Radiation damage in n-type silicon after electron irradiation with energies between 1.5 MeV - 15 MeV

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Outline

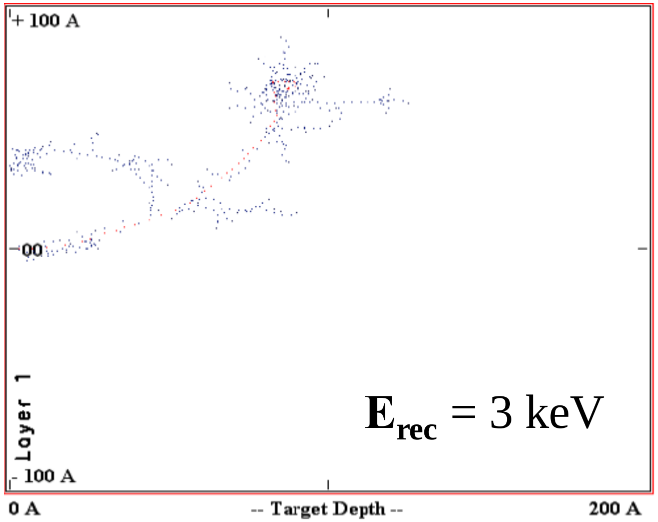
- Motivation
- Modeling damage in silicon
- Material and irradiation
- Experimental results:
  - Macroscopic properties: dark current
  - Microscopic studies:
    - Energy dependence
    - Isothermal and isochronal annealing
    - DLTS- and TSC-measurements
    - “New” defects
- Conclusions

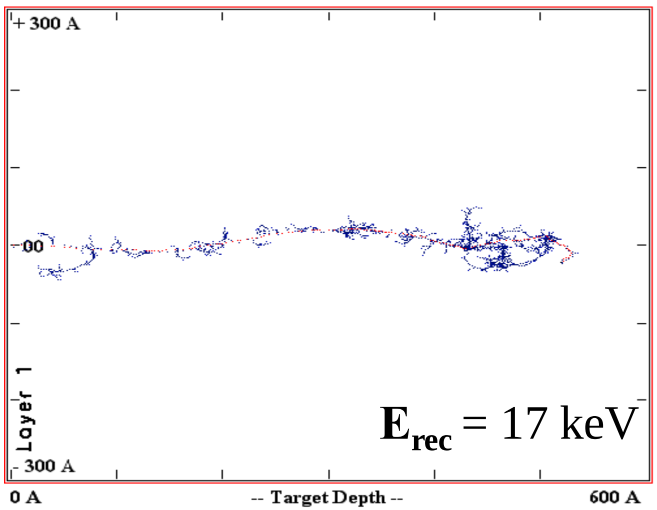
Motivation

Particle type	Damage created
^{60}Co-γ irradiation (1.1 and 1.3 MeV) $E_{rec.max} = 200$ eV	only point defects
Reactor neutron irradiation (1 MeV) $E_{rec.max} \sim 50$ keV	only cluster defects
High energy protons (23 GeV)	both point and cluster defects
Threshold for cluster formation: $E_{rec} \sim 5$ keV	

- Irradiation with electrons in order to get a clear signature for the identification of point and cluster related defects
- Identification of the main defects responsible for radiation damage of silicon as well as their formation kinetics

Modeling damage in silicon





TRIM simulations

TRIM uses energy of Primary Knock-on Atom ($E_{rec.}$) for detailed examination of radiation damage

→ distribution of vacancies and interstitials

E_e = 1 MeV, $E_{rec.max}$ = 140 eV
E_e = 3.5 MeV, $E_{rec.max}$ = 1.2 keV
E_e = 6 MeV, $E_{rec.max}$ = 3 keV
E_e = 15 MeV, $E_{rec.max}$ = 17 keV

High recoil energy → high probability for cluster formation

Material and irradiation

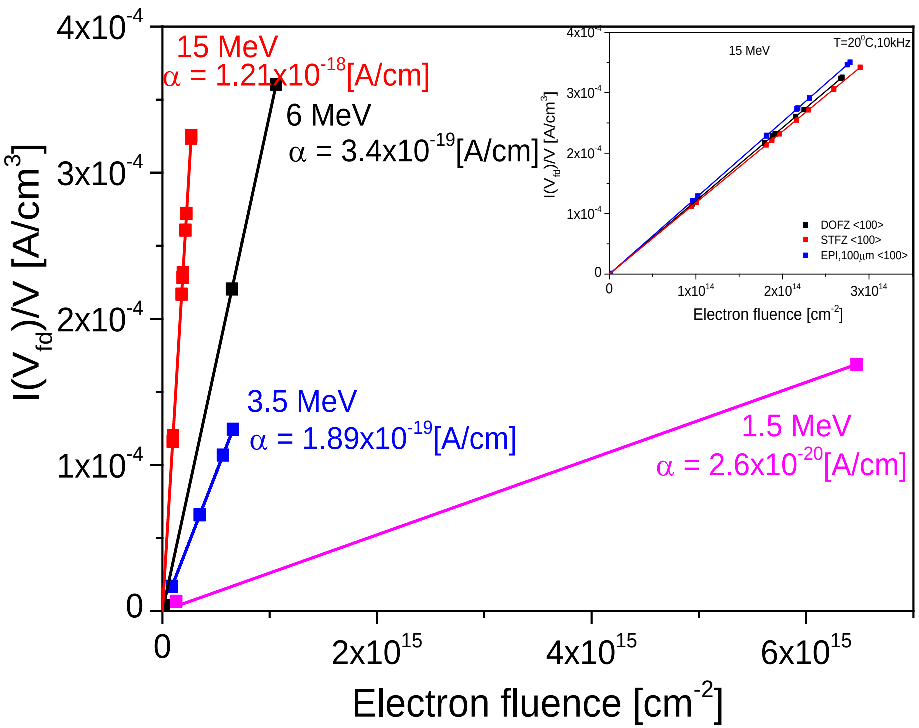
Type	Orientation	d[µm]	N_D[cm^{-3}]	<[O]>[cm^{-3}]	ρ [Ωcm]	Diffusion oxygenated
EPI	<111> <100>	50 100	$6x10^{13}$ $1x10^{13}$	$1x10^{17}$ $2.8x10^{17}$	50 300	- 24 h /1100^0C
ST-FZ	<100>	280	$8x10^{11}$	$1x10^{16}$	$5x10^3$	-
DO-FZ	<100>	280	$8x10^{11}$	$1.2x10^{17}$	$5x10^3$	72 h /1150^0C

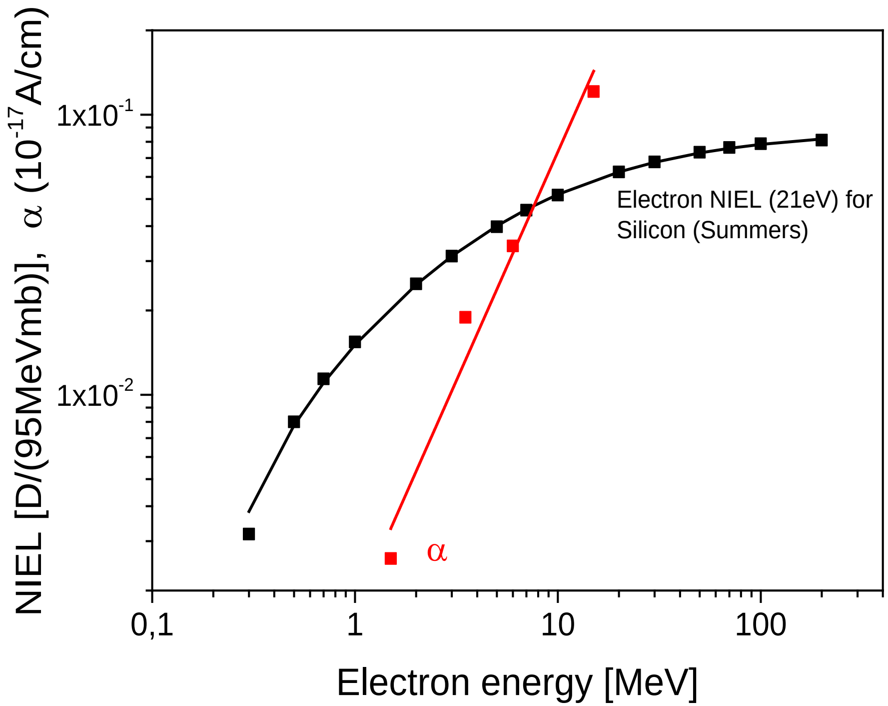
Processing performed at: CiS, Institute for Microsensoric and Photovoltaic GmbH, Erfurt, Germany

Electron energies:

- 1.5 MeV, $\Phi = 1x10^{14} – 6x10^{15}$
- 3.5 MeV, $\Phi = 1x10^{12} – 2x10^{15}$
- 6 MeV, $\Phi = 1x10^{12} – 1.5x10^{15}$
- 15 MeV, $\Phi = 3x10^{11} – 2x10^{14}$

Dark current





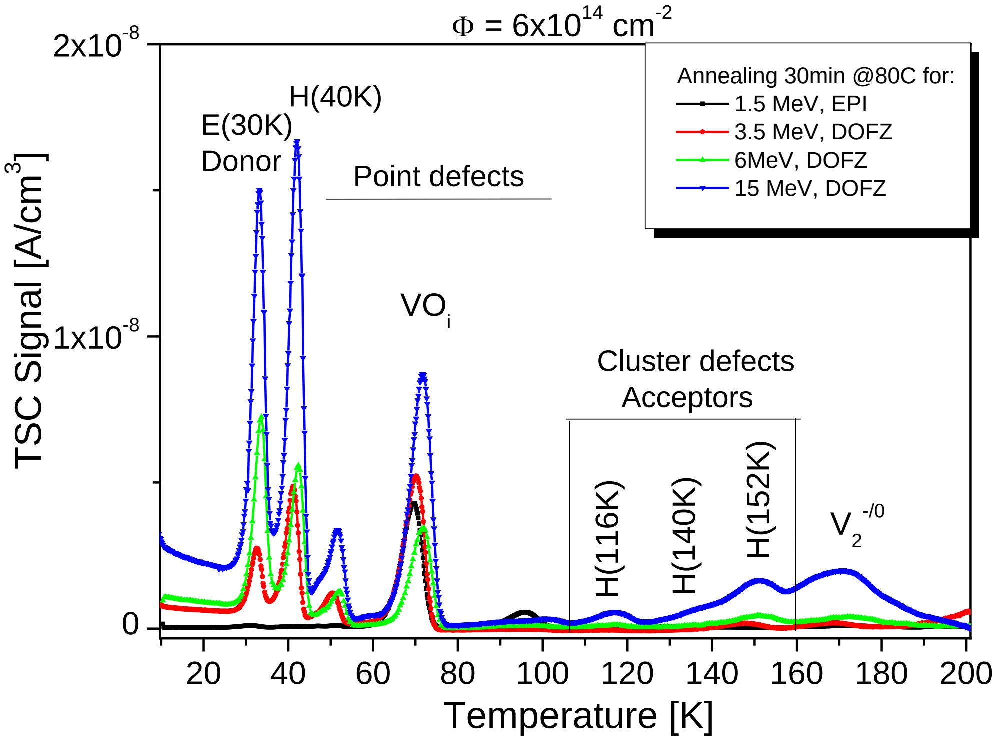
- Dark current increases proportional to Φ for all materials
- Current related damage parameter α increases with increasing energy

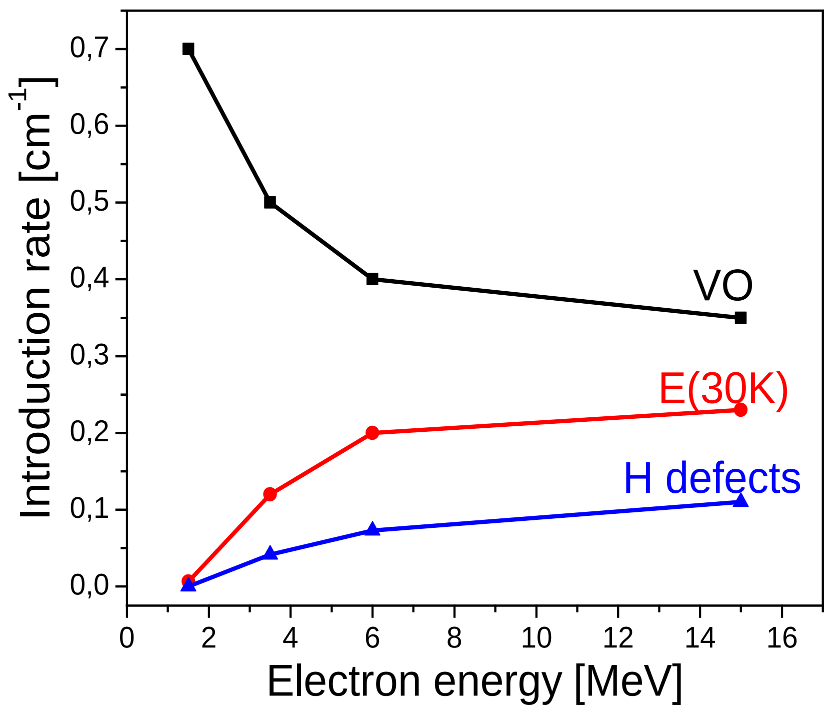
$$\alpha = I(V_{fd})/\Phi_e V$$

NIEL scaling of α for electrons in the range 1-15 MeV violated

Results

TSC measurements – energy dependence

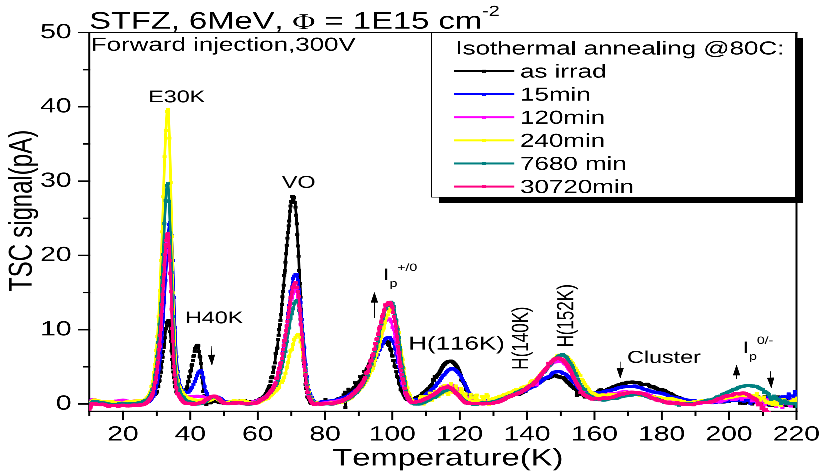


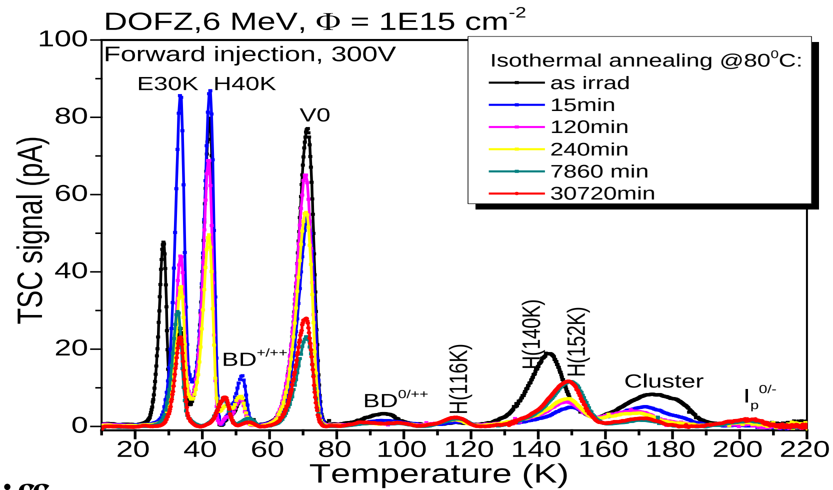


- 1.5 MeV: VO dominant, small signal E(30K), no H-defects
- 3.5 MeV: E(30K) and H-defects visible
- 6 MeV there is a mixture of $V_2^{(-/0)}$ and cluster defects
- 15 MeV: E(30K) and H-defects larger compared to 6 MeV

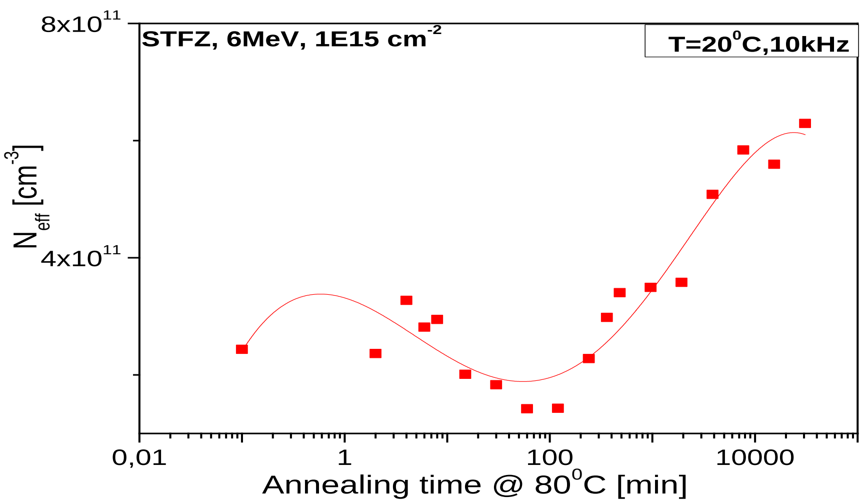
Increasing electron energy → cluster defects increase, point defects decrease

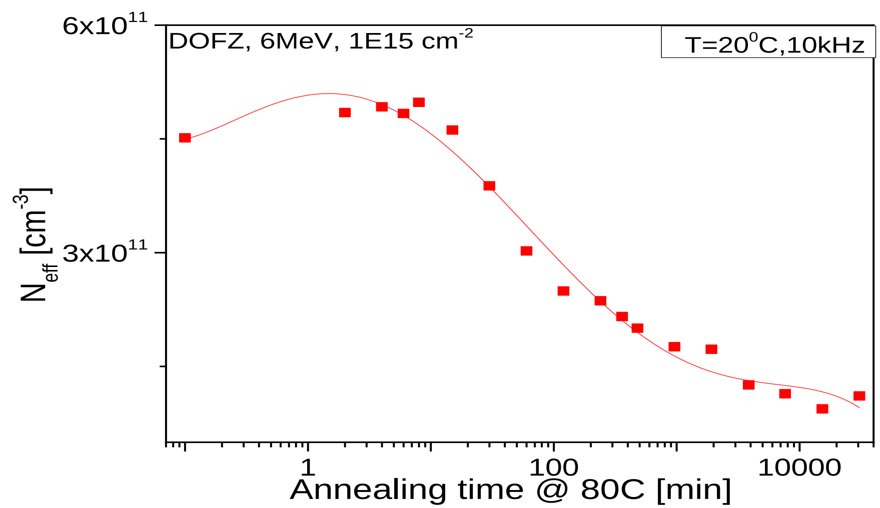
TSC measurements- isothermal annealing





Most obvious differences:





Strongly generated I_p defect in STFZ - the main cause for the type inversion effect

Annealing of E(30K) defect

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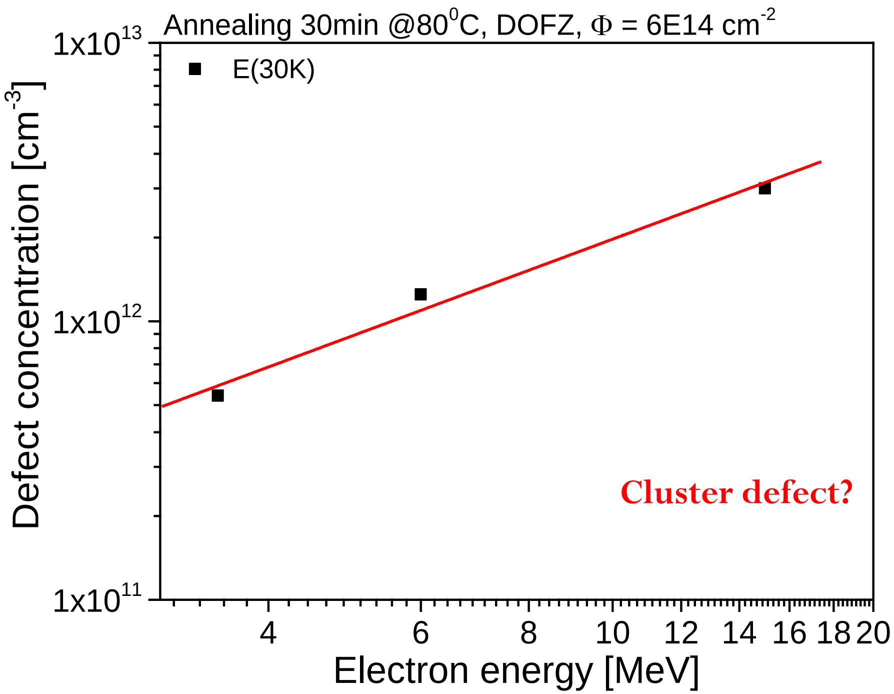
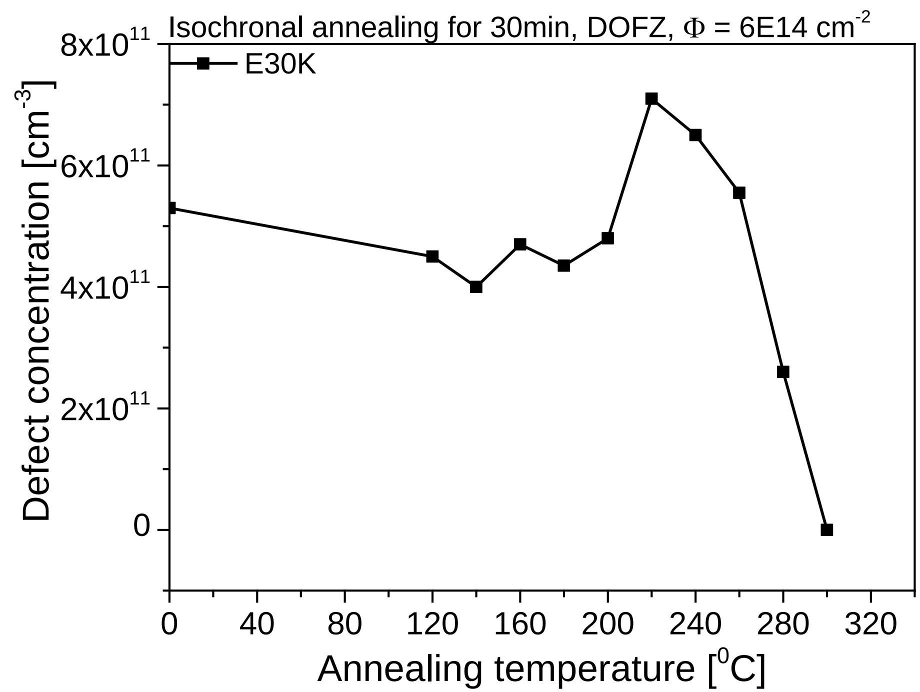
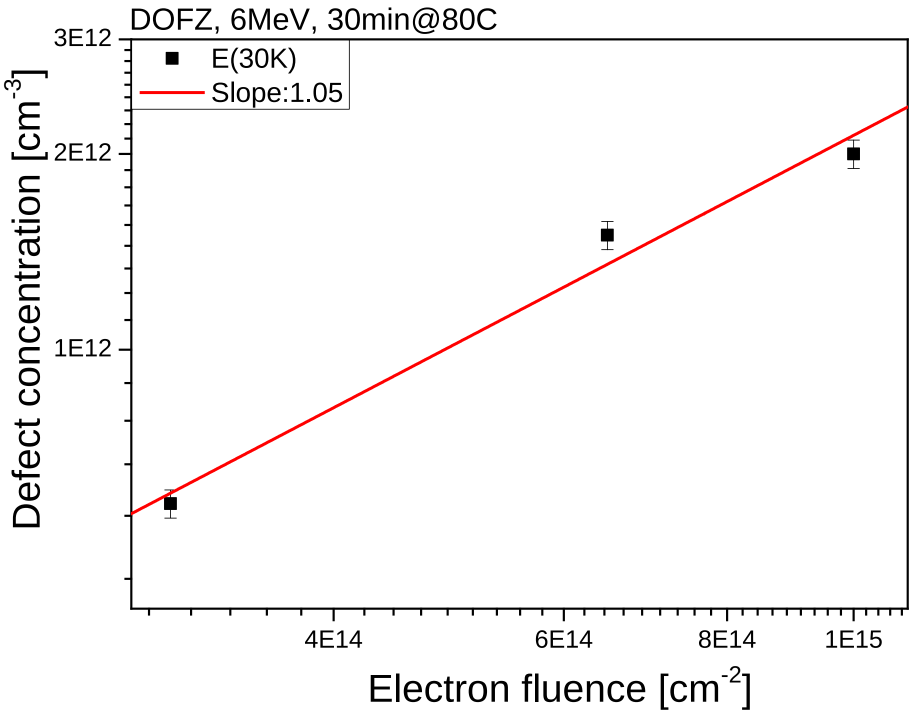


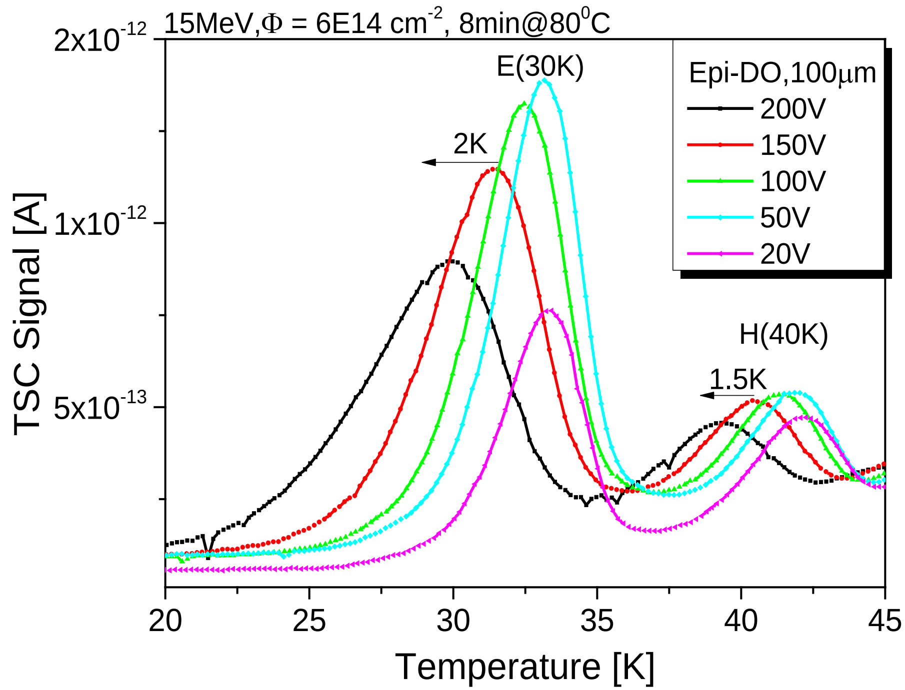


- E(30K) – shallow donor, trap for electrons, not seen after gamma irradiation– no [O] dependence
- Introduction rate increases with energy
- The E(30K) concentration reaches a maximum at 220^0C and anneals out at 300^0C
- Responsible for introduction of positive space charge and "beneficial annealing" after hadron irradiation

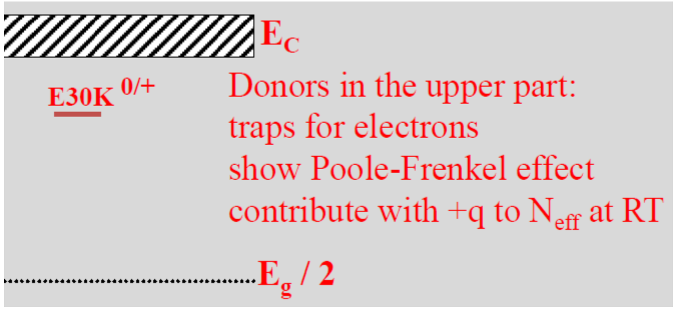
Isochronal annealing → fast overview of defect evolution

TSC measurements- isothermal annealing





- E(30K) defect with enhanced field emission described by Pool-Frenkel effect
- E(30K) linear dependence → first order process
- H(40K) - not seen after gammas irradiation
- H(40K) - unknown mechanism for enhanced field emission



Annealing of H defects

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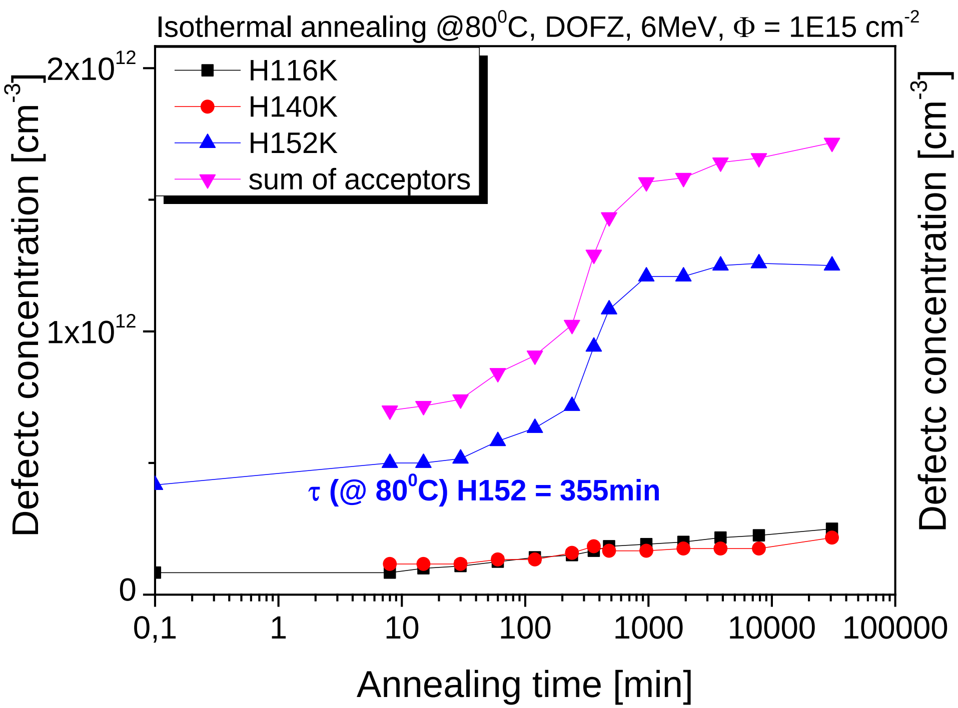
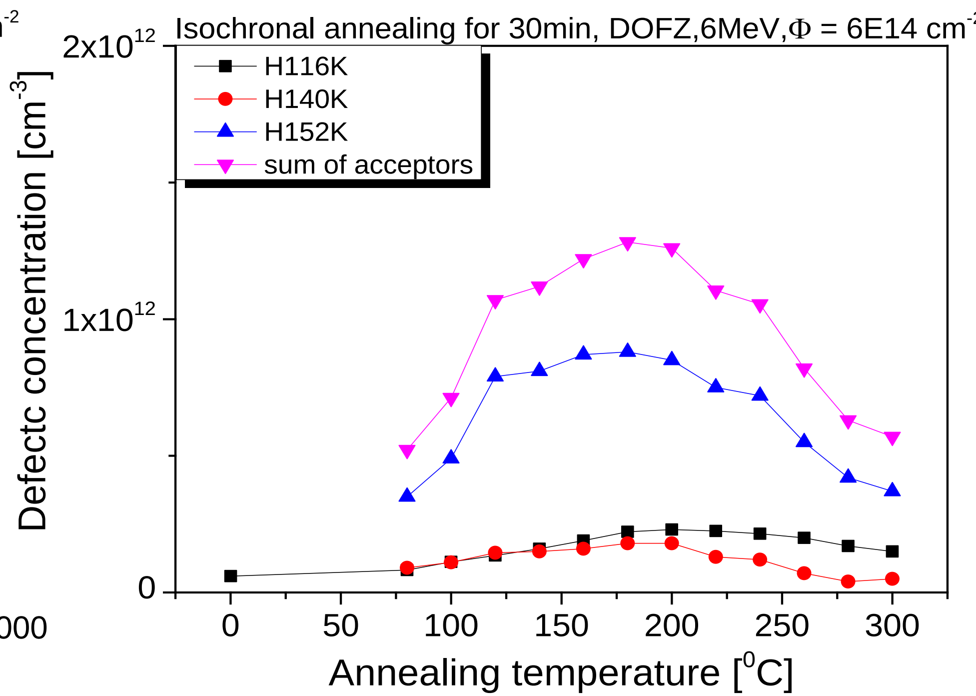
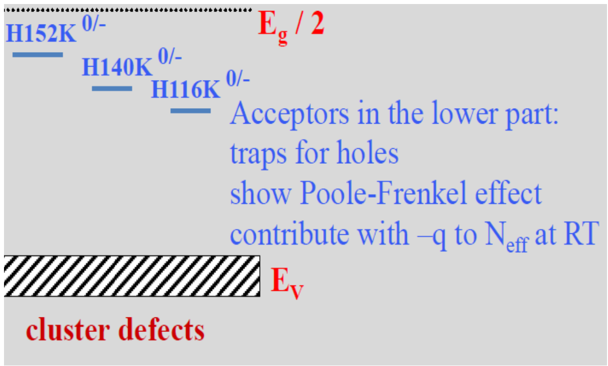


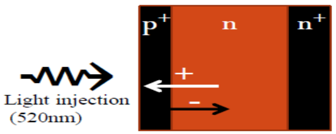


- H defects: deep acceptors in the lower half of the bandgap
- Clusters H(116K) and H(152K)) produced already at 3.5 MeV
- Responsible for introduction of negative space charge and "reverse annealing"
- Increase with increasing energy and annealing

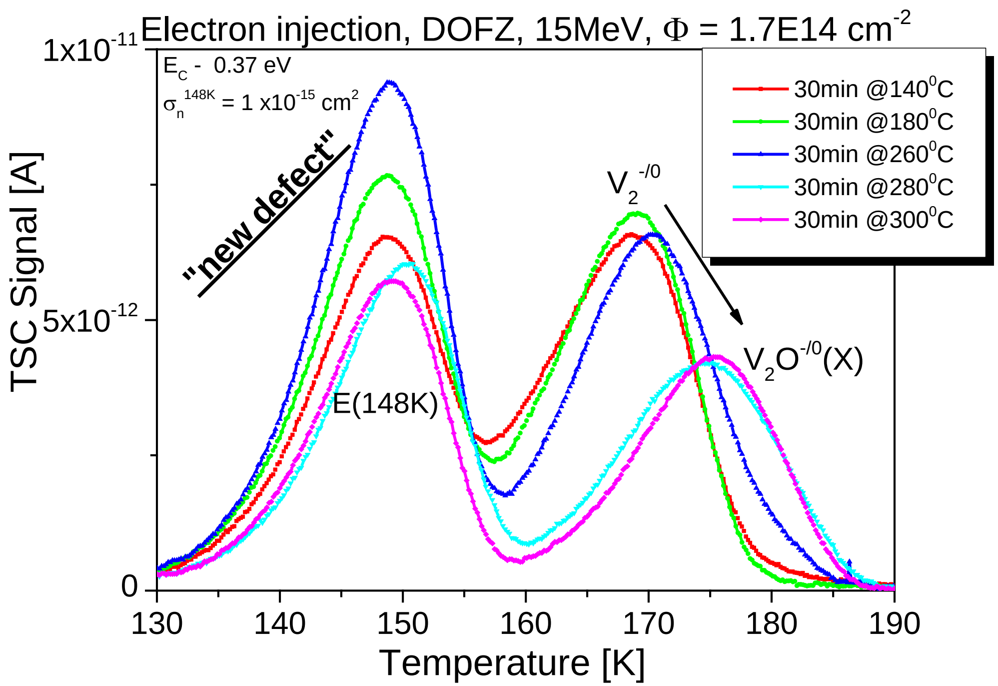
→ type inversion in both STFZ&DOFZ silicon

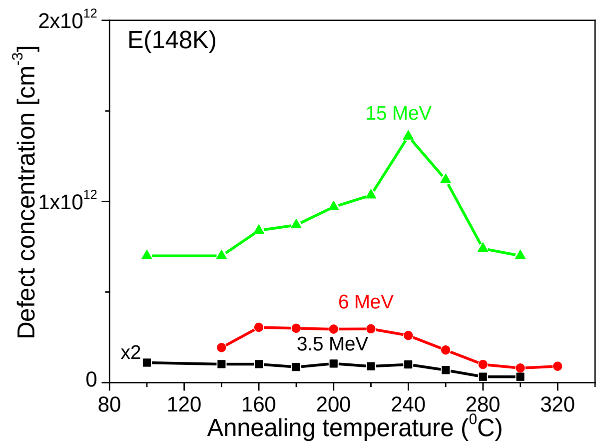


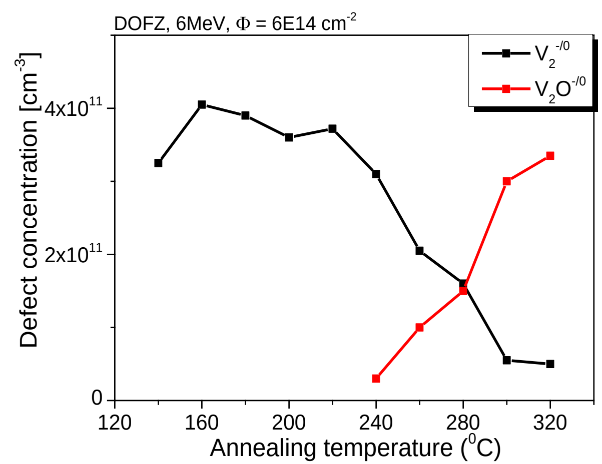
TSC measurements- isochronal annealing



- Front side illumination → electron injection
- Rear side illumination → hole injection

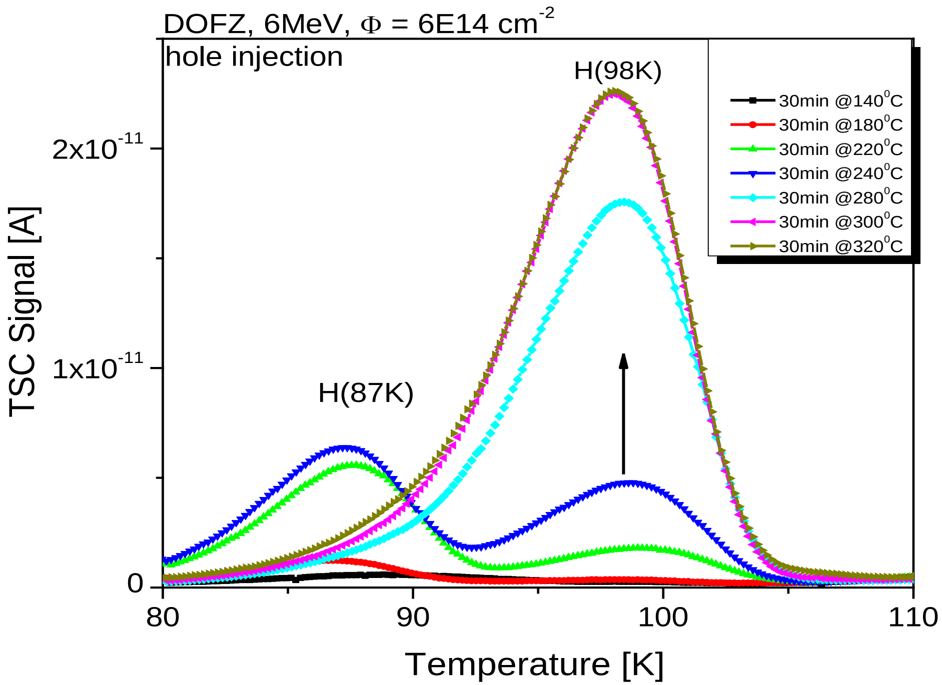


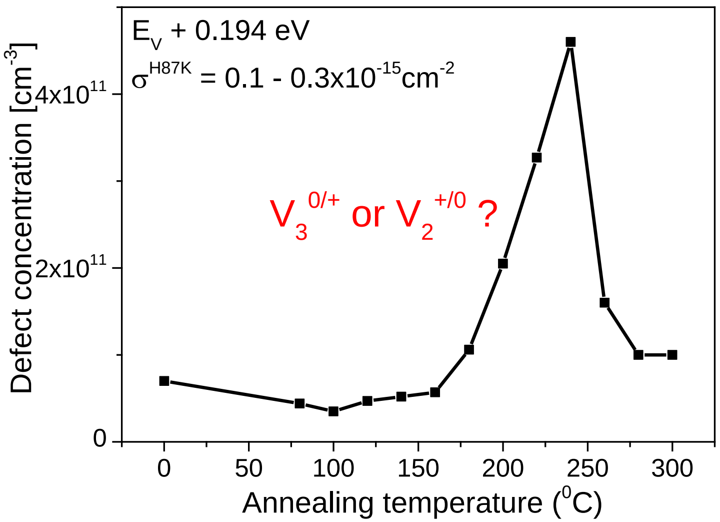


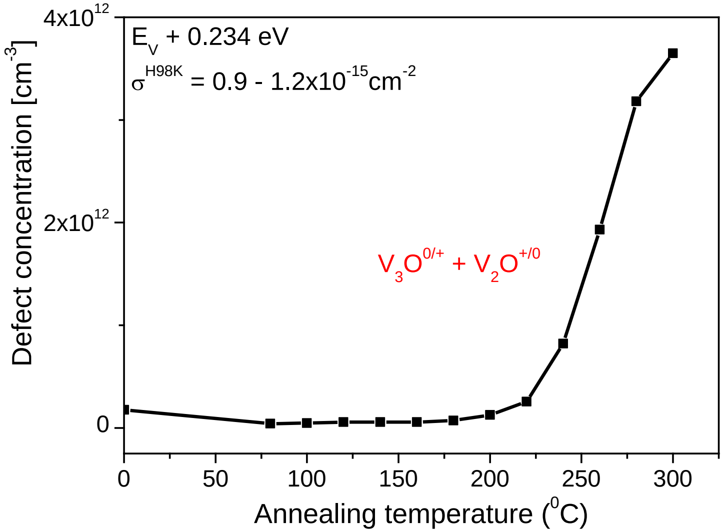


- E(148K) - trap for electrons – no [O] dependence
- E(148K) seen also in isothermal annealing@80C
- Annealing out of V_2 starts at 220^0C and annealing in of V_2O at the same temperature
- Transformation of V_2 in V_2O during annealing starts at the same temperature for all energies

V_2O and V_3O in silicon - isochronal annealing





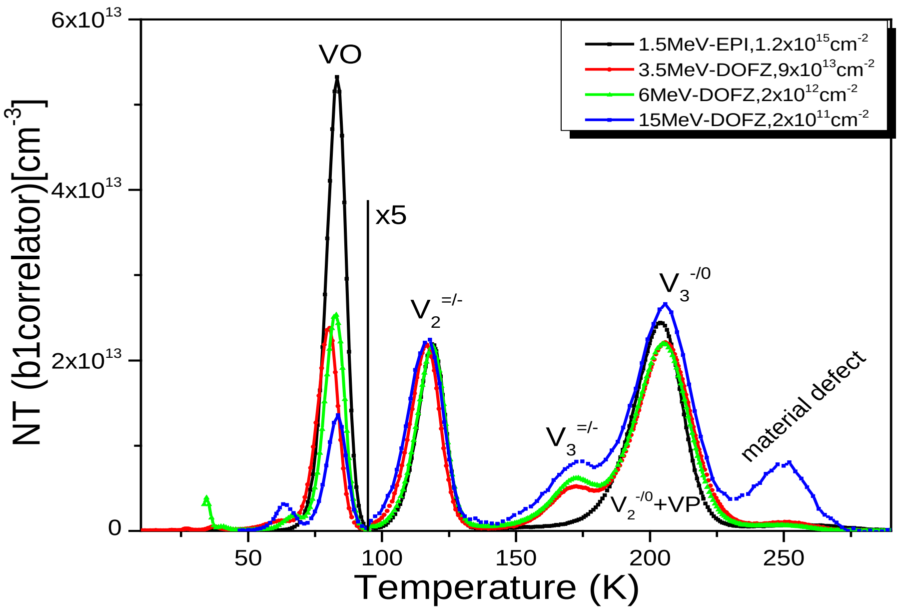


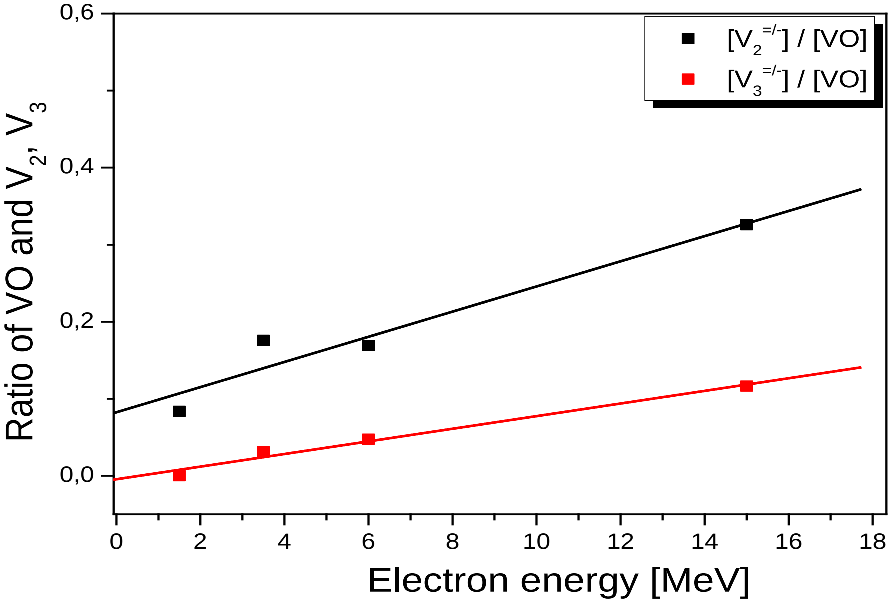
- V_3 and V_3O - donor levels (not seen in STFZ)
- Detected only by hole emission
- Transformation of V_2, V_3 into V_2O, V_3O

→ consistent with *V.P.Markevich et al: Phys.Status Solidi A 208, No3, 568-571, 2011*

- $V_2^{+/0}$ - stable up to 220 ^{0}C
- $V_3^{+/0}$ - changed to the ffc. - configuration

DLTS measurements- energy dependence





1.5 MeV - EPI

$VO, V_2^{(=/-)}, V_2^{(-/0)} + VP$

3.5, 6, 15 MeV - DOFZ

$VO, V_2^{=/-}, V_3^{=/-}, V_2^{-/0} + V_3^{-/0}$

- Introduction rate of single charged vacancies decrease with increasing E_e
- In case of higher $E_{rec.}$ a large introduction of directly generated di-vacancies and tri-vacancies

Conclusions

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Studies of radiation damage due to electron irradiation for different energies revealed:

The classical NIEL for electron is violated between 1.5 MeV – 15 MeV

Main effects of electron energy on defect formation:

- **E_e = 1.5 MeV: only point defects** like VO, V_2, no E(30K) and no H-defects
- Increasing energy $E_e \geq$ 3.5 MeV:
  - Introduction of single vacancy related defect VO decreases
  - Introduction of V_2,V_3 defects increases
  - Defects with impact on N_{eff} : (E30K) and H-defects increase

Defect kinetics (annealing):

- H-defects increase with increasing annealing temperature and time
- E(30K) increases up to 220^{0}C, then anneals out
- Transformation of V_2 ,V_3 $\rightarrow$ V_2O ,V_3O starting at 220^{0}C – observed in TSC, isochronal

Detected new defects by isochronal annealing:

- Electron trap E(148K) - concentration increases with increasing energy
- Hole trap H(87K) unknown, **speculation $V_3^{+/0}$** *(V.P.Markevich et al: Phys.Status Solidi A 208, No3, 568-571, 2011)*
- Hole trap (98K): identified with V_2O + V_3O donor levels

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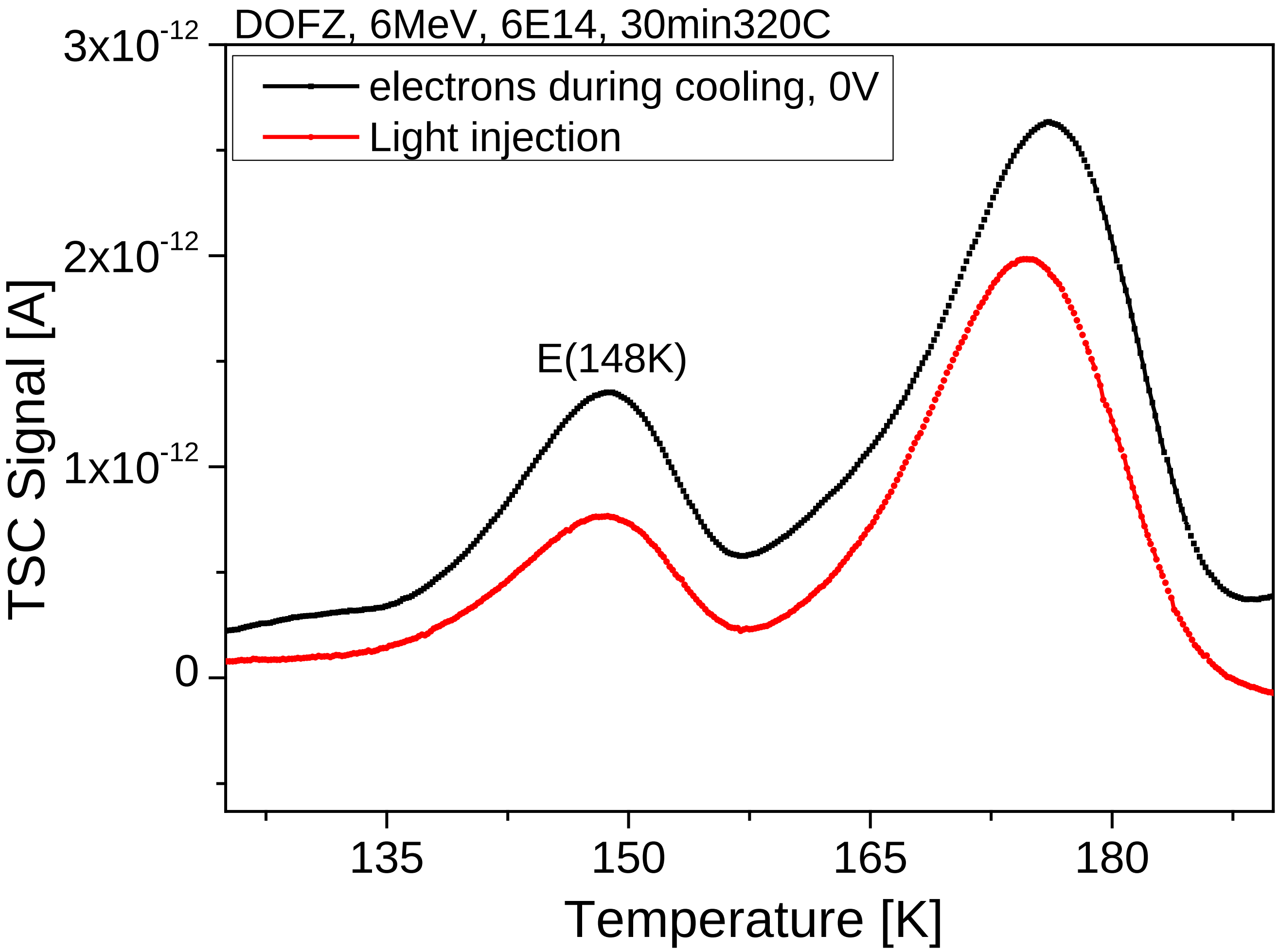
Thank you for you attention

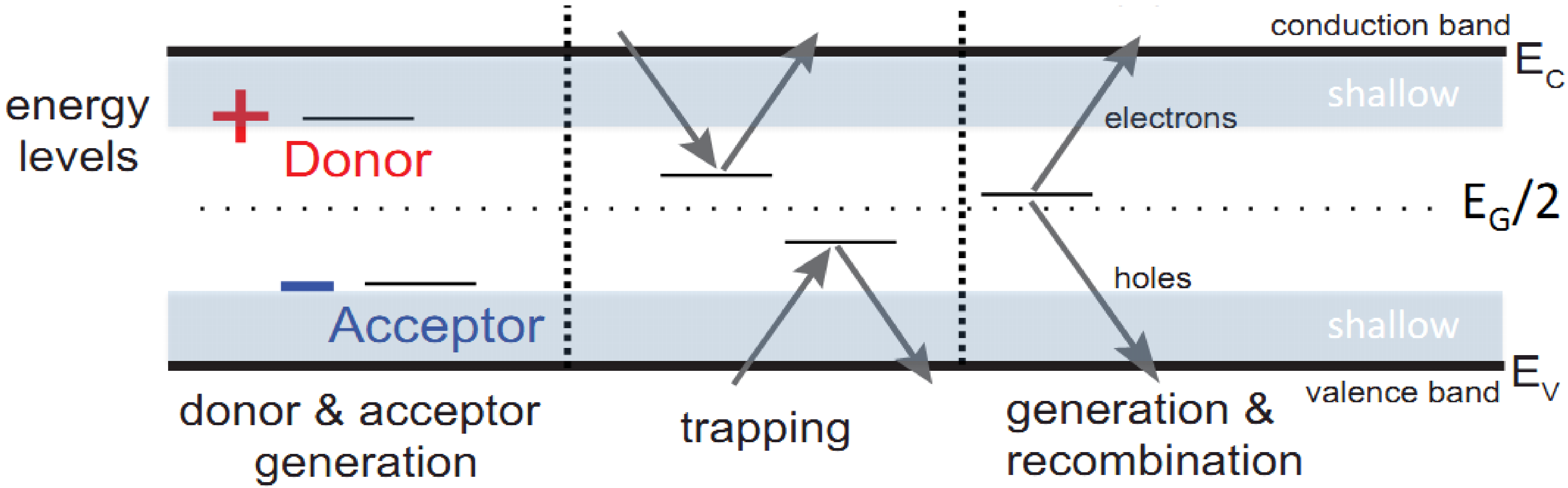
Backup

E(148K)



DOFZ, 6MeV, 6E14, 30min320C
electrons during cooling, 0V
Light injection
E(148K)
TSC Signal [A]
3x10-12
2x10-12
1x10-12
0
135
150
165
180
Temperature [K]

Shockley-Read-Hall statistics



I. Change of N_{eff}, V_{dep}
⇒ type inversion ,
⇒ decrease of signal

II. Increase of charge carrier trapping
⇒ loss of charge

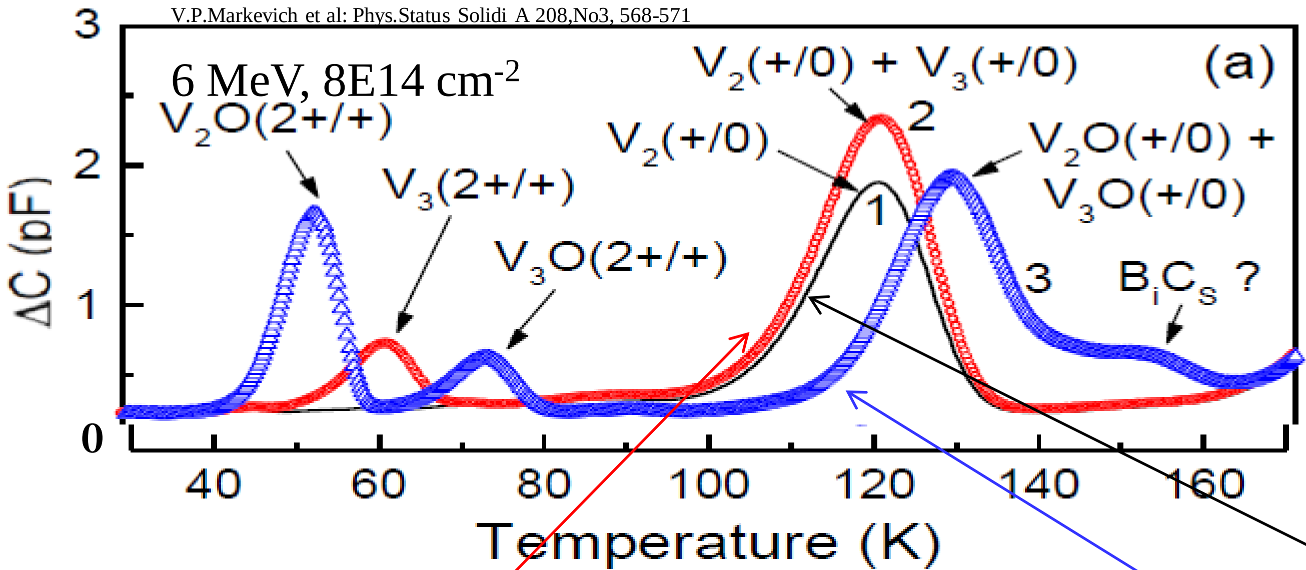
III. Increase of leakage current
⇒ increase of noise
Cooling during operation!

Donor – neutral if filled with an electron and positive if empty
Acceptor – neutral if empty and negative if filled by an electron

Donor states of V_2,$V_3$and V_2O ,V_3O in silicon

DLTS spectra for a n+-p-p+ epi-Si diode ,

V.P.Markevich et al: Phys.Status Solidi A 208,No3, 568-571



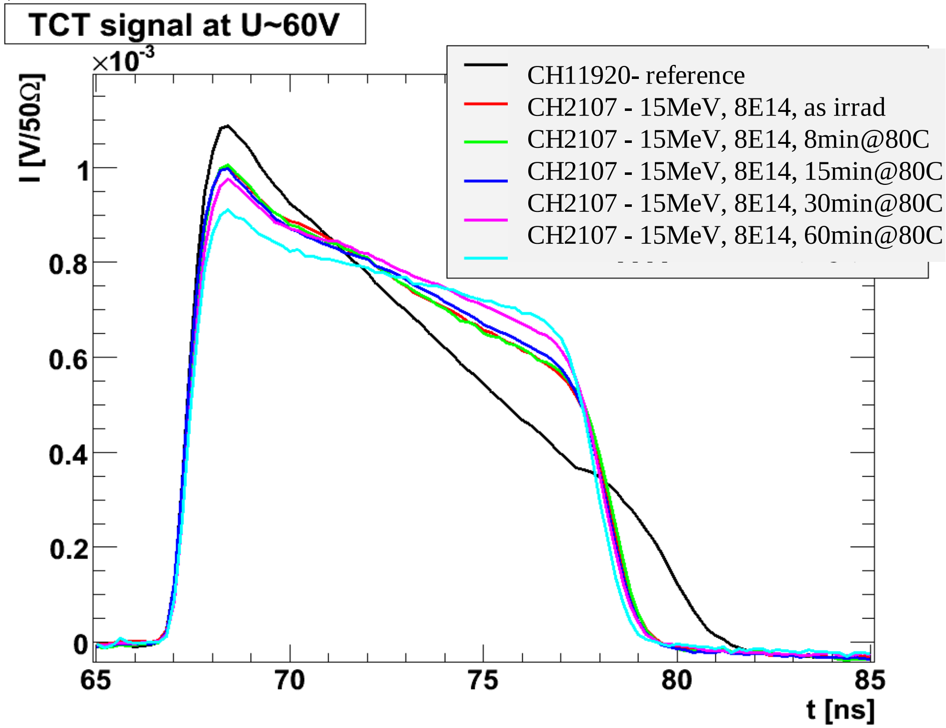
heat-treatment at 100 C for 30 min

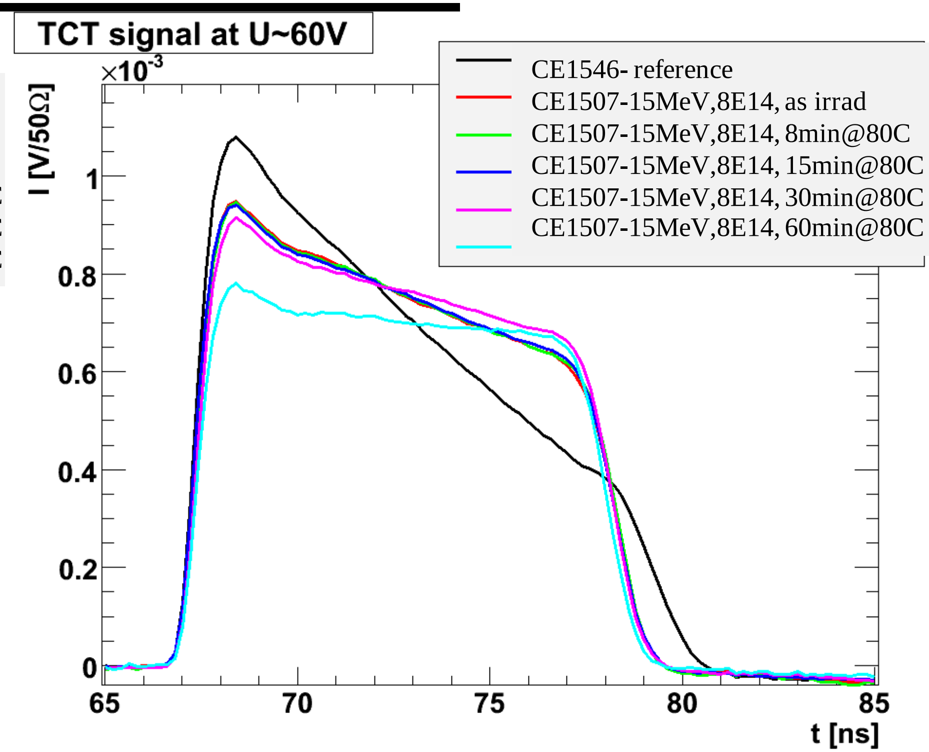
forward bias injection -10 A/cm^2 for 10 min at 300 K after annealing at 100 C

annealing at 300 C for 30 min.

Transformation of V_2 and V_3 into V_2O, V_3O

Charge collection - TCT





I(t) in drift region reflects drift velocity → electric filed distribution or SCR

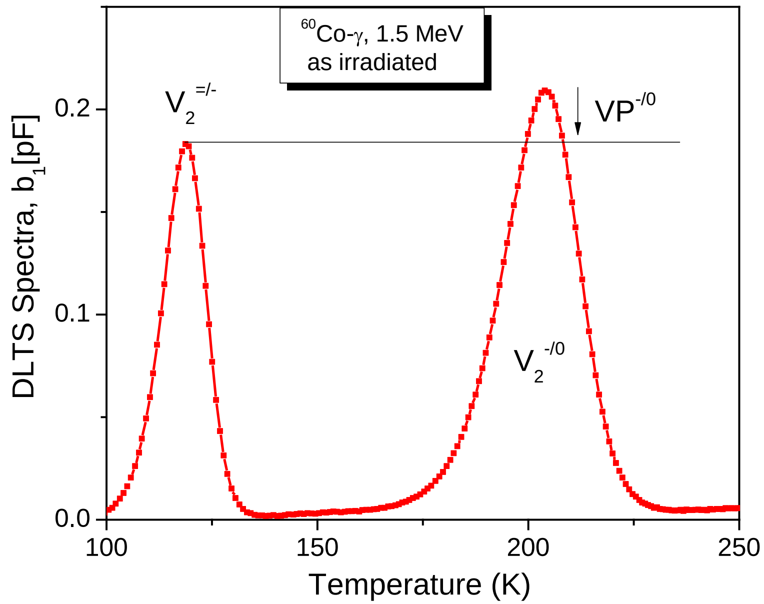
With increasing annealing time the slope decreases

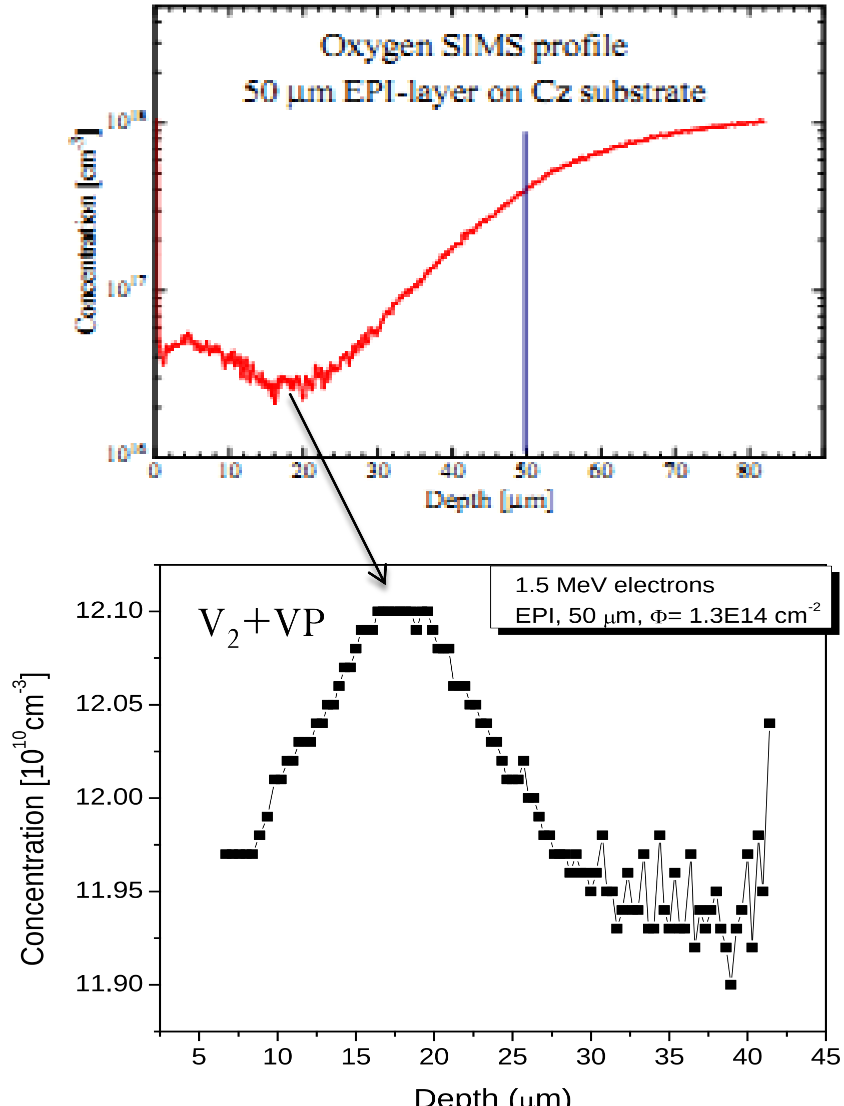
→ SCR decreases → V_{dep} decreases

→ consistent with V_{dep} from C-V

For15 MeV expected to clearly see trapping, but from preliminary analyses of CCE the trapping effect is below 2%

DLTS measurements – 1.5 MeV





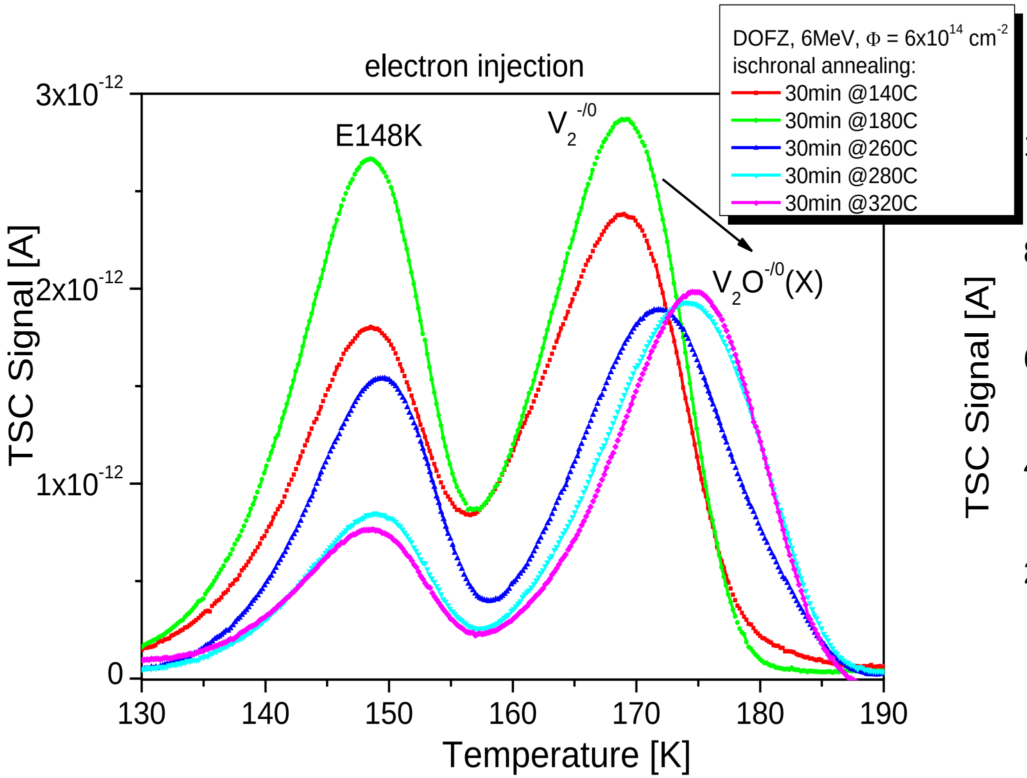
Depth profile of $V_2^{(-/0)}$+VP

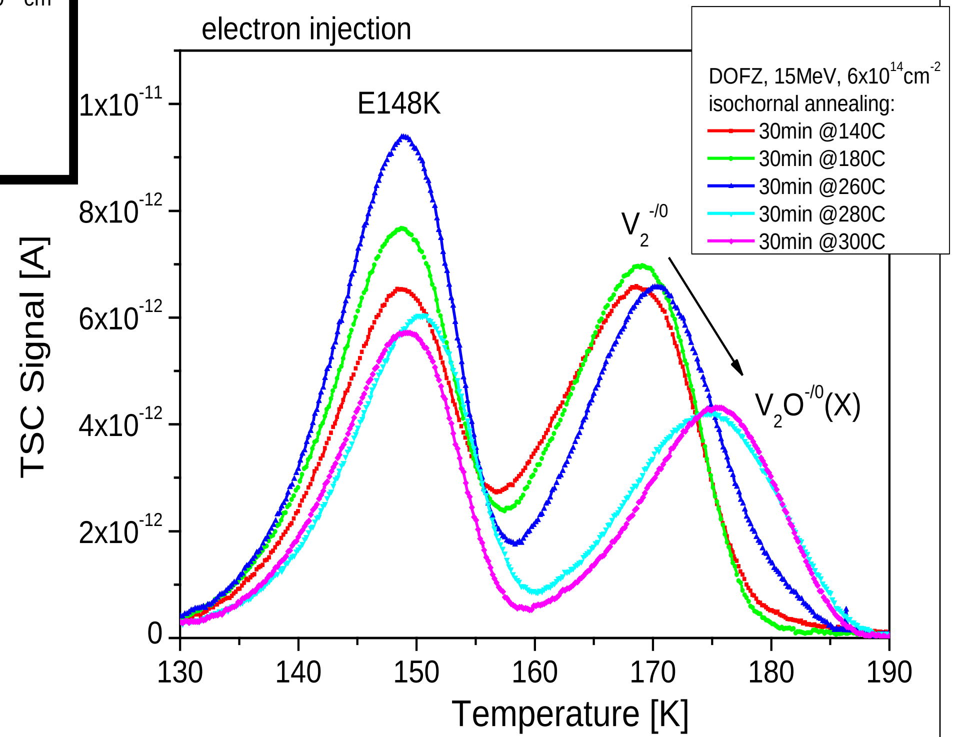
VP anti-correlated with depth profile of oxygen

Signal amplitude $V_2^{(=/-)} < V_2^{(-/0)}$

$V_2^{(-/0)}$ overlaps with VP

TSC measurements- Isochronal annealing





TSC measurements