Investigation of point and extended defects in electron irradiated silicon – dependence on the particle energy

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Outline

- Motivation & Goal & Strategy
- Radiation induced defects after electron irradiation
- Impact of defects upon silicon device properties
- Investigation of defect structure
- Conclusions

Motivation and Goal: New ways to develop radiation hard silicon sensors ↔ bridge the gap between the defect analyses and device performances

I. Joint project between NIMP Bucharest and University of Hamburg – ''Electron irradiation of Si-diodes at E = 1.5 - 27 MeV" presented by Prof. G. Lindström at the last *WODEAN Workshop in Bucharest, 13/14 May 2010*

II. ''Comprehensive investigation on bulk radiation damage in defect engineered silicon - from point defects to clusters'' – Project Director Ioana Pintilie, 2011

Strategy:

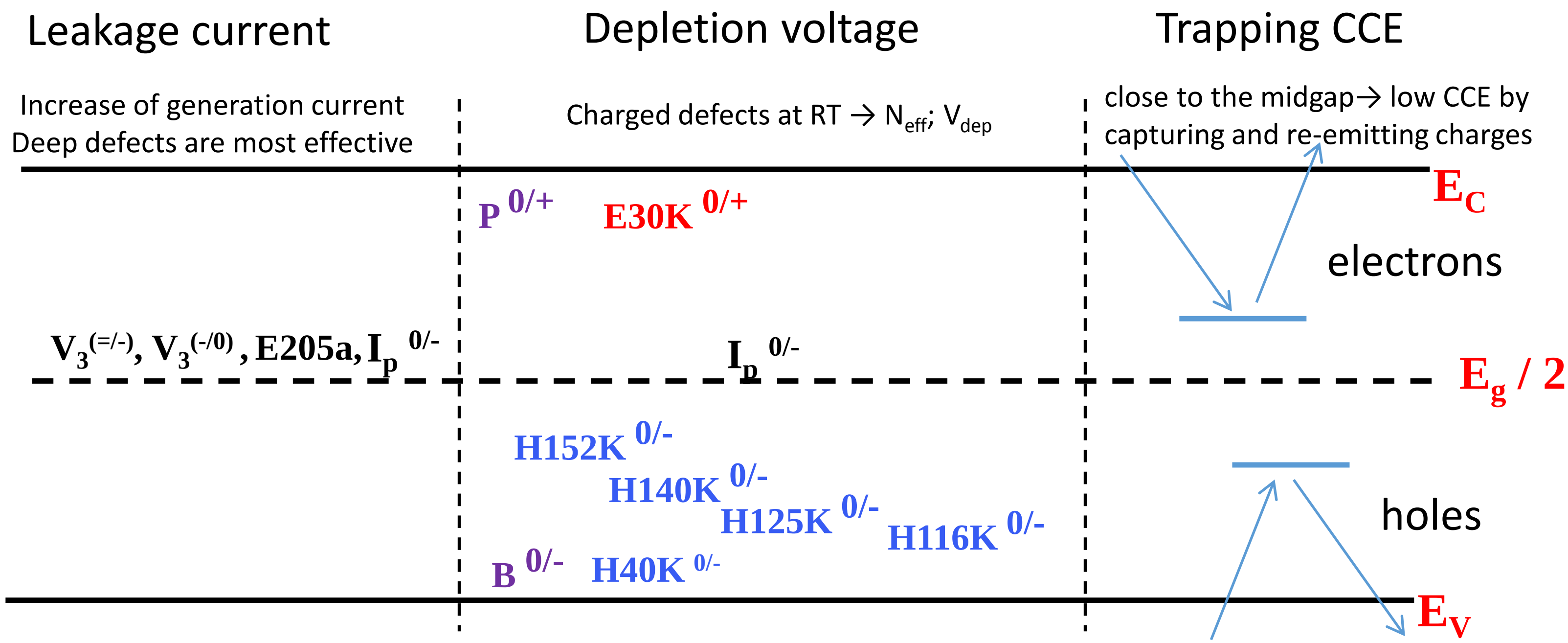
a) Irradiation with electrons with kinetic energies ranging: 1.5 MeV ÷ 27 MeV – studies performed in Hamburg

- CV/IV characterization, before/after irradiation → analysis of electrically active defects by means of DLTS and TSC methods → correlation with results from diode characteristics

b) Electron induced damage in Si implanted with ^{17}O and ^{13}C – investigations performed in Bucharest

- EPR investigation in defect engineered silicon (O enriched, O lean, C rich, C lean) → studies for defect identification (see talk of S. Nistor)
- HRTEM investigation of the extended and clustered defects → identify the structure of the radiation-induced electrically active defects and establish the role of the impurities in their generation and kinetics (see talk of L. Nistor)

Radiation induced defects after electron irradiation - damage effects

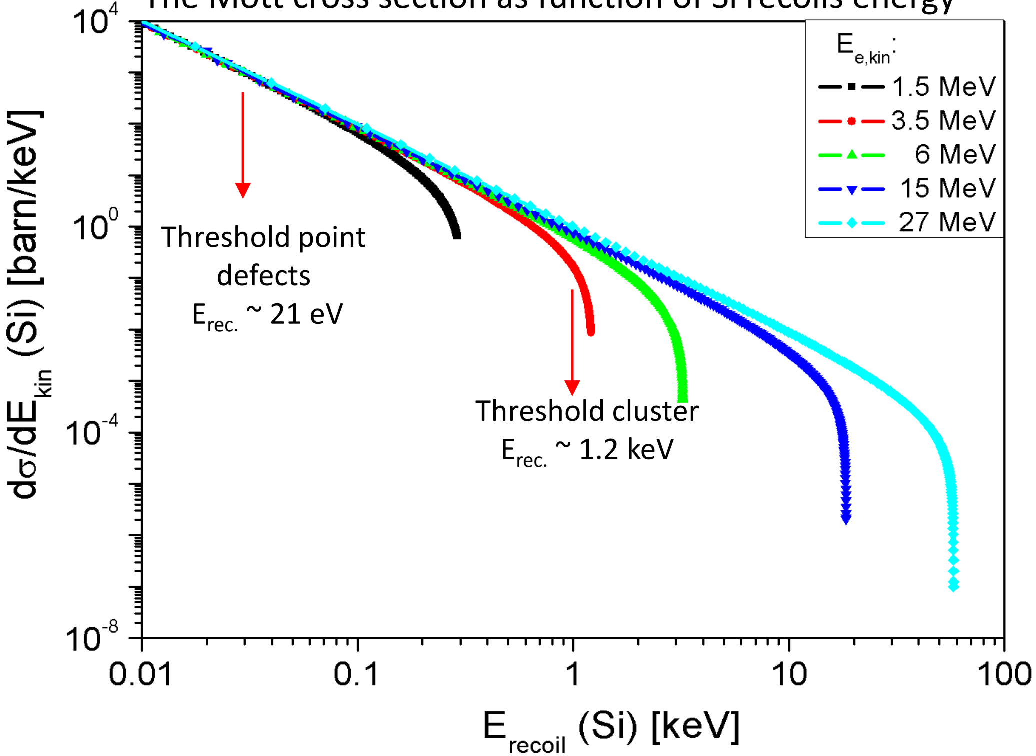


E(30K), E205, Ip, H(40K), H(116K), H(125K), H(140K) and H (152K) - defects with unknown chemical structure (E- electron trap, H- hole trap)

- In semiconductor devices the deep levels kinetics i.e. generation and recombination of charge carrier across the band-gap is the major parameters that govern its characteristics and performances (Shockley-Read-Hall statistics)

From point defects to clusters

The Mott cross section as function of Si recoils energy



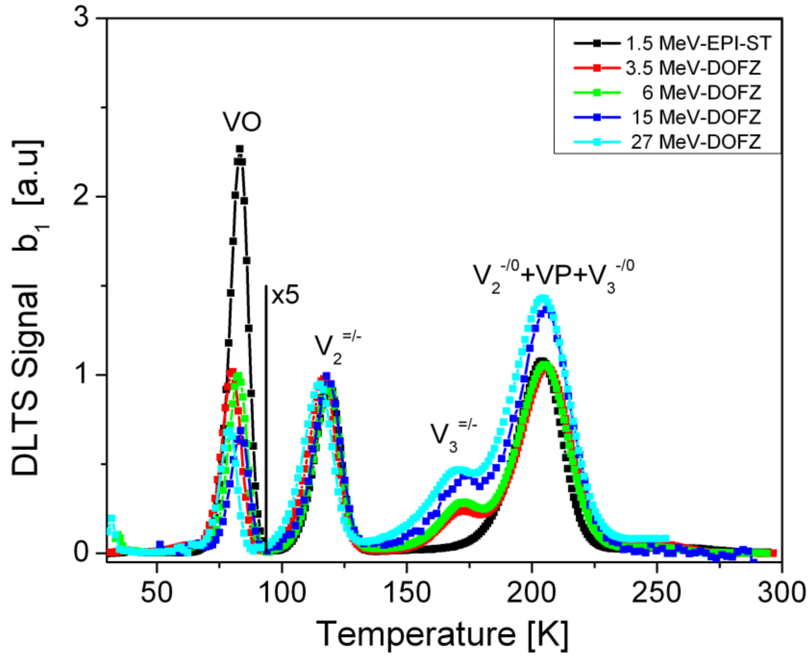
Electron energy	Maximum energy transfer
1.5 MeV	290 eV
3.5 MeV	1.2 keV
6 MeV	3.2 keV
15 MeV	18.3 keV
27 MeV	57 keV

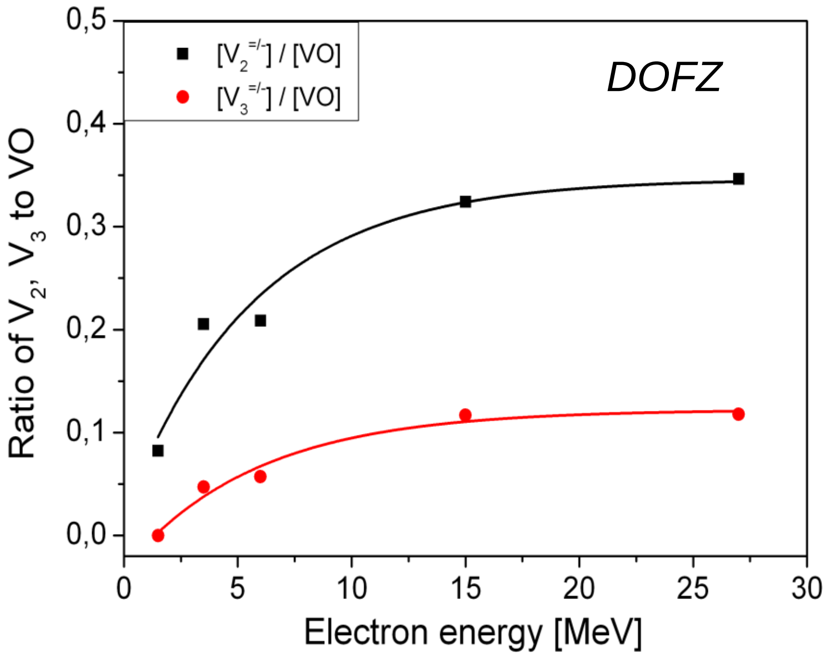
$$T_{max} = \frac{2T_e(T_e + 2m_e c^2)}{M_0 c^2 A}$$

The Mott cross section - description of the scattering of a high energy electron beam from an atomic nucleus-sized positively charged.

- Silicon cascading displacement become relevant for electrons with $T_{max} \geq$ 1keV (equivalent electron kinetic energy ≥ 3.5 MeV)
- As the electron energy decreases , the probability for a single silicon displacement increases

Dependence of defects on electron energy





- VO (Vacancy-Oxygen): point defect
- V_2 (Di-vacancy) point and cluster defect
- V_3 (Tri-vacancy): cluster defect
- E_e = 1.5 MeV: only point defect

- Ratios of di-vacancies (V_2) and tri-vacancies (V_3) to single vacancies increase with energy
- With increasing electron energy di-vacancies and tri-vacancies are directly created

$\sum Vacancies / \sum Interstitials$

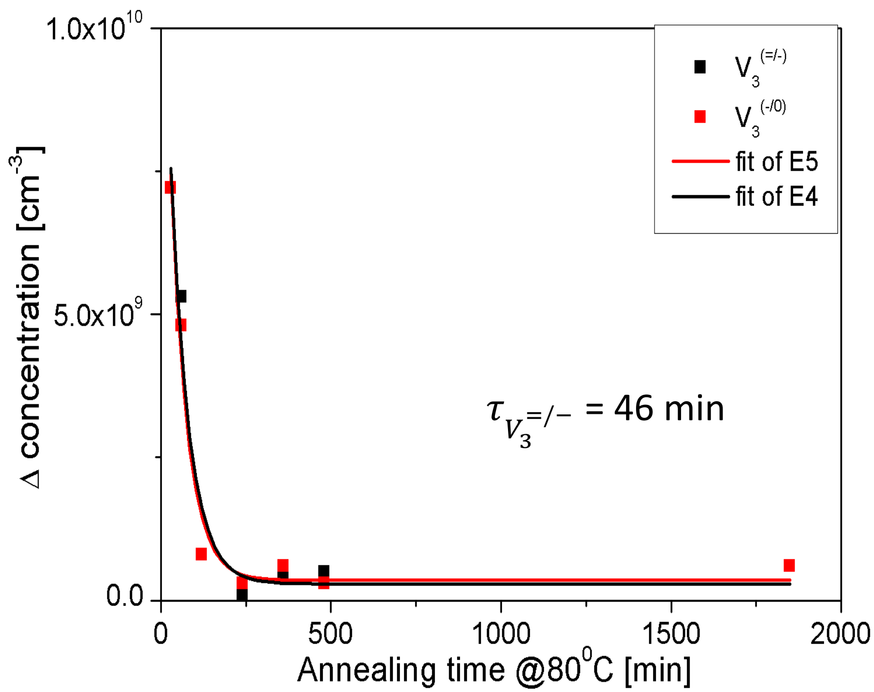
How many vacancies and interstitials are created after electron irradiation?

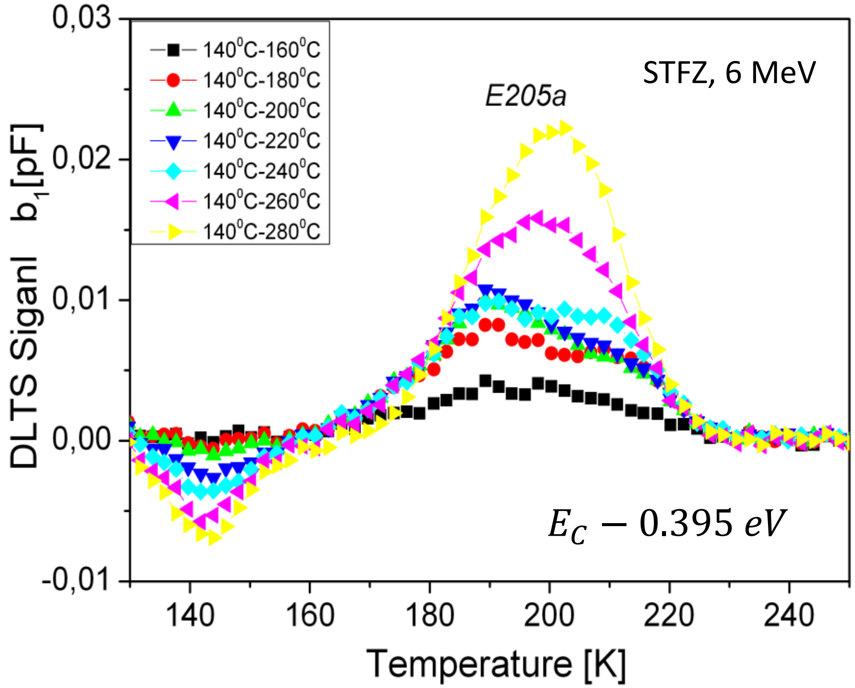
Ratios of defect concentrations *in DOFZ material*	**1.5 MeV**	**3.5MeV**	**6 MeV**	**15 MeV**	**27 MeV**
$[V_2^{=/-}]/[VO_i^{/-0}]$	0.082	0.2	0.21	0.32	0.34
$[V_3^{=/-}]/[VO_i^{/-0}]$	0	0.047	0.057	0.116	0.117
$[V_3^{=/-}]/[V_2^{=/-}]$	0	0.22	0.27	0.36	0.34
$\frac{[VO_i^{/-0}] + 2x[V_2^{=/-}] + 3x[V_3^{=/-}]}{[C_iO_i^{+/0}]}$	**1.30**	**1.08**	**1.45**	**1.21**	**1.50**

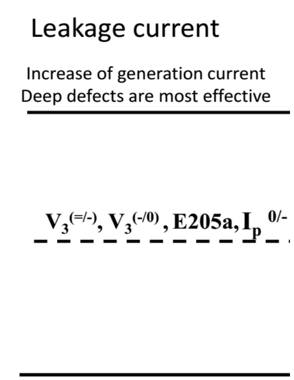
Ratios of defect concentrations *in STFZ material*	**3.5MeV**	**6 MeV**	**15 MeV**	**27 MeV**
$[V_2^{=/-}]/[VO_i^{/-0}]$	0.24	0.17	0.30	0.26
$[V_3^{=/-}]/[VO_i^{/-0}]$	0.05	0.045	0.12	0.12
$[V_3^{=/-}]/[V_2^{=/-}]$	0.21	0.26	0.40	0.48
$\frac{[VO_i^{/-0}] + 2x[V_2^{=/-}] + 3x[V_3^{=/-}]}{[C_iO_i^{+/0}] + [C_iC_S^{+/0}] + [C_i^{+/0}]}$	**1.23**	**2.2**	**1.14**	**1.20**

$\frac{\sum \text{vacancies}}{\sum \text{interstitials}} > 1$ with increasing energy, the I_2 (di-interstitial) and I_3 (tri-interstitial) are not measuread.

Evidence of the influence of cluster-related defects on LC

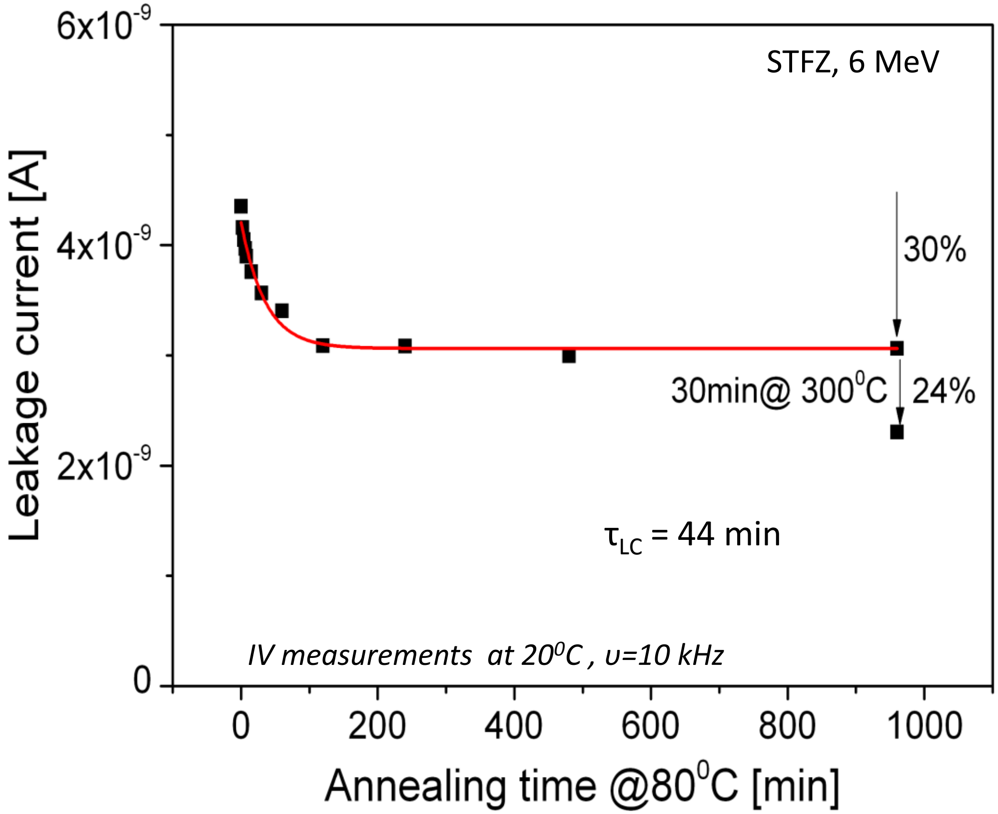


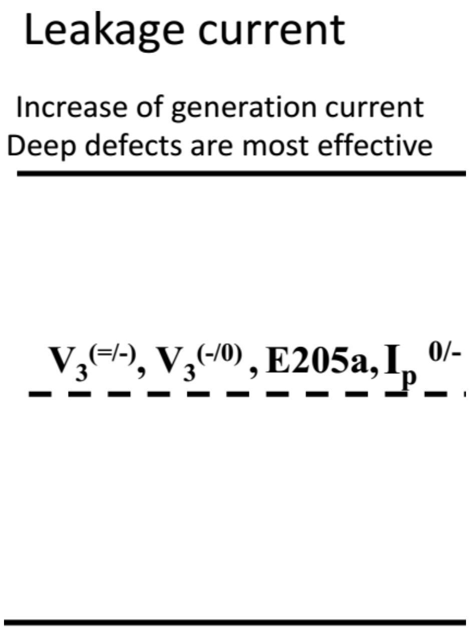




- $V_3^{(=/-)}$, $V_3^{(-/0)}$ - effective generation center → similar annealing behavior like LC
- *E205a* defect starts to anneal in at 200 ^{0}C, when $V_3^{(=/-)}$, $V_3^{(-/0)}$ are not visible
- Increasing T_{ann} the *E205a* defect increases in concentration
- *E205a* defect – responsible for the LC

Evidence of the influence of cluster-related defects on LC

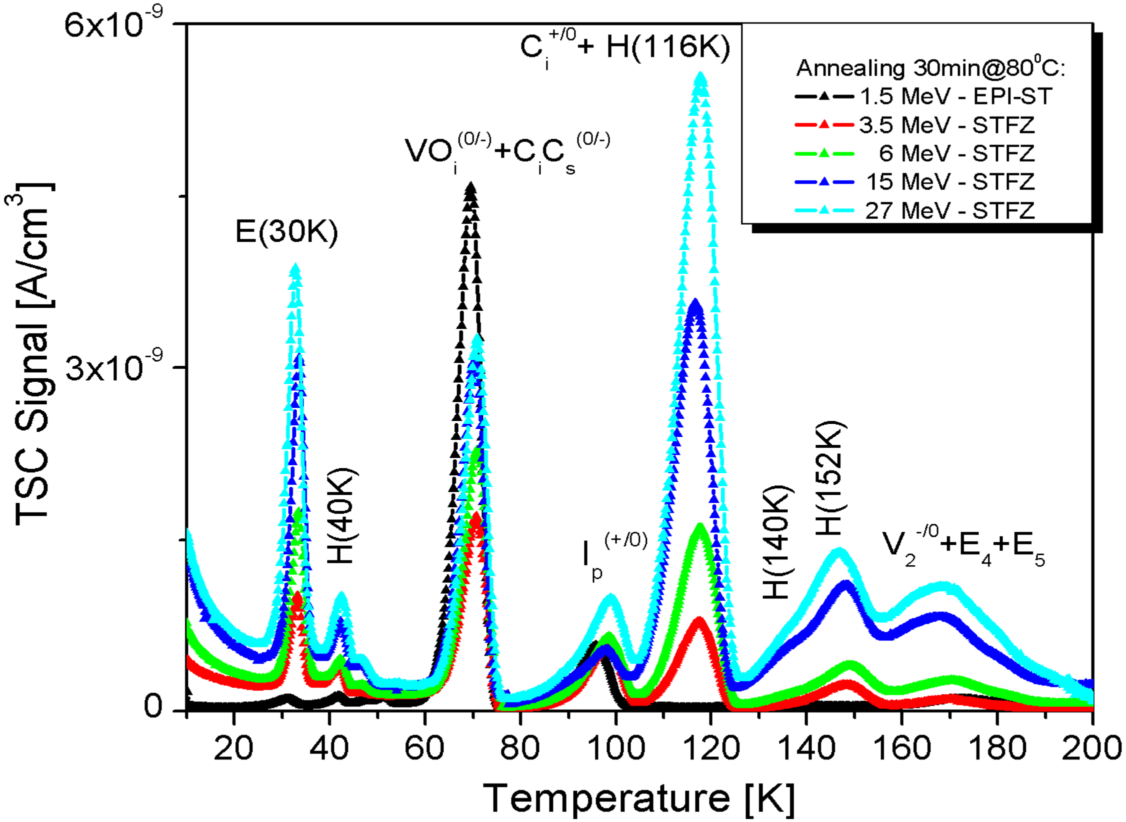




Contribution of defects at the leakage current:

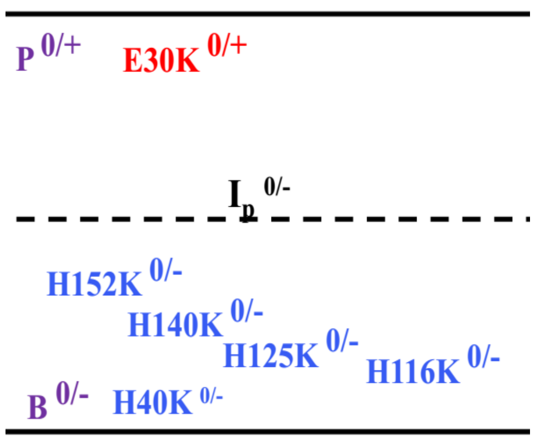
- ~ 60 % of the leakage current, explained by the $V_3^{(-/0)}$ and *E205a* defects:
- 30 % due to the $V_3^{(=/-)}$, $V_3^{(-/0)}$ defect, resulted from the isothermal annealing @80 ^{0}C
- 24 % due to the *E205a* defect, resulted from the isochronal annealing up to 300^{0}C
- LC can also arise from the I_p center, whith E_C - 0.55 eV, and also from the surface currents

Evaluation of the electrically active defects by means of TSC



Depletion voltage

Charged defects at RT → N_{eff}; V_{dep}



- Study of defects which are not detected by DLTS, especially those defects with strong impact on the N_{eff}
- Increasing electron energy → increase of local density of vacancies and interstitials → cluster defects

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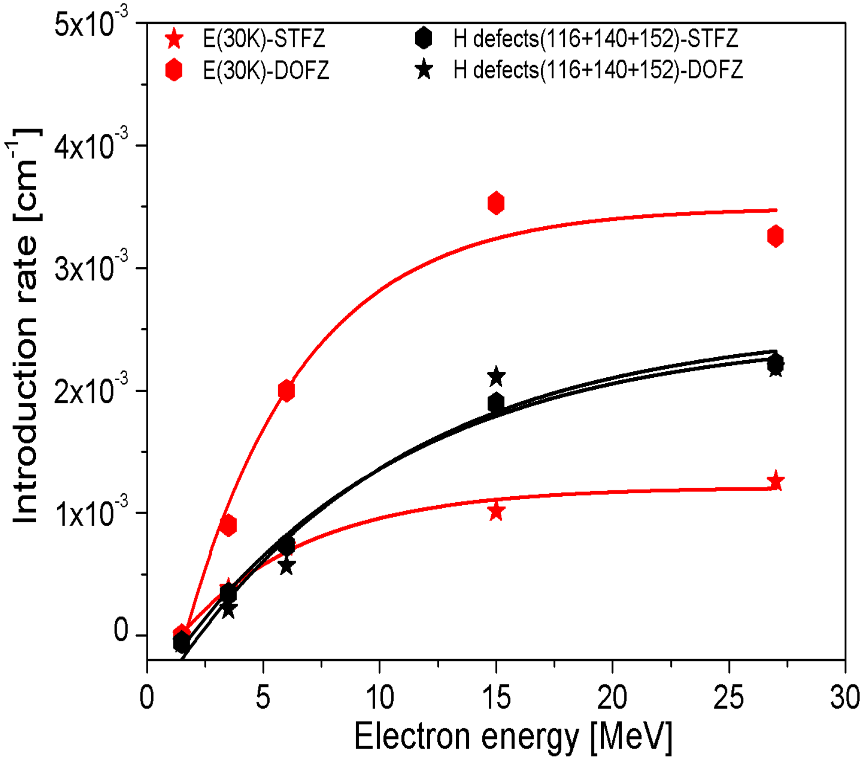
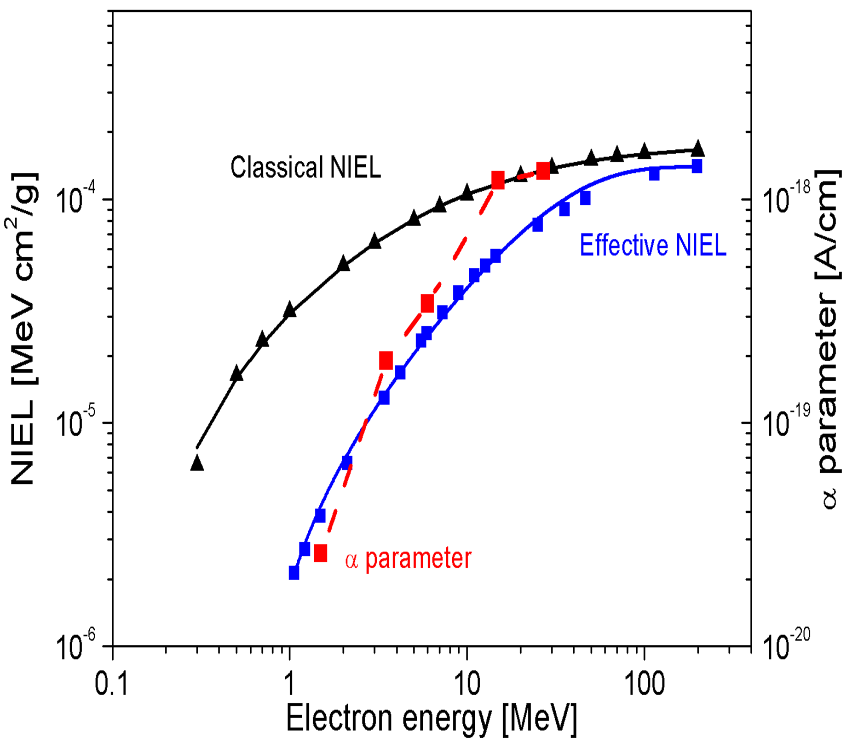
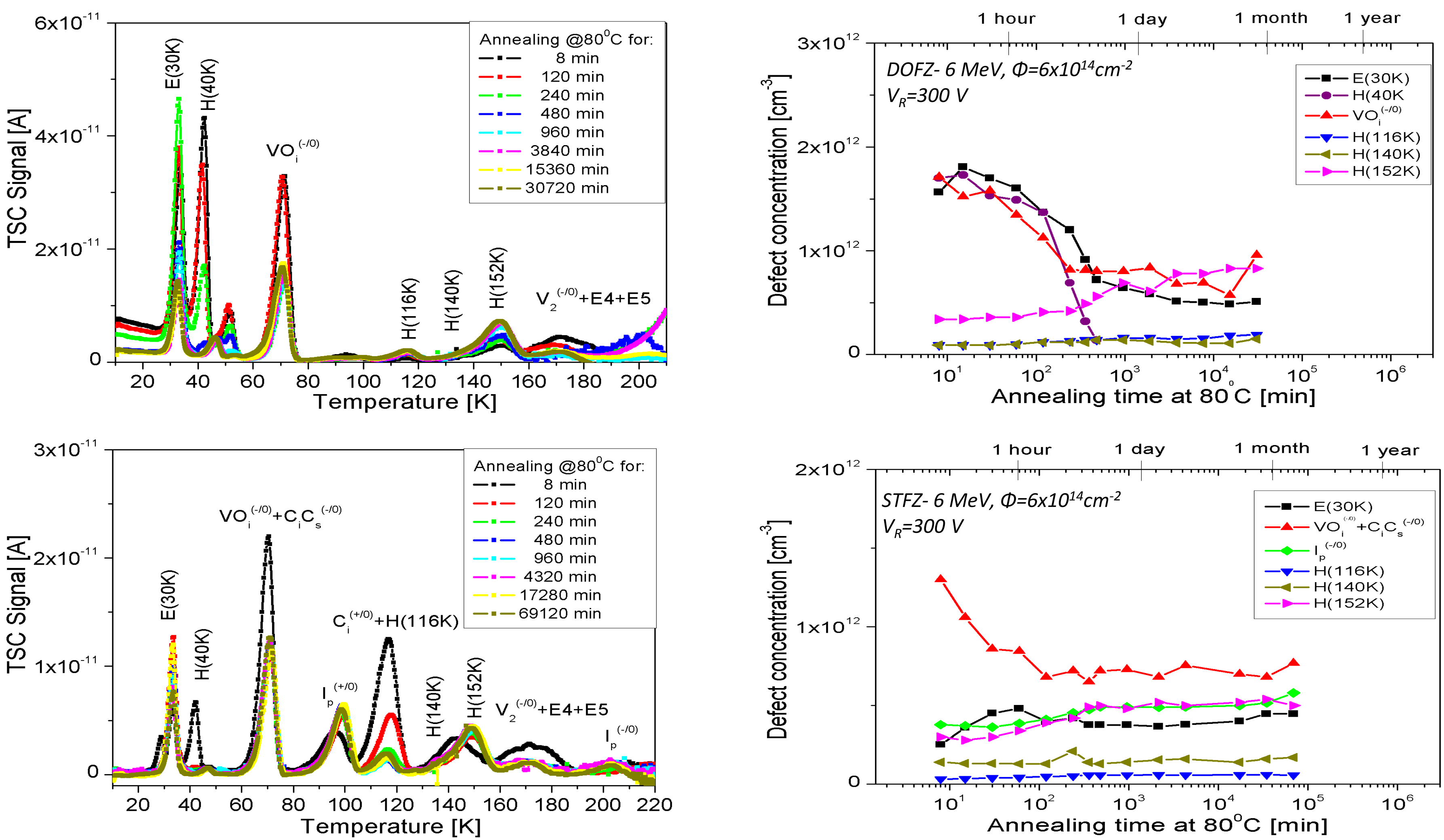
Oxygen influence on the IR of E(30K) and H defects





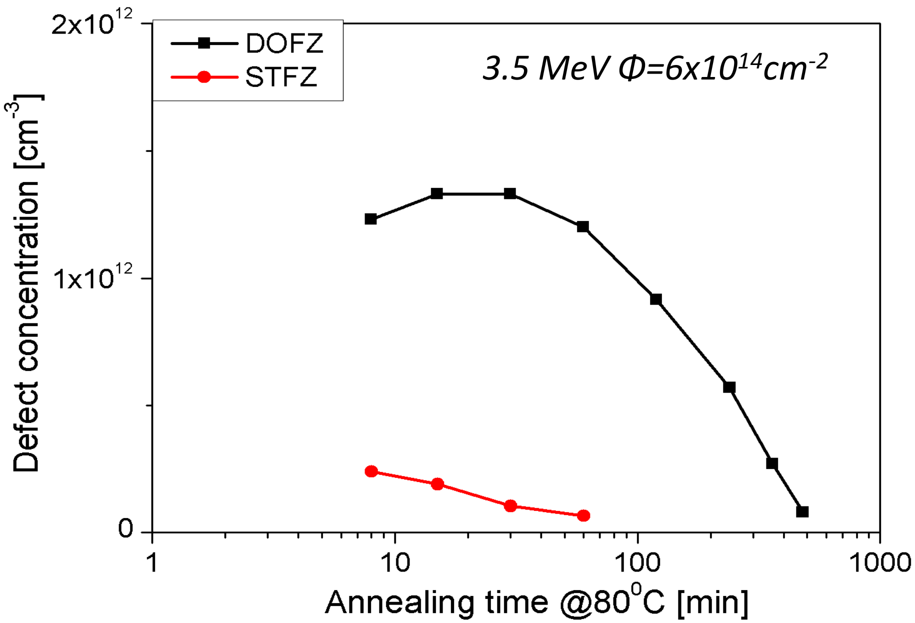
- Introduction rates vs. E_e show a saturation tendency → expected from NIEL
- Introduction rates for H defects for DOFZ & STFZ are similar
  → no [O] dependent, → **related to the higher order vacancies**
  → to be identified via HRTEM investigations
- Introduction rate for E (30K) is 3 times larger in DOFZ material
  → [O] dependent, to be identified via EPR studies

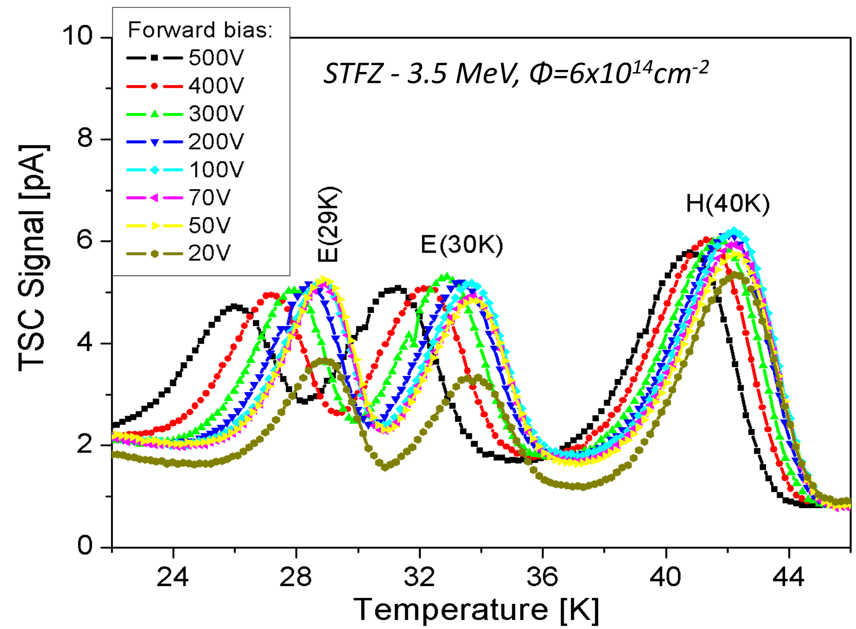
Isothermal annealing at 80^{0}C



- Elevated temperatures (up to 80 ^{0}C) are used to accelerate the effect of annealing to study the expected changes of the sensor performances over several years of room temperature equivalent time.

The H(40K) defect

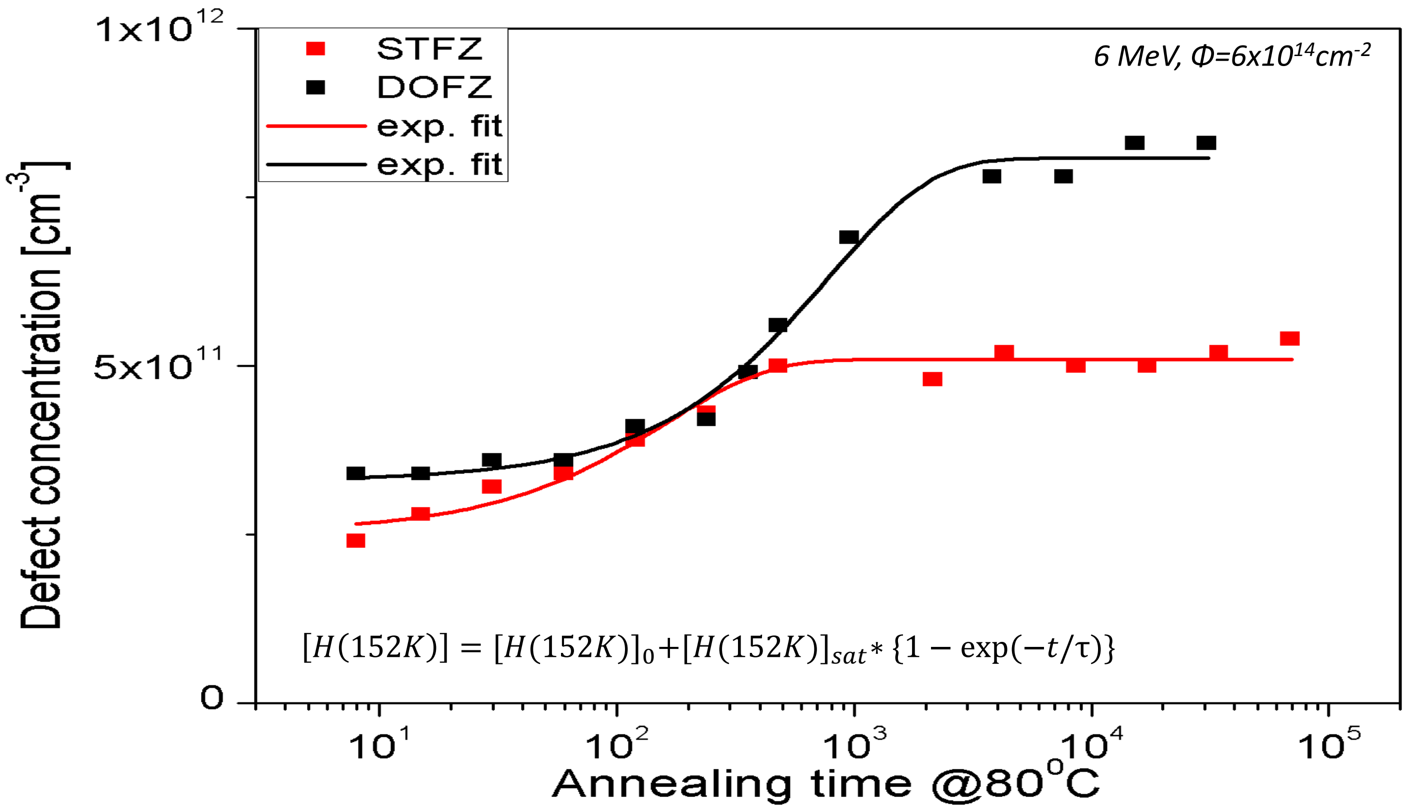




IR [cm^{-1}]	3.5 MeV	6 MeV	15 MeV	27 MeV
DOFZ	6.3E-4	0.0032	0.006	0.0058
STFZ	1.75E-4	2E-4	4.5E-4	5.2E-4

- Annealing out of the H(40K) – [O] dependence
- Introduction rate [O] dependence: H(40K) $_{DOFZ}$ ≥ 6 H(40K) $_{STFZ}$
- The shift of the peak maximum to lower T with V_R → Poole-Frenkel effect → assume to be a shallow acceptor, negatively charged at RT, which can partially compensate the high [E(30K)]

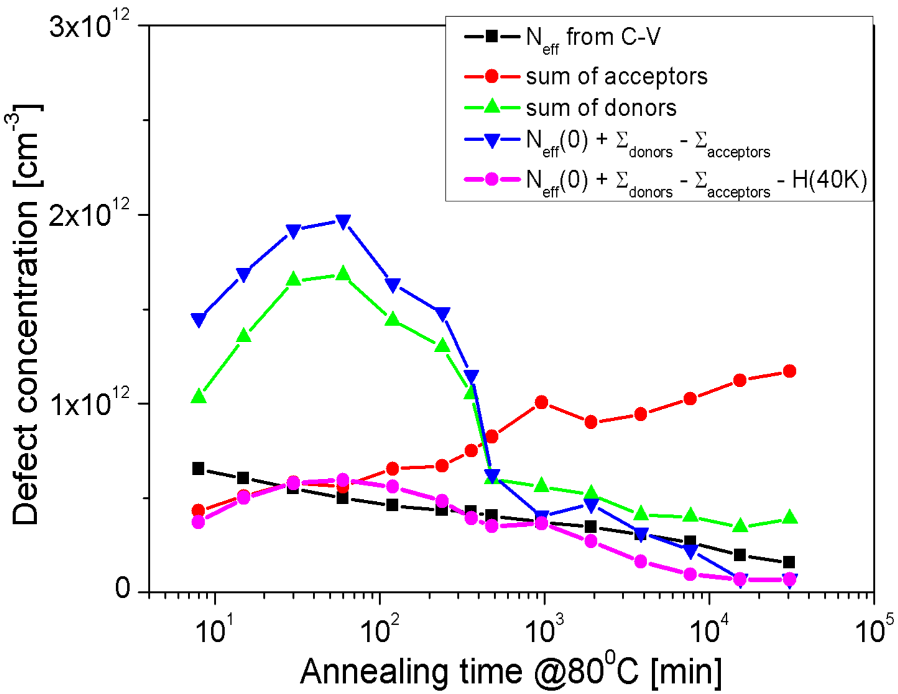
Annealing-in of the H (152K) defect

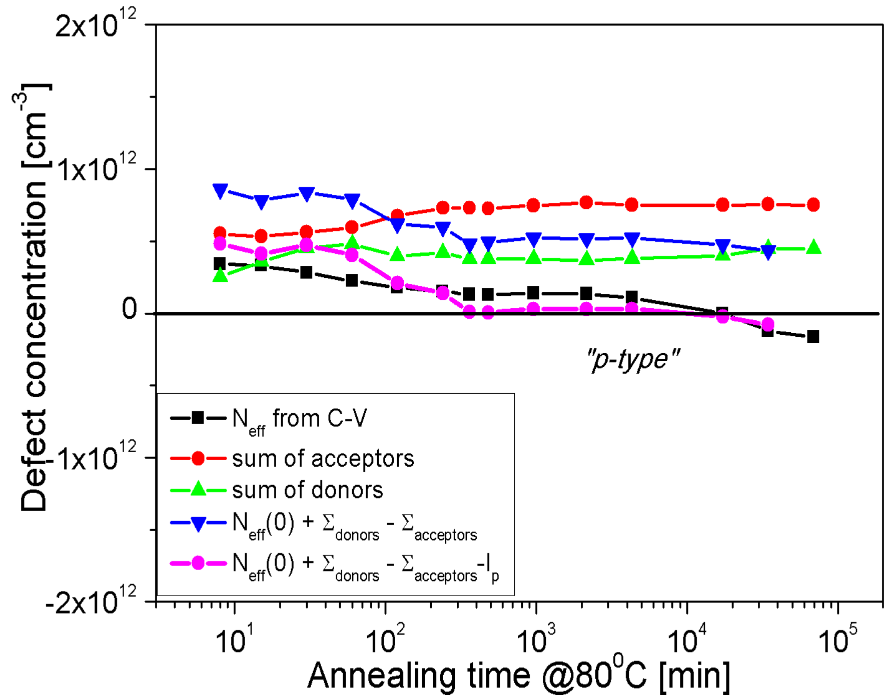


Time constants [min]	3.5 MeV	6 MeV	15 MeV
DOFZ	480÷53	724÷87	556÷29
STFZ	65÷12	200÷33	132÷18

Annealing in of the H(152K) – [O] dependence

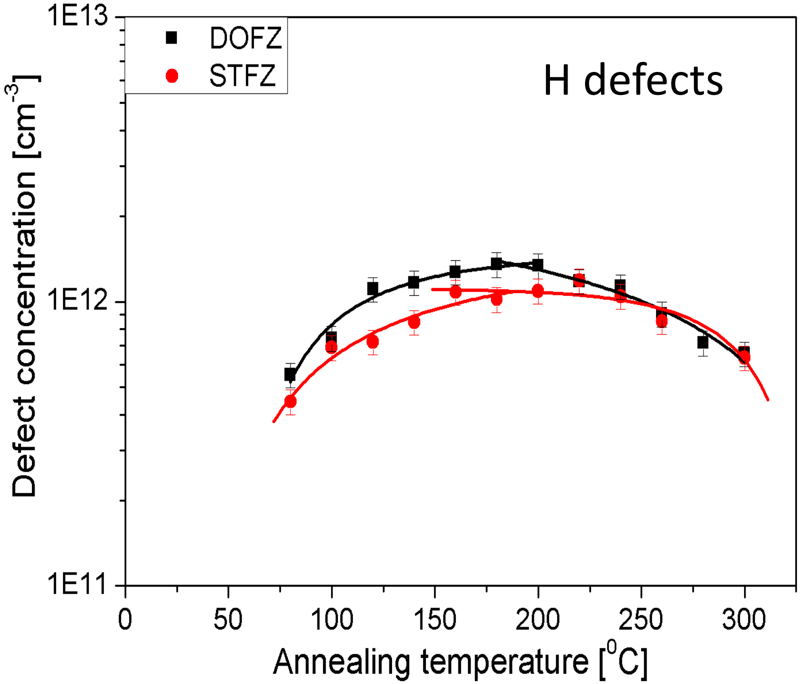
Impact of defects upon macroscopic properties: N_{eff} and V_{dep}

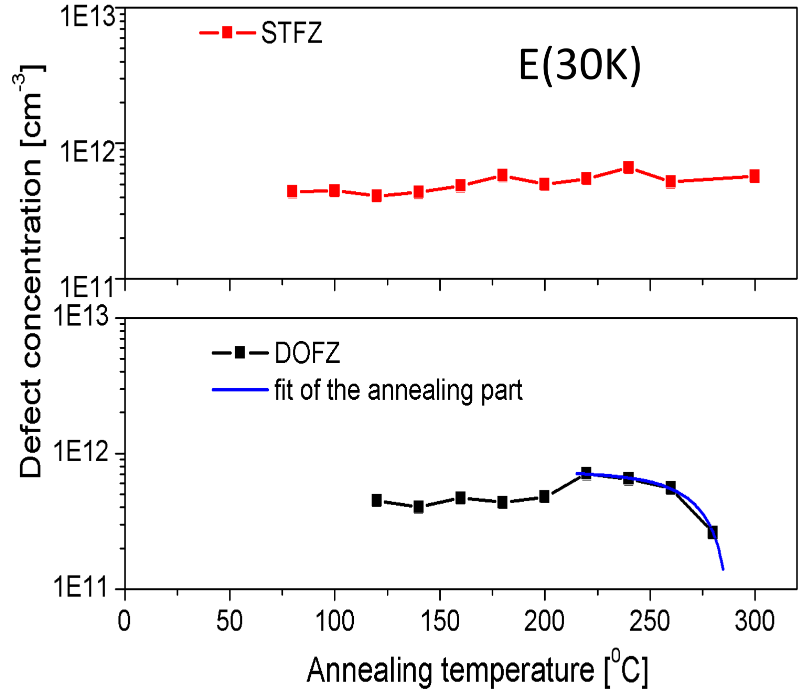




- Change of N_{eff}, with the annealing time (also with the aneealing temperature), well described by accounting only the E(30K), H(40K), Ip, H(116K), H(140K) and H (152K) – **defects with unknown chemical structure**

Kinetics of cluster-related defects



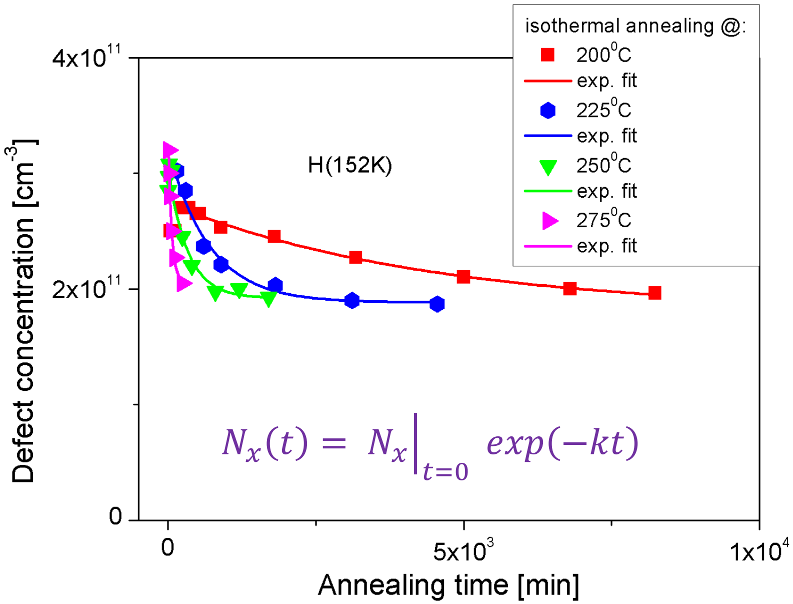


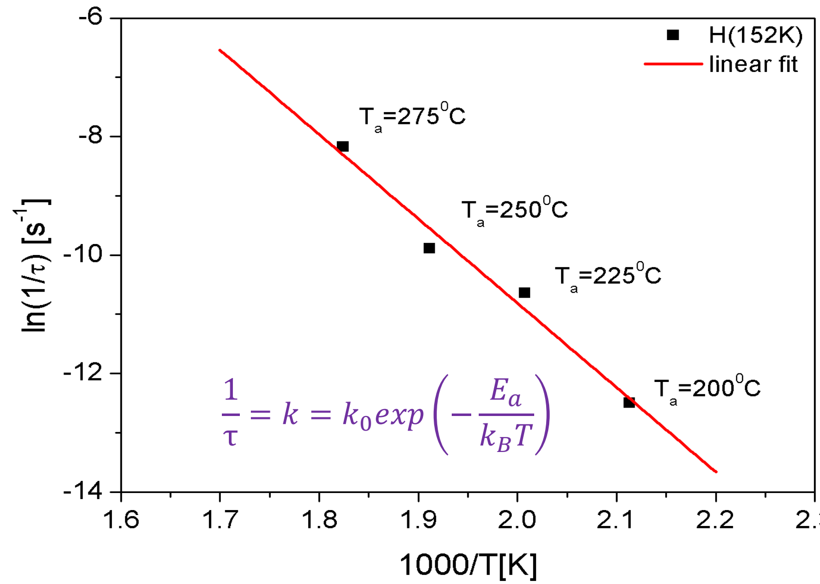
- Concentration of the H defects increases with T_{an} up to ~ 180^{0}C for DOFZ and ~ 240^{0}C for STFZ materials followed by a decrease at higher T_{an}
- In DOFZ, the E(30K) defect increases with the annealing temperature, having a maximum at ~ 220 ^{0}C followed by a fast decrease; in STFZ shows only a small increase - **to be identified via EPR studies**

Defect Type	$E_a\ [eV]$	$k_0 [s^{-1}]$
E(30K)	1.98 ± 0.57	$\approx 2x10^{14}$

Annealing out of H defects strongly depends on O concentration !!!

Annealing mechanisms of H defects





The clusters may dissociate/migrate/diffuse at higher T_{ann}

Time constants [min]	200 ^{0}C	225 ^{0}C	250 ^{0}C	275 ^{0}C	290 ^{0}C
DOFZ	530	193	76	36	10
STFZ	4462	699	330	59	-

Defect Type	$E_a\ [eV]$	$k_0 [s^{-1}]$
H(116K)	1.18 ± 0.03	$3.2x10^7 \pm 1$
H(140K)	1.25 ± 0.08	$1.8x10^8 \pm 6$
H(152K)	0.98 ± 0.08	$1x10^6 \pm 7$

Assuming dissociation process - High chances to be identified via HRTEM investigations

Conclusions

- **Threshold for cluster defects : $E_{rec.}$ ~ 1.2 keV**
- **Contribution of defects at the leakage current ~ 60 % of the leakage current, explained by the $V_3^{(=/-)}$, $V_3^{(-/0)}$ and E205a defects**
- **Change of N_{eff} with the annealing time, well described by accounting the E(30K), H(40K), Ip, H(116K), H(140K) and H (152K) defects**
- **Introduction rates for H defects for DOFZ & STFZ are similar → no [O] dependent but the annealing out of H(140K&152K) is different → High chances to be identified via HRTEM investigations**
- **Introduction rate for E(30K) is 3 times larger in DOFZ material → [O] dependent, to be identified via EPR studies**

Thank you for your attention

Special thanks to Ioana Pintilie, Gunnar Lindstroem, Eckhart Fretwurst