# List of Figures:

**Fig. 1:**
Oxygen and Carbon concentrations in substrates investigated by the RD48/ROSE Collaboration.

**Fig. 2:**
Oxygen-concentration profiles for standard and oxygen enriched FZ silicon wafers as measured by SIMS.

**Fig 3a:**
Fluence dependence of leakage current for detectors produced by various process technologies from different silicon materials. The current was measured after a heat treatment for 80 min at 60°C [9]

**Fig 3b:**
Current related damage rate $\alpha$ as function of cumulated annealing time at 60°C. Comparison between data obtained for oxygen diffused silicon and parameterisation given in Ref. [9].

**Fig 4a:**
Dependence of $N_{eff}$ on the accumulated 1 MeV neutron equivalent fluence for standard and oxygen enriched FZ silicon irradiated with reactor neutrons (Ljubljana), 23 GeV protons (CERN PS) and 192 MeV pions (PSI).

**Fig 4b:**
Effective space charge density and full depletion voltage versus proton fluence for standard, carbon-enriched and three types of oxygen diffused samples: 24, 48 and 72 hour diffusion at 1150°C.

**Fig 5a:**
24 GeV/c proton irradiation of O-rich diodes with different resistivity.

**Fig 5b:**
Reactor neutron irradiation of O-rich diodes with different resistivity.

**Fig 6**
Annealing behaviour of the radiation induced change in the effective doping concentration ΔNeff at 60°C [9].

**Fig 7:**
Systematic analysis of annealing data. Change of effective doping concentration $\Delta N_{eff}$ during isothermal annealing at 60°C of oxygen enriched silicon detectors irradiated with different neutron fluences.

**Fig 8a:**
Stable Damage component $N_C$ for neutron irradiated oxygen enriched silicon

**Fig 8b:**
Reverse Annealing $N_Y$ for neutron irradiated oxygen enriched silicon

**Fig 9a:**
Damage parameters $N_C$ for oxygenated and standard material as obtained from annealing experiments at 60°C after irradiation with 24 GeV/c protons.

**Fig 9b:**
Damage parameters $N_Y$ for oxygenated and standard material as obtained from annealing experiments at 60°C after irradiation with 24 GeV/c protons.

**Fig 10a:**
Current pulse shapes obtained after annealing for 8 min at 80°C on a proton irradiated oxygen enriched sample.

**Fig 10b:**
Current pulse shapes obtained after annealing for 960 min at 80°C on a proton irradiated oxygen enriched sample.

**Fig 11:**
Determination of depletion voltage from CCE-V and $C_s$-V measurements.

**Fig 12:**
ΔNeff extracted from Cs-V and CCE-V measurements.

**Fig. 13:**
Depletion voltage normalised to 300μm detector thickness as a function of gamma dose for 1.1 kΩcm and 2.2 kΩcm oxygenated and standard silicon detectors.

**Fig 14a:**
Damage projections for the B-Layer of the ATLAS Pixel Detector.

**Fig 14b:**
Damage projections for ATLAS strip detectors located 30cm from the interaction point.

**Fig 15:**
Isochronal annealing ($\Delta T = 20°C$, $\Delta t = 20$ min) of DLTS spectra after radiation damage with $10^{11}$ <5.3 MeV> neutrons per $cm^2$ (3 kΩcm n-type epitaxial material).

**Fig 16:**
DLTS spectra (normalised to introduction rate at 200K) obtained after irradiation with neutrons and a subsequent 80 min heat treatment at 60°C for different materials (see legend).

**Fig 17:**
DLTS spectra obtained on samples from the same wafer obtained after irradiation with different particles (see legend) and a 80 min lasting heat treatment at 60°C. The spectra are normalised to the 1 MeV neutron equivalent introduction rate at 200 K.

**Fig 18a:**
Evolution of the DLTS spectrum at 60°C for a neutron irradiated sample produced from Cz silicon.

**Fig 18b:**
Correlation between trap E4b and leakage current.

**Fig 19:**
Relative damage efficiency for different particles as function of recoil energy.

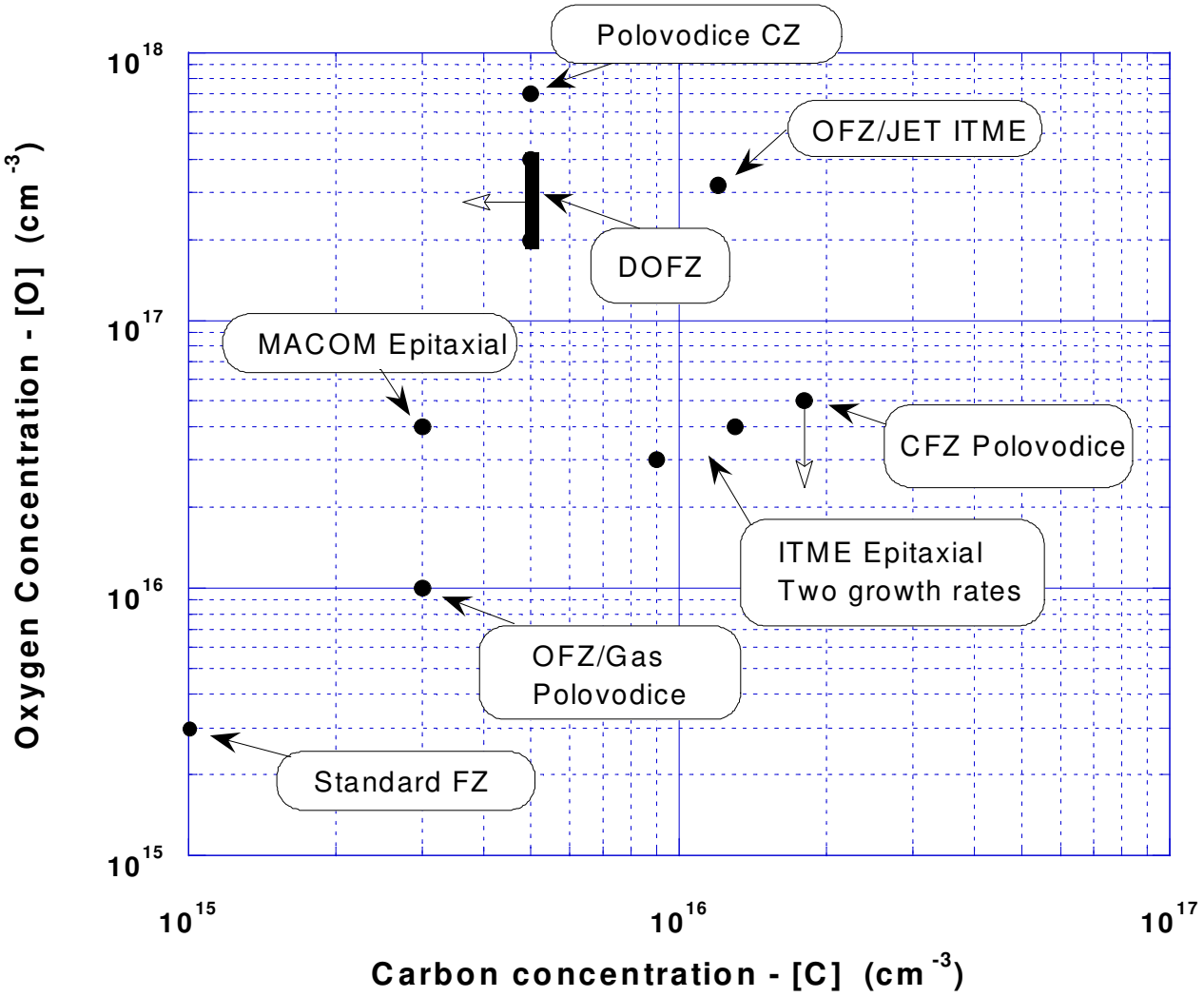
Polovodice CZ
OFZ/JET ITME
DOFZ
MACOM Epitaxial
CFZ Polovodice
ITME Epitaxial
Two growth rates
OFZ/Gas
Polovodice
Standard FZ
10^18
10^17
10^16
10^15
10^15
10^16
10^17
Oxygen Concentration - [O] (cm^-3)
Carbon concentration - [C] (cm^-3)

Fig. 1

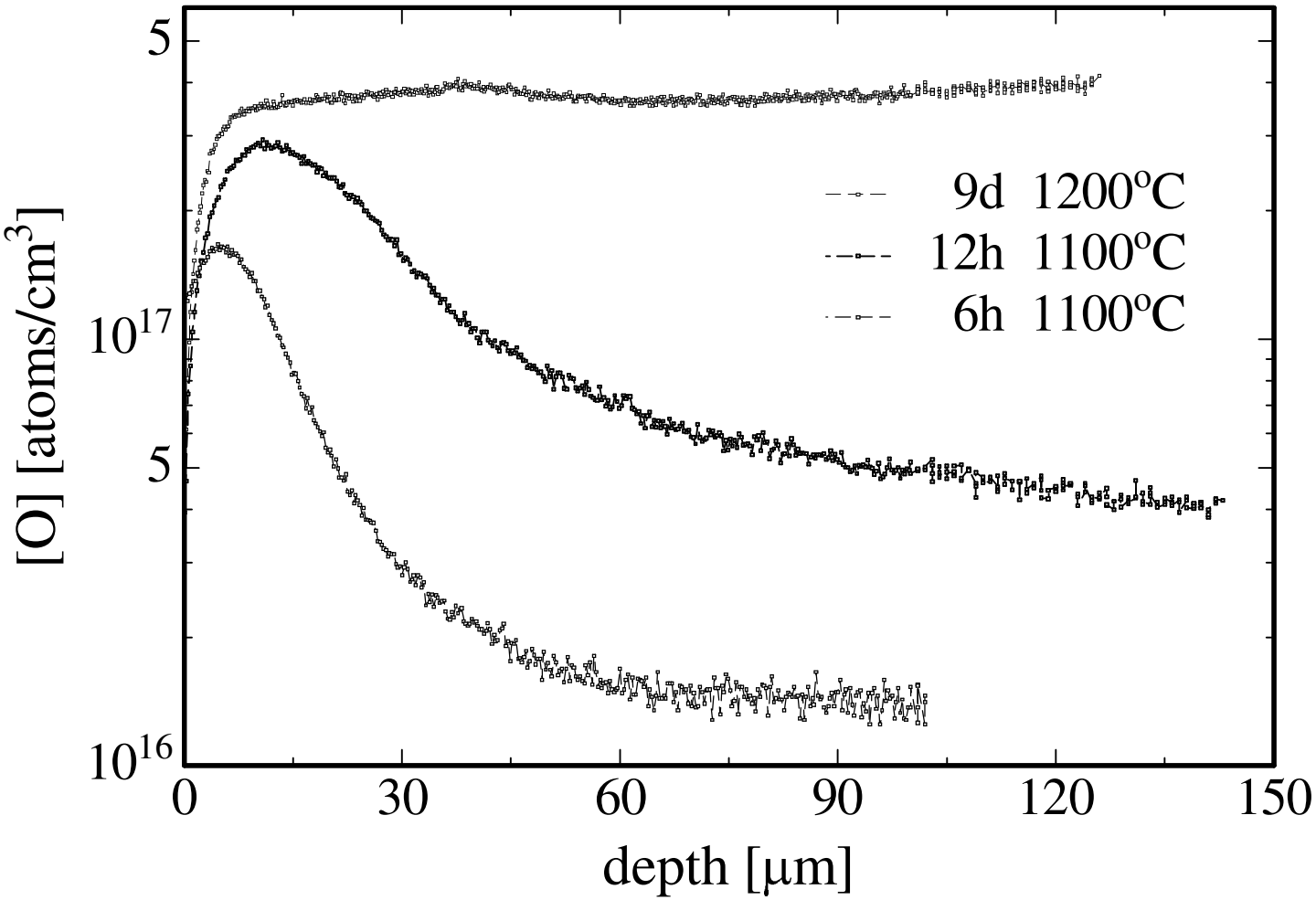
5
$10^{17}$
5
$10^{16}$
[O] [atoms/cm$^3$]
0
30
60
90
120
150
depth [μm]
9d 1200ºC
12h 1100ºC
6h 1100ºC

Fig. 2

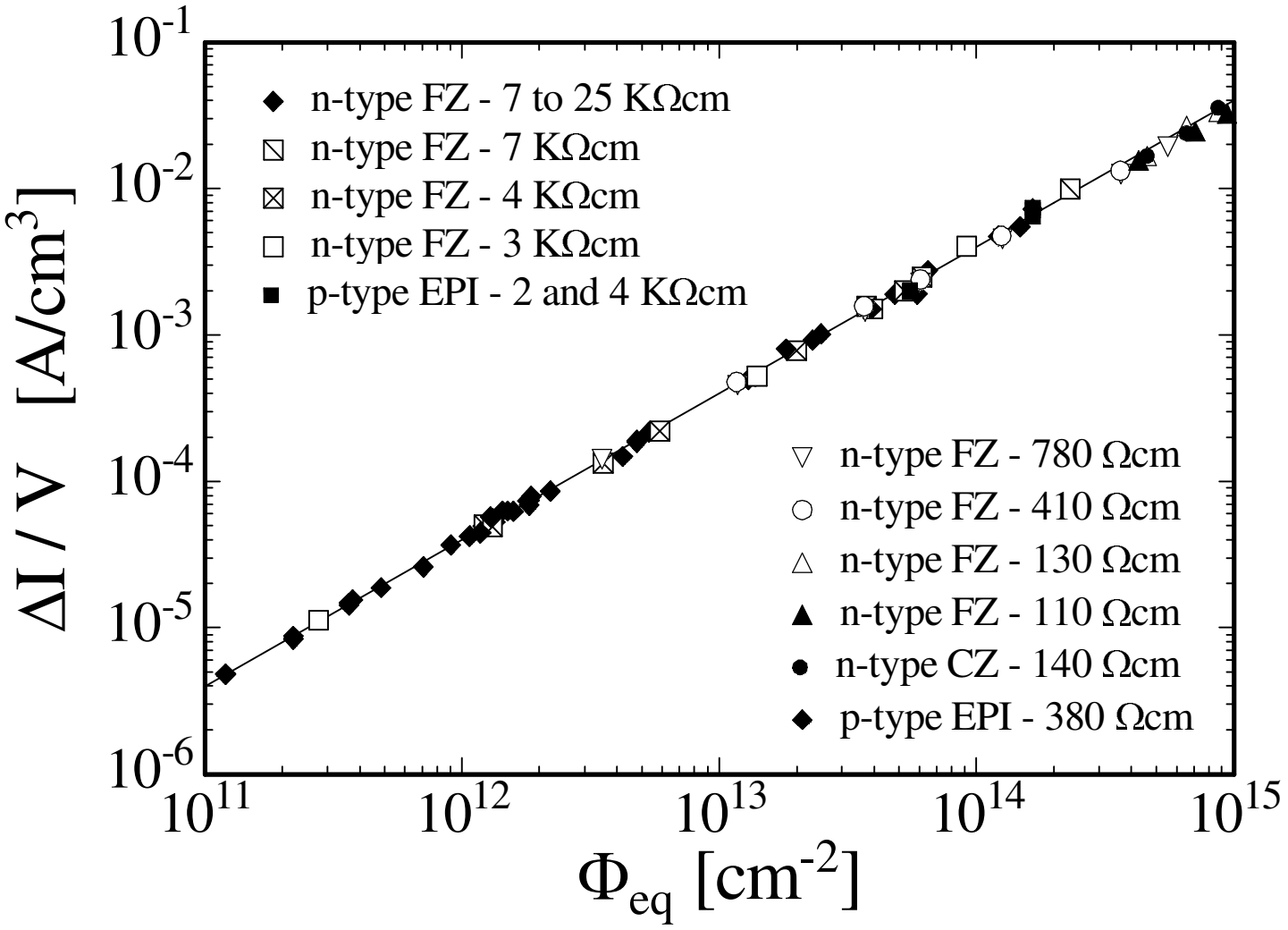
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$\Delta I / V$ [A/cm$^3$]
$10^{11}$
$10^{12}$
$10^{13}$
$10^{14}$
$10^{15}$
$\Phi_{eq}$ [cm$^{-2}$]
n-type FZ - 7 to 25 KΩcm
n-type FZ - 7 KΩcm
n-type FZ - 4 KΩcm
n-type FZ - 3 KΩcm
p-type EPI - 2 and 4 KΩcm
n-type FZ - 780 Ωcm
n-type FZ - 410 Ωcm
n-type FZ - 130 Ωcm
n-type FZ - 110 Ωcm
n-type CZ - 140 Ωcm
p-type EPI - 380 Ωcm

**Fig. 3a**

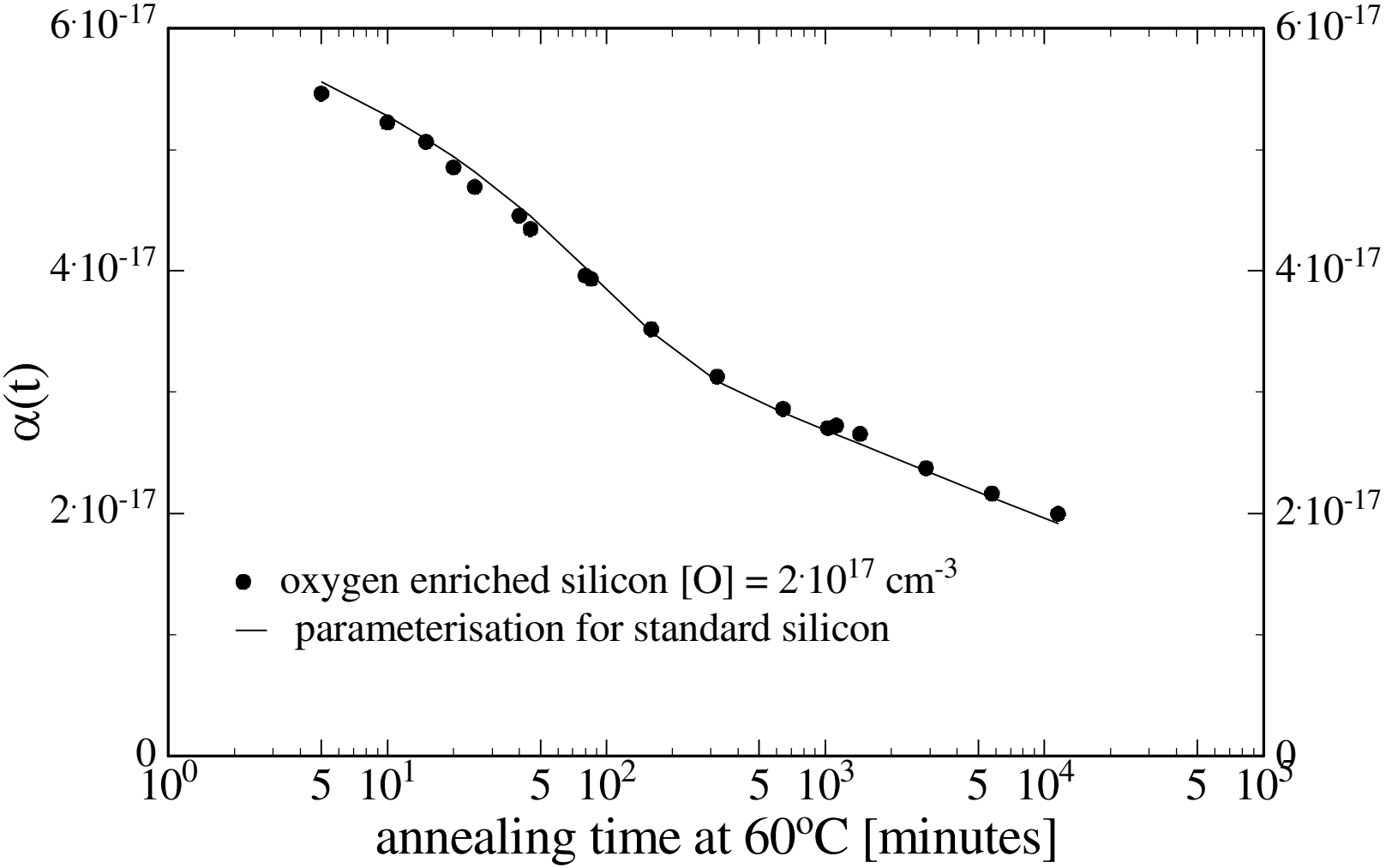
6·10-17
4·10-17
2·10-17
0
α(t)
oxygen enriched silicon [O] = 2·10^17 cm^-3
parameterisation for standard silicon
10^0
5 10^1
5 10^2
5 10^3
5 10^4
5 10^5
annealing time at 60°C [minutes]

**Fig 3b**

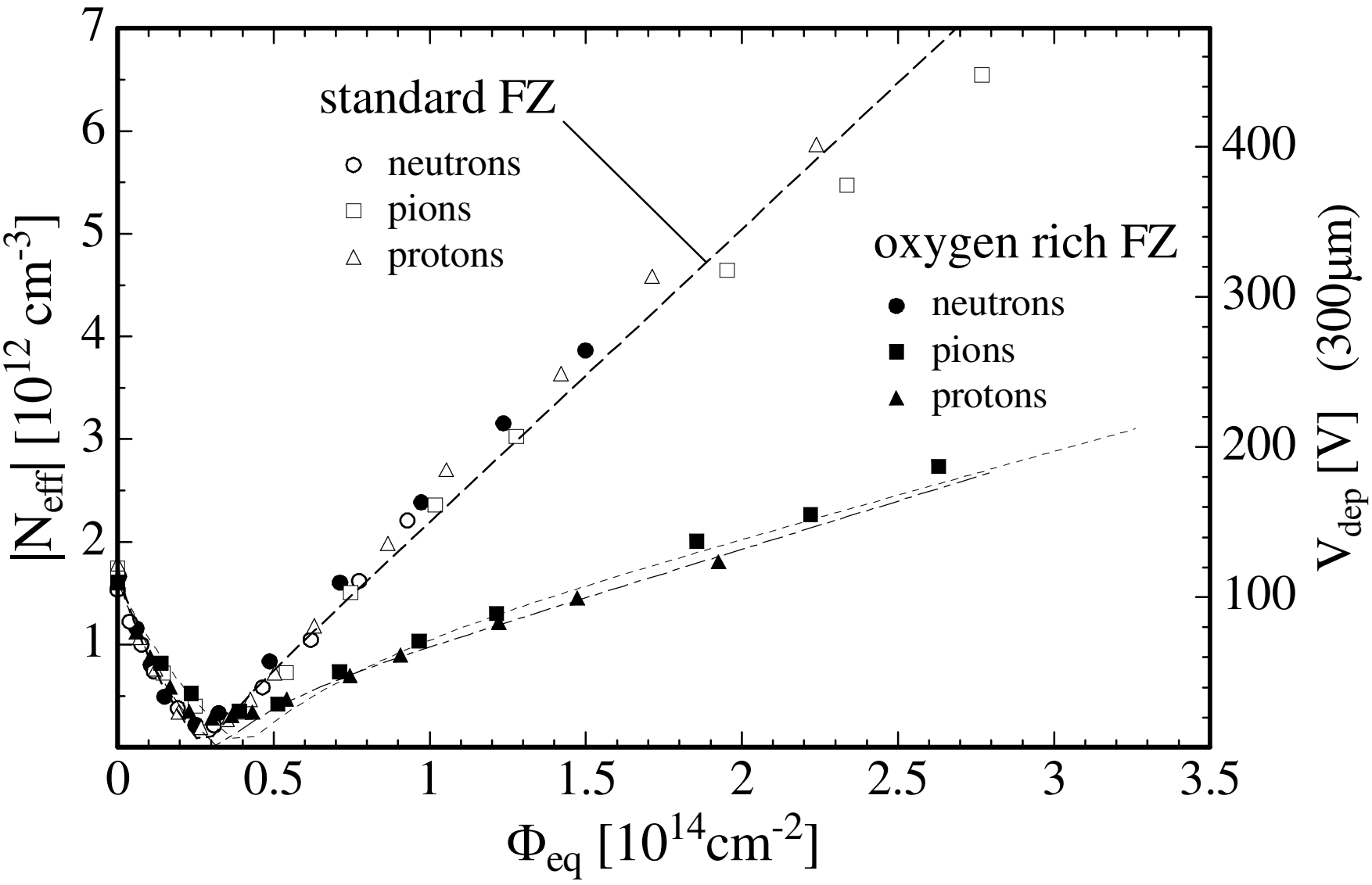
standard FZ
neutrons
pions
protons
oxygen rich FZ
neutrons
pions
protons
|N_eff| [10^12 cm^-3]
V_dep [V] (300μm)
Φ_eq [10^14cm^-2]
0
0.5
1
1.5
2
2.5
3
3.5
1
2
3
4
5
6
7
100
200
300
400

**Fig. 4a**

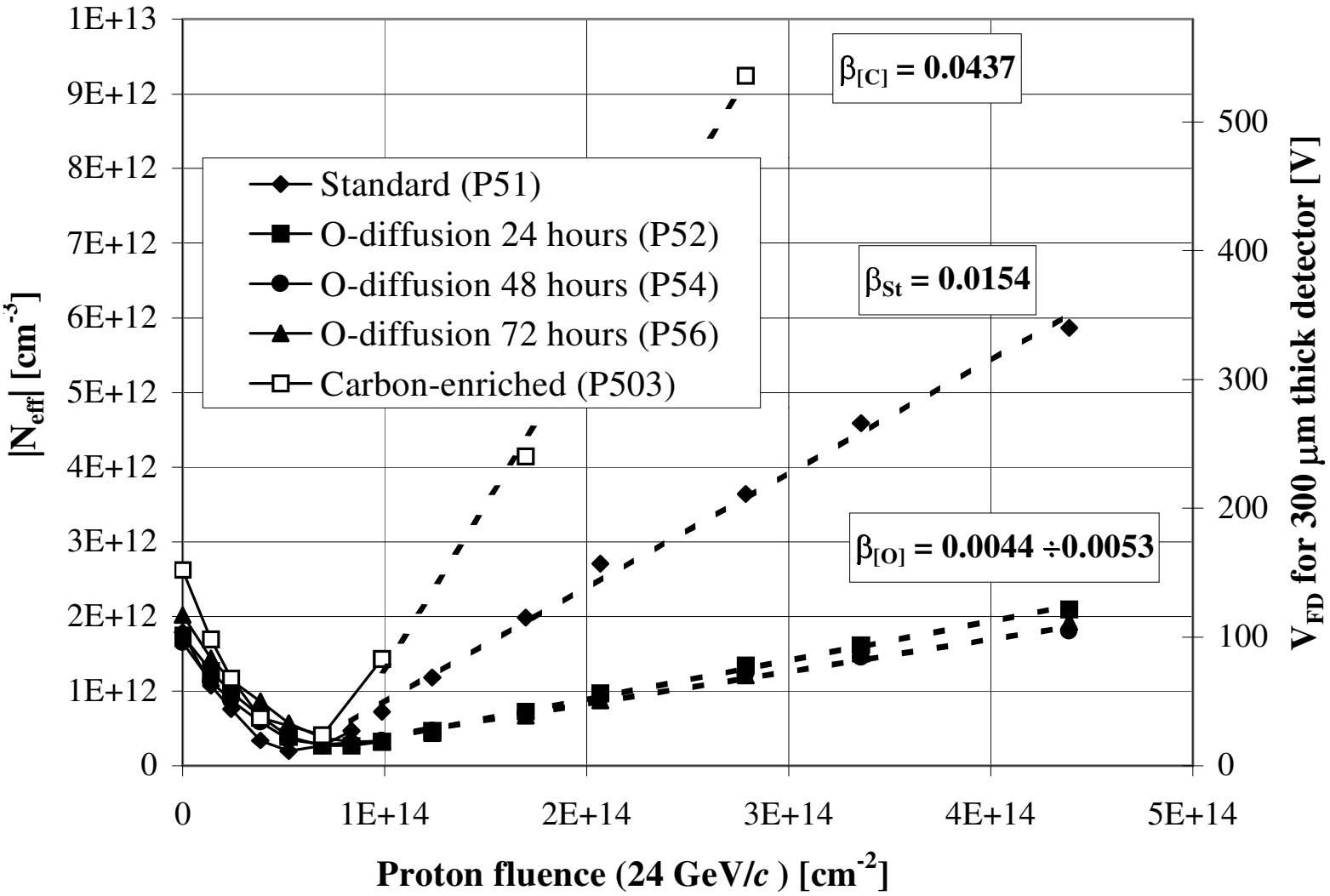
1E+13
9E+12
8E+12
7E+12
6E+12
5E+12
4E+12
3E+12
2E+12
1E+12
0
|Neff| [cm-3]
0
1E+14
2E+14
3E+14
4E+14
5E+14
Proton fluence (24 GeV/c ) [cm-2]
500
400
300
200
100
0
VFD for 300 μm thick detector [V]
Standard (P51)
O-diffusion 24 hours (P52)
O-diffusion 48 hours (P54)
O-diffusion 72 hours (P56)
Carbon-enriched (P503)
β[C] = 0.0437
βSt = 0.0154
β[O] = 0.0044 ÷0.0053

**Fig. 4b**

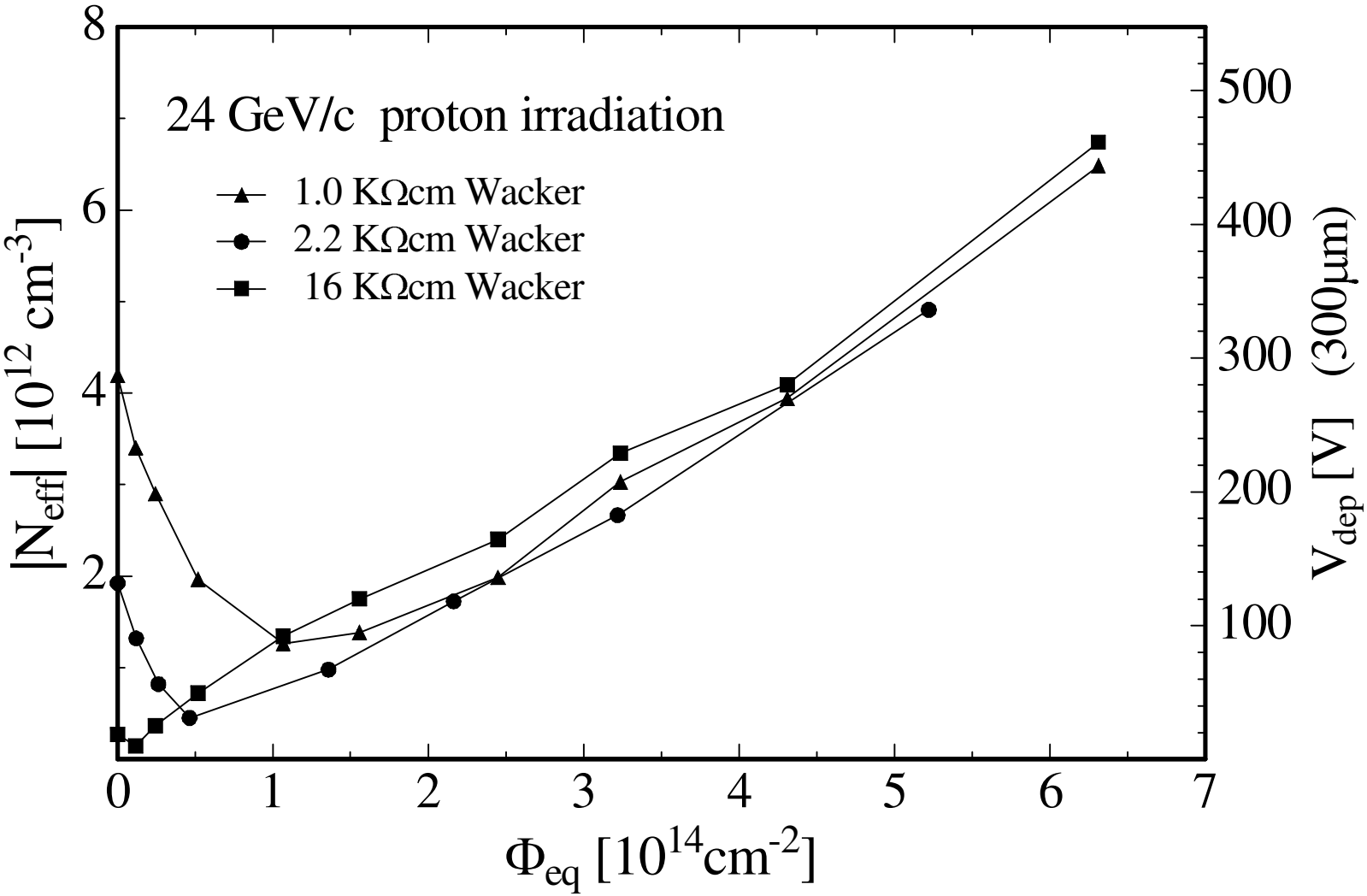
24 GeV/c proton irradiation
1.0 KΩcm Wacker
2.2 KΩcm Wacker
16 KΩcm Wacker
|N_eff| [10^12 cm^-3]
V_dep [V] (300μm)
Φ_eq [10^14cm^-2]
0
1
2
3
4
5
6
7
2
4
6
8
100
200
300
400
500

**Fig. 5a**

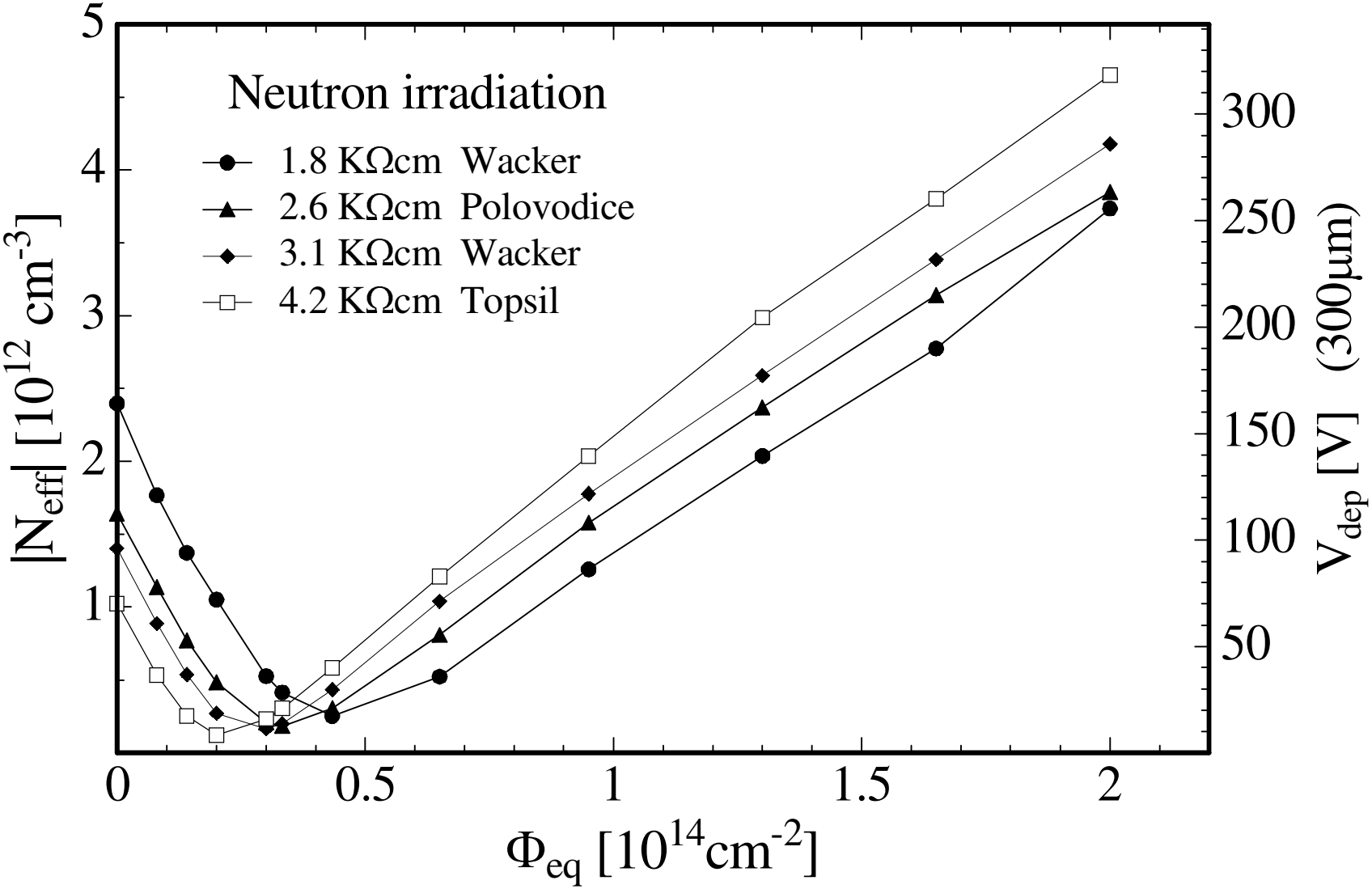
Neutron irradiation
1.8 KΩcm Wacker
2.6 KΩcm Polovodice
3.1 KΩcm Wacker
4.2 KΩcm Topsil
|Neff| [10^12 cm^-3]
Vdep [V] (300μm)
Φeq [10^14cm^-2]
0
0.5
1
1.5
2
1
2
3
4
5
50
100
150
200
250
300

**Fig. 5b**

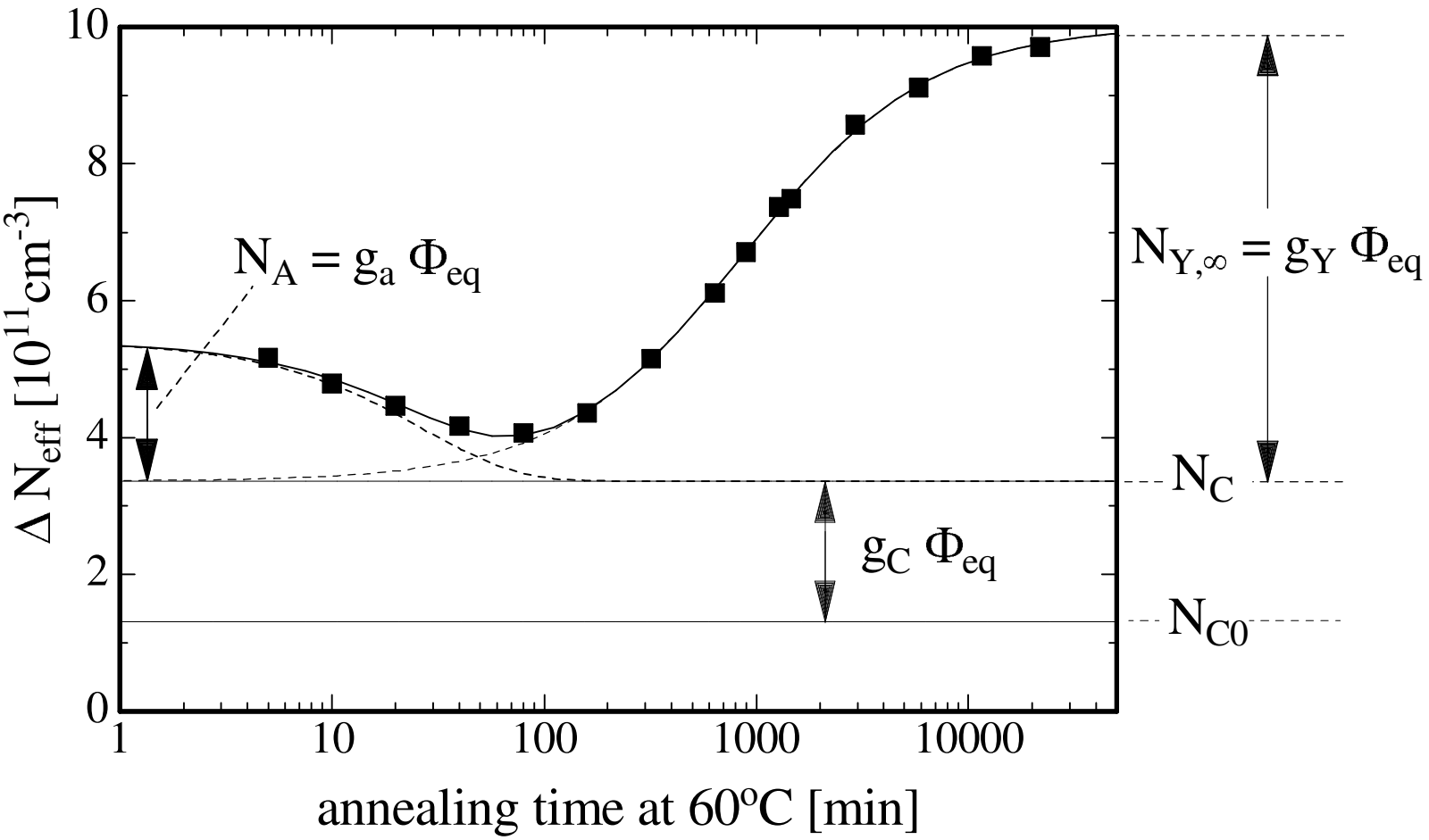
10
8
6
4
2
0
1
10
100
1000
10000
ΔN_eff [10^11 cm^-3]
annealing time at 60°C [min]
N_A = g_a Φ_eq
N_Y,∞ = g_Y Φ_eq
N_C
g_C Φ_eq
N_C0

**Fig. 6**

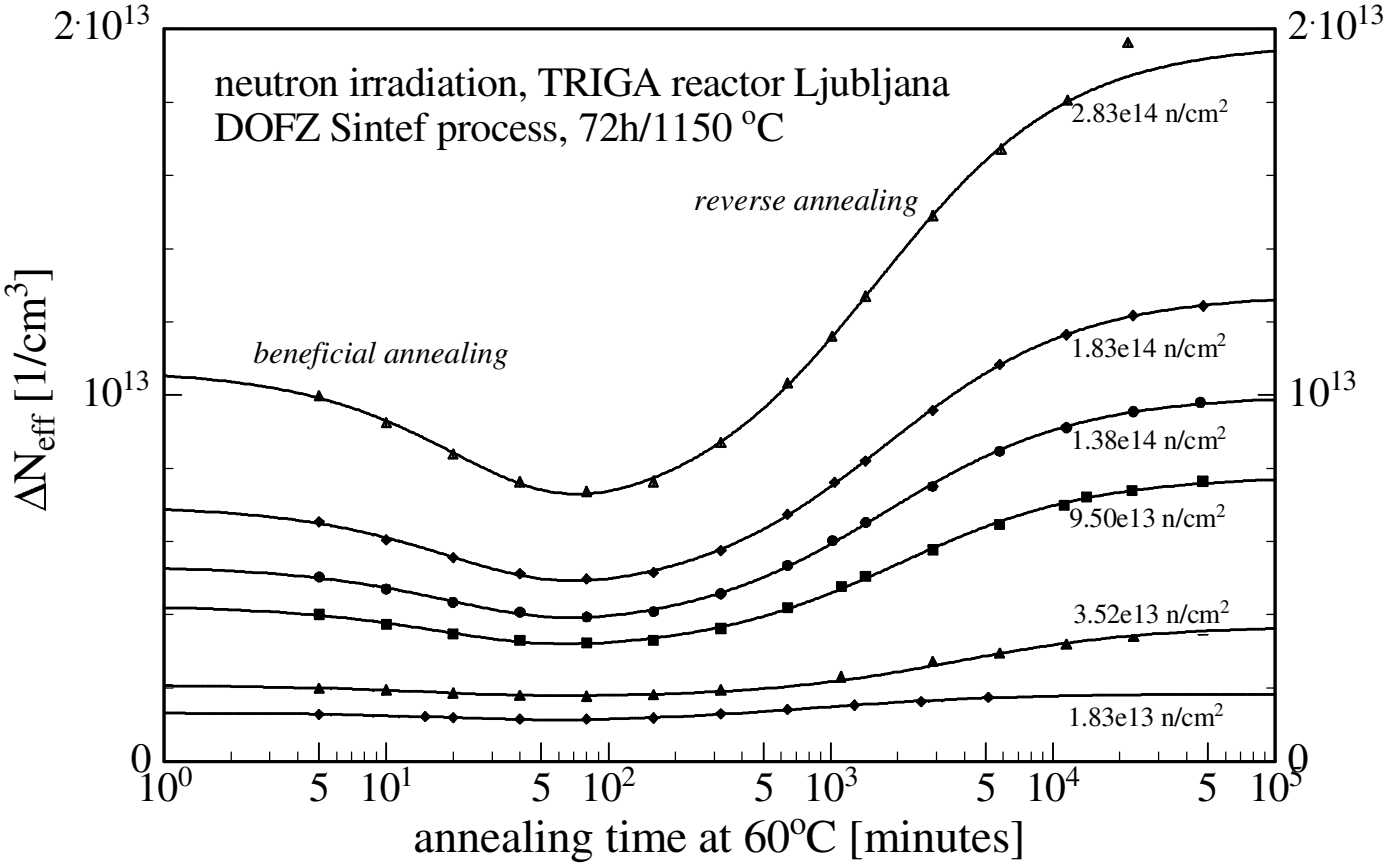
neutron irradiation, TRIGA reactor Ljubljana
DOFZ Sintef process, 72h/1150 °C
reverse annealing
beneficial annealing
2.83e14 n/cm2
1.83e14 n/cm2
1.38e14 n/cm2
9.50e13 n/cm2
3.52e13 n/cm2
1.83e13 n/cm2
2·10^13
10^13
0
ΔNeff [1/cm3]
10^0 5 10^1 5 10^2 5 10^3 5 10^4 5 10^5
annealing time at 60°C [minutes]

**Fig. 7**

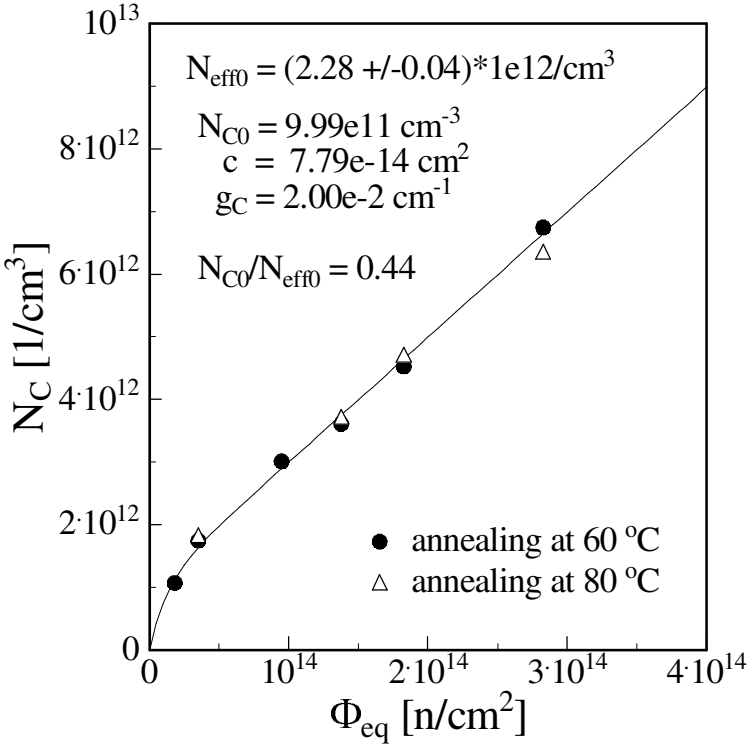
$N_{eff0}$ = (2.28 +/-0.04)*1e12/cm$^3$
$N_{C0}$ = 9.99e11 cm$^{-3}$
c = 7.79e-14 cm$^2$
$g_C$ = 2.00e-2 cm$^{-1}$
$N_{C0}/N_{eff0}$ = 0.44
annealing at 60 °C
annealing at 80 °C
$N_C$ [1/cm$^3$]
$\Phi_{eq}$ [n/cm$^2$]
$10^{13}$
$8\cdot10^{12}$
$6\cdot10^{12}$
$4\cdot10^{12}$
$2\cdot10^{12}$
0
$10^{14}$
$2\cdot10^{14}$
$3\cdot10^{14}$
$4\cdot10^{14}$

**Fig. 8a**

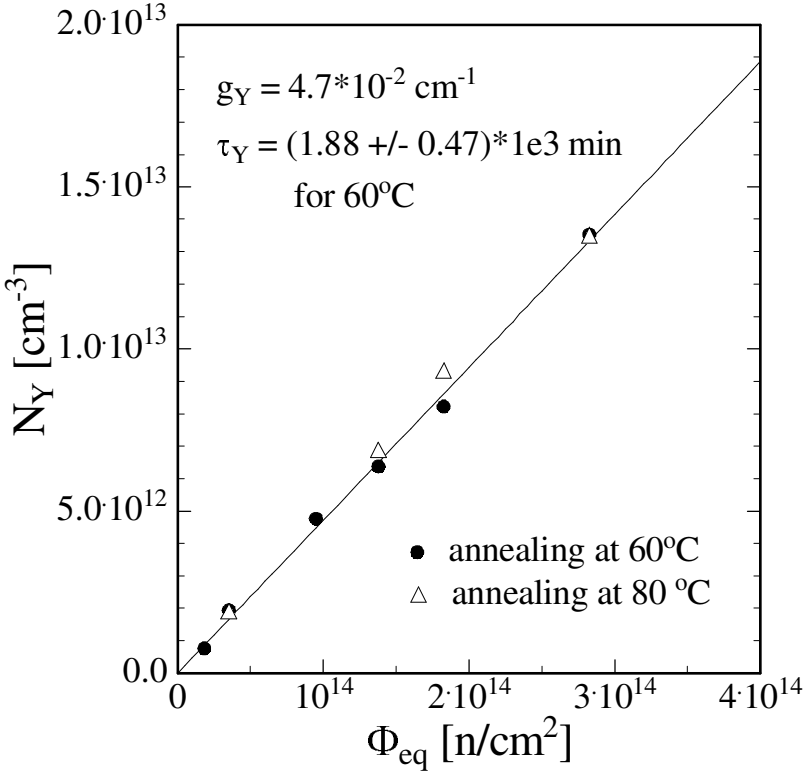
$g_Y$ = 4.7*10$^{-2}$ cm$^{-1}$
$\tau_Y$ = (1.88 +/- 0.47)*1e3 min
for 60°C
annealing at 60°C
annealing at 80 °C
$N_Y$ [cm$^{-3}$]
$\Phi_{eq}$ [n/cm$^2$]
$2.0\cdot10^{13}$
$1.5\cdot10^{13}$
$1.0\cdot10^{13}$
$5.0\cdot10^{12}$
0.0
$10^{14}$
$2\cdot10^{14}$
$3\cdot10^{14}$
$4\cdot10^{14}$

**Fig 8b**

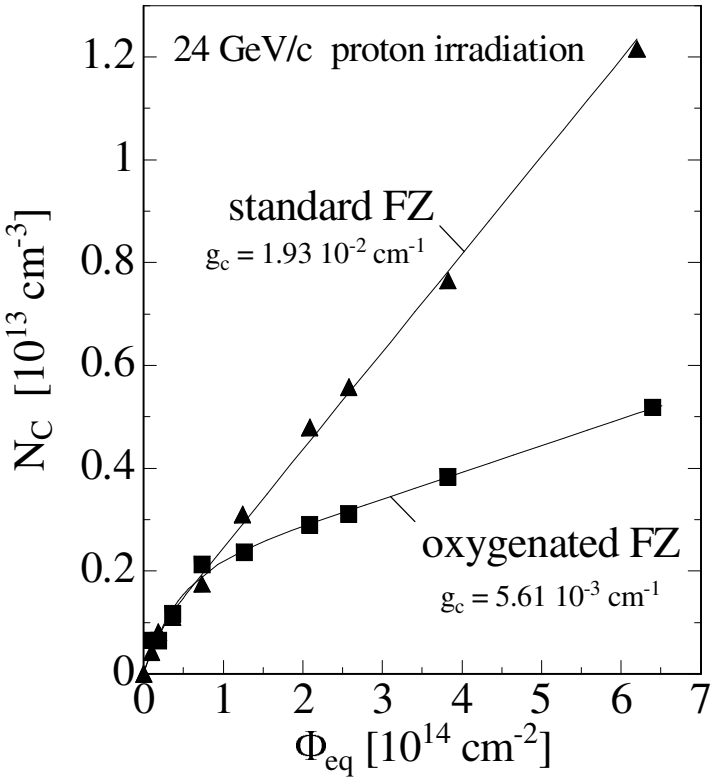
24 GeV/c proton irradiation
standard FZ
$g_c = 1.93\ 10^{-2}\ cm^{-1}$
oxygenated FZ
$g_c = 5.61\ 10^{-3}\ cm^{-1}$
$N_C\ [10^{13}\ cm^{-3}]$
$\Phi_{eq}\ [10^{14}\ cm^{-2}]$

**Fig. 9a**

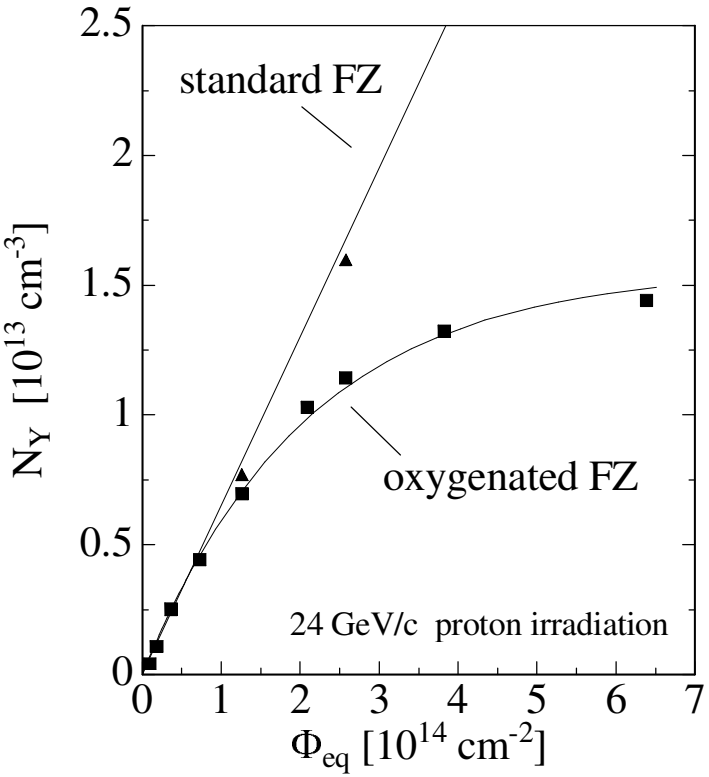
standard FZ
oxygenated FZ
24 GeV/c proton irradiation
$N_Y\ [10^{13}\ cm^{-3}]$
$\Phi_{eq}\ [10^{14}\ cm^{-2}]$

**Fig 9b**

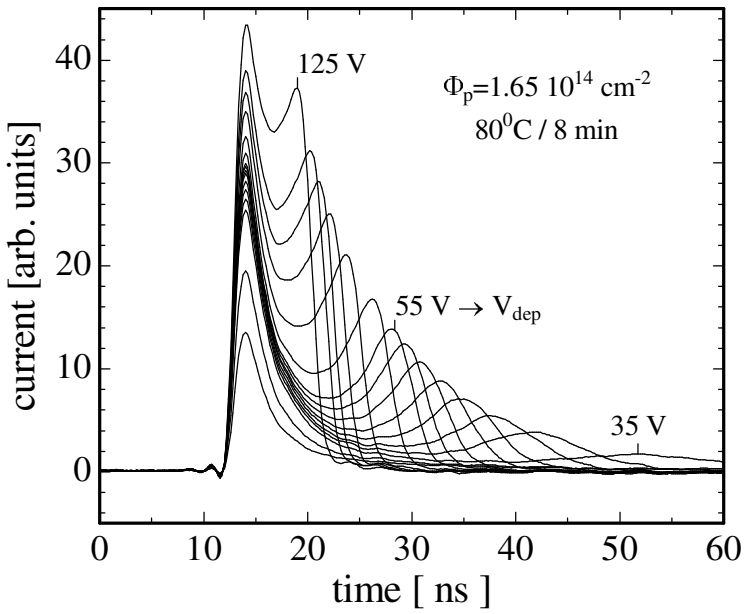


**Fig. 10a**

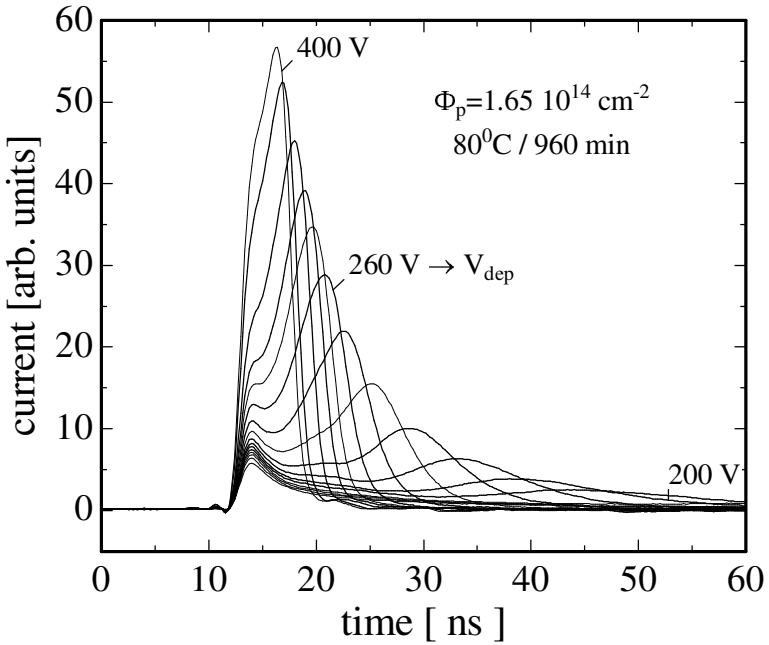


**Fig 10b**

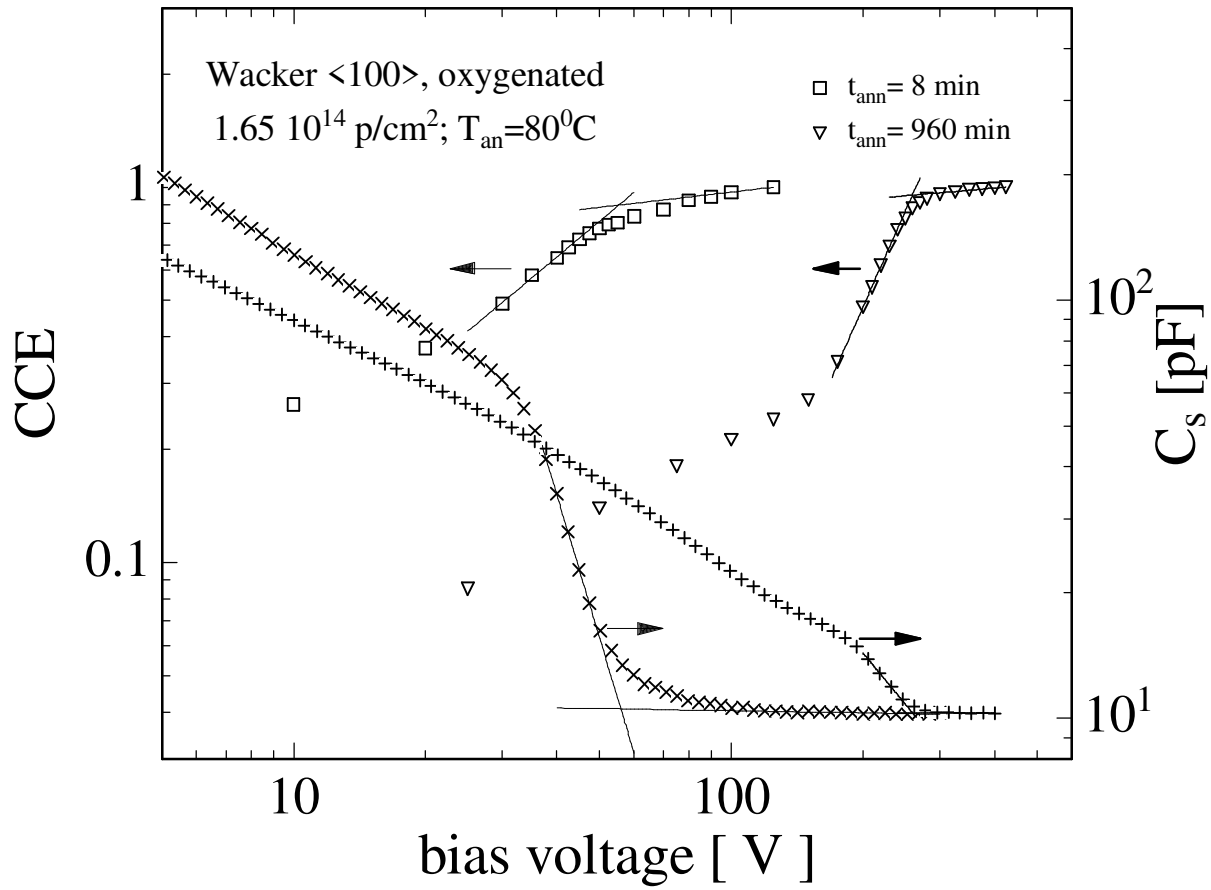
Wacker <100>, oxygenated
1.65 10^14 p/cm^2; T_an=80^0C
t_ann= 8 min
t_ann= 960 min
CCE
C_s [pF]
1
0.1
10^2
10^1
10
100
bias voltage [ V ]

**Fig. 11**

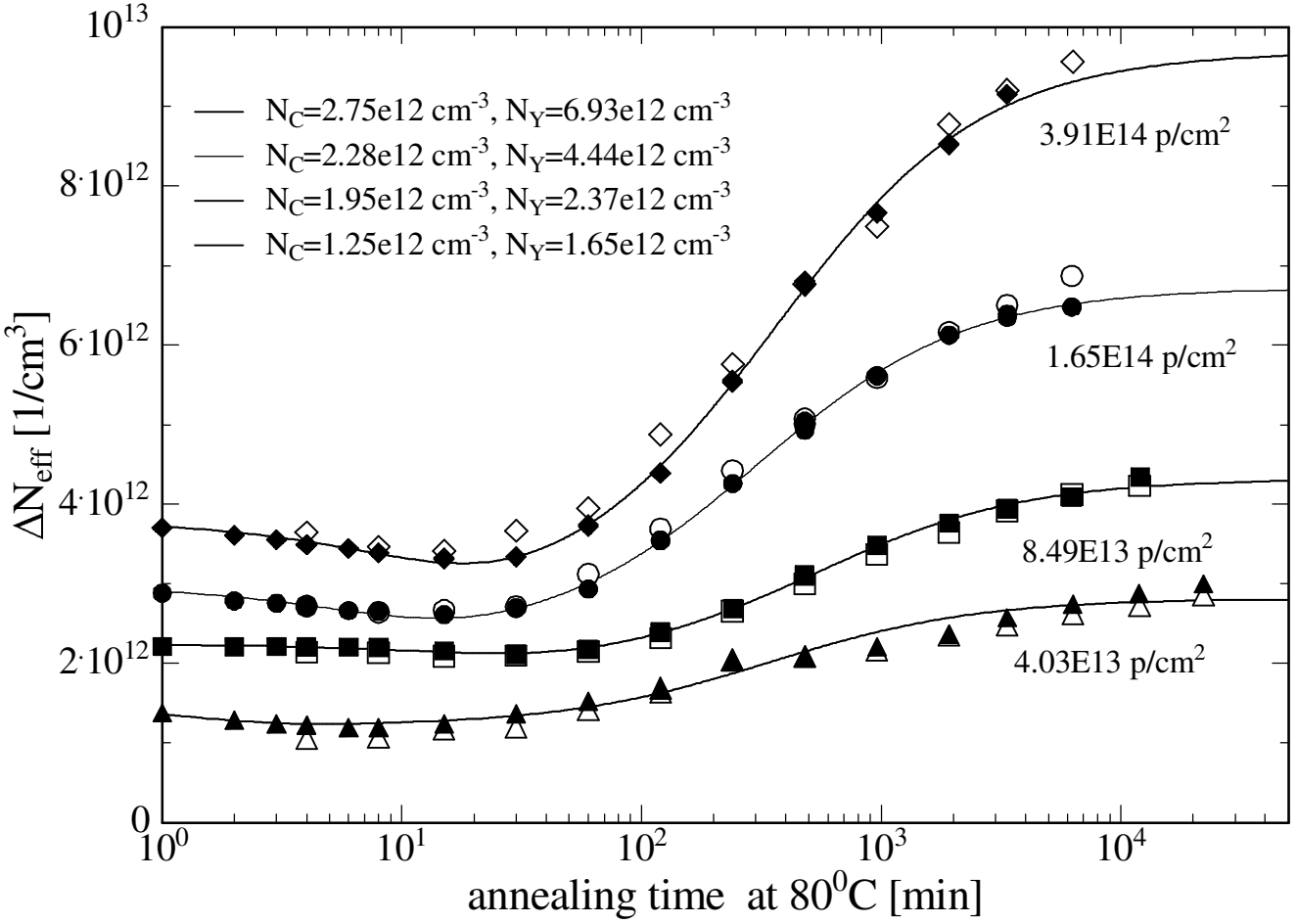
$10^{13}$
$8\cdot10^{12}$
$6\cdot10^{12}$
$4\cdot10^{12}$
$2\cdot10^{12}$
0
$\Delta N_{eff}$ [1/cm$^3$]
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
annealing time at 80$^0$C [min]
$N_C$=2.75e12 cm$^{-3}$, $N_Y$=6.93e12 cm$^{-3}$
$N_C$=2.28e12 cm$^{-3}$, $N_Y$=4.44e12 cm$^{-3}$
$N_C$=1.95e12 cm$^{-3}$, $N_Y$=2.37e12 cm$^{-3}$
$N_C$=1.25e12 cm$^{-3}$, $N_Y$=1.65e12 cm$^{-3}$
3.91E14 p/cm$^2$
1.65E14 p/cm$^2$
8.49E13 p/cm$^2$
4.03E13 p/cm$^2$

**Fig. 12**

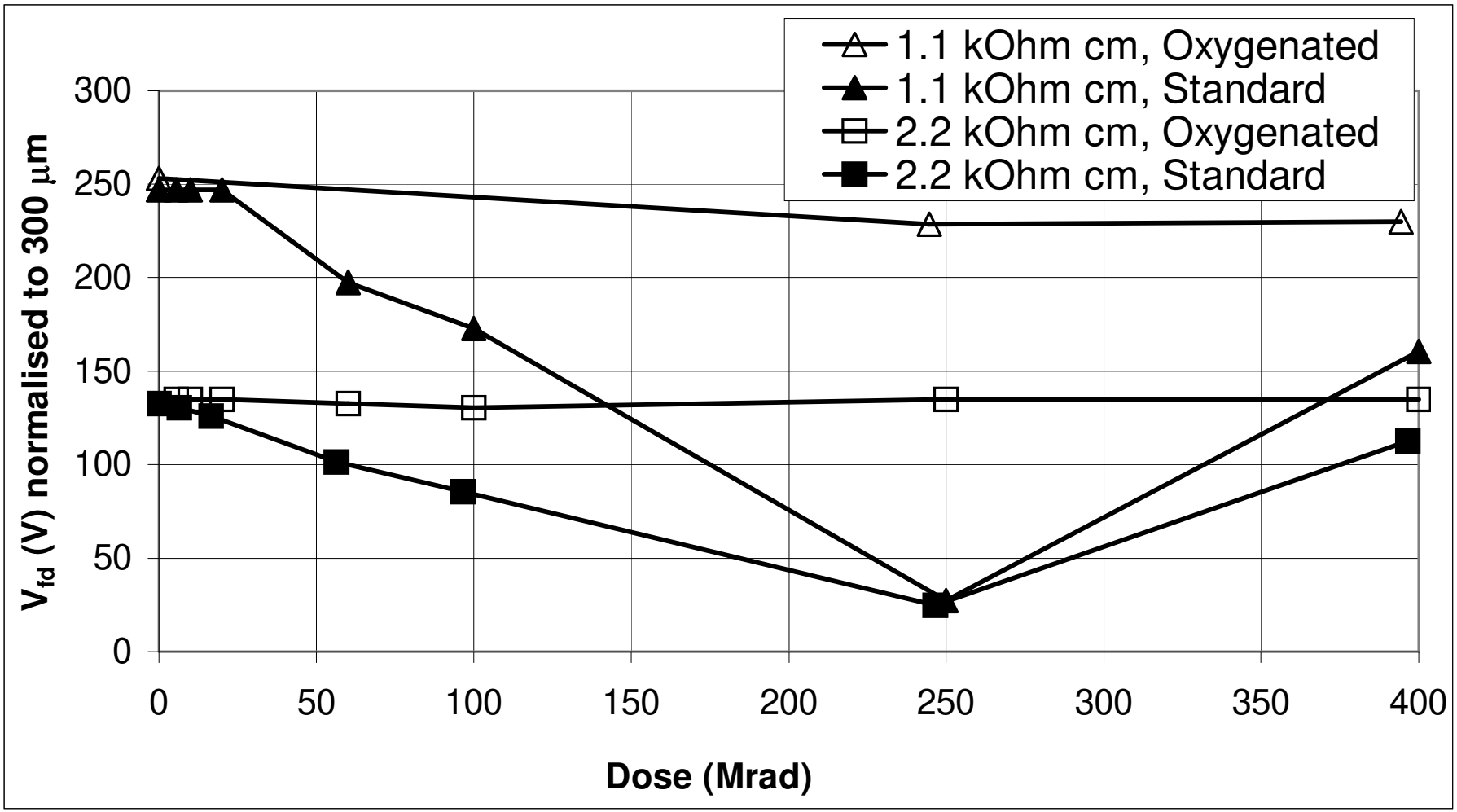
1.1 kOhm cm, Oxygenated
1.1 kOhm cm, Standard
2.2 kOhm cm, Oxygenated
2.2 kOhm cm, Standard
300
250
200
150
100
50
0
$V_{fd}$ (V) normalised to 300 μm
0
50
100
150
200
250
300
350
400
Dose (Mrad)

**Fig.13:**

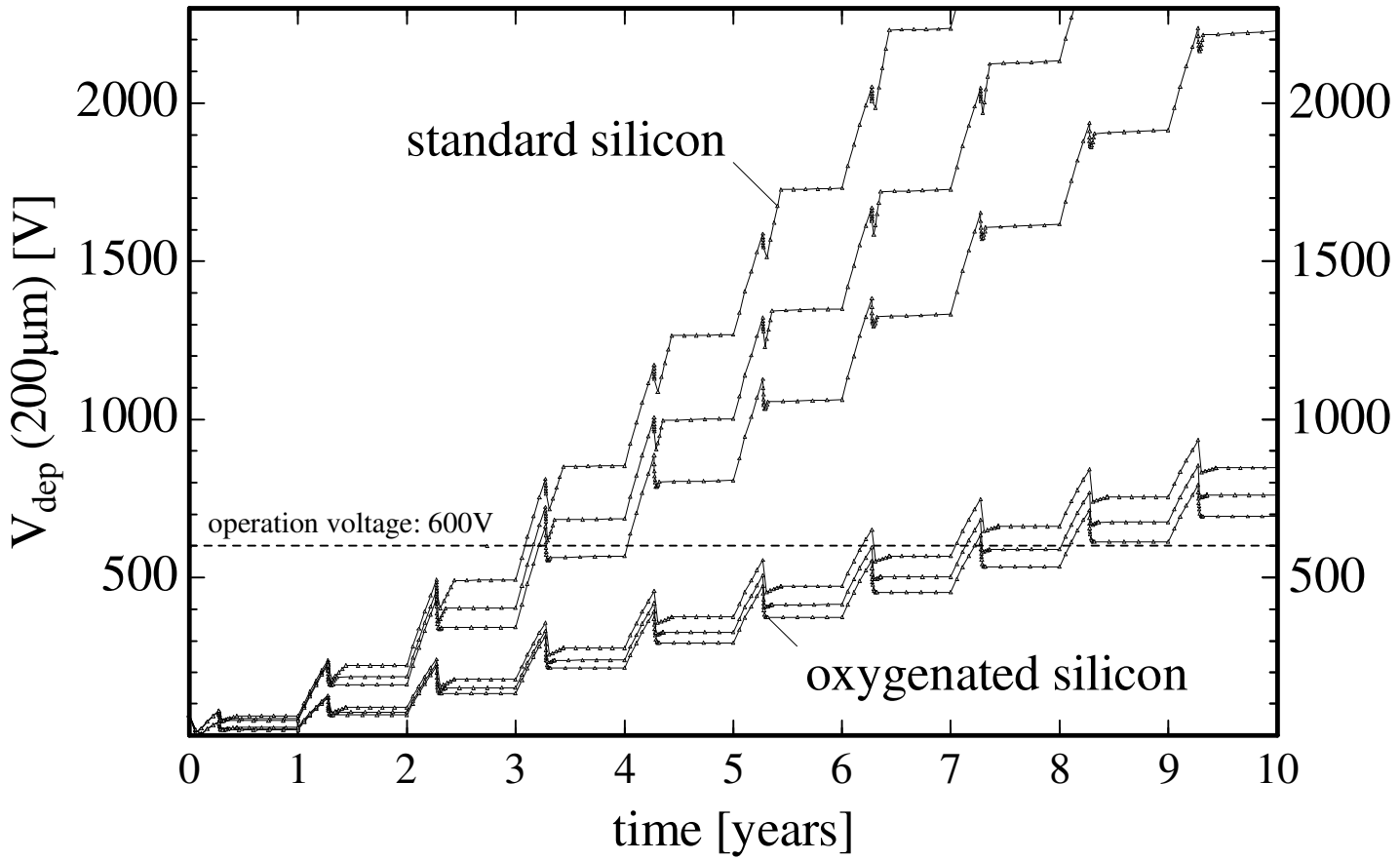
standard silicon
oxygenated silicon
operation voltage: 600V
$V_{dep}$ (200µm) [V]
time [years]
2000
1500
1000
500
0
1
2
3
4
5
6
7
8
9
10

**Fig. 14a**

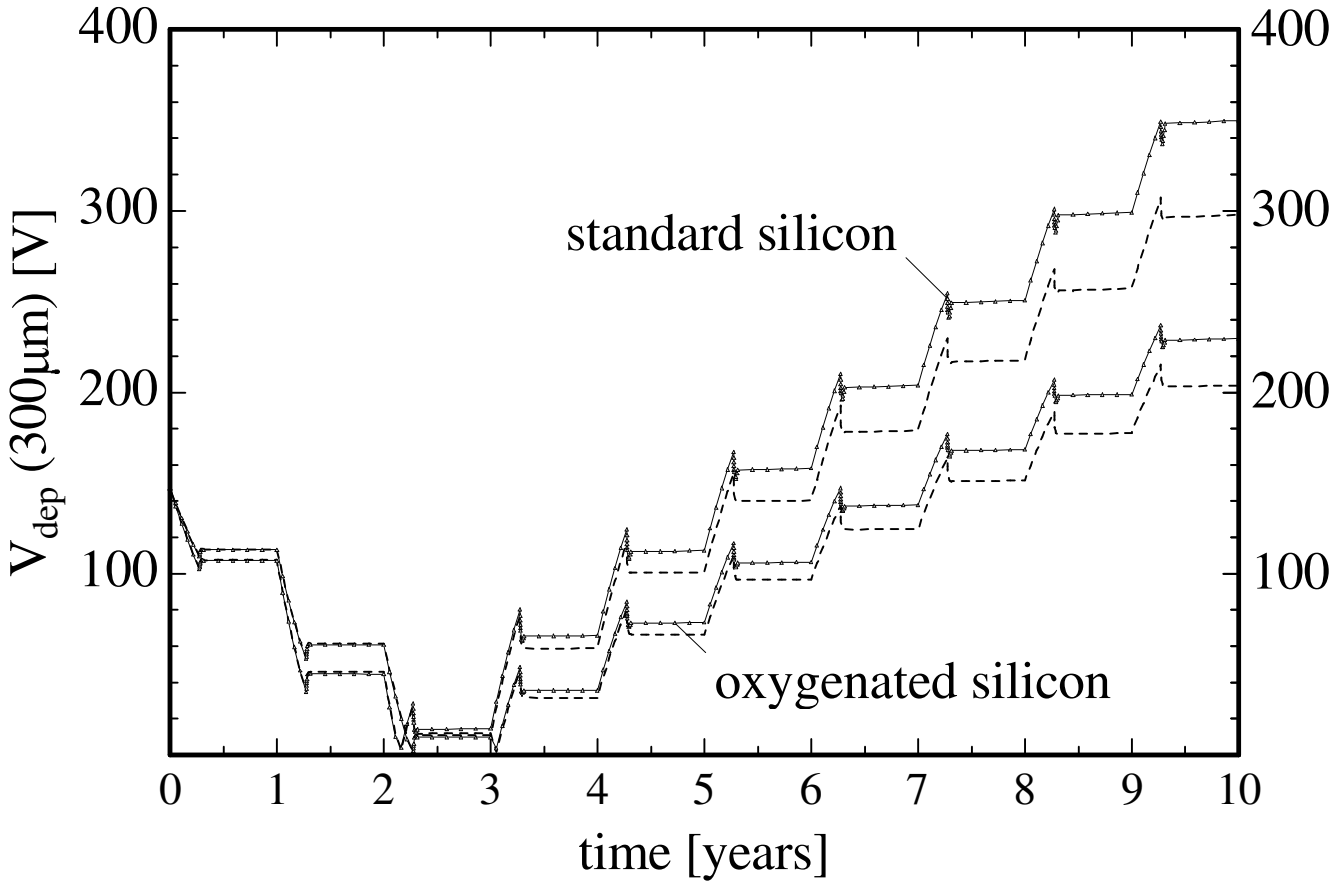
400
300
200
100
0
1
2
3
4
5
6
7
8
9
10
$V_{dep}$ (300μm) [V]
time [years]
standard silicon
oxygenated silicon

**Fig. 14b**

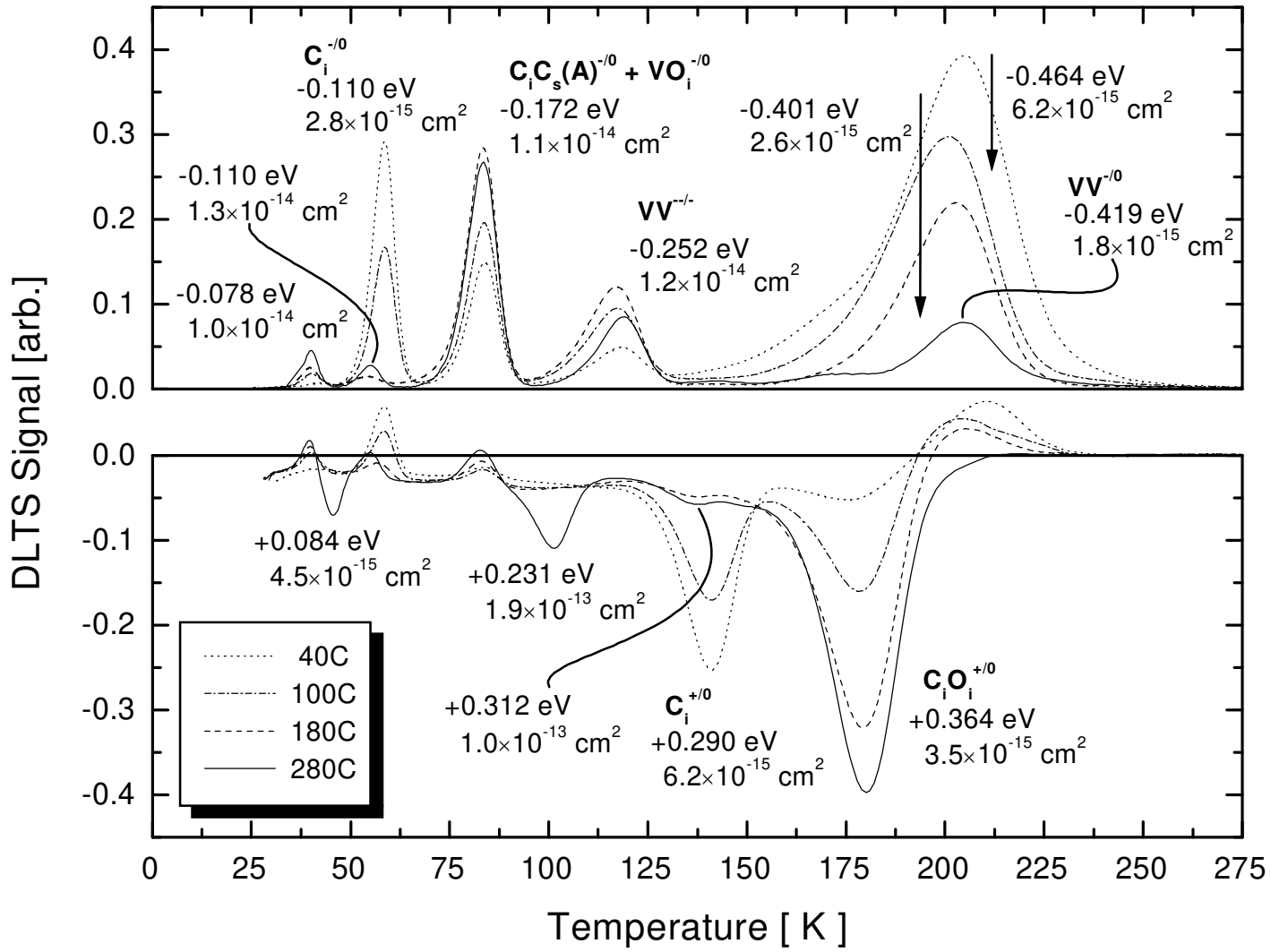
DLTS Signal [arb.]
Temperature [ K ]
C_i^-/0
-0.110 eV
2.8×10^-15 cm^2
C_iC_s(A)^-/0 + VO_i^-/0
-0.172 eV
1.1×10^-14 cm^2
-0.401 eV
2.6×10^-15 cm^2
-0.464 eV
6.2×10^-15 cm^2
-0.110 eV
1.3×10^-14 cm^2
VV^-/-
-0.252 eV
1.2×10^-14 cm^2
VV^-/0
-0.419 eV
1.8×10^-15 cm^2
-0.078 eV
1.0×10^-14 cm^2
+0.084 eV
4.5×10^-15 cm^2
+0.231 eV
1.9×10^-13 cm^2
40C
100C
180C
280C
+0.312 eV
1.0×10^-13 cm^2
C_i^+/0
+0.290 eV
6.2×10^-15 cm^2
C_iO_i^+/0
+0.364 eV
3.5×10^-15 cm^2

**Fig. 15**

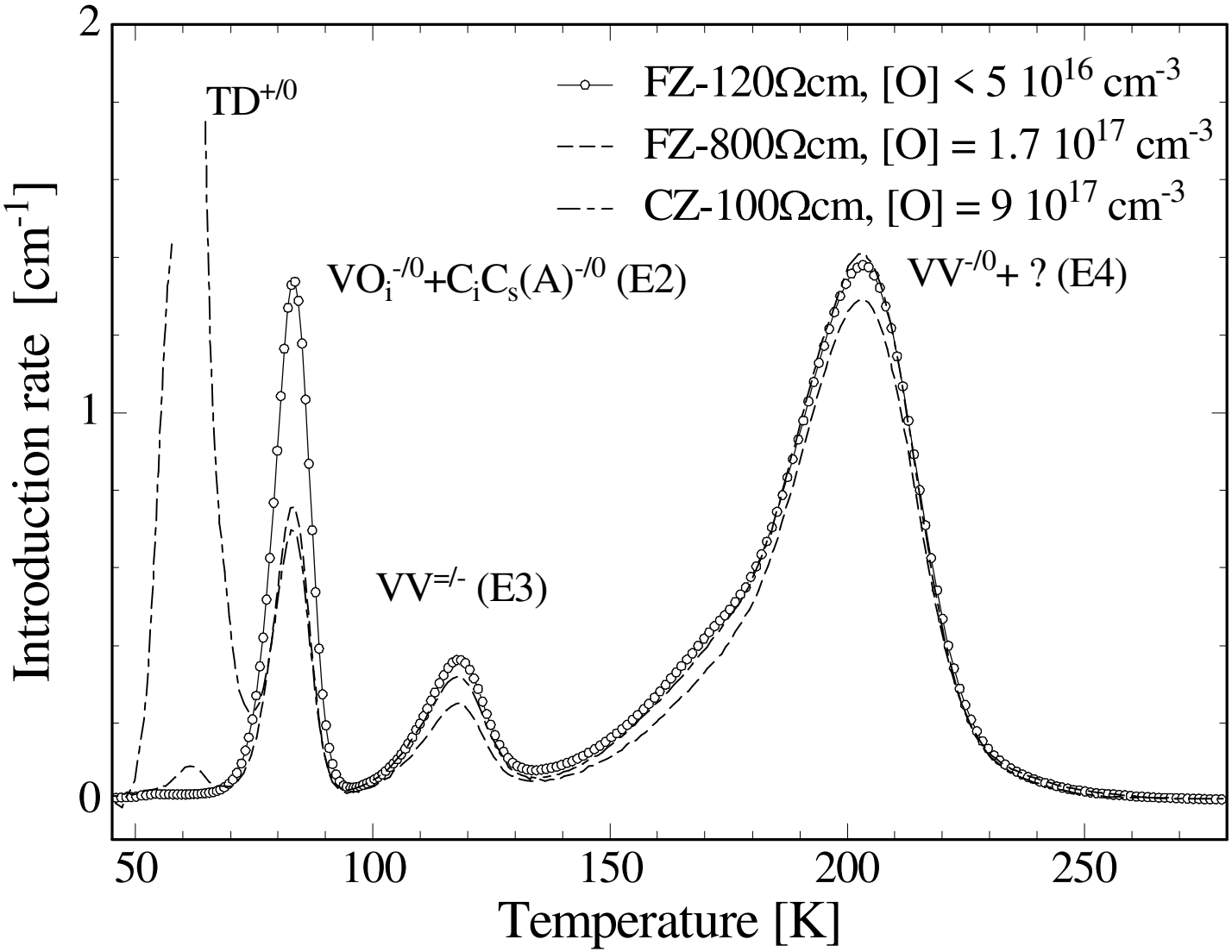
FZ-120Ωcm, [O] < 5 10^16 cm^-3
FZ-800Ωcm, [O] = 1.7 10^17 cm^-3
CZ-100Ωcm, [O] = 9 10^17 cm^-3
TD+/0
VOi-/0+CiCs(A)-/0 (E2)
VV=/- (E3)
VV-/0+ ? (E4)
Introduction rate [cm-1]
Temperature [K]
0
1
2
50
100
150
200
250

**Fig. 16**

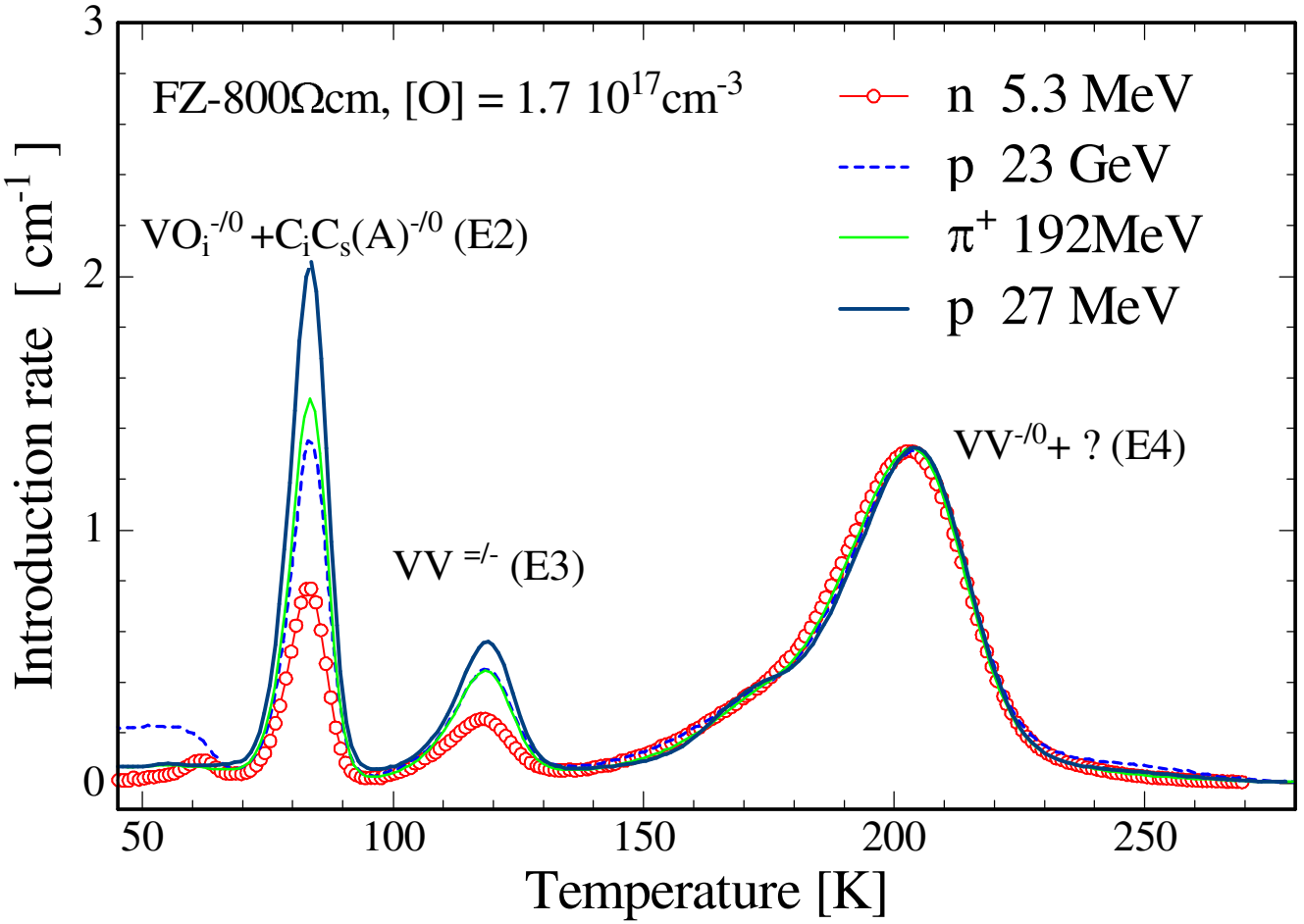
FZ-800Ωcm, [O] = 1.7 10^17cm^-3
n 5.3 MeV
p 23 GeV
π+ 192MeV
p 27 MeV
VOi-/0 +CiCs(A)-/0 (E2)
VV =/- (E3)
VV-/0+ ? (E4)
Introduction rate [ cm-1 ]
Temperature [K]
0
1
2
3
50
100
150
200
250

**Fig. 17**

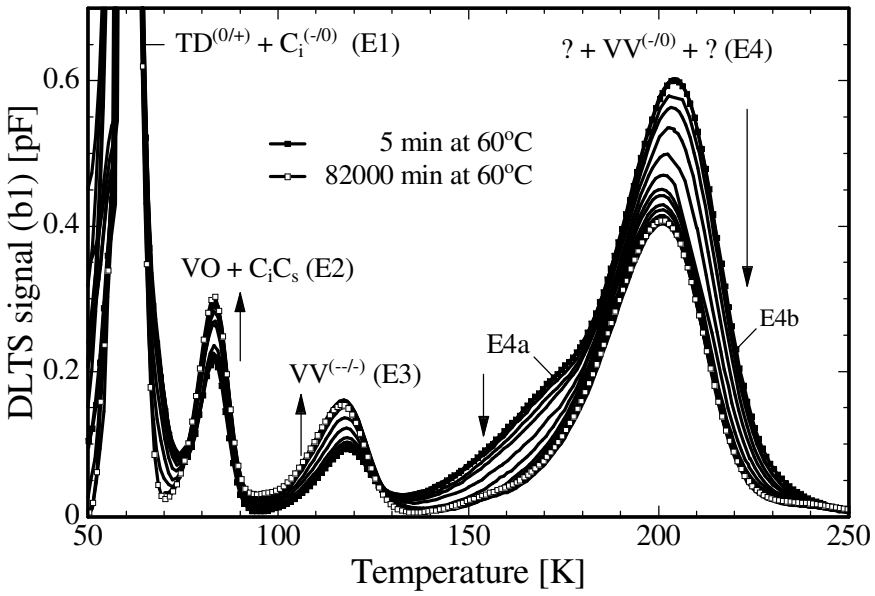


**Fig. 18a**

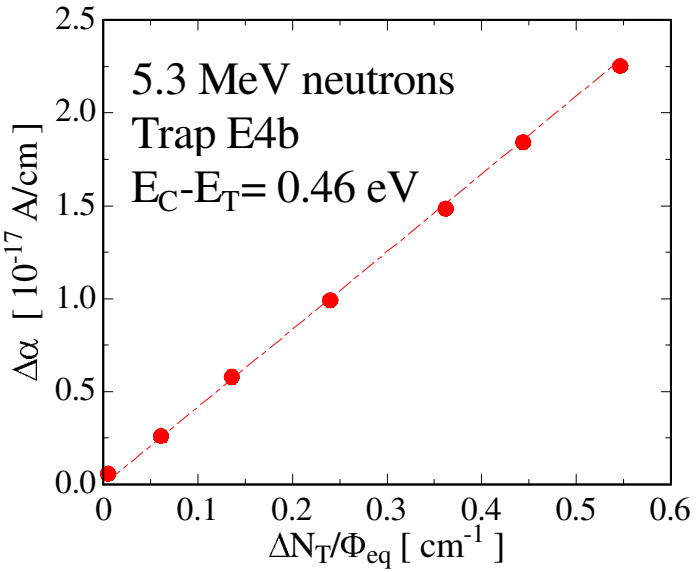


**Fig18b**

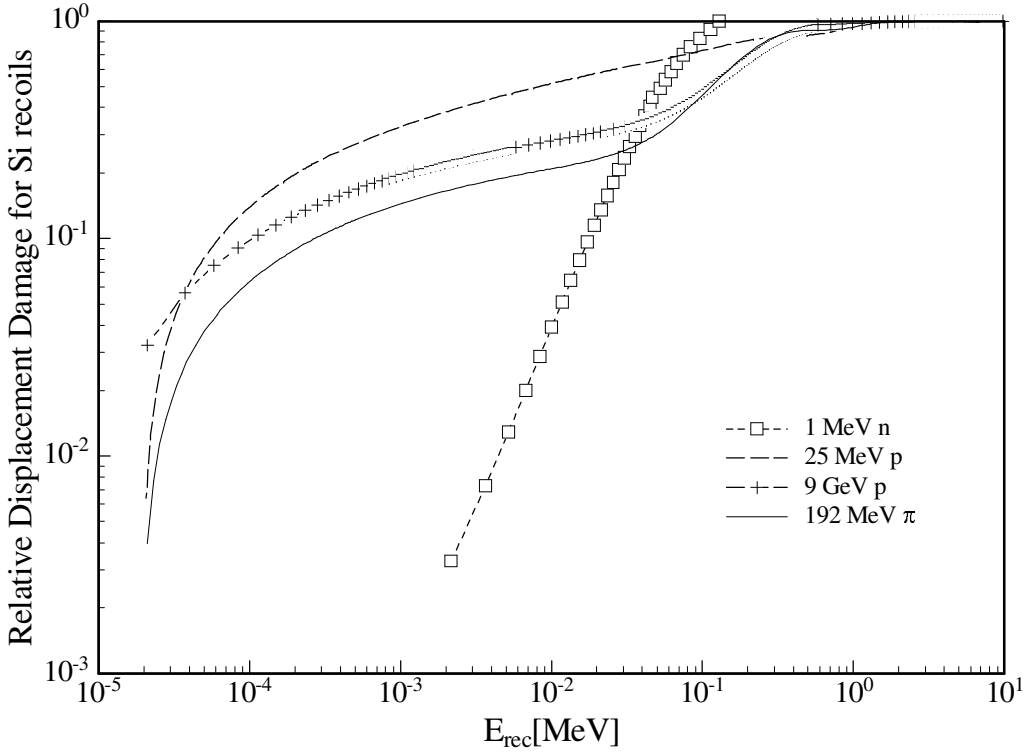
Relative Displacement Damage for Si recoils
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$E_{rec}$[MeV]
1 MeV n
25 MeV p
9 GeV p
192 MeV π

**Fig. 19**