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 [6]

Fig 3b:
Current related damage rate α as function of cumulated annealing time at 60°C. Comparison between data obtained for oxygen diffused silicon and parameterisation given in Ref. [6].

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 [6].

Fig 7:
Systematic analysis of annealing data. Change of effective doping concentration ΔN_{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 13a:
Damage projections for the B-Layer of the ATLAS Pixel Detector.

Fig 13b:
Damage projections for ATLAS strip detectors located 30cm from the interaction point.

Fig 14:
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 15:
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) [16].

Fig 16:
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 [16].

Fig 17a:
Evolution of the DLTS spectrum at 60°C for a neutron irradiated sample produced from Cz silicon [16].

Fig 17b:
Correlation between trap E4b and leakage current [16].

Fig 18:
Relative damage efficiency for different particles as function of recoil energy.

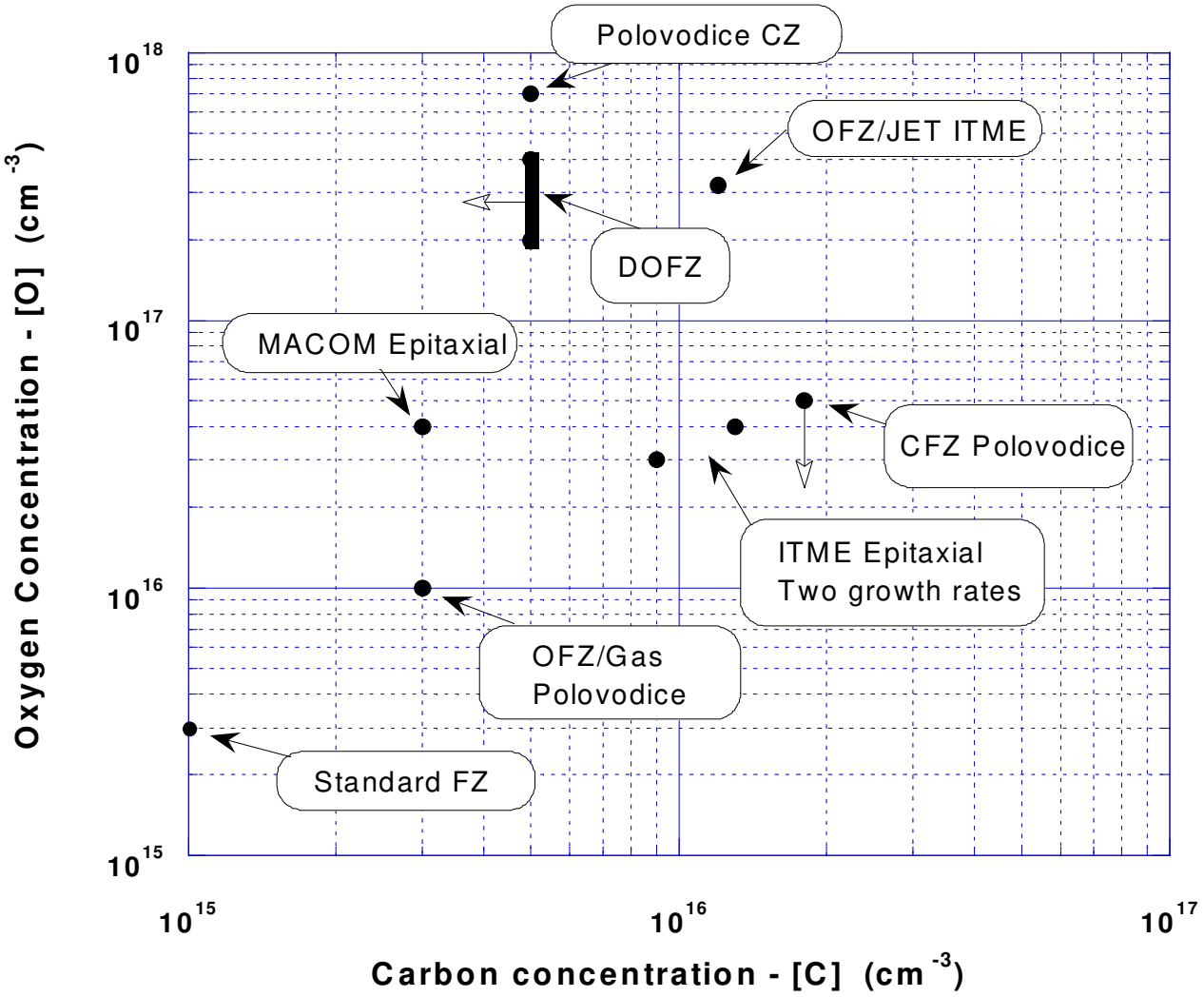
Polovodice CZ
OFZ/JET ITME
DOFZ
MACOM Epitaxial
CFZ Polovodice
ITME Epitaxial
Two growth rates
OFZ/Gas
Polovodice
Standard FZ
10^18
10^17
10^16
10^15
10^15
10^16
10^17
Oxygen Concentration - [O] (cm^-3)
Carbon concentration - [C] (cm^-3)

Fig. 1

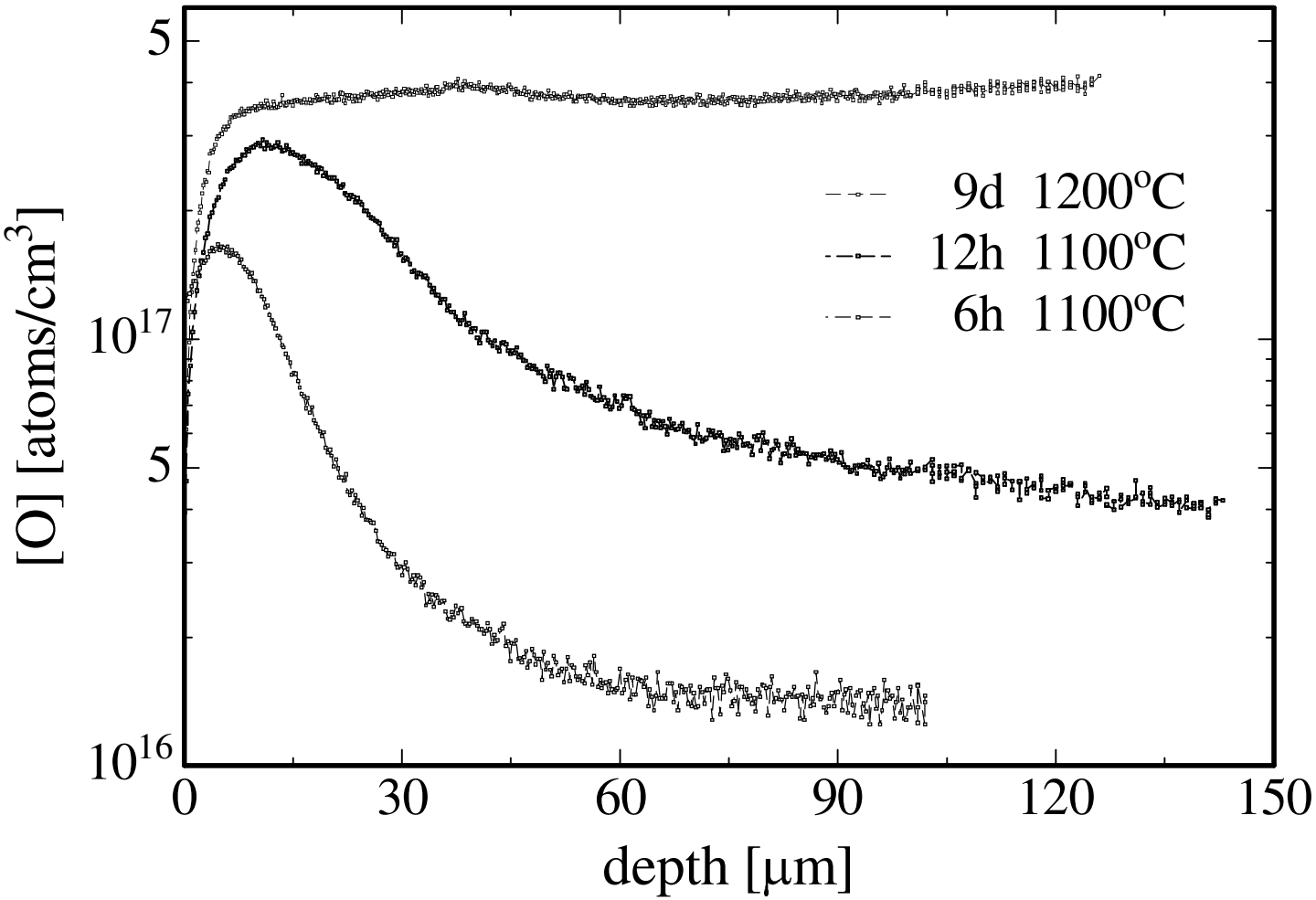
5
10^{17}
5
10^{16}
[O] [atoms/cm^3]
0
30
60
90
120
150
depth [μm]
9d 1200°C
12h 1100°C
6h 1100°C

Fig. 2

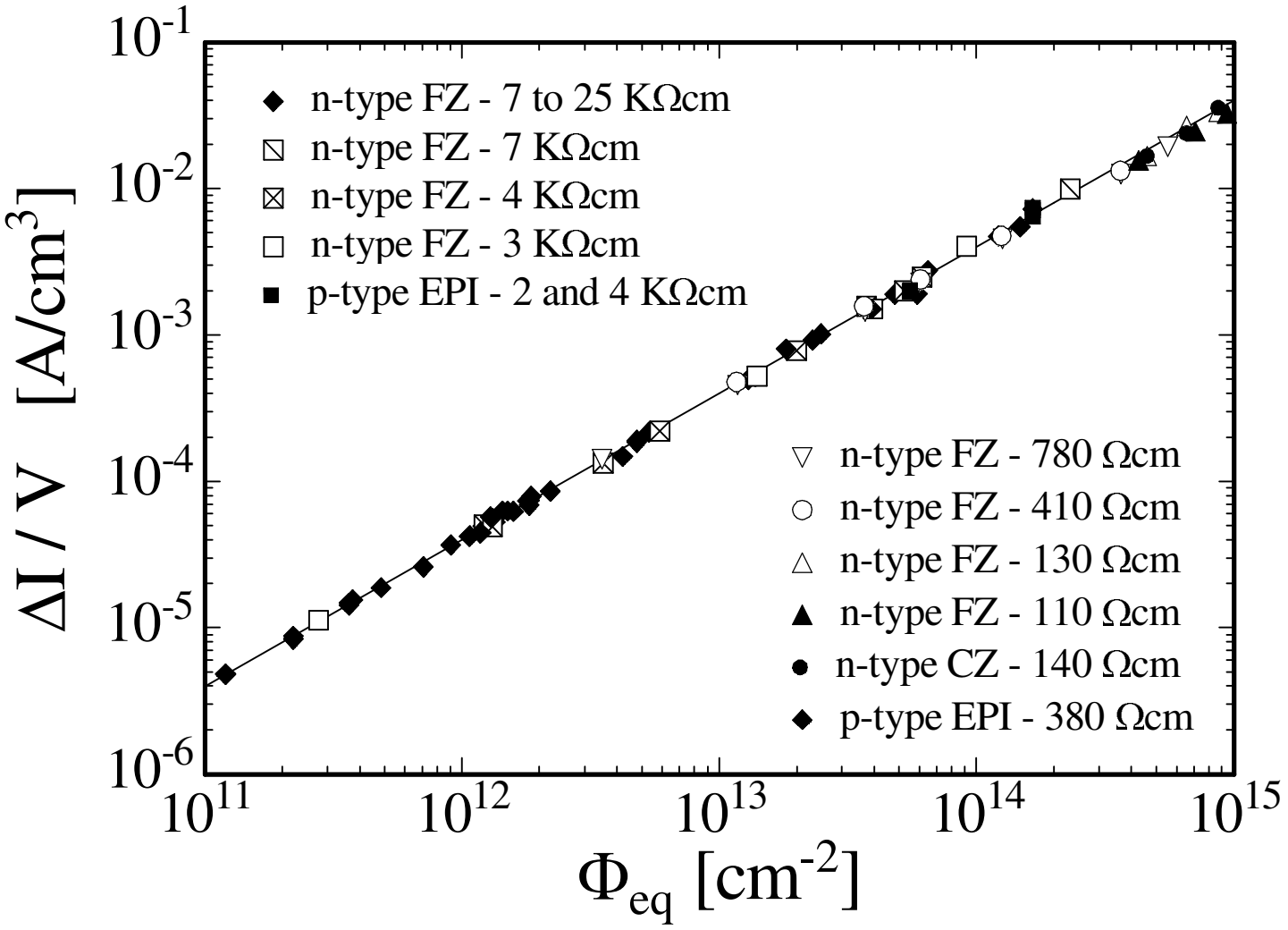
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\Delta I / V$ [A/cm^3]
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Φ_{eq} [cm^{-2}]
n-type FZ - 7 to 25 KΩcm
n-type FZ - 7 KΩcm
n-type FZ - 4 KΩcm
n-type FZ - 3 KΩcm
p-type EPI - 2 and 4 KΩcm
n-type FZ - 780 Ωcm
n-type FZ - 410 Ωcm
n-type FZ - 130 Ωcm
n-type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

Fig. 3a

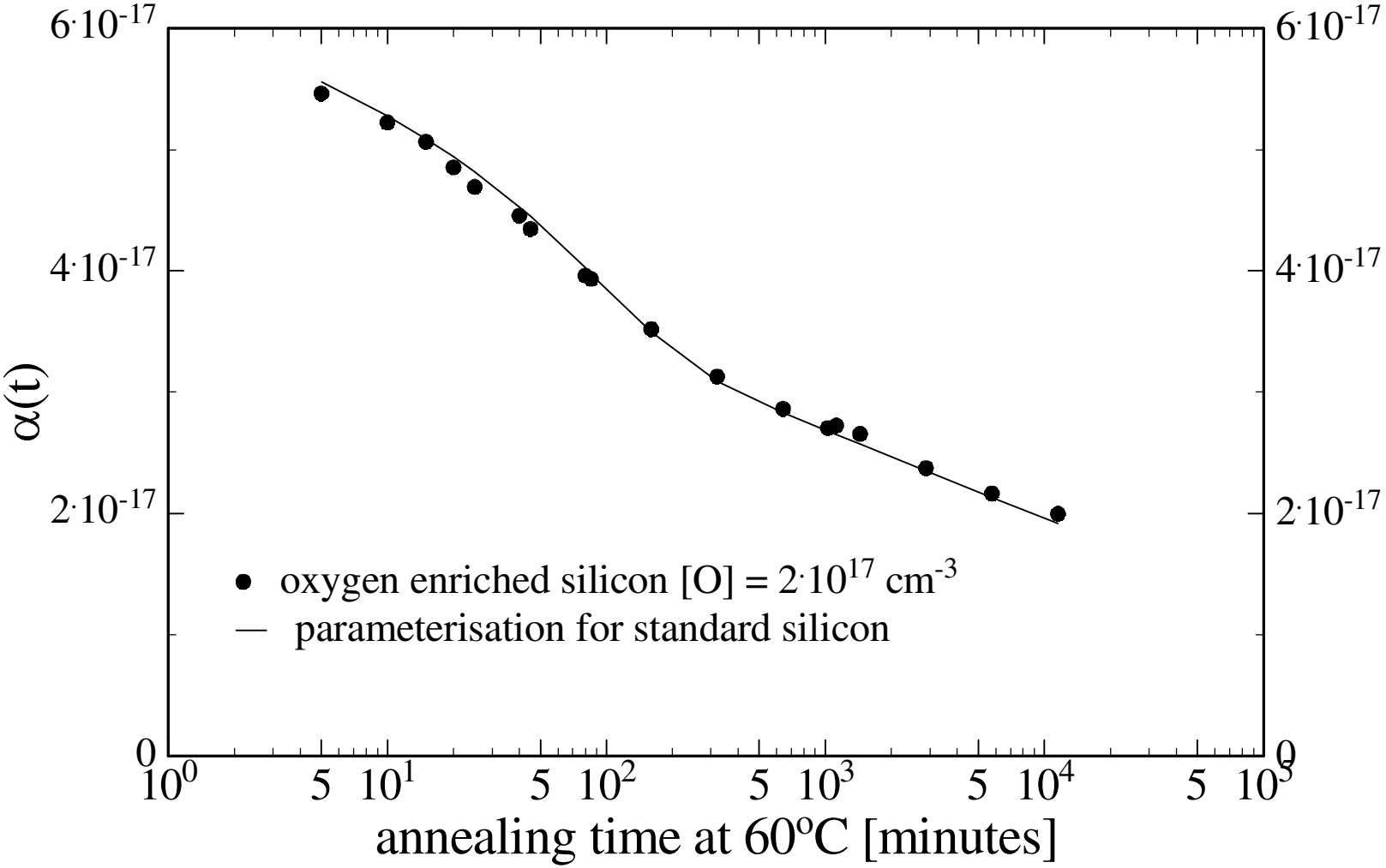
6·10-17
4·10-17
2·10-17
0
α(t)
oxygen enriched silicon [O] = 2·10^17 cm^-3
parameterisation for standard silicon
10^0
5 10^1
5 10^2
5 10^3
5 10^4
5 10^5
annealing time at 60°C [minutes]

Fig 3b

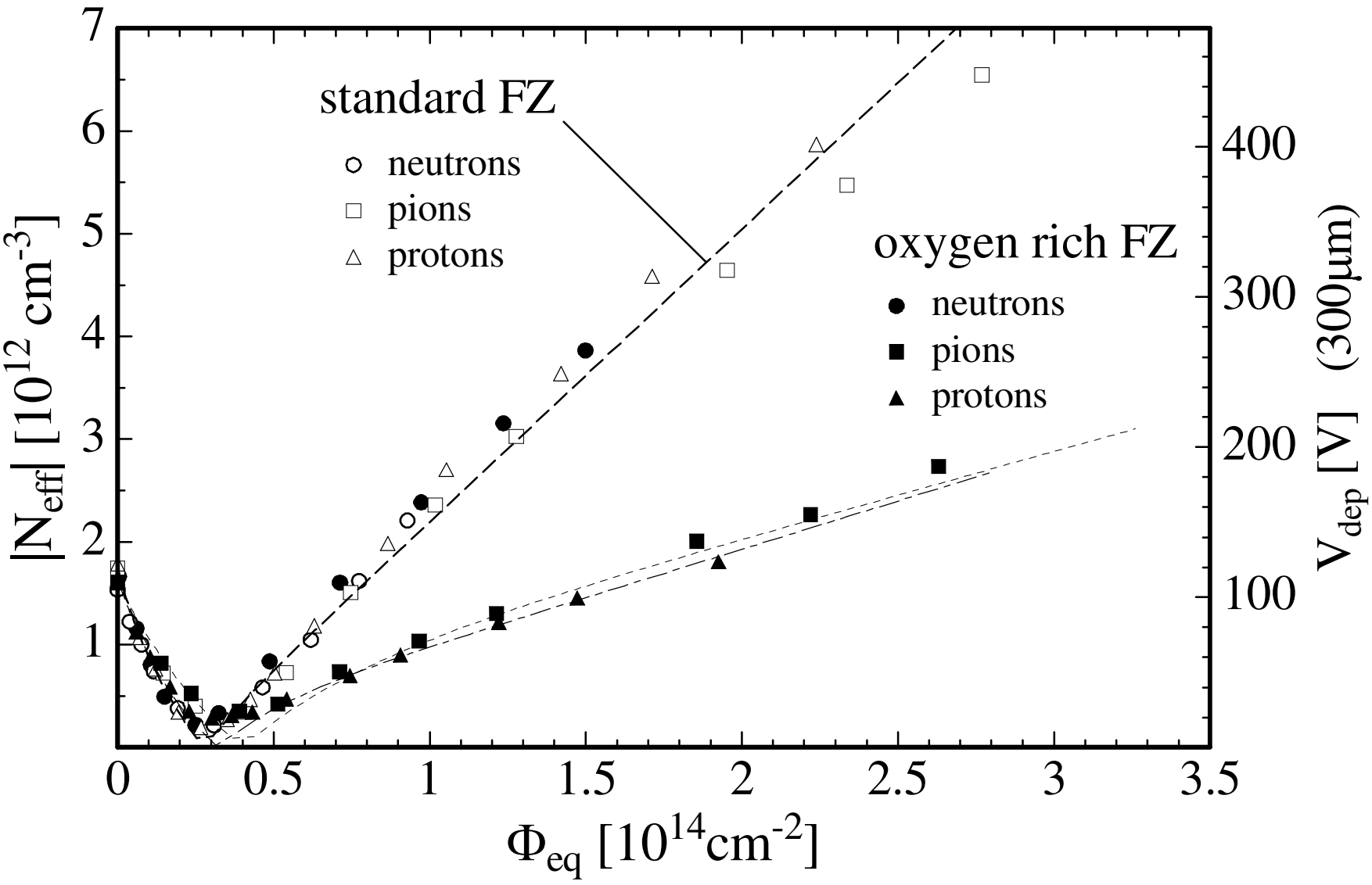
standard FZ
neutrons
pions
protons
oxygen rich FZ
neutrons
pions
protons
|N_eff| [10^12 cm^-3]
V_dep [V] (300μm)
Φ_eq [10^14cm^-2]
0
0.5
1
1.5
2
2.5
3
3.5
1
2
3
4
5
6
7
100
200
300
400

Fig. 4a

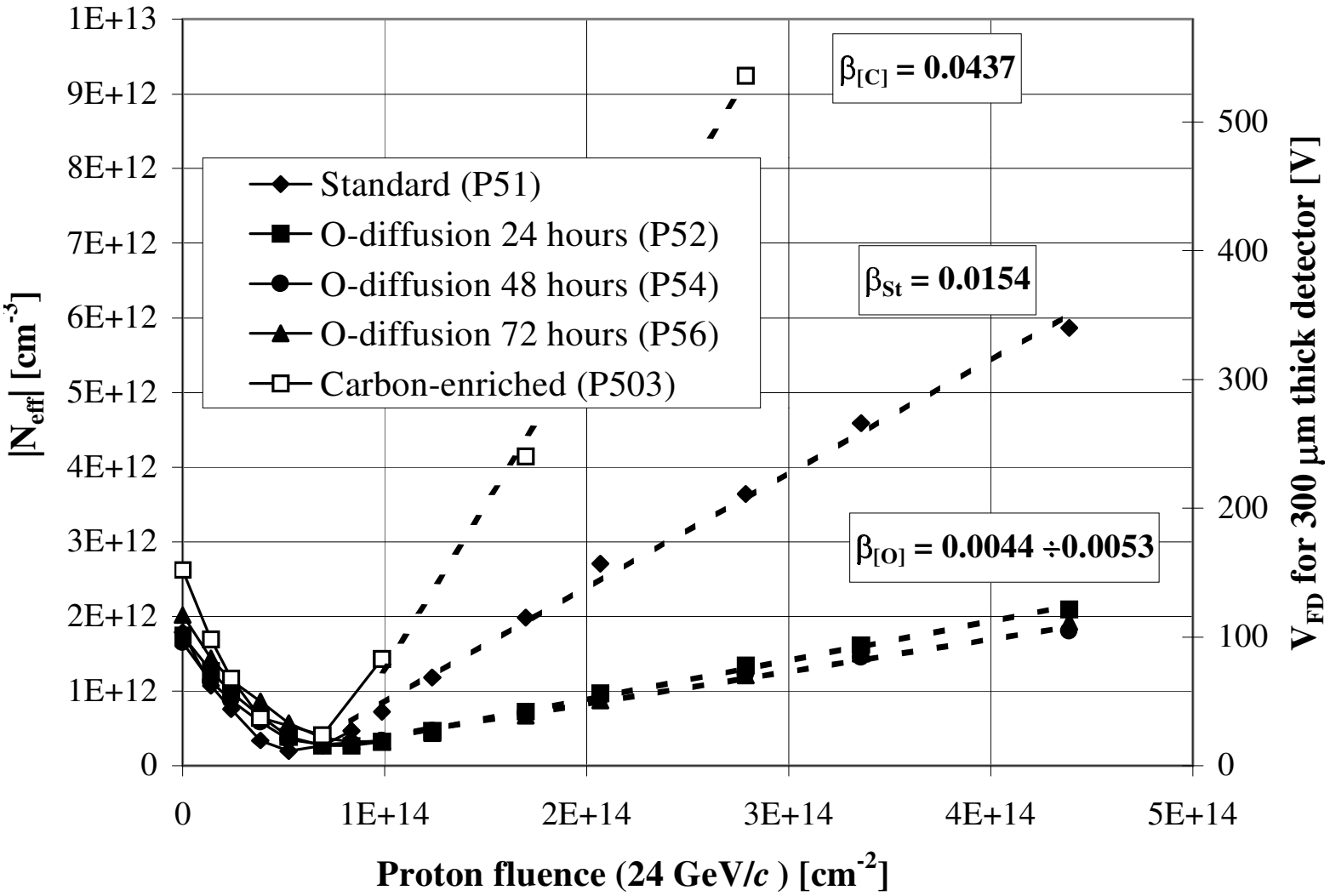
1E+13
9E+12
8E+12
7E+12
6E+12
5E+12
4E+12
3E+12
2E+12
1E+12
0
|Neff| [cm-3]
0
1E+14
2E+14
3E+14
4E+14
5E+14
Proton fluence (24 GeV/c) [cm-2]
500
400
300
200
100
0
VFD for 300 μm thick detector [V]
Standard (P51)
O-diffusion 24 hours (P52)
O-diffusion 48 hours (P54)
O-diffusion 72 hours (P56)
Carbon-enriched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

Fig. 4b

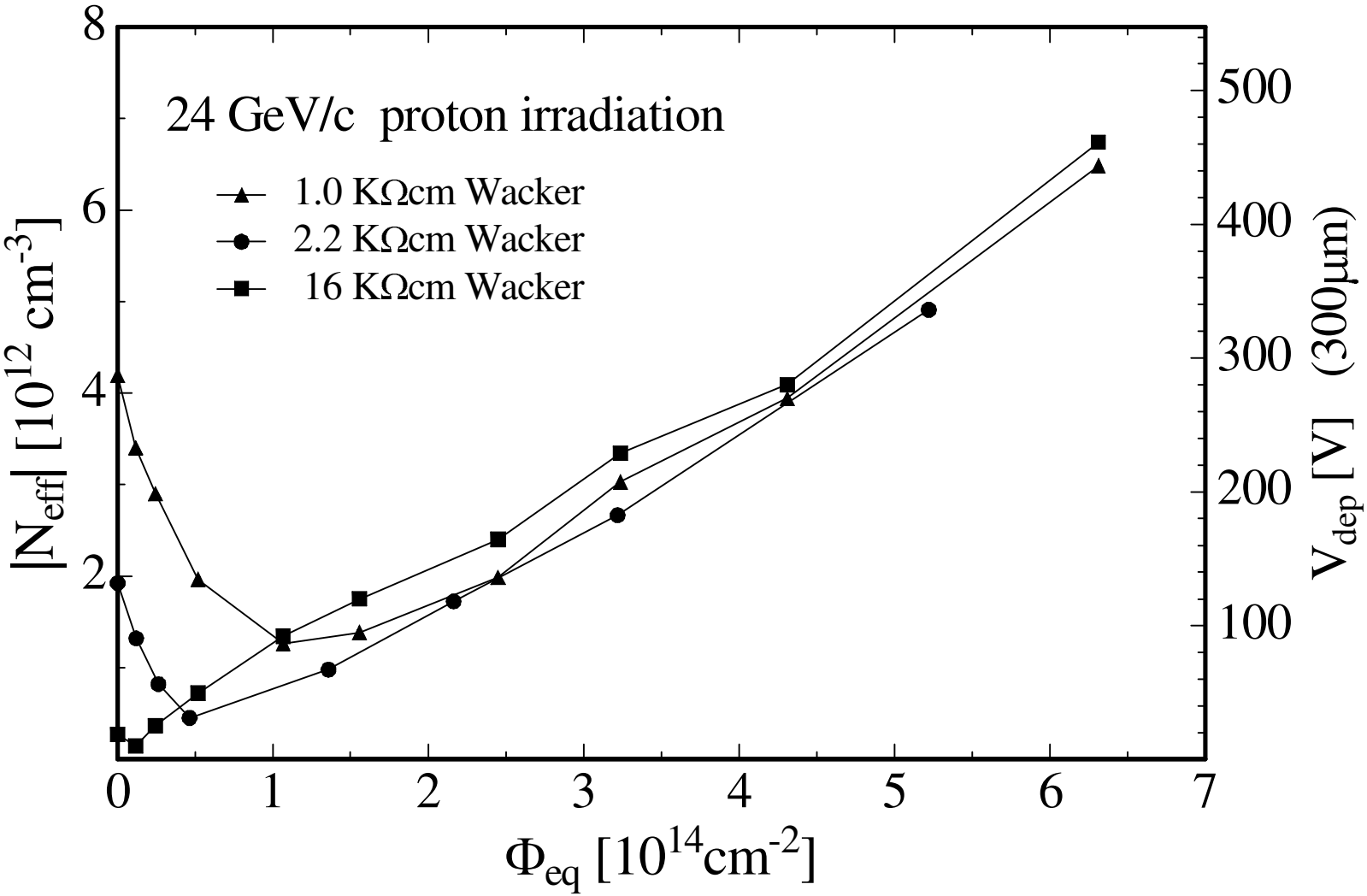
24 GeV/c proton irradiation
1.0 KΩcm Wacker
2.2 KΩcm Wacker
16 KΩcm Wacker
|N_eff| [10^12 cm^-3]
V_dep [V] (300μm)
Φ_eq [10^14cm^-2]
0
1
2
3
4
5
6
7
2
4
6
8
100
200
300
400
500

Fig. 5a

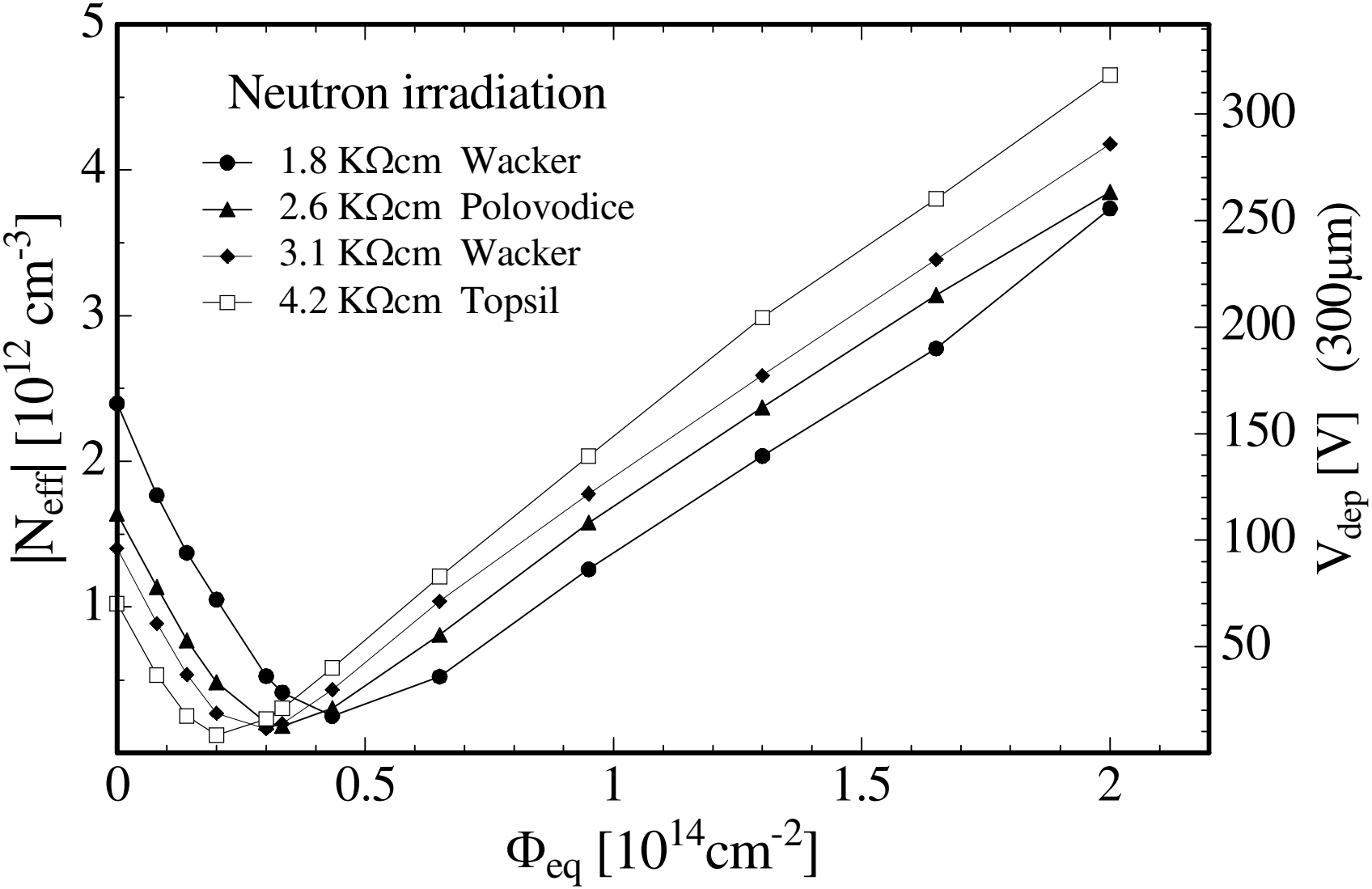
Neutron irradiation
1.8 KΩcm Wacker
2.6 KΩcm Polovodice
3.1 KΩcm Wacker
4.2 KΩcm Topsil
|Neff| [10^12 cm^-3]
Vdep [V] (300μm)
Φeq [10^14cm^-2]
0
0.5
1
1.5
2
1
2
3
4
5
50
100
150
200
250
300

Fig. 5b

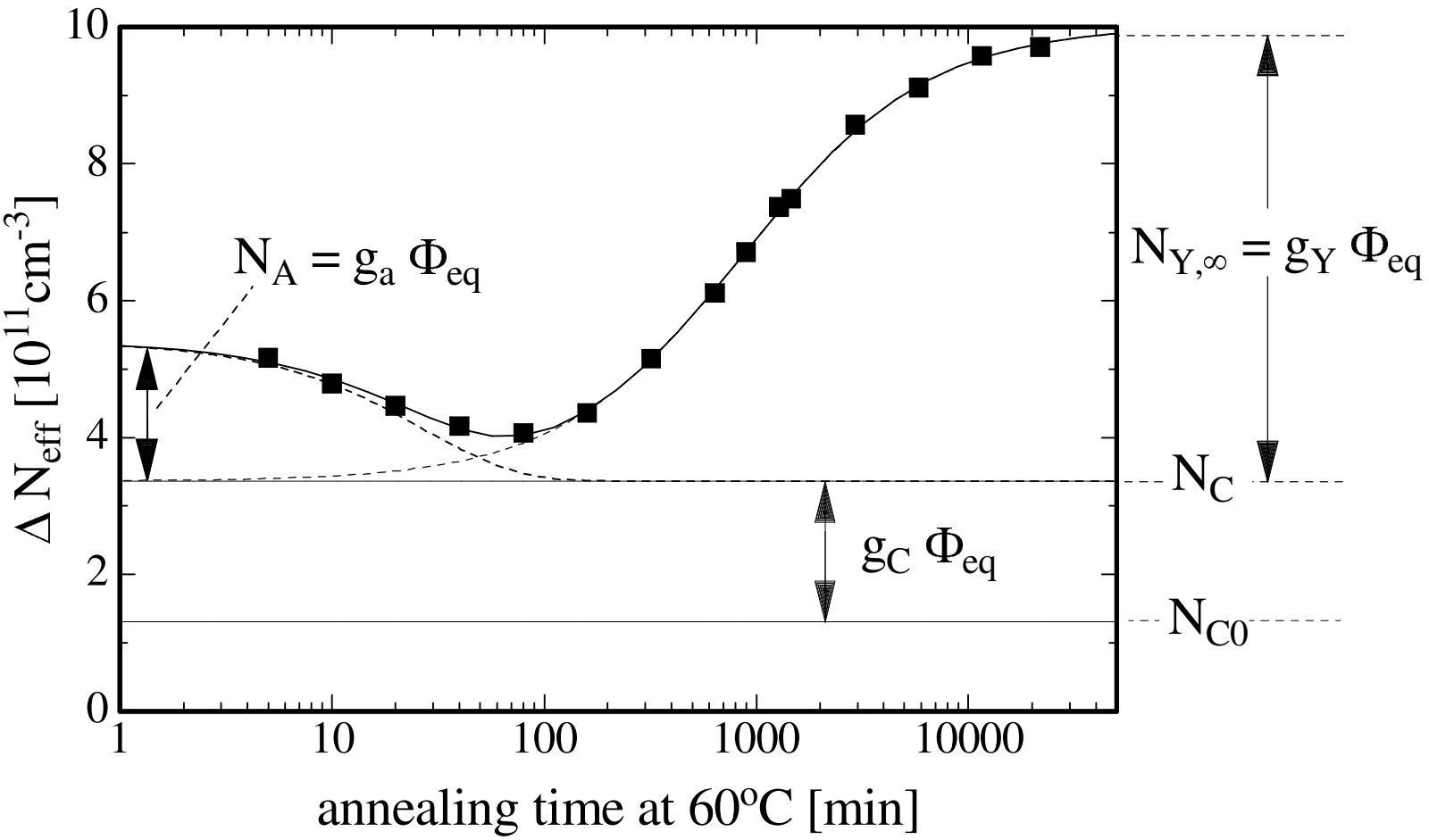
10
8
6
4
2
0
1
10
100
1000
10000
ΔN_eff [10^11 cm^-3]
annealing time at 60°C [min]
N_A = g_a Φ_eq
N_Y,∞ = g_Y Φ_eq
N_C
g_C Φ_eq
N_C0

Fig. 6

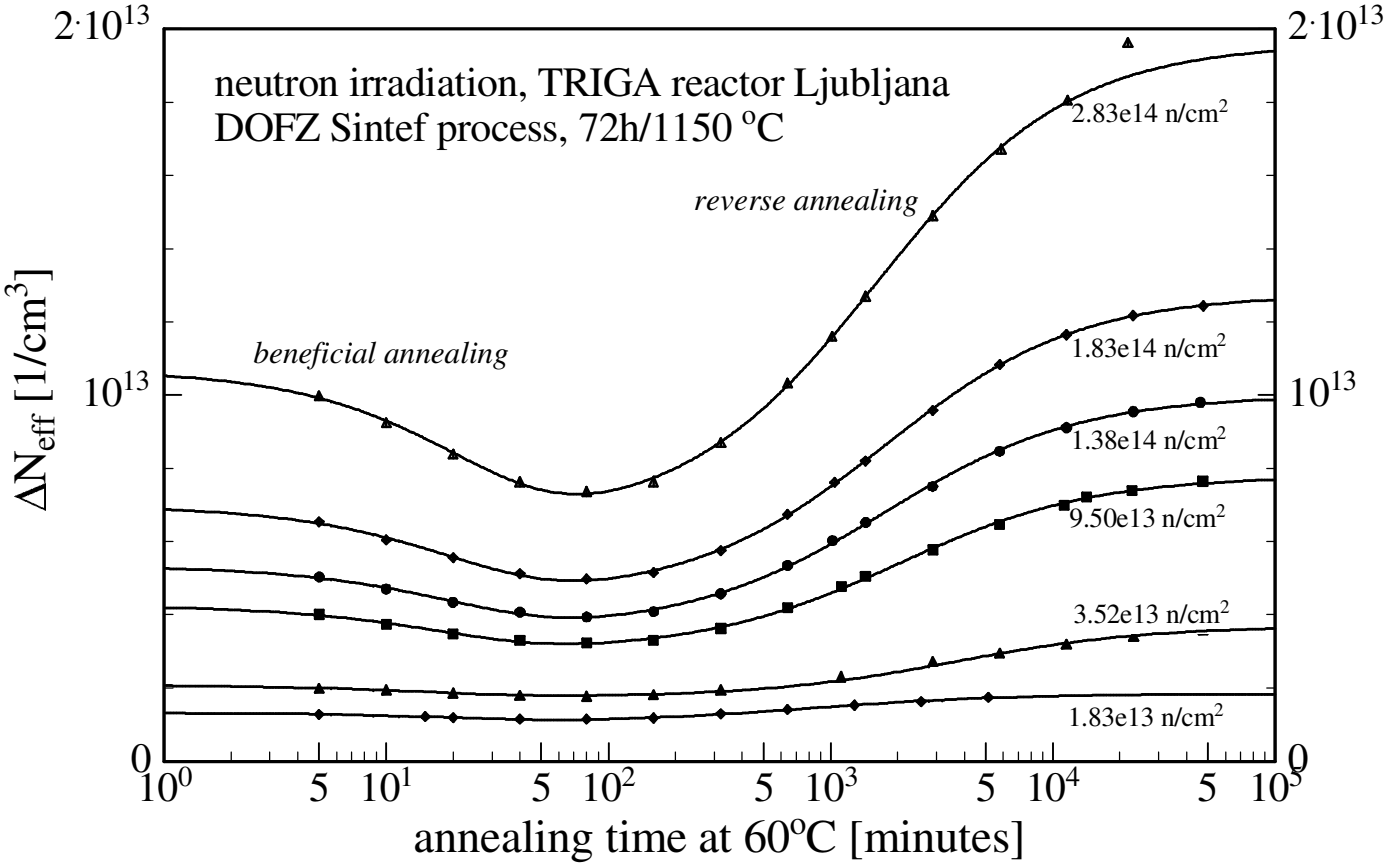
neutron irradiation, TRIGA reactor Ljubljana
DOFZ Sintef process, 72h/1150 °C
reverse annealing
beneficial annealing
2.83e14 n/cm2
1.83e14 n/cm2
1.38e14 n/cm2
9.50e13 n/cm2
3.52e13 n/cm2
1.83e13 n/cm2
2·10^13
10^13
0
ΔNeff [1/cm3]
10^0 5 10^1 5 10^2 5 10^3 5 10^4 5 10^5
annealing time at 60°C [minutes]

Fig. 7

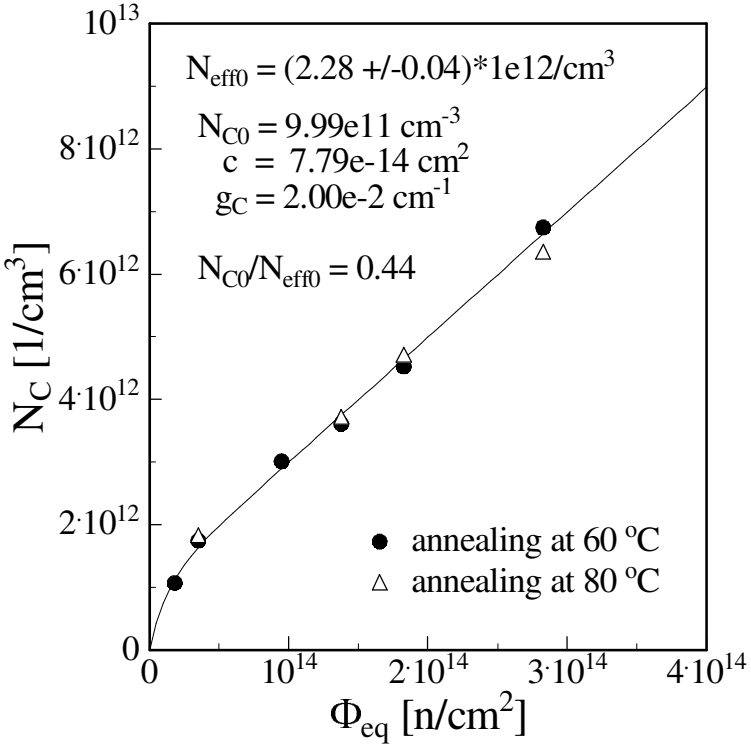
N_{eff0} = (2.28 +/-0.04)*1e12/cm^3
N_{C0} = 9.99e11 cm^{-3}
c = 7.79e-14 cm^2
g_C = 2.00e-2 cm^{-1}
N_{C0}/N_{eff0} = 0.44
annealing at 60 °C
annealing at 80 °C
N_C [1/cm^3]
Φ_{eq} [n/cm^2]
10^{13}
$8\cdot10^{12}$
$6\cdot10^{12}$
$4\cdot10^{12}$
$2\cdot10^{12}$
0
10^{14}
$2\cdot10^{14}$
$3\cdot10^{14}$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

Fig. 8a

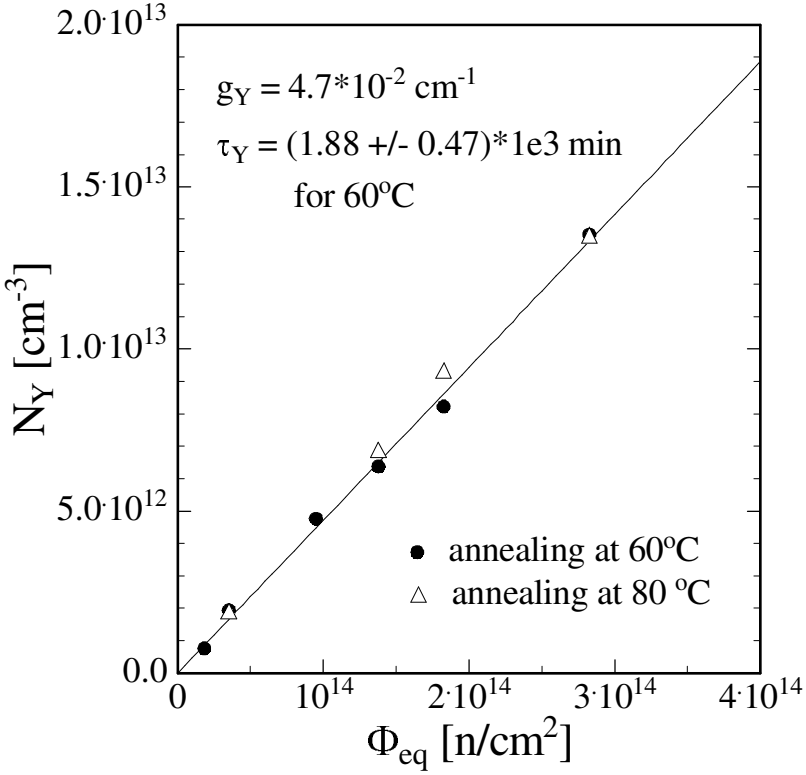
g_Y = 4.7*10^{-2} cm^{-1}
τ_Y = (1.88 +/- 0.47)*1e3 min
for 60°C
annealing at 60°C
annealing at 80 °C
N_Y [cm^{-3}]
Φ_{eq} [n/cm^2]
$2.0\cdot10^{13}$
$1.5\cdot10^{13}$
$1.0\cdot10^{13}$
$5.0\cdot10^{12}$
0.0
10^{14}
$2\cdot10^{14}$
$3\cdot10^{14}$
$4\cdot10^{14}$

Fig 8b

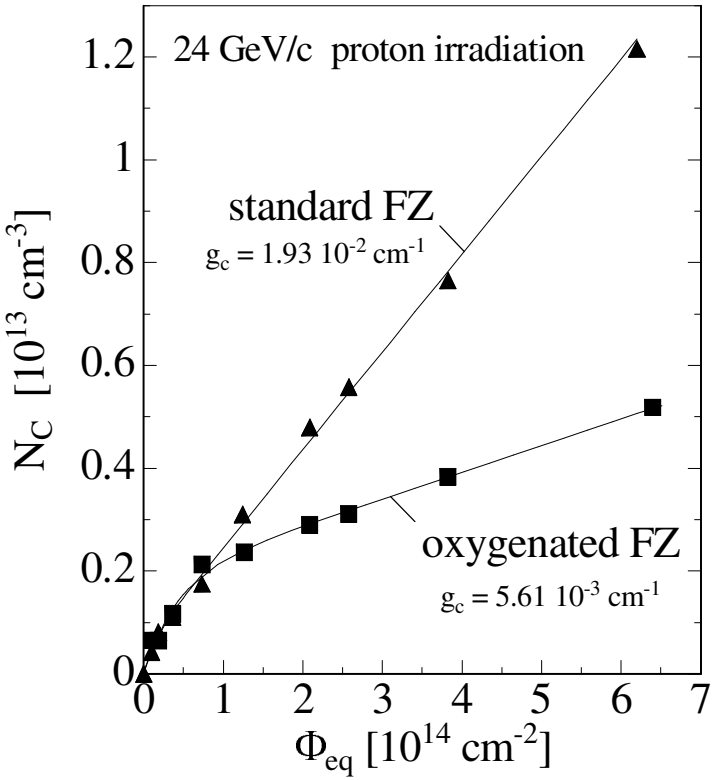
24 GeV/c proton irradiation
standard FZ
$g_c = 1.93\ 10^{-2}\ cm^{-1}$
oxygenated FZ
$g_c = 5.61\ 10^{-3}\ cm^{-1}$
$N_C\ [10^{13}\ cm^{-3}]$
$\Phi_{eq}\ [10^{14}\ cm^{-2}]$

Fig. 9a

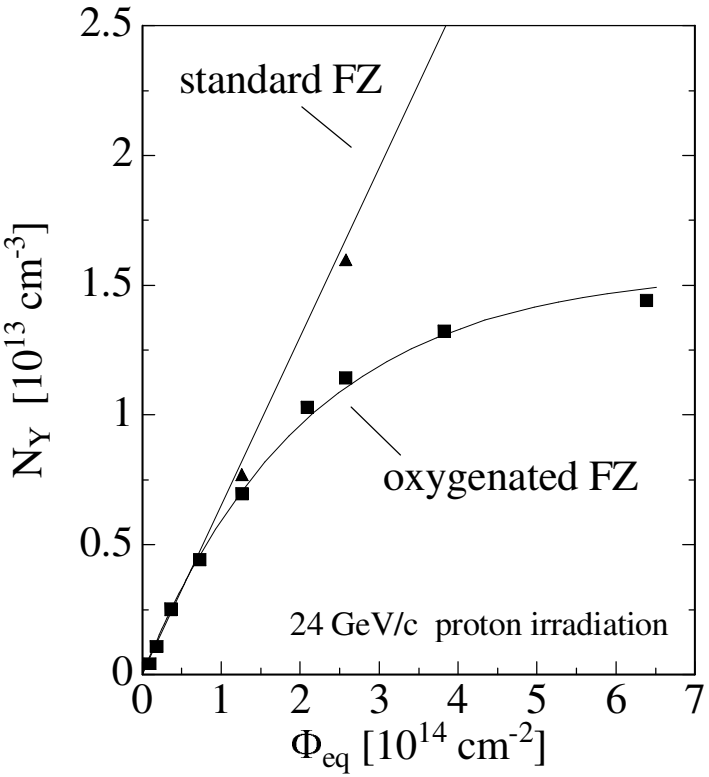
standard FZ
oxygenated FZ
24 GeV/c proton irradiation
$N_Y\ [10^{13}\ cm^{-3}]$
$\Phi_{eq}\ [10^{14}\ cm^{-2}]$

Fig 9b

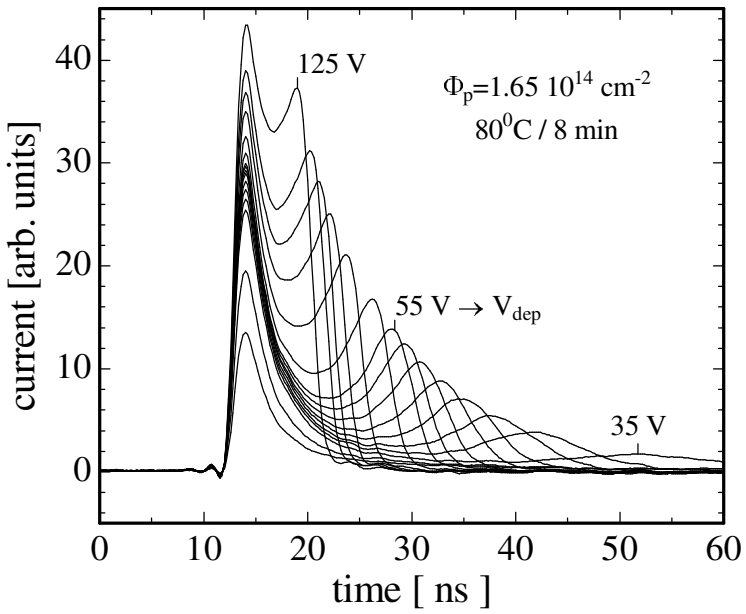

Fig. 10a

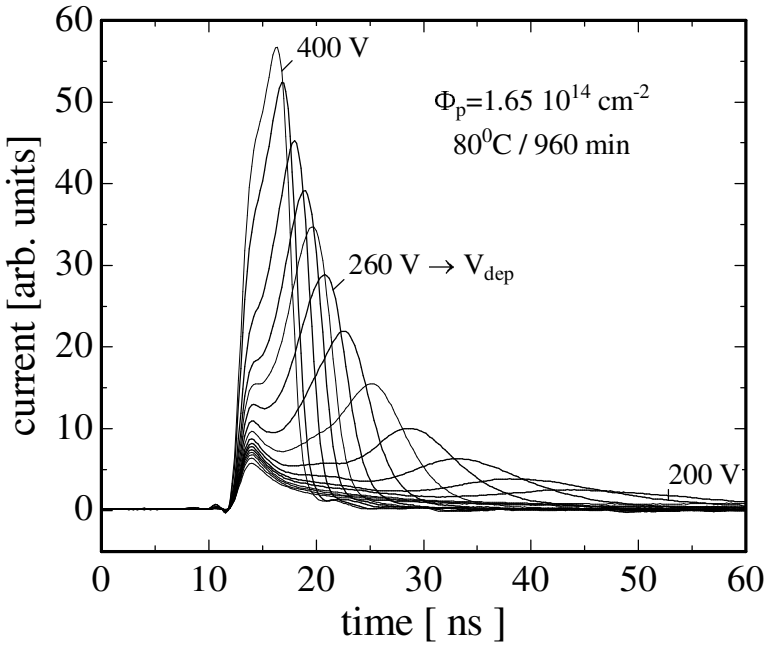

Fig 10b

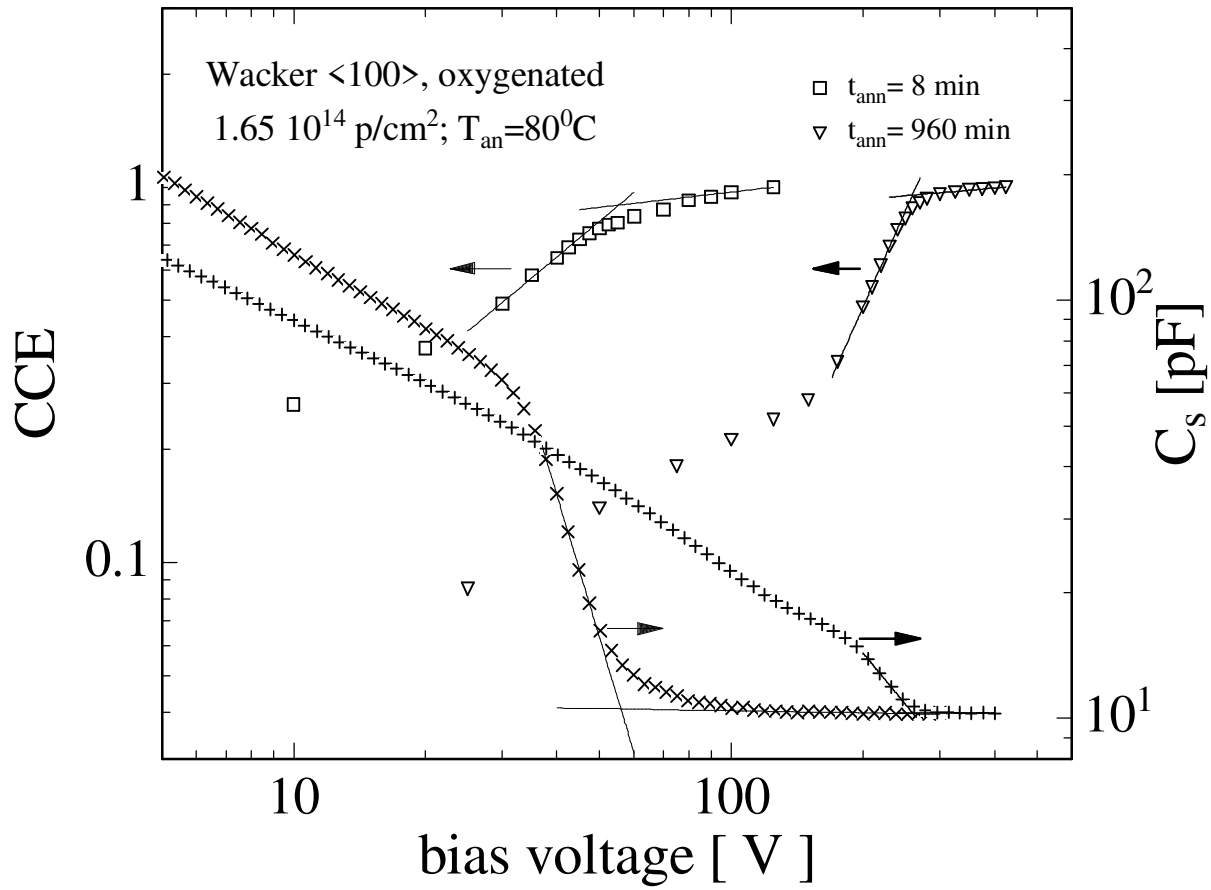
Wacker <100>, oxygenated
1.65 10^14 p/cm^2; T_an=80^0C
t_ann= 8 min
t_ann= 960 min
CCE
C_s [pF]
1
0.1
10^2
10^1
10
100
bias voltage [V]

Fig. 11

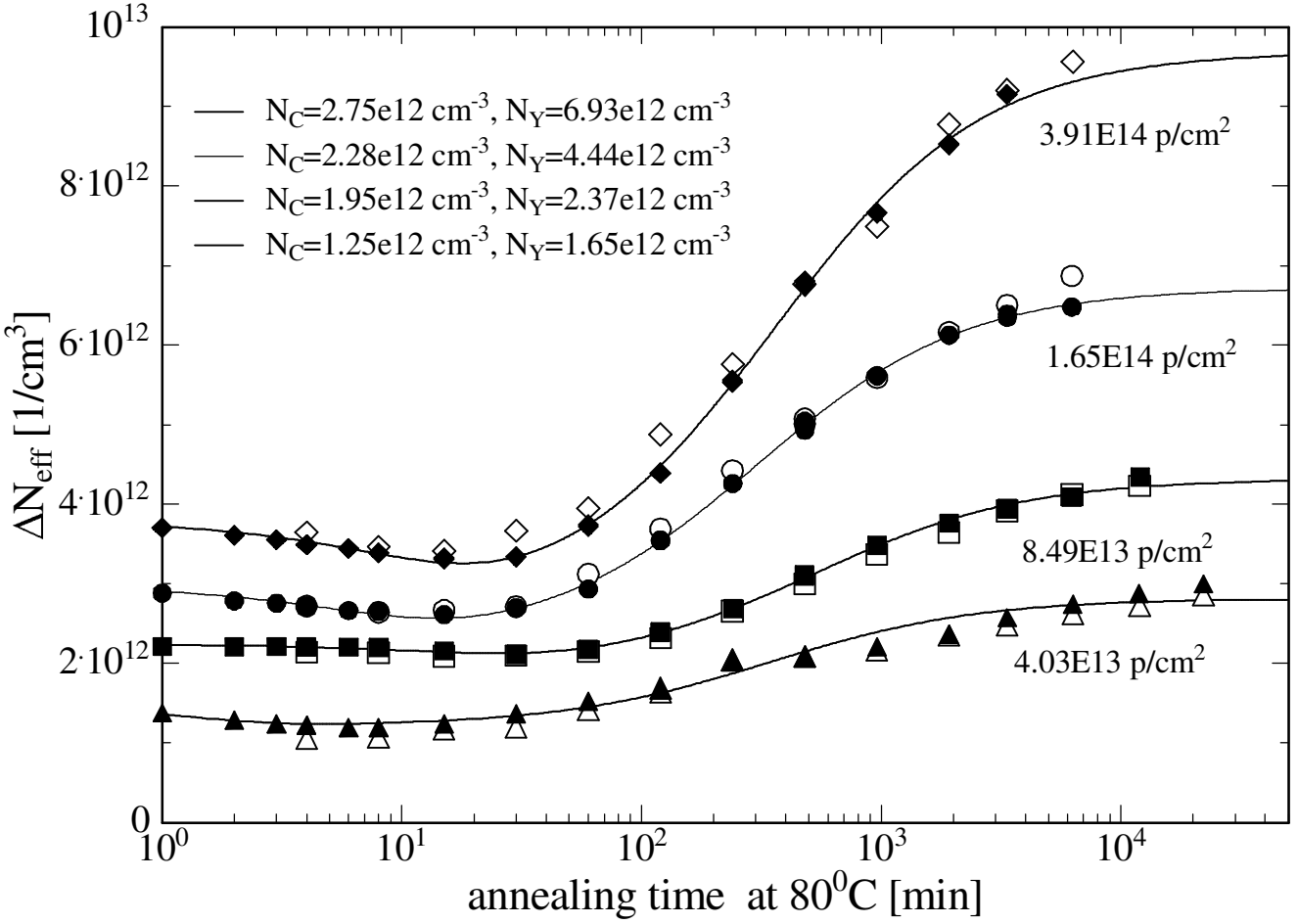
10^{13}
$8\cdot10^{12}$
$6\cdot10^{12}$
$4\cdot10^{12}$
$2\cdot10^{12}$
0
ΔN_{eff} [1/cm^3]
10^0
10^1
10^2
10^3
10^4
annealing time at 80^{0}C [min]
N_C=2.75e12 cm^{-3}, N_Y=6.93e12 cm^{-3}
N_C=2.28e12 cm^{-3}, N_Y=4.44e12 cm^{-3}
N_C=1.95e12 cm^{-3}, N_Y=2.37e12 cm^{-3}
N_C=1.25e12 cm^{-3}, N_Y=1.65e12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

Fig. 12

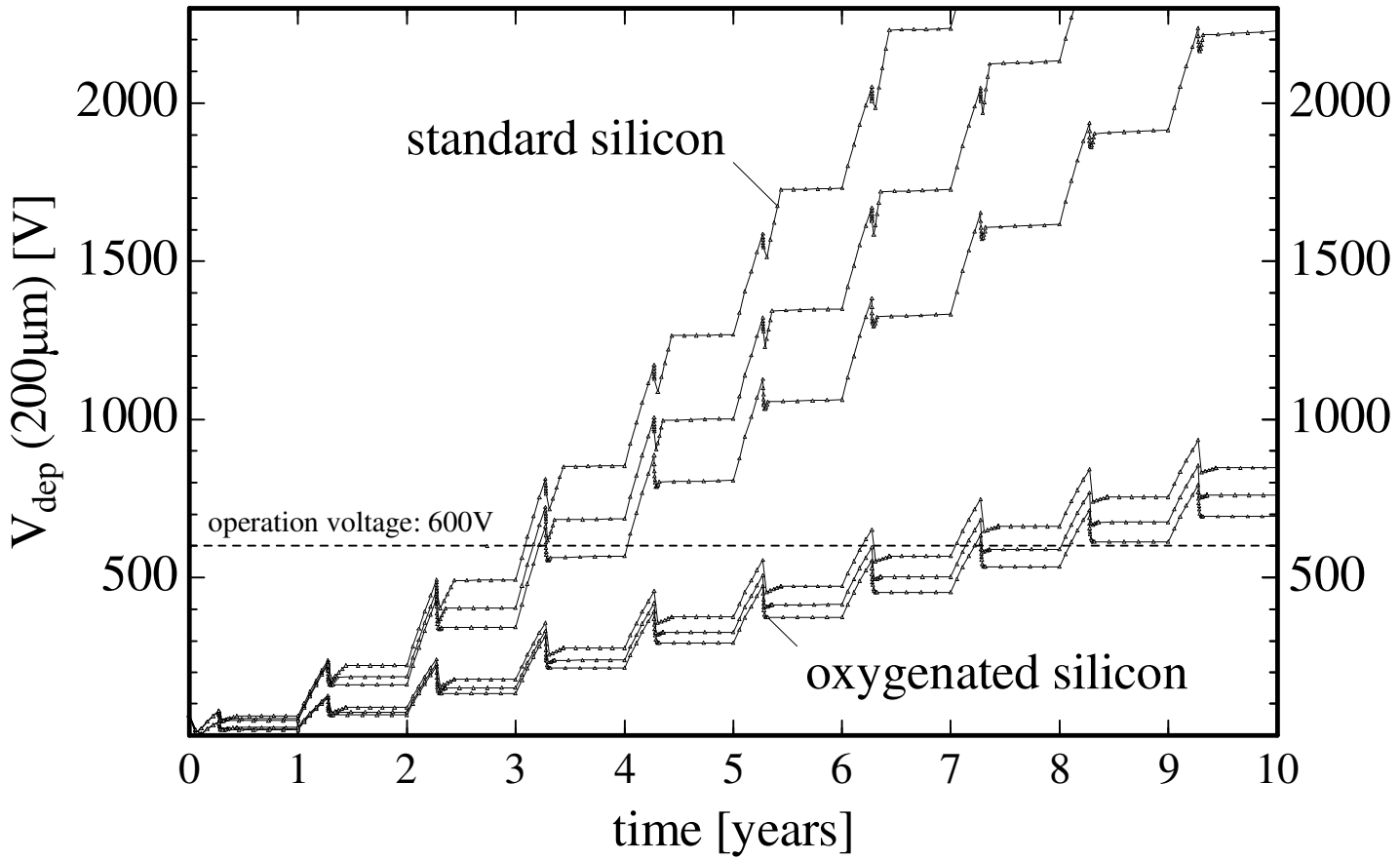
standard silicon
oxygenated silicon
operation voltage: 600V
V_{dep} (200µm) [V]
time [years]
2000
1500
1000
500
0
1
2
3
4
5
6
7
8
9
10

Fig. 13a

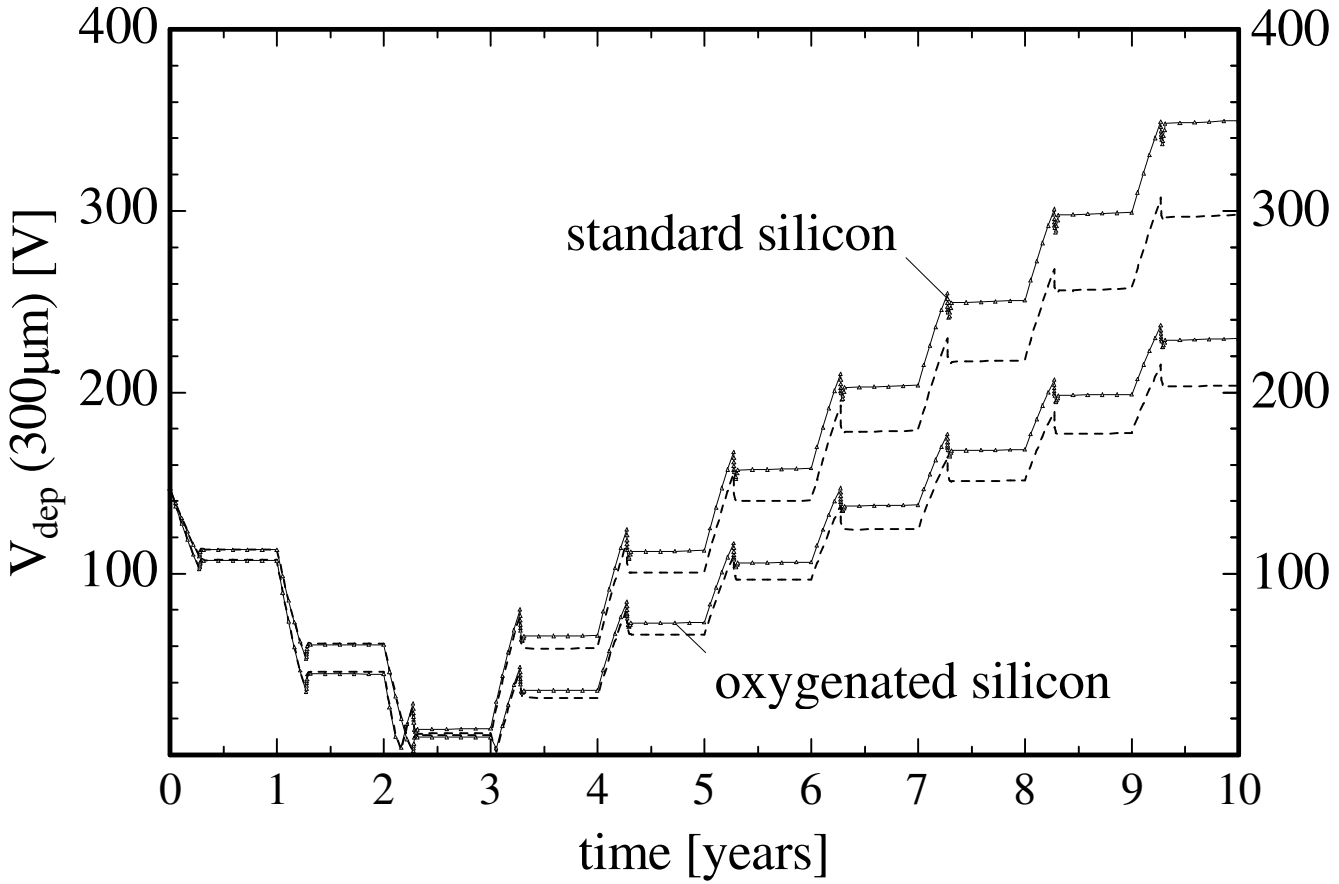
400
300
200
100
0
1
2
3
4
5
6
7
8
9
10
V_{dep} (300μm) [V]
time [years]
standard silicon
oxygenated silicon

Fig. 13b

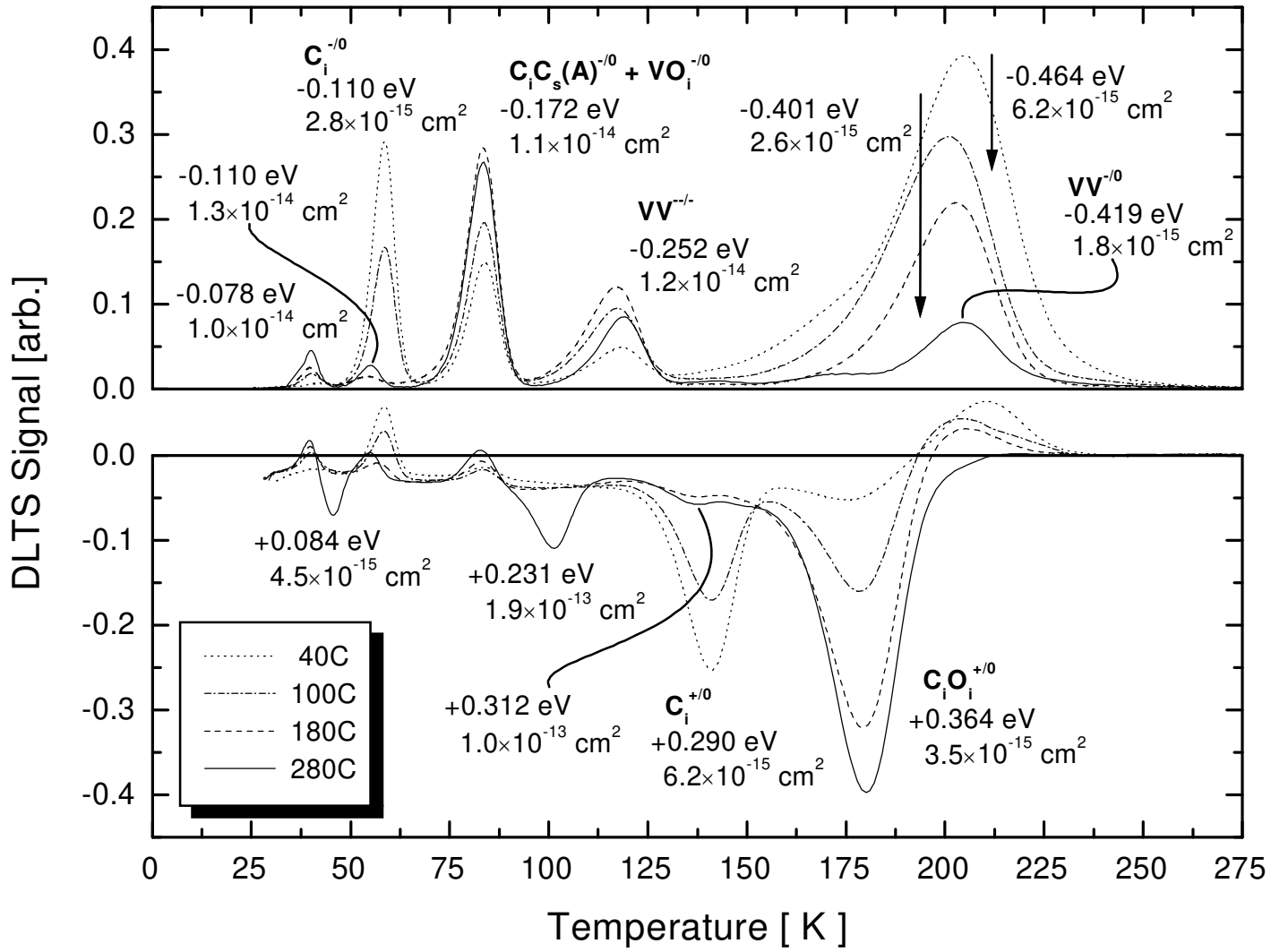
DLTS Signal [arb.]
Temperature [K]
C_i^-/0
-0.110 eV
2.8×10^-15 cm^2
C_iC_s(A)^-/0 + VO_i^-/0
-0.172 eV
1.1×10^-14 cm^2
-0.401 eV
2.6×10^-15 cm^2
-0.464 eV
6.2×10^-15 cm^2
-0.110 eV
1.3×10^-14 cm^2
VV^-/-
-0.252 eV
1.2×10^-14 cm^2
VV^-/0
-0.419 eV
1.8×10^-15 cm^2
-0.078 eV
1.0×10^-14 cm^2
+0.084 eV
4.5×10^-15 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. 14

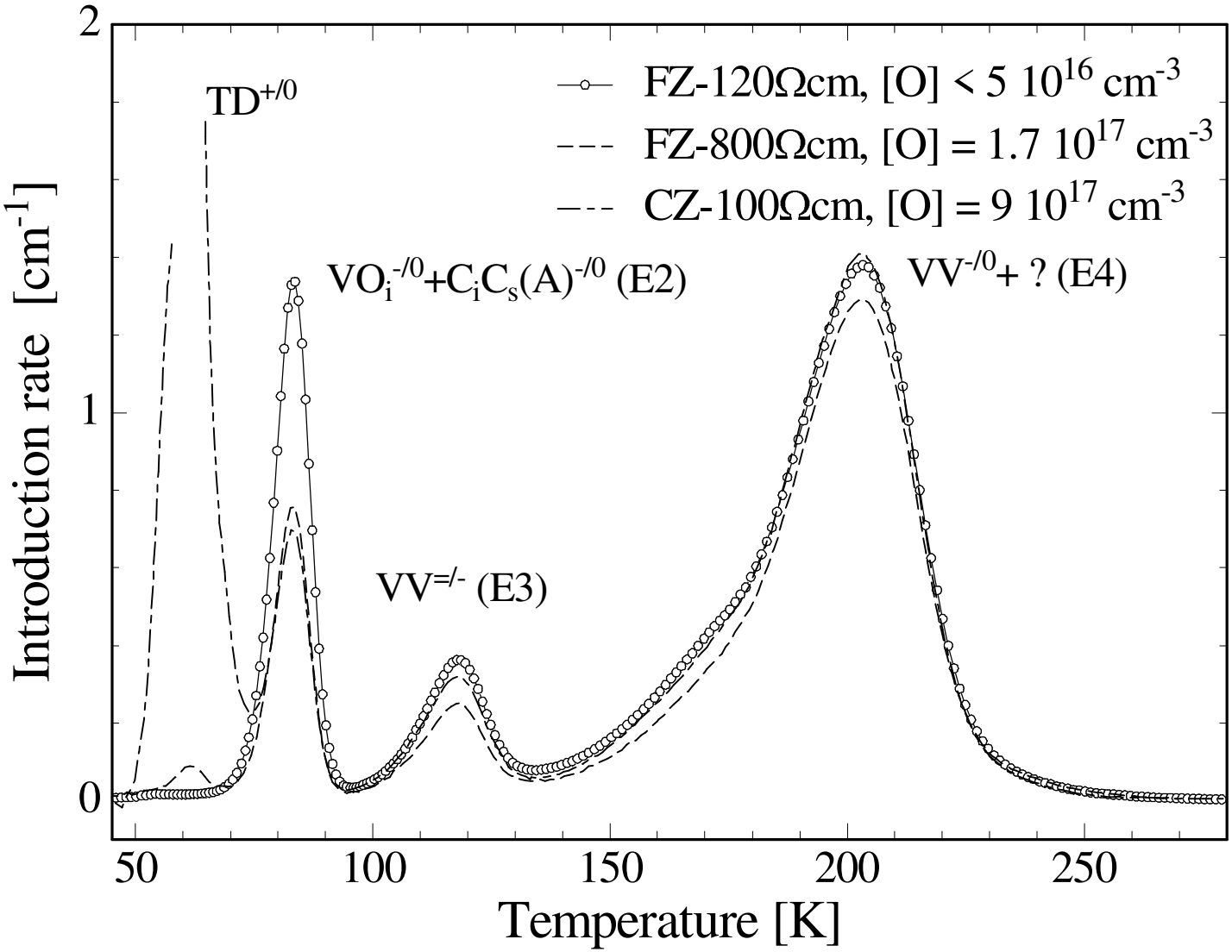
FZ-120Ωcm, [O] < 5 10^16 cm^-3
FZ-800Ωcm, [O] = 1.7 10^17 cm^-3
CZ-100Ωcm, [O] = 9 10^17 cm^-3
TD+/0
VOi-/0+CiCs(A)-/0 (E2)
VV=/- (E3)
VV-/0+ ? (E4)
Introduction rate [cm-1]
Temperature [K]
0
1
2
50
100
150
200
250

Fig. 15

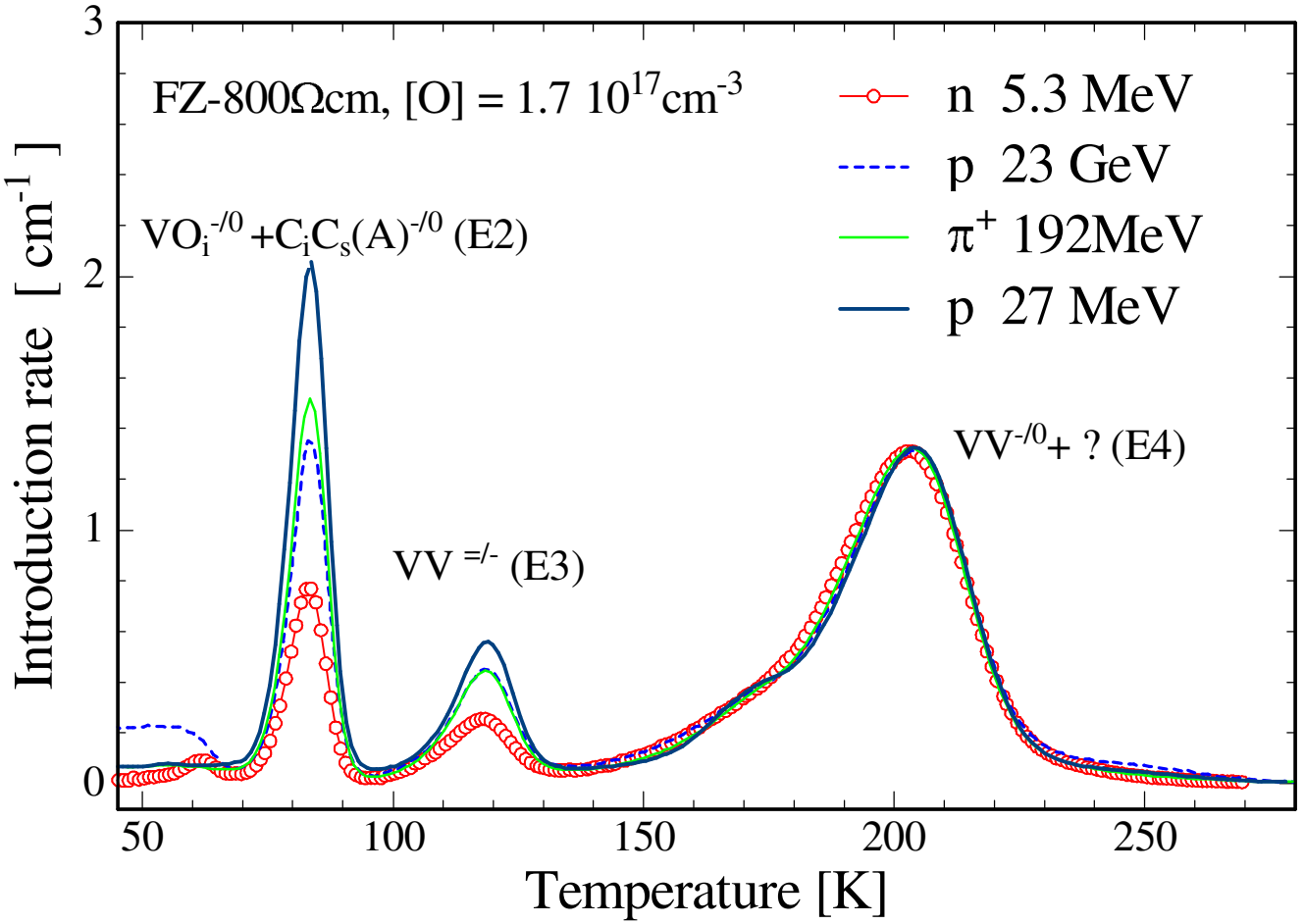
FZ-800Ωcm, [O] = 1.7 10^17cm^-3
n 5.3 MeV
p 23 GeV
π+ 192MeV
p 27 MeV
VOi-/0 +CiCs(A)-/0 (E2)
VV =/- (E3)
VV-/0+ ? (E4)
Introduction rate [cm-1]
Temperature [K]
0
1
2
3
50
100
150
200
250

Fig. 16

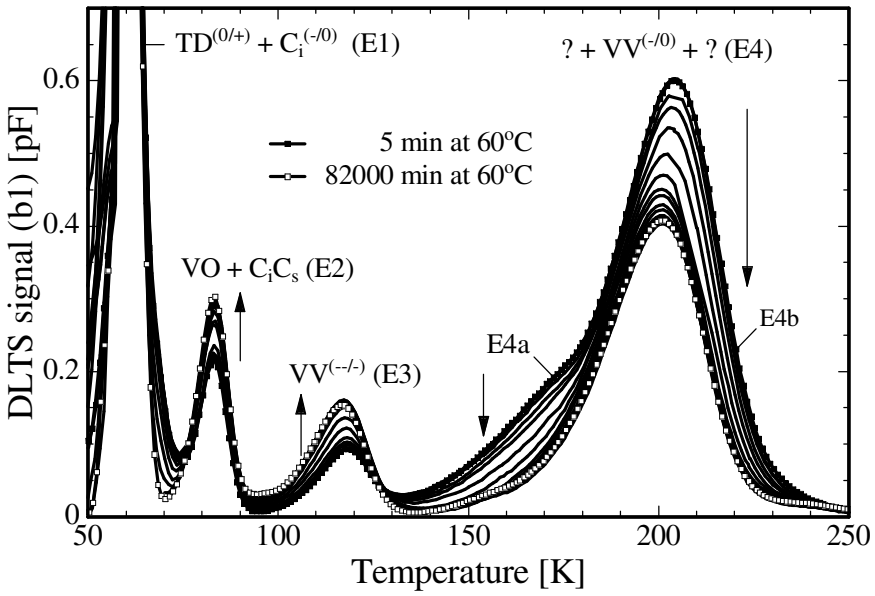

Fig. 17a

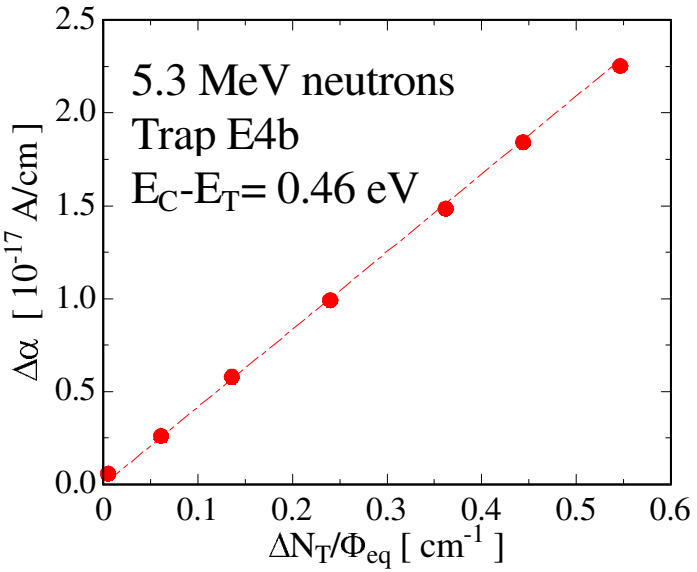

Fig17b

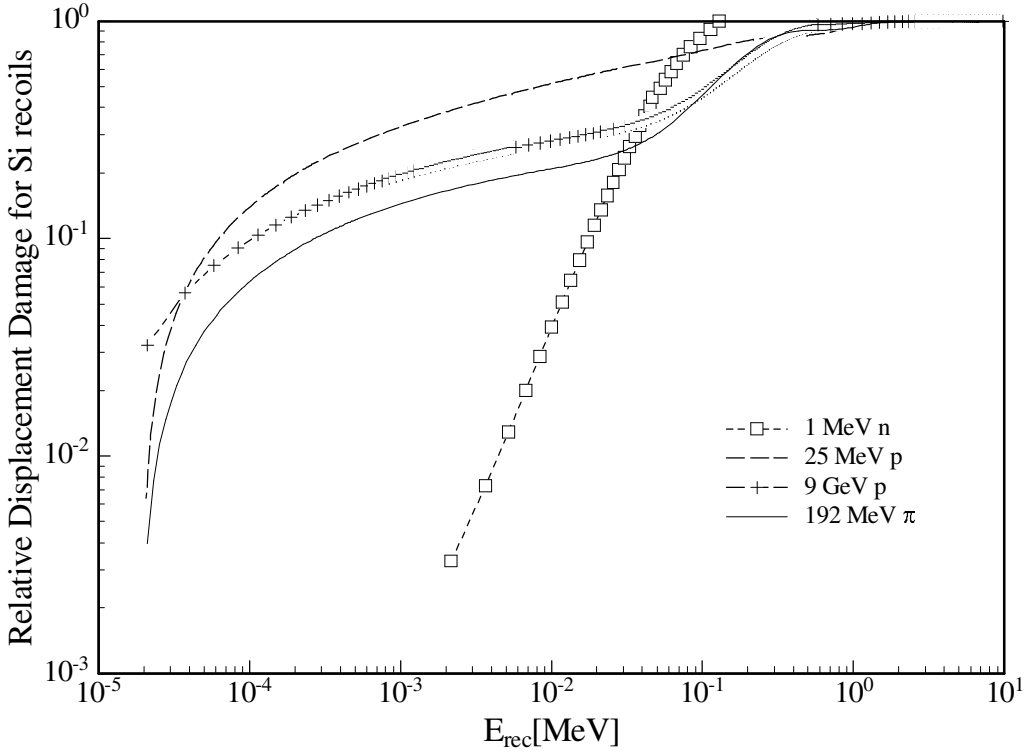
Relative Displacement Damage for Si recoils
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
E_{rec}[MeV]
1 MeV n
25 MeV p
9 GeV p
192 MeV π

Fig. 18