Improved Radiation Tolerance of silicon detectors for HEP applications; results from the CiS-HH project

G. Lindtstroem[1], D. Contarato[1], E.Fretwurst[1], J. Harkonen[4], F. Hoenniger[1], G.Kramberger[3], I.Pintilie[1,2], R. Roeder[5], A. Schramm[1], J. Stahl[1]

[1]*Institute for Experimental Physics, University of Hamburg*
[2]*National Institute for Material Physics, Bucharest*
[3]*DESY, Hamburg*
[4]*Helsinki Institute of Physics, University of Helsinki*
[5]*CiS Institute for Microsensors, Erfurt, Germany*

- **Motivation**
- **Material under investigation**
- **Material and device characterization**
- **Recent results on hadron damage**
- **Further developments**

MOTIVATION

- **For pixel devices near to the IP thin layers (low X_0) are needed**

  Thin active layers:

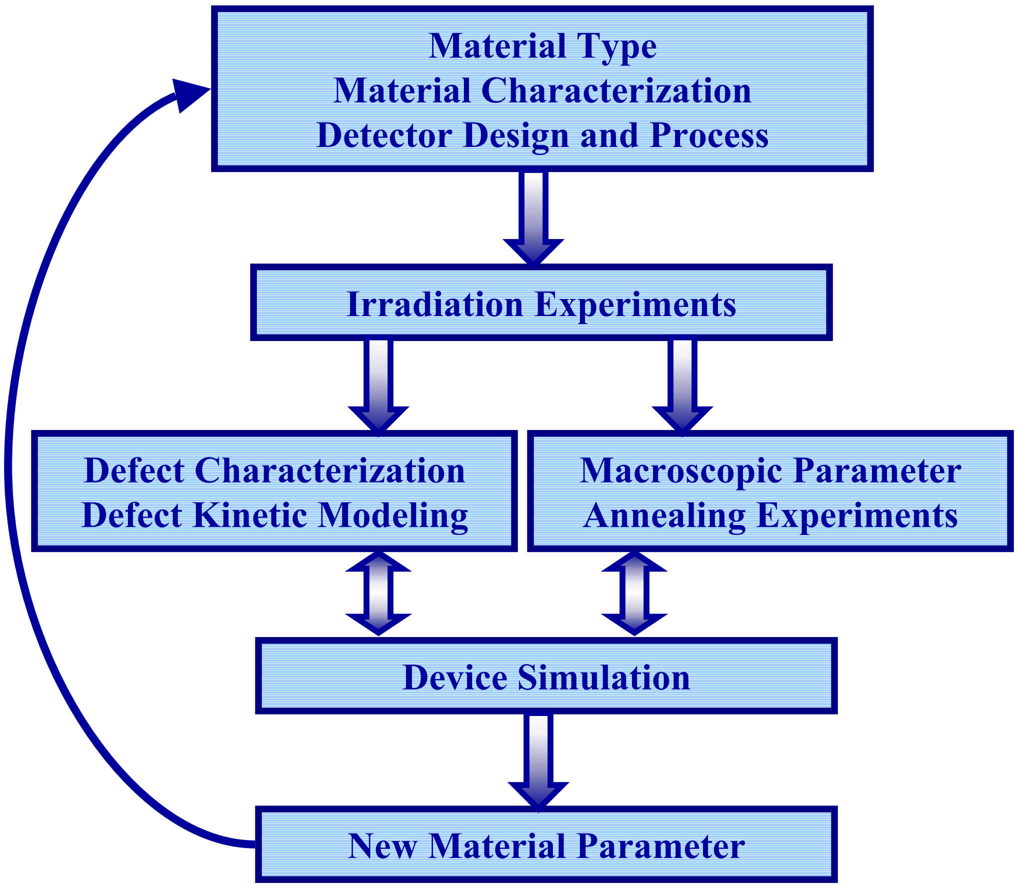
  High doping at moderate bias voltage possible

  Shift of type inversion to much higher fluences expected

- **Alternative Si-material:**

  EPI-silicon with thickness: 50 µm resistivity: 50 Ωcm

Defect engineering strategy



MATERIAL UNDER INVESTIGATION

FZ-Silicon wafers:

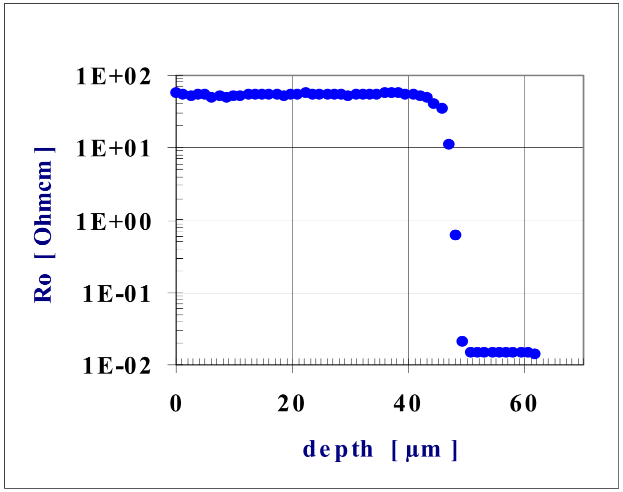
Wacker Siltronic	**<111>, n/P, 2-5 kΩcm, 285±10 µm, double sided polished**
process CiS only	**standard Oxidation and DOFZ: 24,48,72 h/1150C**
	<100>, n/P, 1-6 kΩcm, 280±15 µm, double sided polished
8 different types	**standard Oxidation and DOFZ: 24,48,72 h/1150C**

Wacker Siltronic	**<111>, n/P, 4-8 kΩcm, 300 µm, single sided polished**
process CiS only	**standard Oxidation and DOFZ: 72 h/1150C**
SINTEF/CiS	**<111>, n/P, 4-8 kΩcm, 300 µm, single sided polished**
	Oxide+DOFZ at SINTEF: standard Oxidation and DOFZ: 72 h/1150C
4 different types	**All other processing at CiS**

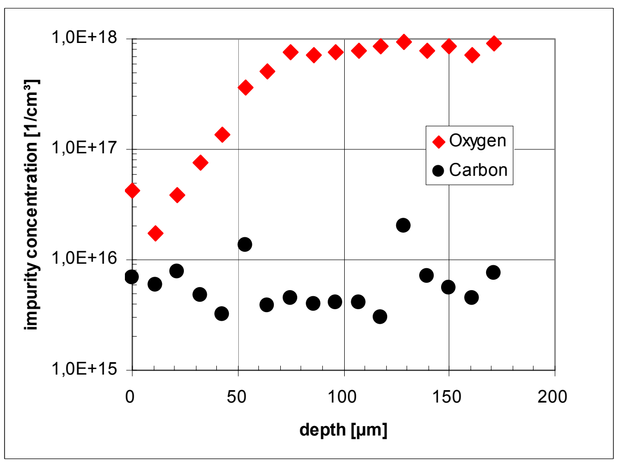
Cz-Silicon wafers:	**<100>, n/P, > 600 Ωcm, 280 ±15 µm, double sided polished, CiS process**
Sumitomo-Sitix	**ITME: TD-kill and TD-generation**
2 different types	

EPI-Silicon wafers:	**<111>, n/P, 50 Ωcm, 50 µm on 300 µm Cz-substrate, CiS process**
ITME	

CHARACTERIZATION OF EPI - SAMPLES



- <ρ> between 0-40 µm:
  54.8 ± 2.1 Ωcm
- Thickness of epi-layer:
  49.5 ± 1.6 µm
- <ρ> after device process:
  62.9 ± 2.8 Ωcm

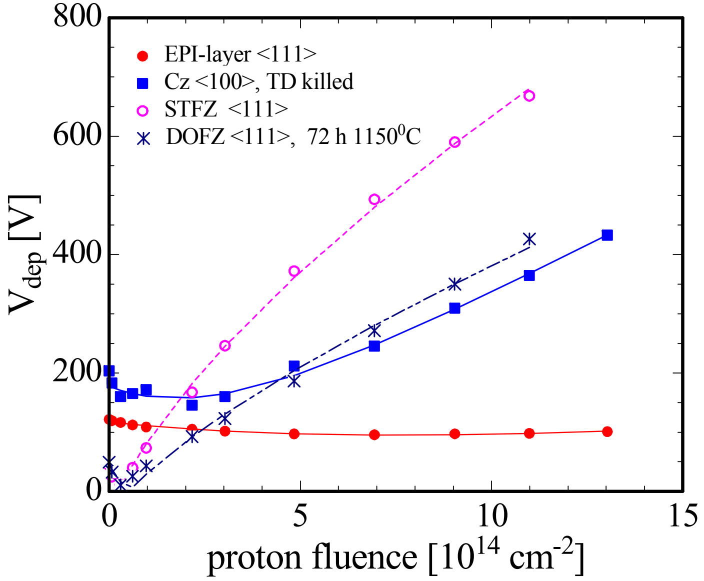


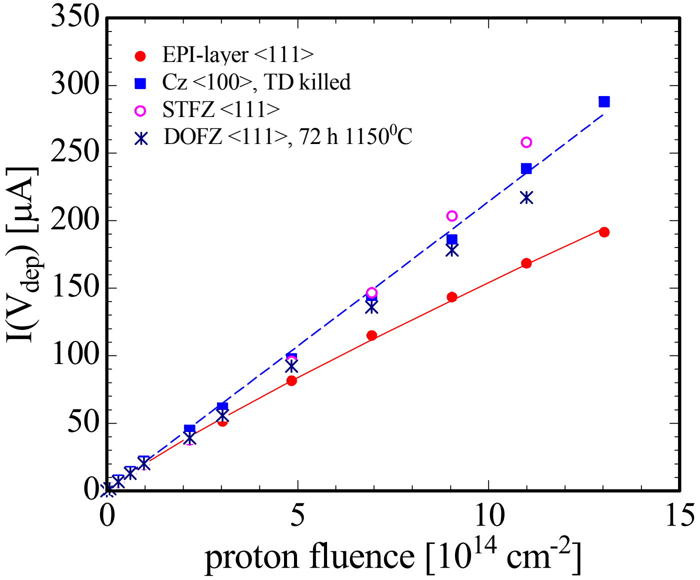
- Oxygen diffusion from Cz-substrate into epi-layer
  $<[O]> \approx 6.2\times10^{16}$ cm^{-3}
- Carbon concentration at detection limit
  $[C] \approx 5.7\times10^{15}$ cm^{-3}

IRRADIATION EXPERIMENTS

- **24 GeV/c protons, PS-CERN**
  up to 1.3*1015 cm-2
- **10 MeV protons, Jyvaskyla +Helsinki**
  up to 3*1014 cm-2
- **TRIGA reactor neutrons, Ljubljana**
  up to 8*1015 cm-2
- **58 MeV Li ions, Legnaro/Padova**
  →see talk presented by A. Candelori

COMPARISON STFZ-, DOFZ-, Cz- and EPI-SI
24 GeV/c PROTONS
CERN-SCENARIO MEASUREMENTS (4min/80°C treatment after each step)





EPI-silicon:
- **No type inversion**
- **Small change in depletion voltage up to $1.3 \cdot 10^{15}$ p/cm²**

- **No difference in reverse current between STFZ, DOFZ & Cz**
- **Small reduction for EPI-silicon at high fluences**

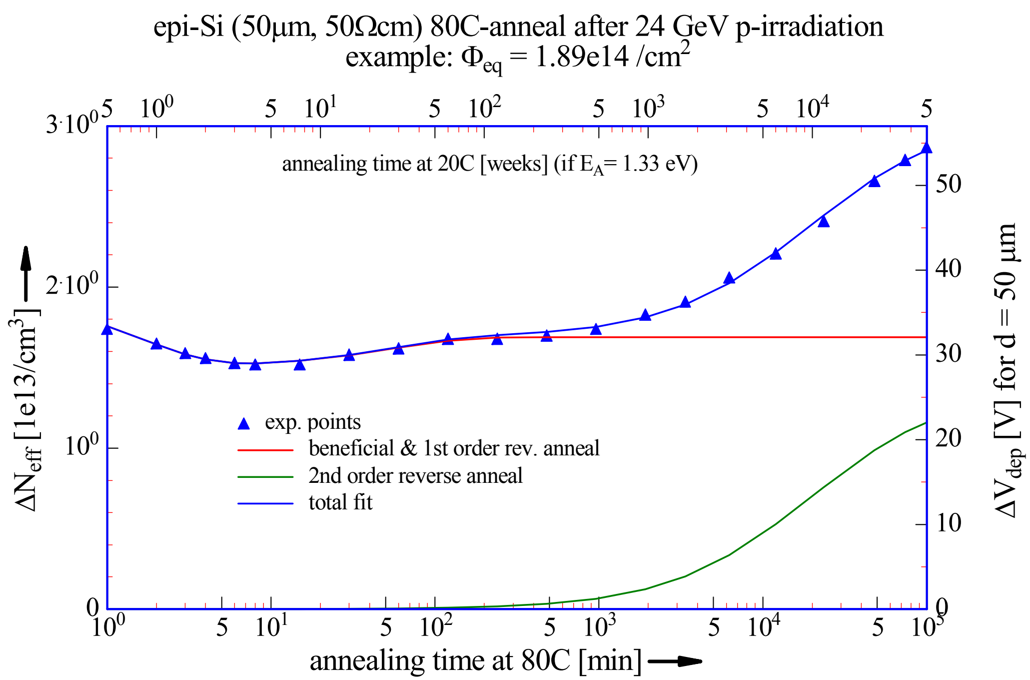
ANNEALING EXPERIMENTS AT ELEVATED TEMPERATURES

$\Delta N_{eff} = N_A(t,T) + N_C + N_{Y1}(t,T) + N_{Y2}(t,T)$

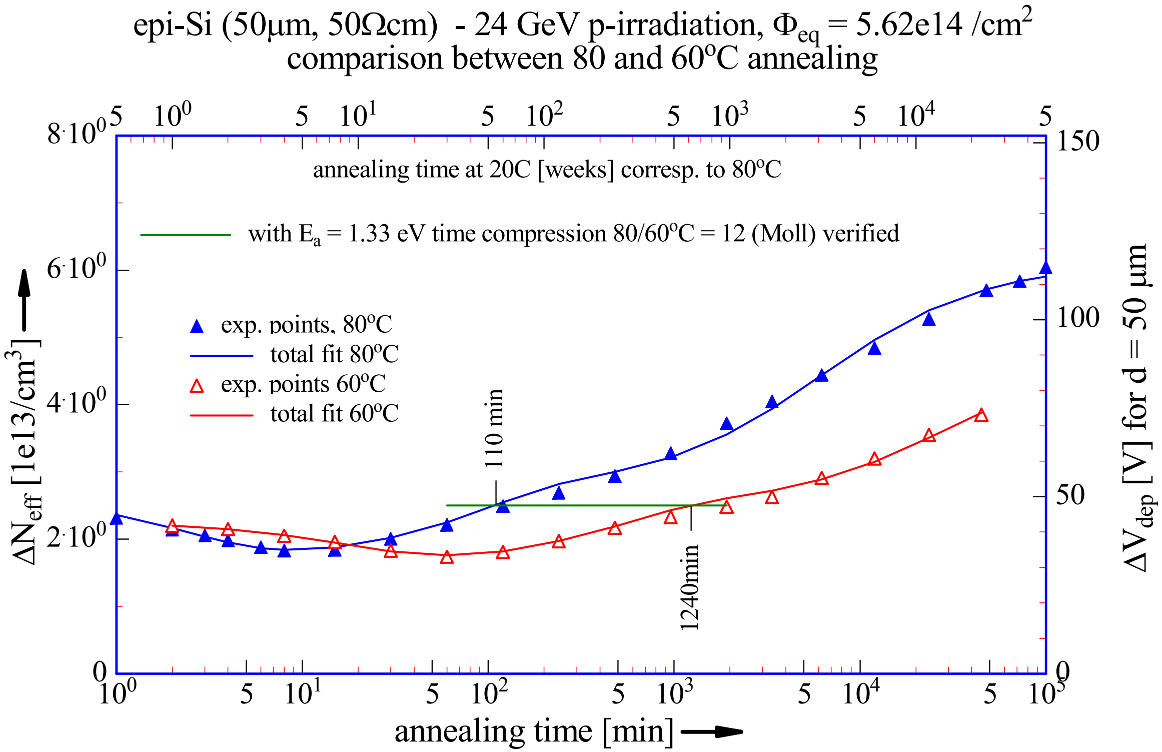
N_A : beneficial annealing
N_C : stable damage
$N_{Y1,2}$: reverse annealing has 2 components

- **First component N_{Y1} assumed to be first order process**

- **Second component N_{Y2} assumed to be second order process**



COMPARISON BETWEEN 80°C and 60°C ANNEALING



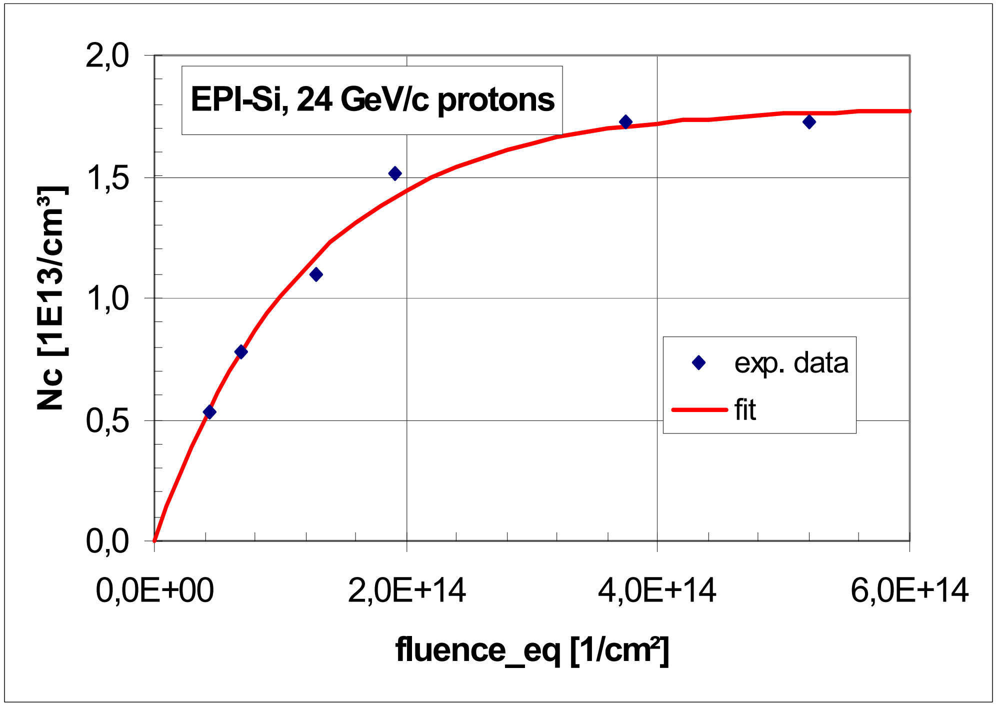
- **Time compression factor 80°C/60°C in agreement with activation energy of E_a=1.33 eV**

STABLE DAMAGE AFTER 24 GeV/c PROTON IRRADIATION

- **Irradiation at fixed fluences, Individual annealing at 80°C**
- **Stable damage can be described by one component:**

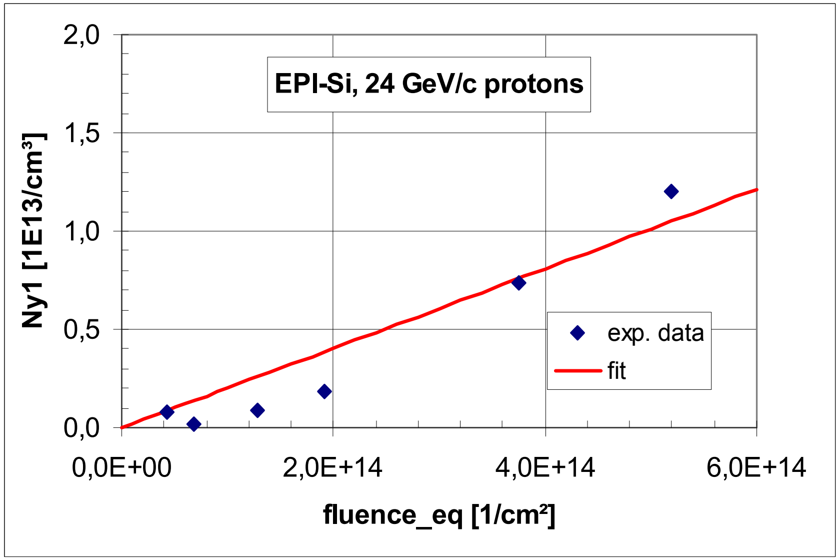
  $$N_C = N_{C0}*\{1-\exp(-c*\Phi)\}$$

  so called "donor removal" with
  $c = 1.48*10^{-15}$ cm²
  $NC0*c = 0.15$ cm^{-1},
  (Moll: 0.075 cm^{-1})

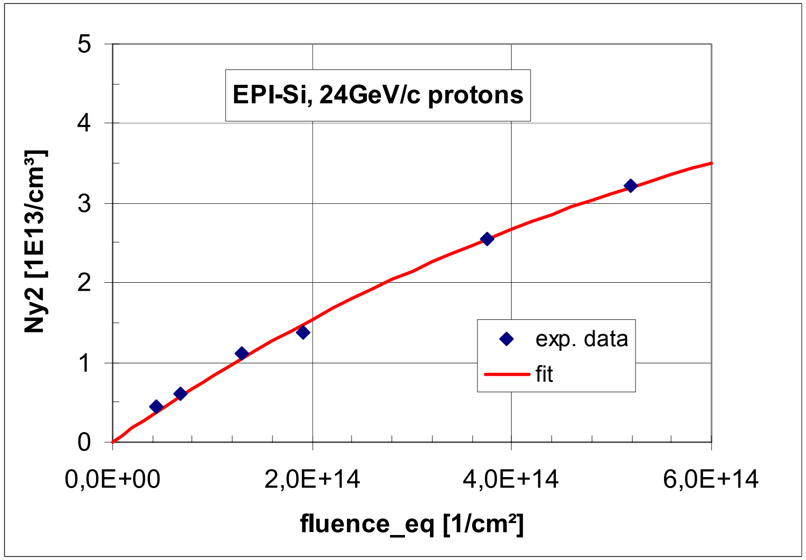


REVERSE ANNEALING AMPLITUDES
24 GeV/c protons

N_{Y1} component

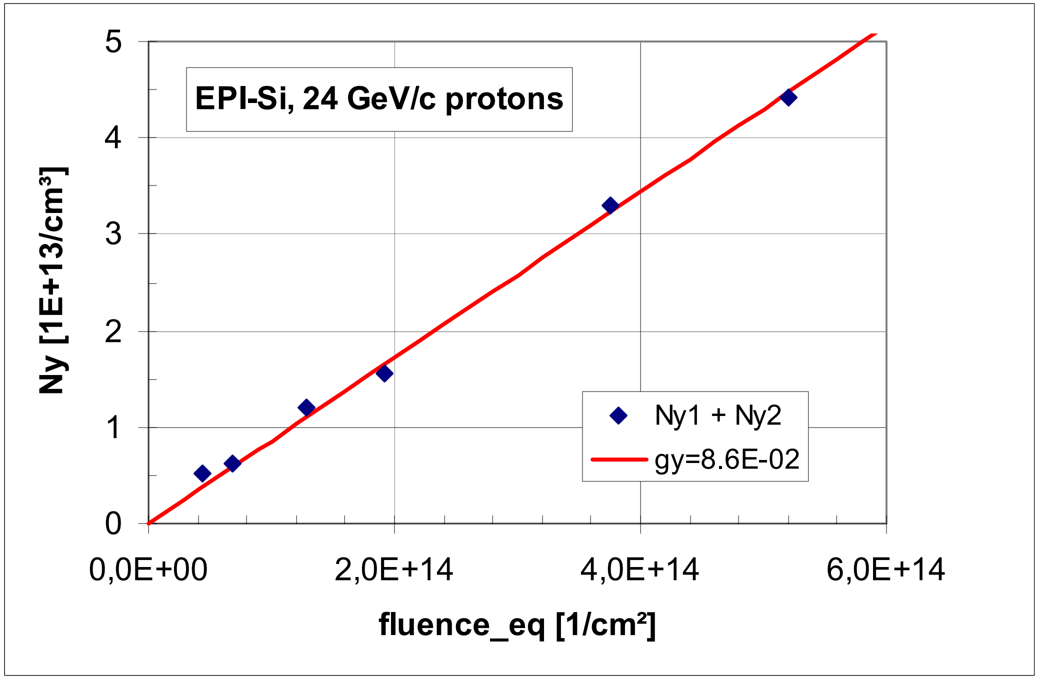


N_{Y2} component



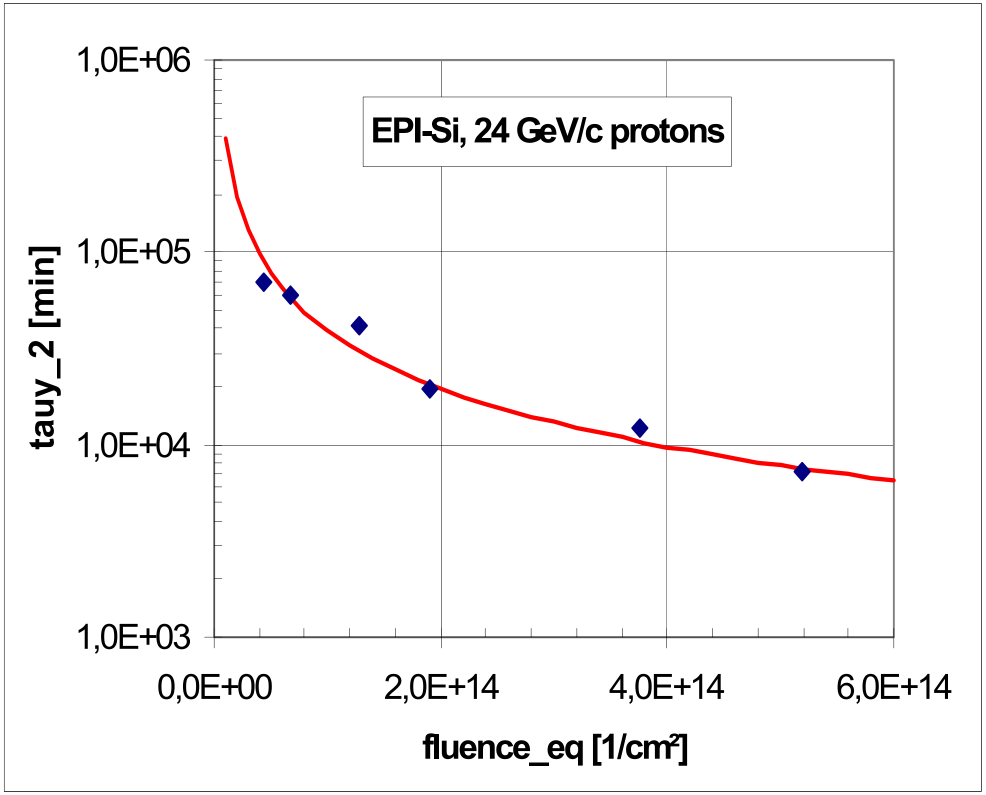
- N_{Y1} component: introduction rate $g_{Y1} \approx 2*10^{-2}$ cm^{-1} (Moll: $5.2*10^{-2}$), $\tau_{Y1} \approx 10 - 100$ min (Moll: 90 min)
- N_{Y2} component: saturation character, initial introduction rate $g_{Y2,0} \approx 8.9*10^{-2}$ cm^{-1}

REVERSE ANNEALING AMPLITUDE N_Y
24 GeV/c protons



- **Sum of both components is proportional to proton fluence, introdution rate $g_Y \approx 8.6*10^{-2}$ cm^{-1}**

REVERSE ANNEALING TIME CONSTANT AT 80⁰C after 24 GeV/c proton irradiation



- **Long time constant of second reverse annealing component decreases with increasing fluence**
  ⇒ second order process

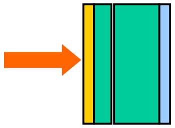
- **The fit results in:**

  $\tau_{Y2} * N_{Y2} = 3.37 * 10^{17}$ **min/cm³**

CCE VERSUS 24 GeV/c PROTON FLUENCE

Measurements performed before annealing

5.8 MeV α-particles



- Range of α-particles

  R ≈ 20-25 μm

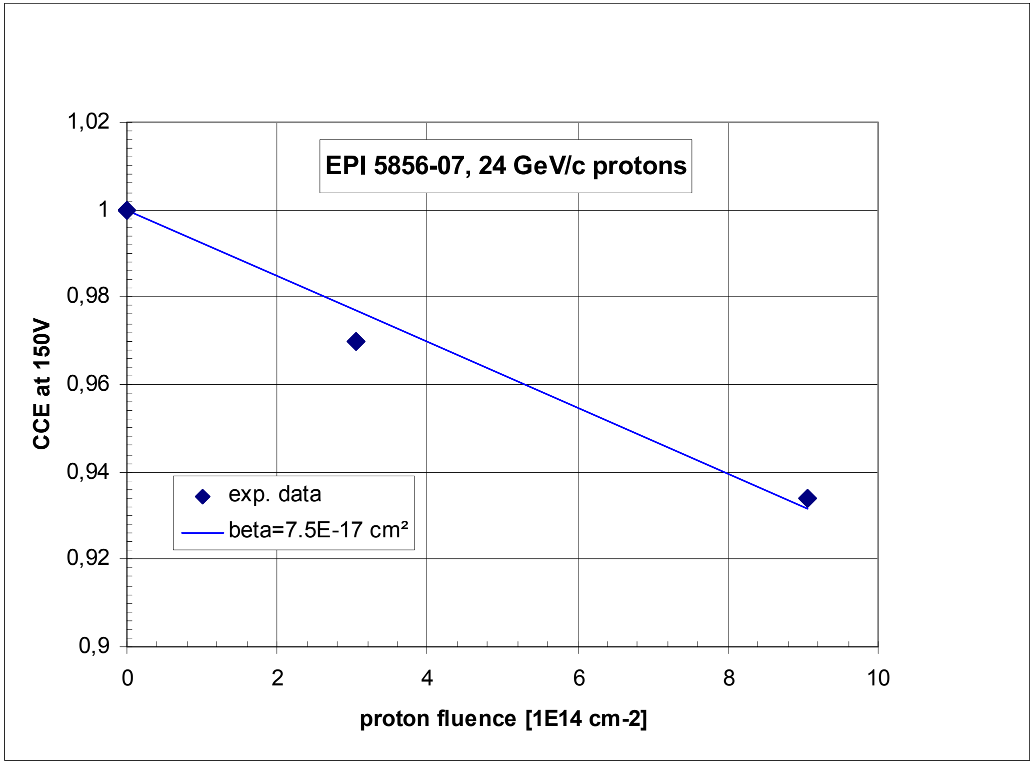
  about ½ of epi layer thickness

  ⇒ degradation of CCE due to electron and hole trapping
  $\beta = 7.5 \cdot 10^{-17}$ cm²

- Applied V_{bias} = 150 V corresponds to

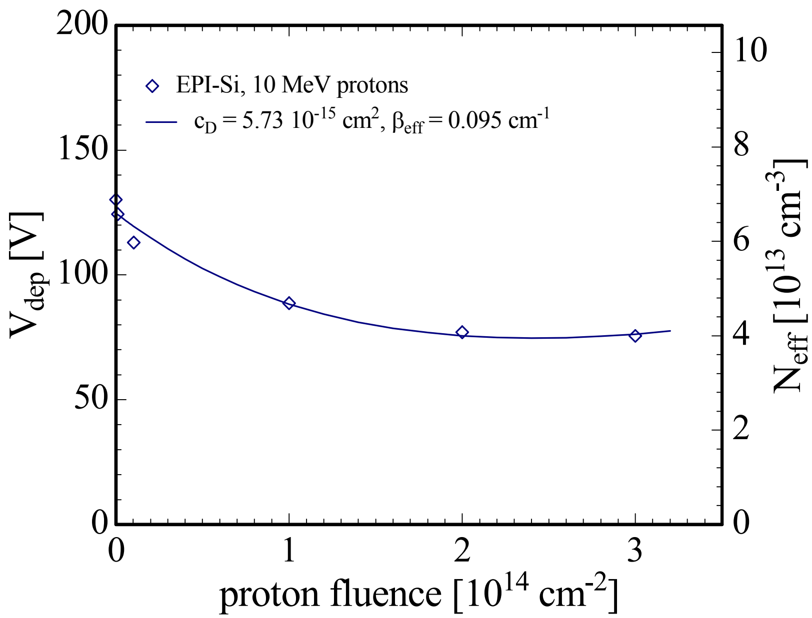
  E = 30 kV/cm

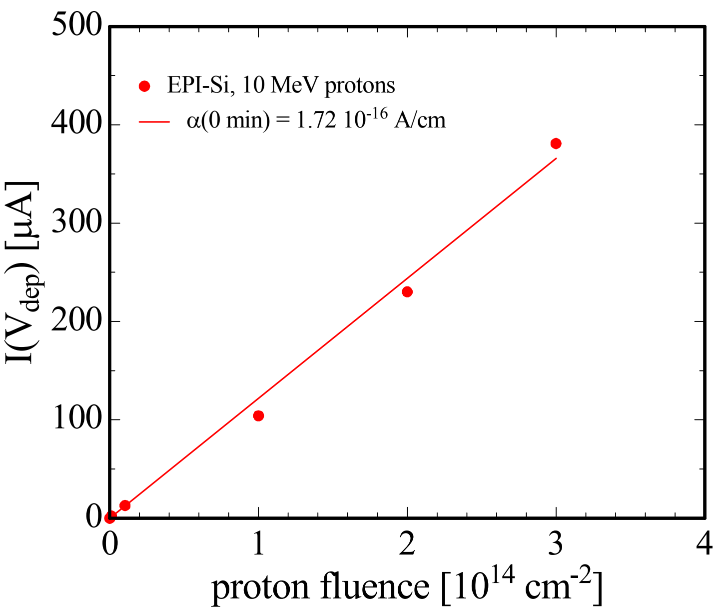
  ⇒ saturation of drift velocity for both electrons and holes



EPI-SILICON – 10 MeV PROTONS

Development of depletion voltage and reverse current with fluence
Measurements performed before annealing





- No type inversion
- Small change in depletion voltage up to $3 \cdot 10^{14}$ p/cm²
- Reverse current linear with fluence

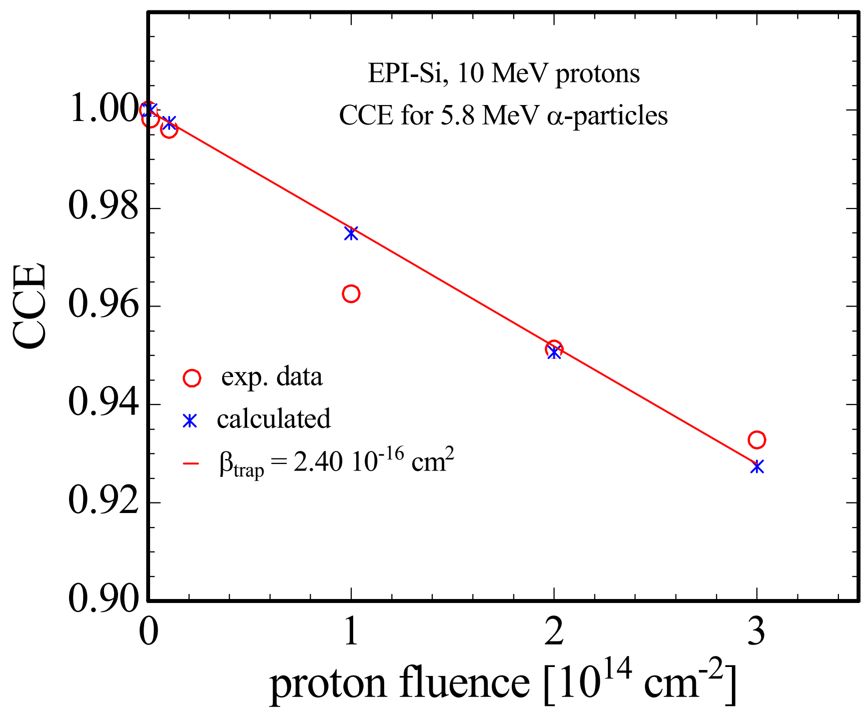
CCE VERSUS 10 MeV PROTON FLUENCE

Measurements performed before annealing

- **Calculation of CCE according to trapping data of G. Kramberger and assuming a hardness factor of 2.5 for 10 MeV protons**

- **β-value compared to 24 GeV/c protons:**

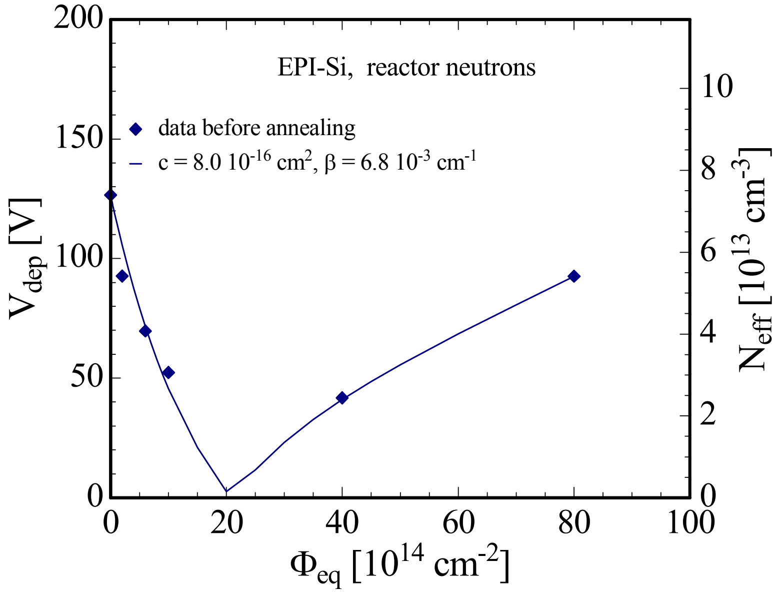
$$\beta_{10MeV} / \beta_{24GeV} = 3.2$$

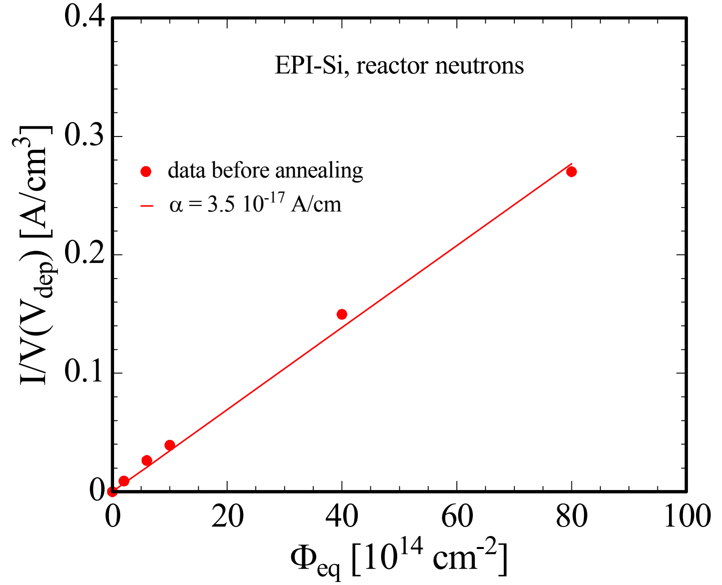


EPI-SILICON – REACTOR NEUTRONS

Development of depletion voltage and reverse current with fluence

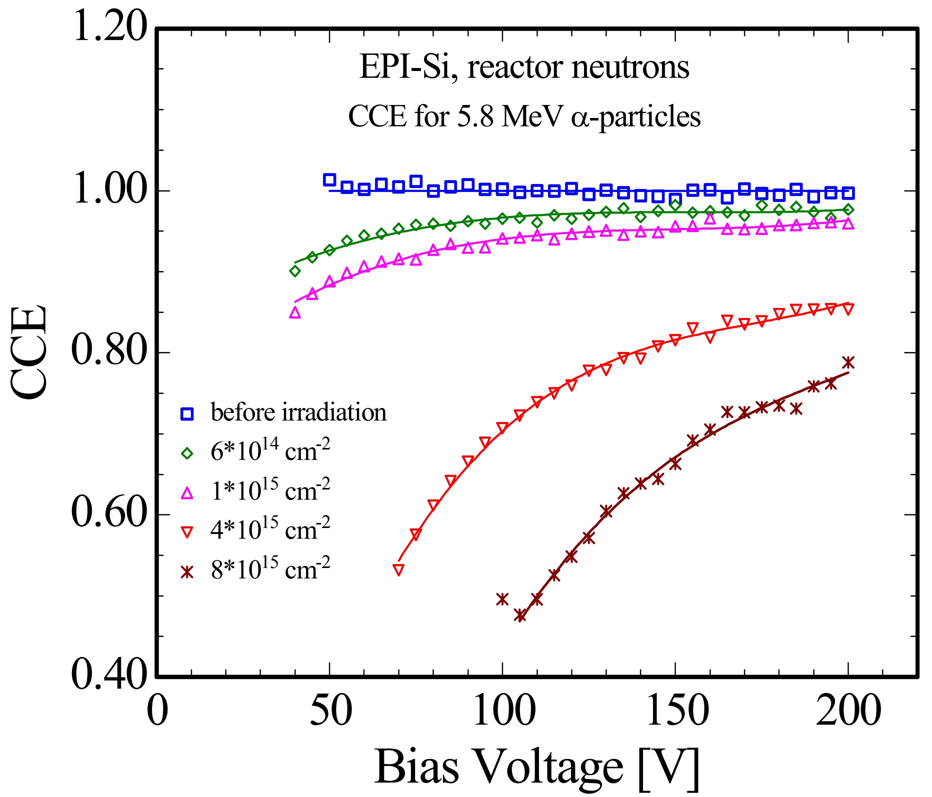
Measurements before annealing





- Type inversion at about $2*10^{15}$ cm^{-2} ,
- Depletion voltage still low at $8*10^{15}$ cm^{-2} (V_{dep} = 96 V)
- Reverse current linear with fluence, α-value smaller than expected

CCE VERSUS BIAS VOLTAGE
AFTER NEUTRON DAMGE



- **Strong voltage dependence at high fluences**
- **Strong CCE degradation at high fluences**

CCE VERSUS NEUTRON FLUENCE

- **Comparison of β-values at 150 V:**

  24 GeV/c protons:

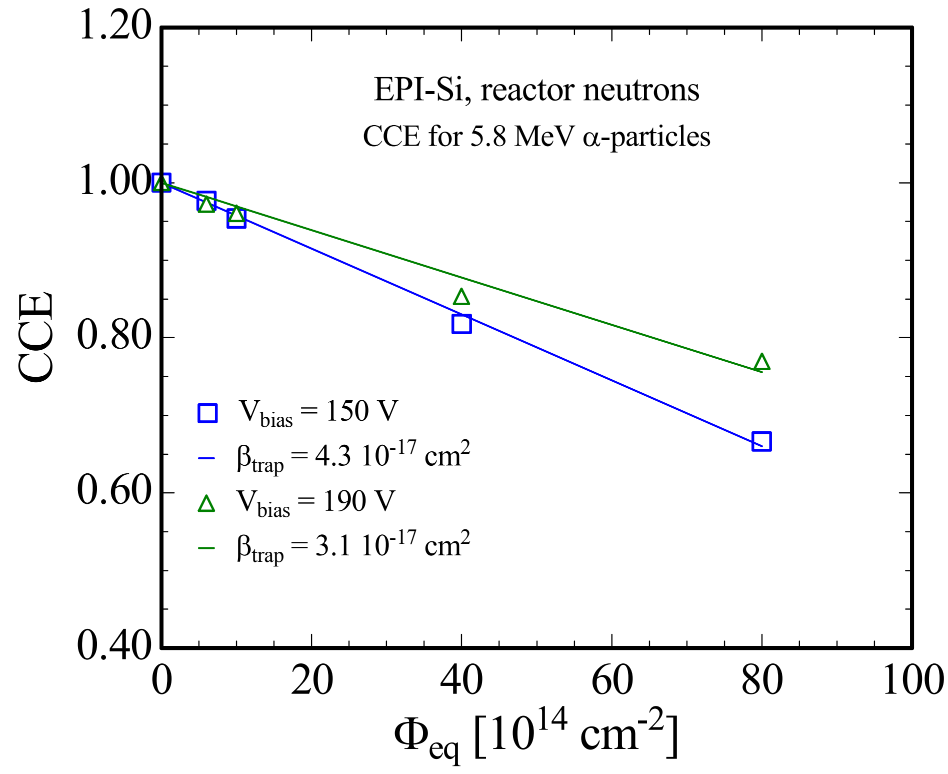
  7.5×10^{-17} cm²

  10 MeV protons:

  2.4×10^{-16} cm²

  Neutrons:

  4.3×10^{-17} cm²



FURTHER DEVELOPMENTS

- Detailed studies on EPI-silicon
  Understanding of radiation induced generation of shallow donors (type of TD´s)
  Understanding of annealing behavior at elevated temperatures
  Systematic investigation on trapping at different temperatures
  Role of substrate: possible diffusion of defects from epi-layer into substrate or vice versa ?
  DLTS- and TSC-studies started

- Irradiation experiments
  up to 10^{16} protons/cm^2 planned for July/October 2003 (PS-CERN)
  ✓ low energy electrons (15 MeV, Oslo/Stockholm)
  started: high energy electrons (900 MeV, Trieste)
  ✓ high energy neutrons (30-60 MeV, Louvain)
  ✓ Heavy ions up to 10^{16} cm^{-2} 1MeV neutron equivalent (58 MeV Li, Legnaro)