5th ROSE WORKSHOP ON
RADIATION HARDENING OF
SILICON DETECTORS
CERN, 17/3/2000

Microscopic studies on various silicon materials irradiated with high energy particle *

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Content:

*Gefördert durch BMBF 05 7HH17I

• Introduction

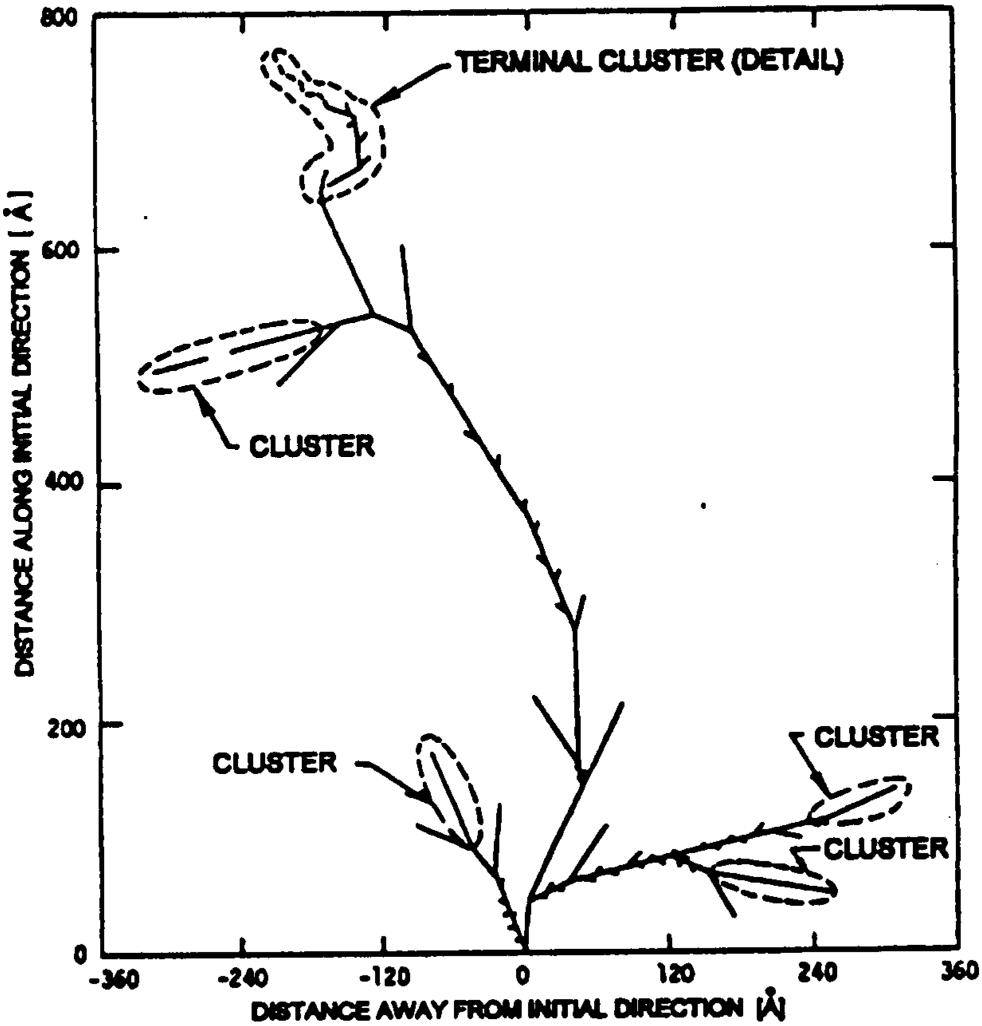
⇒ The use of silicon detectors to track particles in high energy experiments requires radiation hard silicon material.

⇒ „Defect engineering“: Improvement of the radiation hardness by enrichment of silicon with impurities e.g. oxygen

⇒ Correlation of microscopic defect parameters and macroscopic detector properties

⇒ Determination of the defect parameters with the DLTS method
(Deep Level Transient Spectroscopy)

- Defect Generation



- Primary defects: **I**ntertitials , **V**acancies and clusters of **VV + ?**

- Secondary defects: C_i , C_iC_s , C_iO_i and VO_i

• Irradiation sources

- Be(d,n) neutron source
  <E> = 5.3 MeV
  PTB Braunschweig / Germany

- Reactor neutron source
  E = 10 meV .... 10 MeV
  Ljubljana / Slovenia

- 23 GeV proton source
  PS-CERN

- 192 MeV pion source
  PSI-Villigen

- 27 MeV proton source
  Legnaro / Italia

- 7-10 MeV proton source
  Montreal / Canada

• Material

1. FZ-n-type 800Ωcm (ITME)
   (jet oxygenated)

   $[O]= 1.7 \cdot 10^{17}\ cm^{-3}$ $[C]< 2 \cdot 10^{16}\ cm^{-3}$

2. FZ-n-type 1.2KΩcm (ITME)
   (jet oxygenated)

   $[O]= 2.1 \cdot 10^{17}\ cm^{-3}$ $[C]= 1 \cdot 10^{16}\ cm^{-3}$

3. FZ-n-type 2KΩcm (Wacker)
   (oxygen enrichment with HT diffusion)

   $[O]= 1.0 \cdot 10^{16} - 5.7 \cdot 10^{17}\ cm^{-3}$

   $[C]= 4.4 \cdot 10^{15} - 1.8 \cdot 10^{16}\ cm^{-3}$

4. FZ-n-type 4KΩcm (Wacker)
   (oxygen enrichment with HT diffusion)

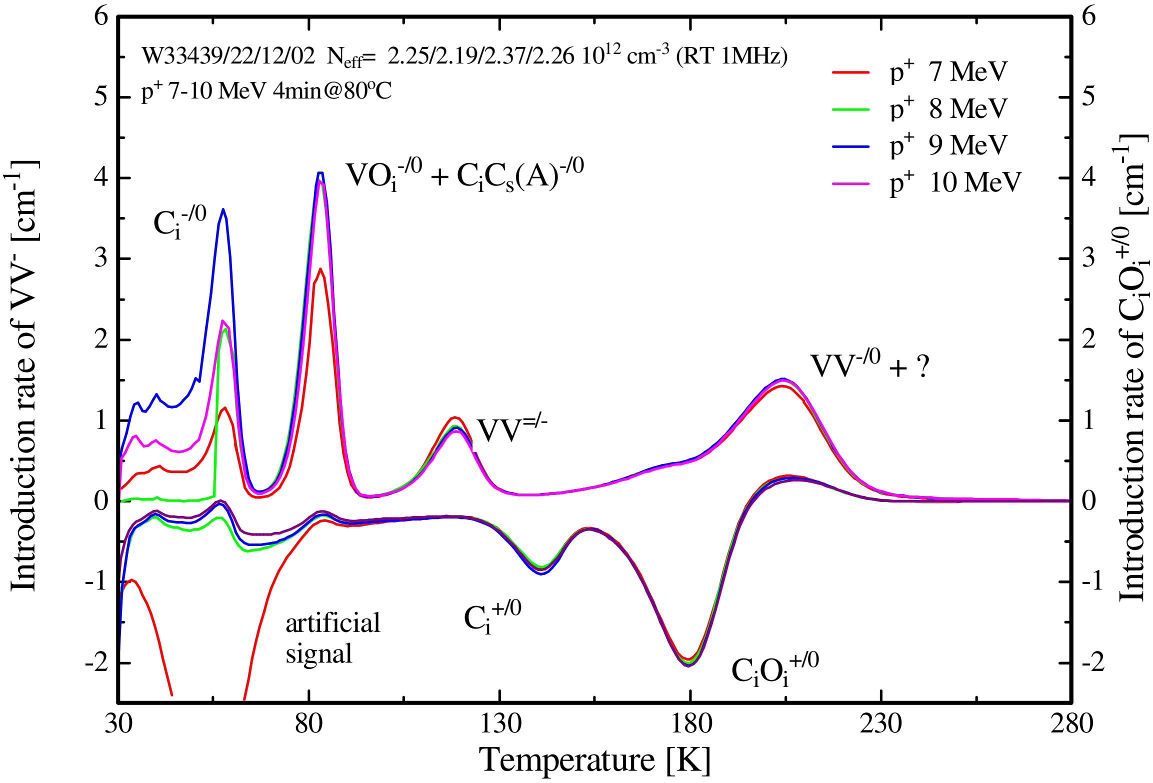
   $[O]= 9.0 \cdot 10^{15} - 3.0 \cdot 10^{17}\ cm^{-3}$

   $[C]= 4.3 \cdot 10^{15} - 6.2 \cdot 10^{15}\ cm^{-3}$

• Results

- 2kΩcm Standard FZ

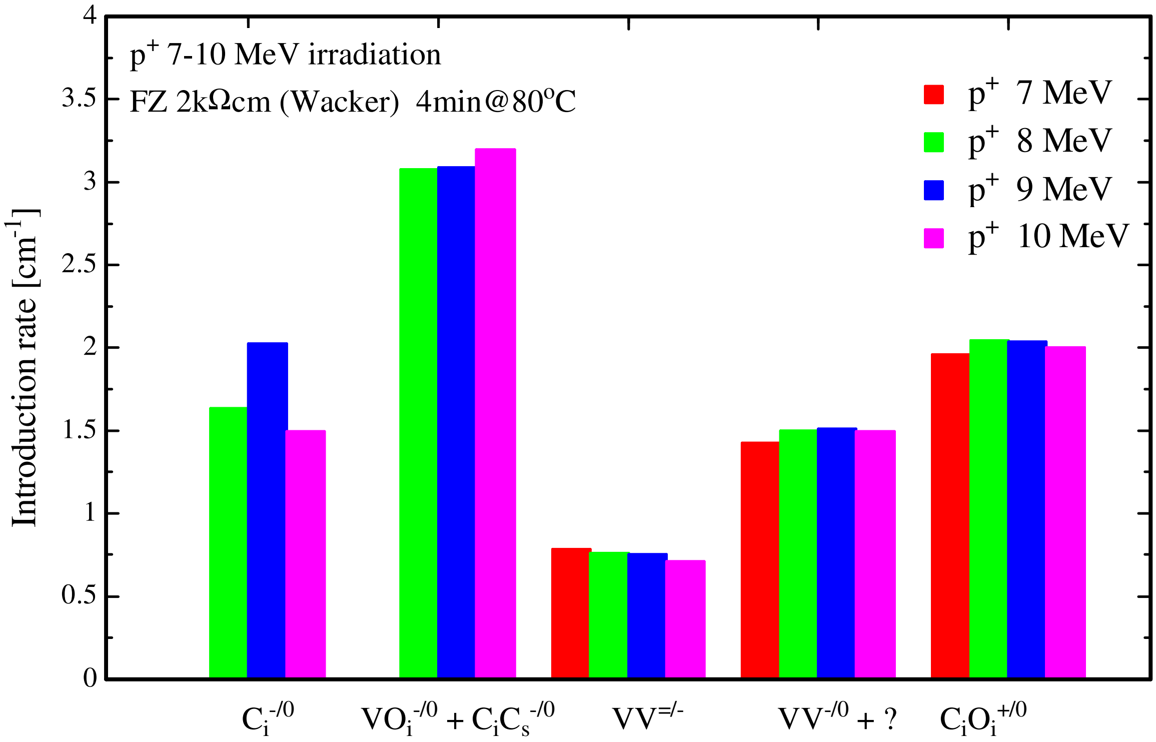
- Material processed by Thomson (7-10 MeV p^+)



- VO_i , C_iC_s , C_iO_i and C_i are attributed to point defect damage.

- VV + is attributed to cluster damage.

- 2kΩcm FZ (Wacker)
- Material processed by Thomson (7-10 MeV p^+)

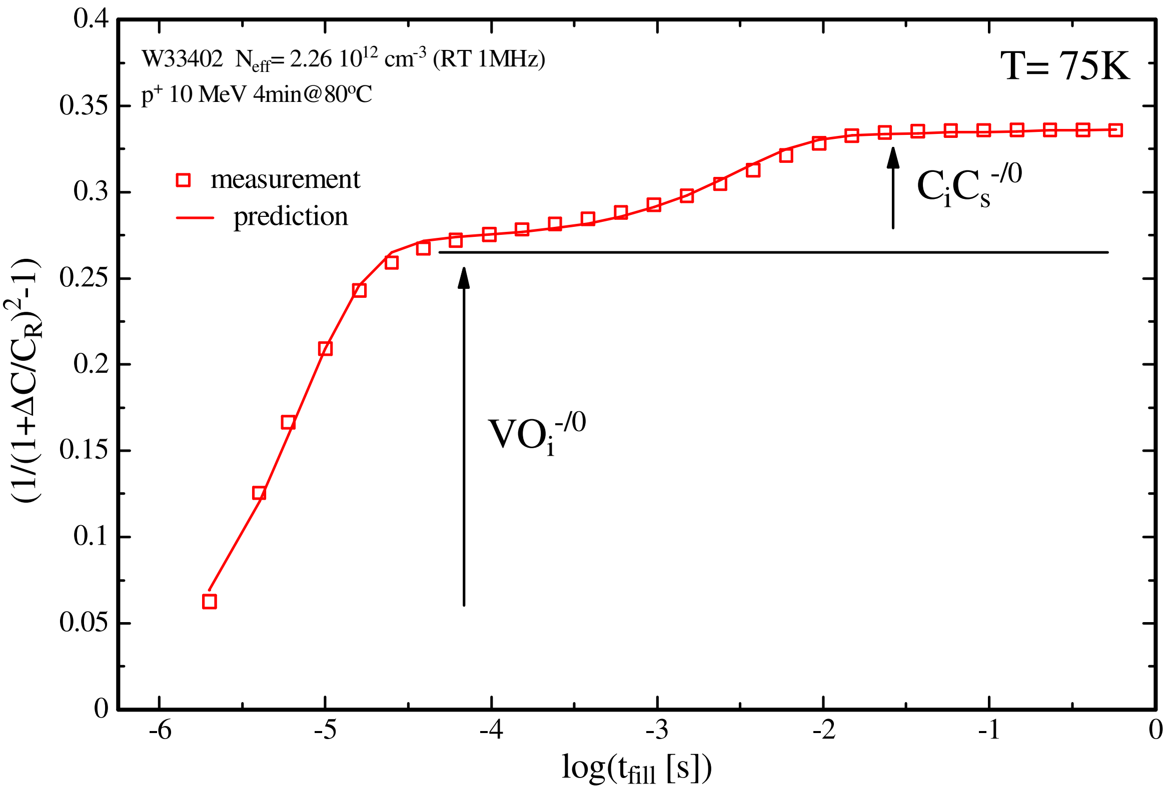


- The point defect and cluster damage is t the same for protons with a energy of 7-10 MeV.
- The annealing of C_i is not accomplished after the heating step because of the loe oxygen content.

- 2kΩcm Standard FZ

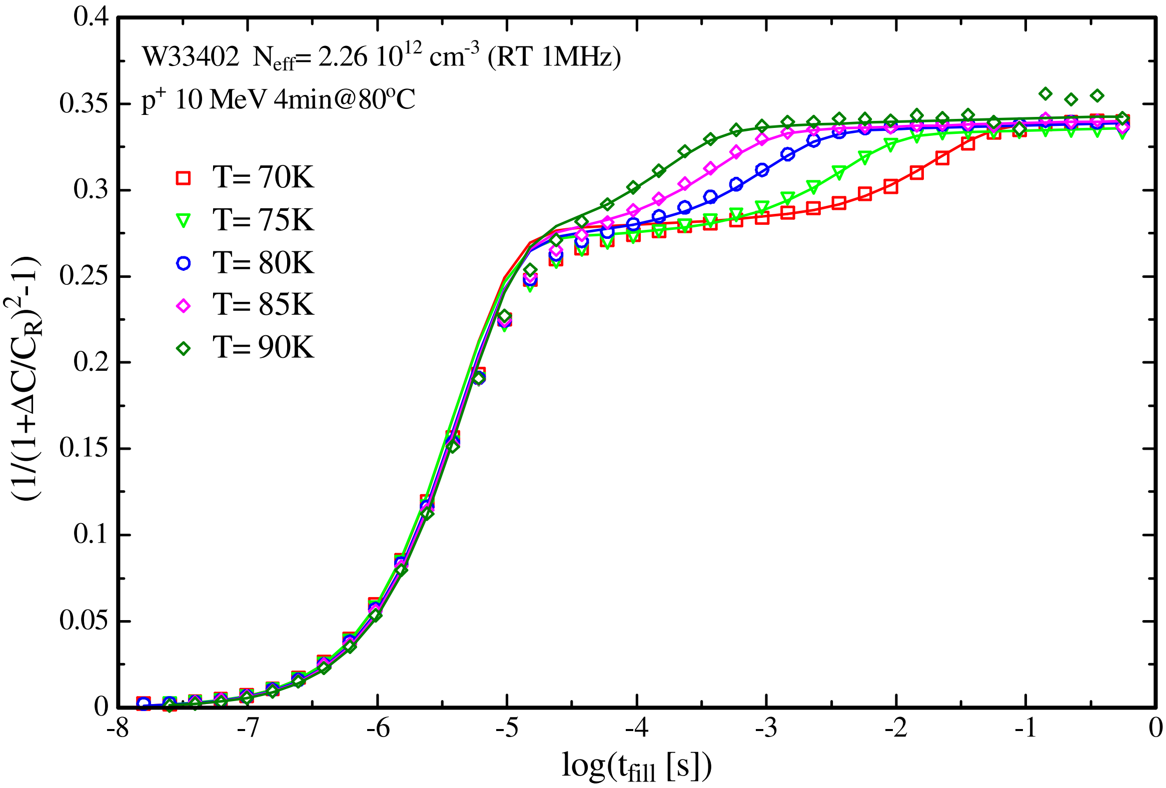
- Material processed by Thomson (10 MeV p^+)

- Separation of the defects VO_i und C_iC_s with a capture measurement



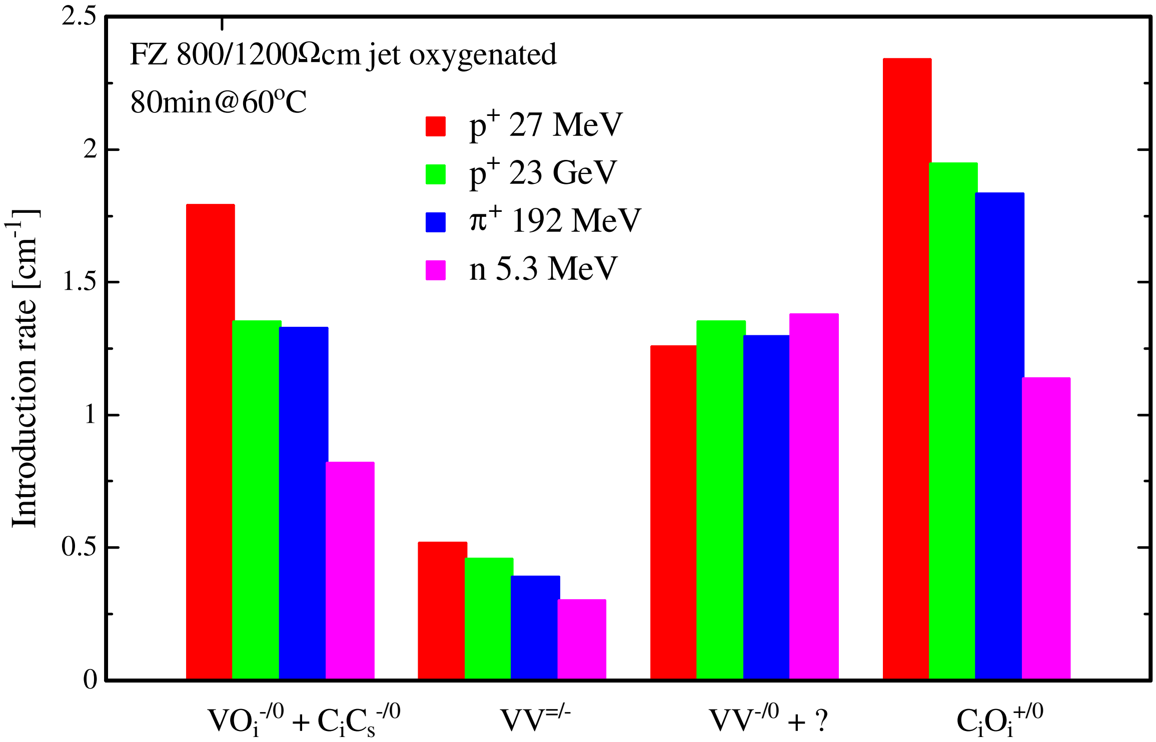
- During capture the free charge carrier density is constant.

- 2kΩcm FZ (Wacker)
- Material processed by Thomson (10 MeV p^+)
- Electrical filling of $VO_i^{-/0}$ and $C_iC_s(A)^{-/0}$



- The majority charge carrier density and the configuration switching of C_iC_s is only slightly effected by the cluster damage of 10MeV protons.

- 800/1200Ωcm jet-oxygenated FZ
- Material processed by ITE
- Particle dependence of the introduction rates



- The generation of point defects is higher for charged particles.
- The generation of VV is independent on the particle type and energy (cluster damage).

- Tables of introduction rates

- 800/1200Ωcm jet-oxygenated FZ
- Material processed by ITE

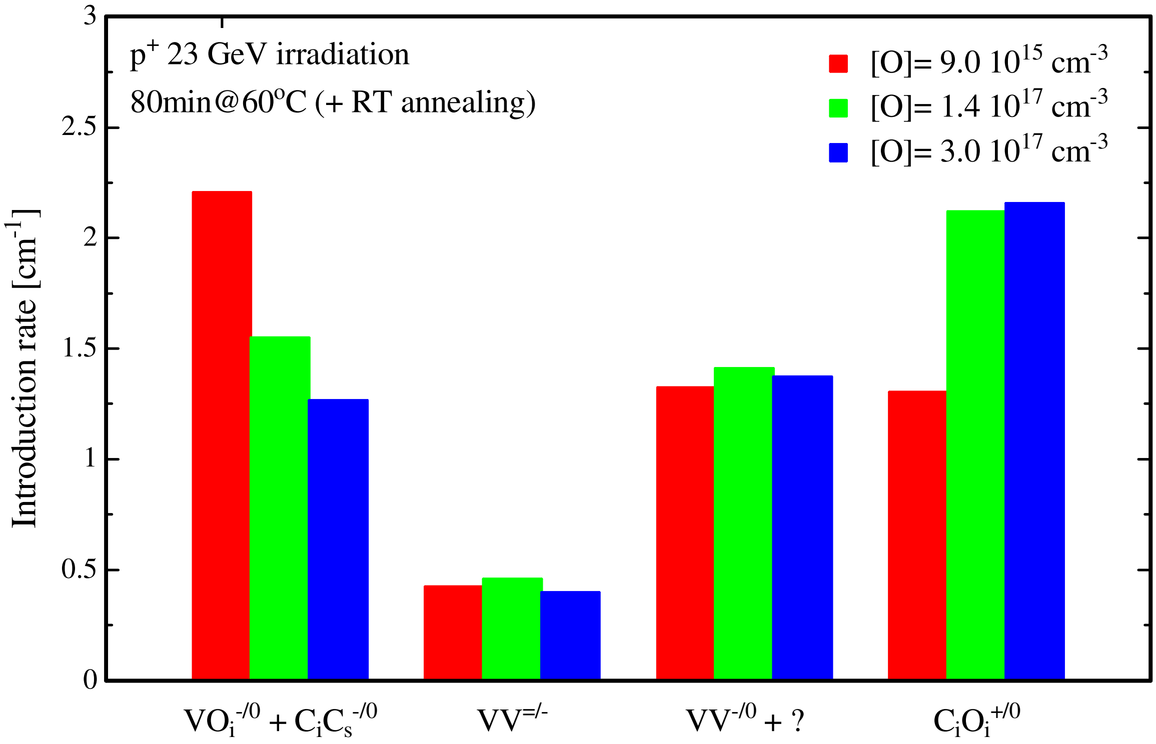
Particle	$g(VO_i+C_iC_s)$ [cm^{-1}]	$g(C_iO_i)$ [cm^{-1}]	$g(VV)$ [cm^{-1}]	$g(VO_i)/g(C_iC_s)$
p^+ 27 MeV	1.79	2.34	1.26	3.18
p^+ 23 GeV	1.35	1.95	1.35	1.54
π^+ 192 MeV	1.33	1.83	1.30	1.00
n 5.3 MeV	0.82	1.14	1.38	–

- 2kΩcm Standard FZ
- Material diffused and processed by Thomson (23 GeV p^+)

[O] [cm^{-3}]	Orientation	$g(VO_i+C_iC_s)$ [cm^{-1}]	$g(C_iO_i)$ [cm^{-1}]	$g(VV)$ [cm^{-1}]	$g(VO_i)/g(C_iC_s)$
$3.6\cdot10^{17}$	<111>	1.14	1.63	1.17	2.14
$2.6\cdot10^{17}$	<100>	1.20	1.72	1.28	1.76
$5.7\cdot10^{17}$	<111>	1.12	1.59	1.15	1.81
$2.2\cdot10^{17}$	<100>	1.18	1.72	1.27	1.76

- 4kΩcm Standard FZ

- Material diffused and processed by CiS (23 GeV p^+)



- Table of introduction rates

[O] [cm^{-3}]	$g(VO_i+C_iC_s)$ + $g(C_iO_i)$ [cm^{-1}]	$g(VV)$ [cm^{-1}]
$9.0 \cdot 10^{15}$	3.51	1.32
$1.4 \cdot 10^{17}$	3.67	1.41
$3.0 \cdot 10^{17}$	3.42	1.37

- The generation rates of C_i und VO_i are independent on the oxygen content.

$$I + C_s \rightarrow C_i$$
$$V + O_i \rightarrow VO_i$$

- The generation rates of C_iC_s and C_iO_i depend on the oxygen content.

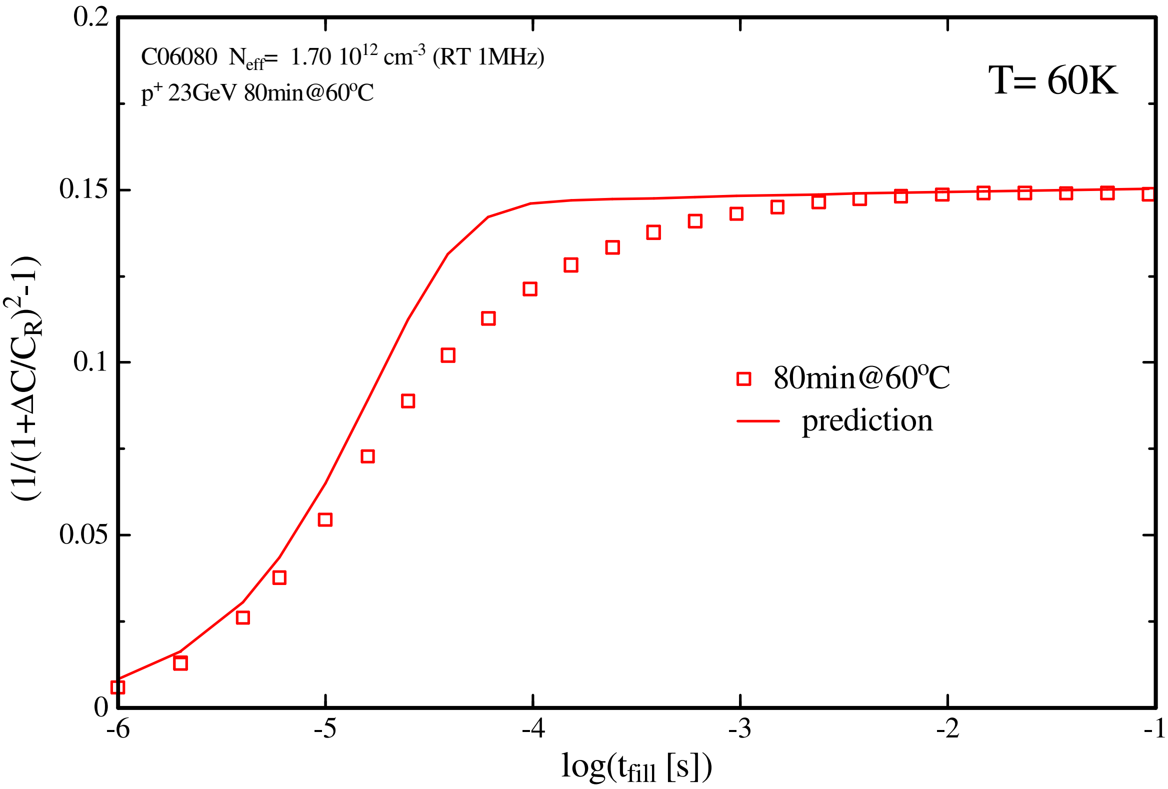
$$C_i + O_i \rightarrow C_iO_i$$
$$C_i + C_s \rightarrow C_iC_s$$

- The radiation hardness of oxygen enriched silicon is due to the suppression of the generation of V_2O ($E_T = 0.50$ eV).

$$V + O_i \rightarrow VO_i$$

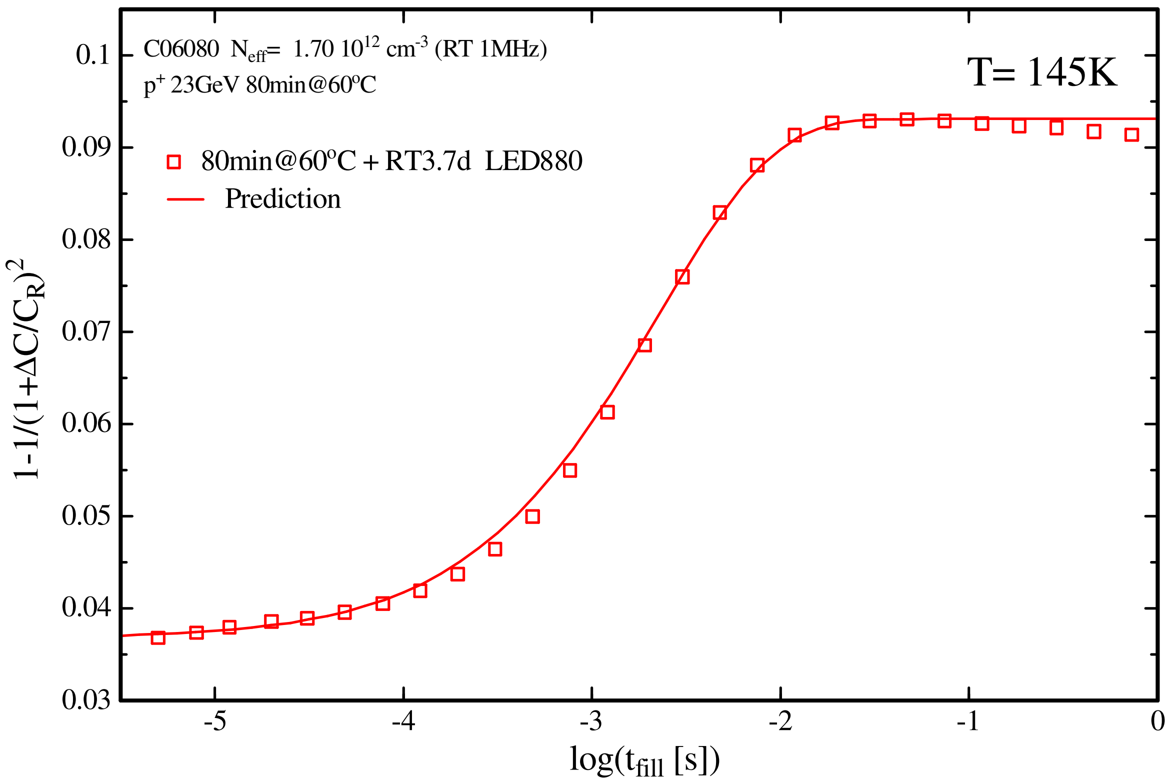
$$V + VO_i \rightarrow V_2O$$

- 4kΩcm Standard FZ
- Material processed by CiS (23 GeV p^+)
- Capture of free charge carriers into C_i



- During capture the free charge carrier density is not constant, because the density of radiation induced defects is high in the proximity of the clusters.

- 4kΩcm Standard FZ
- Material processed by CiS (23 GeV p^+)
- Capture of optical generated charge carriers into C_i



- The density of optical generated charge carriers is not influcent by the high density of radiation induced defects in the proximity of the clusters.

• Summary

- The damage in the crystal lattice is separated into point defect damage and cluster damage.
- The generation rate of point defects depends on the particle type and is higher for charged particles.
- The generation rate of the cluster defect VV is particle independent.
- A high generation of point defects is connected with the radiation hardness of oxygen enriched silicon.
- The defect V_2O is a possible candidat to explain the radiation hardness of oxygen enriched silicon.

- The density of radiation induced defects is proposed to be high in the proximity of the clusters.