O_2 @ 1050°C + 60 hour diffusion in N_2 @ 1050°C)

Effective dopant concentration: CZ & MCZ

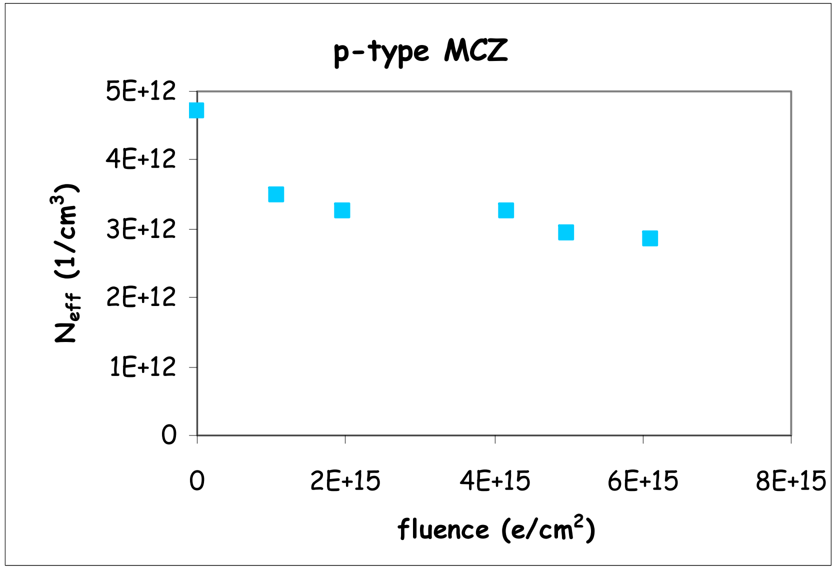


n-type CZ & MCZ devices:

- N_{eff} decreases, reaches a minimum at ~4×10^{15} e/cm^2 and then increases again
- type inversion not observed even if the pre-irradiation dopant concentration is comparable with FZ & DOFZ made in Helsinki
- the oxygen concentration is higher than for DOFZ (under investigation)

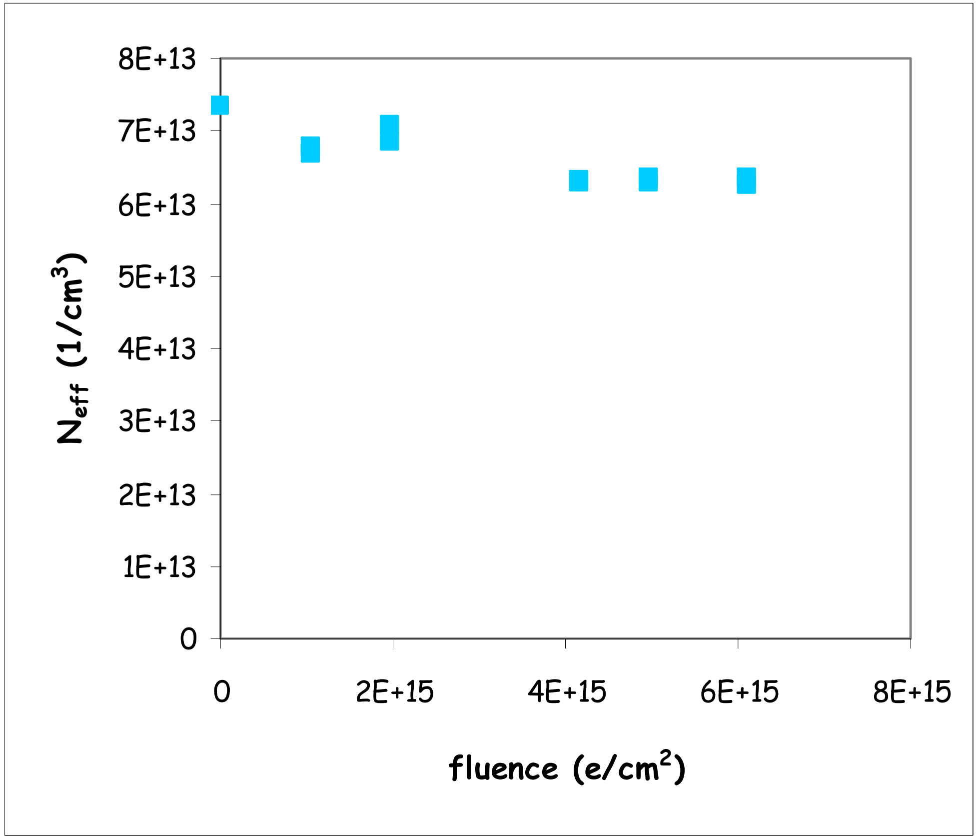
p-type MCZ devices:

- substrate type inversion is not approched
- very slow rate of decrease in N_{eff} (1.2×10^{-4} cm^{-1})



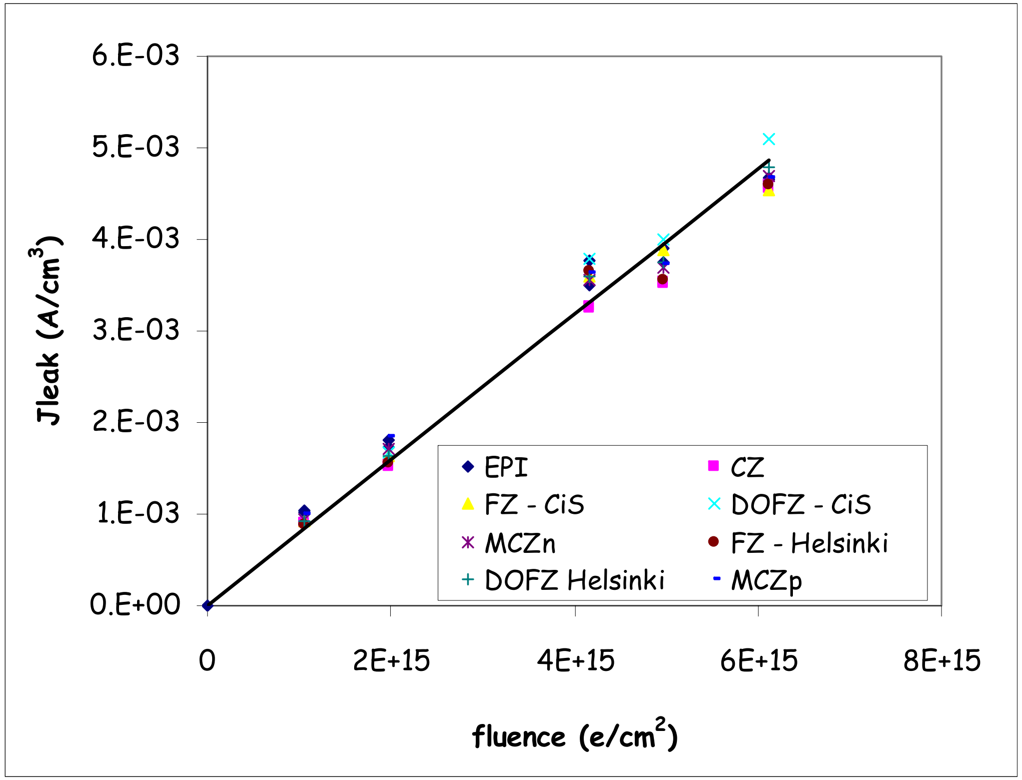
Effective dopant concentration: EPI

- type inversion not observed: the pre-irradiation dopant concentration is even higher than for CZ substrates...
- the variations of N_{eff} are small (<15%)
- the rate of decrease in N_{eff} is slow (1.5×10^{-3} cm^{-1})



Leakage current & damage constant α

the increase in leakage current does not depend on substrate material
(as already observed after hadron irradiations)



after ~1 day @ room temperature
$\alpha = 7.9\times10^{-19}$ A/cm

hardness factor
$k_{exp} = \alpha(900\ \text{MeV}\ e^-)/\alpha(1\ \text{MeV}\ n) = 2.0\times10^{-2}$

at equal NIEL, high energy electrons are ~4.1 times less effective than 1 MeV neutrons in degrading the carrier generation lifetime of substrate material

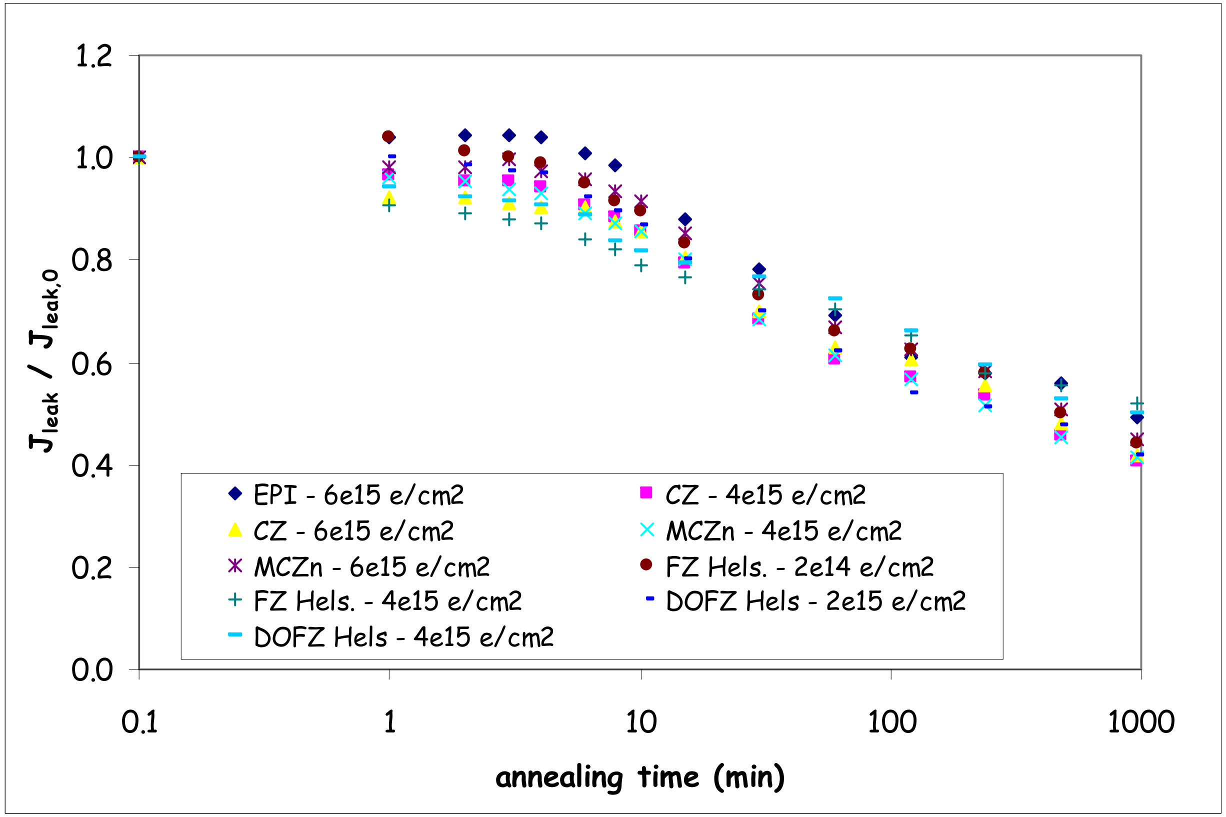
$k_{theo} = \text{NIEL}(900\ \text{MeV}\ e^-)/\text{NIEL}(1\ \text{MeV}\ n) = 8.1\times10^{-2}$

$k_{theo} / k_{exp} = 4.1$

the NIEL scaling hypothesis is not adequate when comparing electrons with hadrons

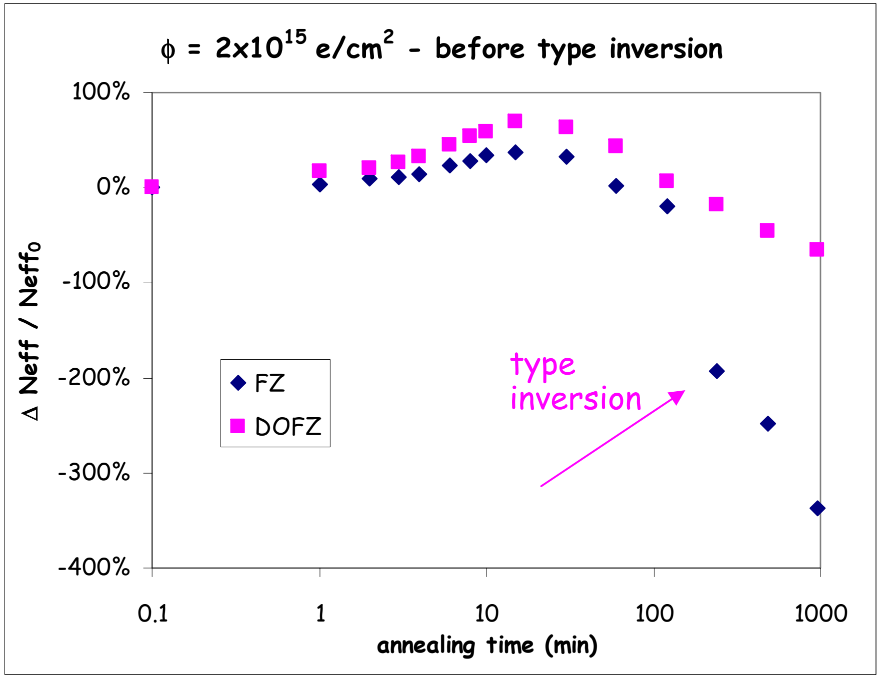
Annealing of leakage current

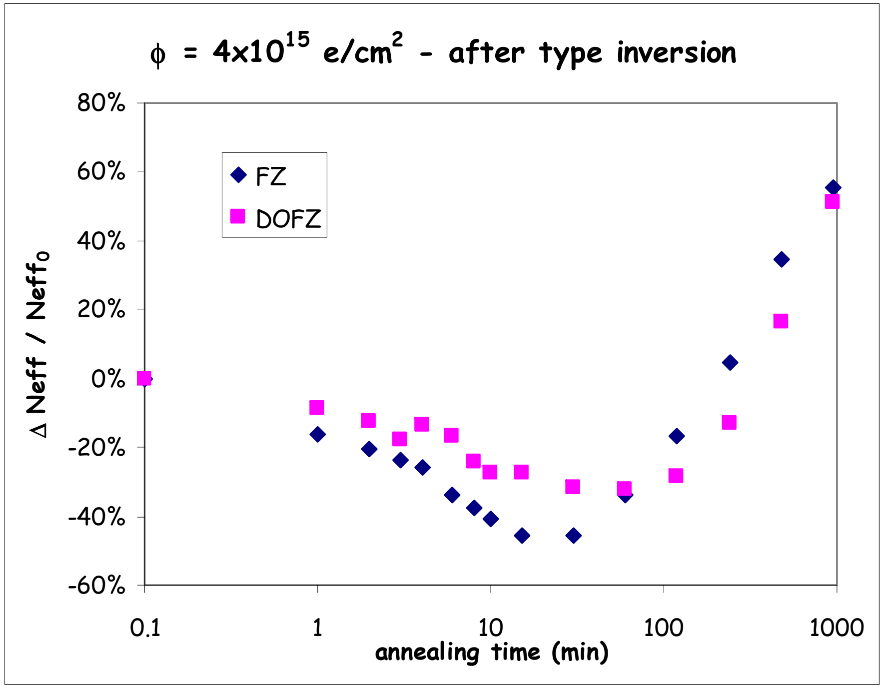
- The time evolution of the leakage current density for devices made on different substrates and irradiated at different fluences follows a common functional dependence on the annealing time



Annealing of N_{eff}: FZ and DOFZ by Helsinki

- before type inversion, a maximun in the effective acceptor concentration is reached after ~15 minutes, followed by a decrease
  - in FZ device, substrate type inversion is observed after 4 hours @ 80°C
- after type inversion, a minimum in the effective acceptor concentration is reached after ~15 (FZ)-60 (DOFZ) minutes (beneficial annealing), followed by an increase (reverse annealing)
- slightly higher effect in FZ devices

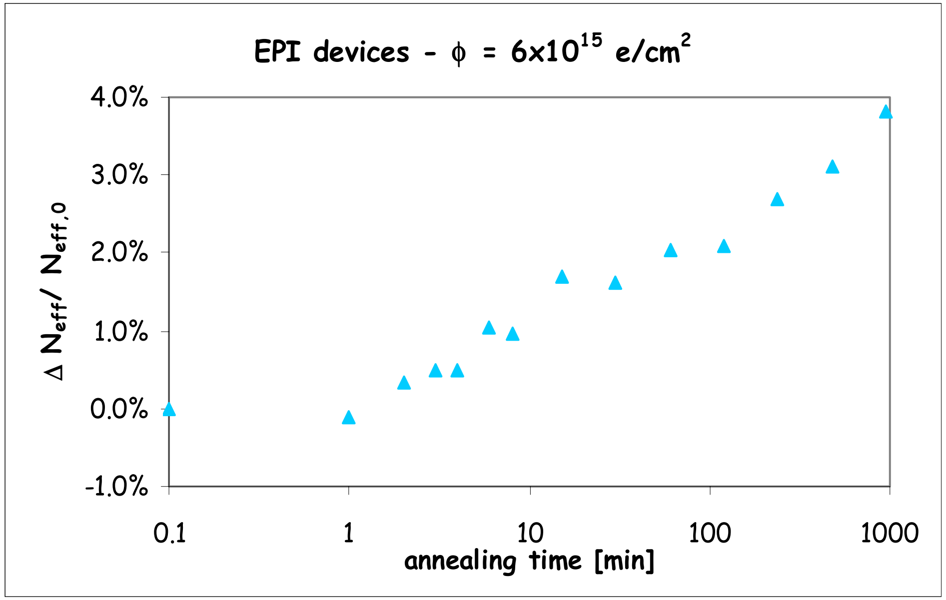


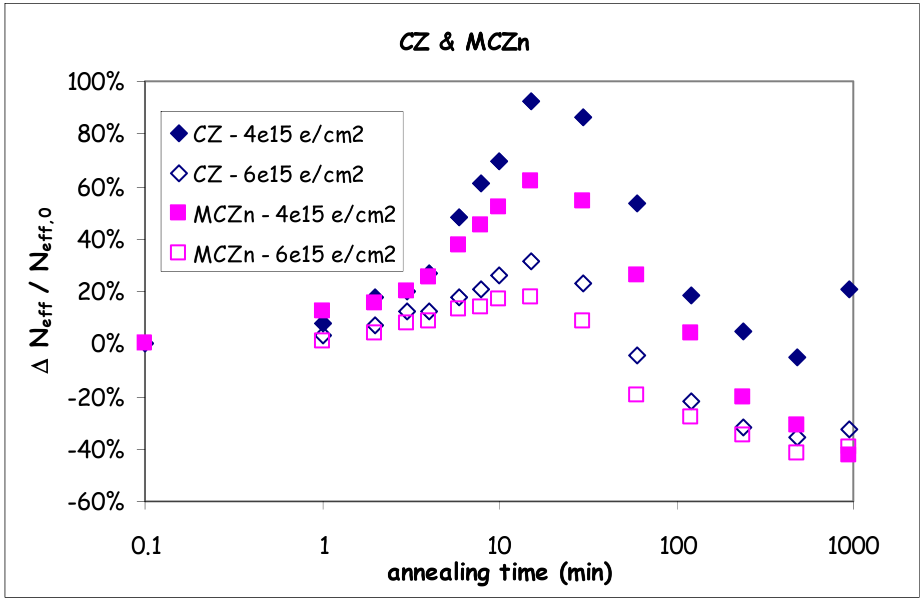


Annealing of N_{eff}: CZ, MCZn and EPI

EPI devices (non-inverted):

- after highest fluence (6×10^{15} e/cm^2), show an increase of effective donor concentration with time
- variations of the order of a few %





CZ and MCZn devices (non-inverted):

- show an oscillating behaviour, observed also after hadron irradiation. Possible reasons under investigation...
- oscillation amplitude is larger at lower fluences and for CZ devices

Conclusions

- **Leakage current:** no difference is observed among different materials, as already known after hadron irradiation

- N_{eff}:

  - **FZ & DOFZ:** a slightly beneficial effect of oxygen diffusion is observed; both show a saturation trend beyond 4×10^{15} e/cm^2

  - **n-type CZ & MCZ:** high fluence irradiations show that the linear trend observed at lower fluences does not continue up to type inversion; instead, N_{eff} goes back up after reaching a minimun at ~4×10^{15} e/cm^2

  - **EPI & p-type MCZ:** substrate type inversion is not even approched up to 6×10^{15} e/cm^2 ; very slow rate of decrease in N_{eff} (1.5×10^{-3} cm^{-1} in EPI, 1.2×10^{-4} cm^{-1} in p-MCZ)

α: comparison with other particles

- Use asymptotic value of displacement cross section for 200 MeV electrons [G.P.Summers et al., IEEE Trans.Nucl.Sci. 40(6) (1993), 1372-1378] (no higher-energy values available)

NIEL(900 MeV e)/NIEL(1 Mev n) = 8.106×10^{-2}

particles	α(A/cm)	
	measured	1 MeV n equiv.
1.8 MeV e-	4.5×10^{-20}	1.9×10^{-18}
900 MeV e-	9.06×10^{-19}	1.12×10^{-17}
1 MeV n	4.0×10^{-17}(*)	

$$\frac{\alpha(\text{900 MeV e})/\alpha(\text{1 MeV n})}{\text{NIEL(900 MeV e) / NIEL(1 MeV n)}} = 0.24 = \frac{1}{4.1}$$

(*) M.Moll et al., NIM, vol. A426, pp.87-93, 1999