Defect investigation on n-type Schottky diodes based on 4H-SiC before and after irradiation with 6 MeV electrons

BONI Andra-Georgia, PATRU Roxana Elena, NITESCU Andrei, PINTILIE Ioana, BESLEAGA STAN Cristina, GEAMBASU Dragos Cezar

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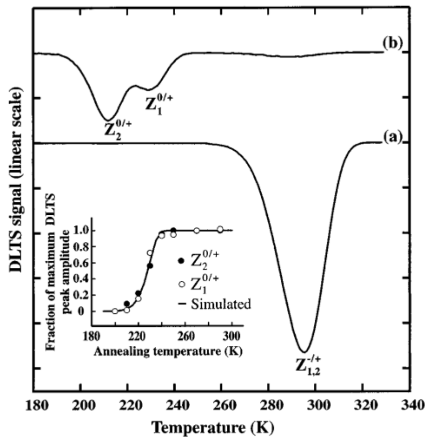
WG3/WP3 - Extreme fluence and radiation damage characterization

OUTLINE

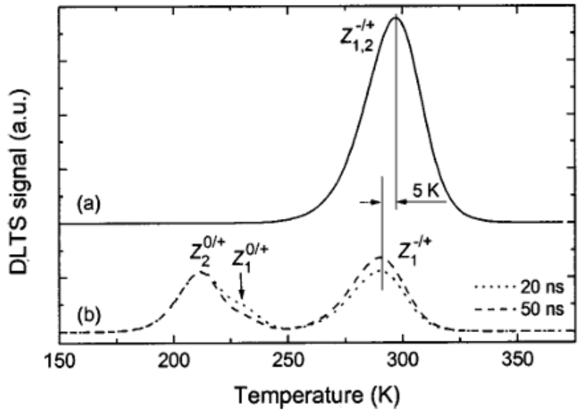
- Motivations
- Samples & Experimental details
- DLTS Measurements
- Evaluations and Simulations
- Summary and Conclusion

Motivation

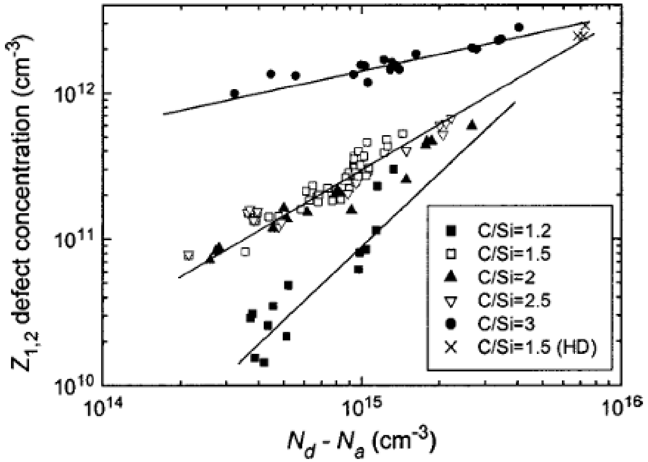
Contradictions related to chemical structure of the two most common defect detected in 4H-SiC layers: $Z_{1,2}$ and $EH_{6,7}$ (intrinsic and also induced by irradiation)



DLTS spectras observed in a 4H SiC diode. The measurements were performed a) with a pulse width of 100 ms and b) with a pulse width of 50 ns and illumination with light 470 nm from a GaN LED before each filling pulse.
C. G. Hemmingsson et all., Phys. Rev. B ***58*** *, 16, 1998*



DLTS performed with a) voltage pulses of 100 ms width and b) with double pulses consisting of a short voltage pulse ~20 or 50 ns! followed by an optical one from a GaN LED ~5ms!.



Dependence of the $Z_{1,2}$ defect concentration on the net donor concentration (N) in 4H-SiC CVD layers grown at different C/Si ratios.

I. Pintilie et al., Appl. Phys. Lett., Vol. 81, No. 25, 16 2002

- $Z_{1,2}$ defect with negative-U behavior (bistable), 2 energy levels in the bandgap; when fully occupied, emission of two electrons occurs simultaneous through a (−/+) transition, giving rise to a DLTS peak at ~280 K. It is stable up to 2000ºC.
- By adjusting the occupancy of the defect, the shallower level (emission of one eletron) is detected at ~210 K, corresponding to a (−/0) transition.
- Defect center increases in concentration with C/Si ratio and Nitrogen doping → suggesting that both Nitrogen and Carbon are part of the defect structure.
- *T. A. G. Eberlein et all., Phys. Rev. Lett. 90, 225502 , 2003:* DFT calculations have shown that a $N_i - C_i$ complex is exceptionally thermally stable, bistable, exhibits negative-U behavior, with donor and acceptor levels close to those detected for the $Z_{1,2}$ center.

- the $Z_{1,2}$ peak position and concentration is independent of the dopant.

L.Storasta et all., Materials Science Forum Vols 457-460 (2004) pp 469-472

- Later on, $Z_{1,2}$ defect was associated with V_C, exhibiting negative-U behavior with (=/−) and (=/0) transitions:
  - *increased concentration at irradiation with lower energies (by which only carbon atoms may be displaced K. Danno; T. Kimoto., J. Appl. Phys. 100, 113728 (2006); L. Storasta et all, J. Appl. Phys. 96, 4909–4915 (2004)),*
  - Studies showing *annealing if additional source of carbon interstitials exists (L. Storasta, H. Tsuchida, Appl. Phys. Lett. 90, 062116 (2007))*
  - DFT and Laplace DLTS studies showing *relation* showed that the Z_1 and Z_2 transitions are related to V_c at the hexagonal and pseudocubic sites of the lattice *(I. Capan et all., J. Appl. Phys. 124, 245701 (2018))*

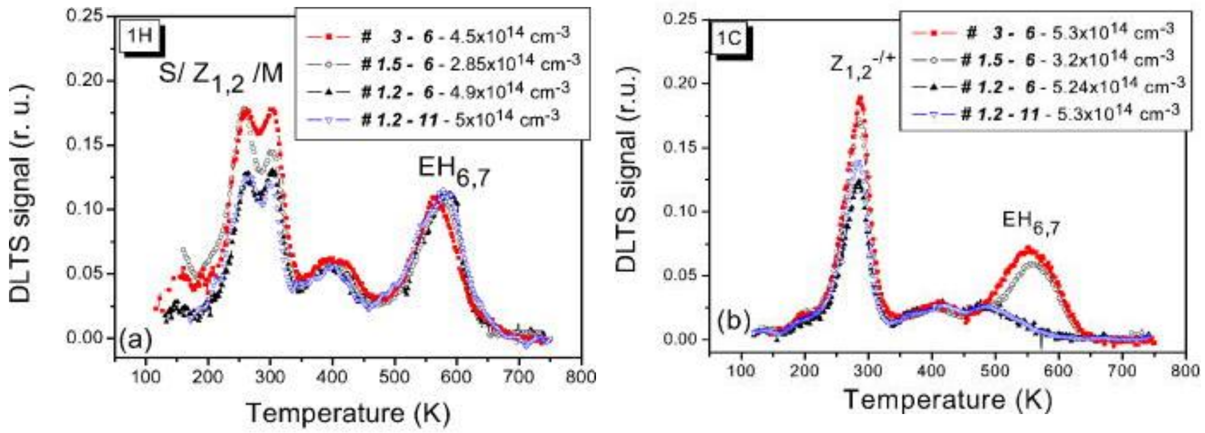
- $EH_{6,7}$ is associated also with V_C corresponding to a (0/+) donor energy level; *L Torpo et al 2001 J. Phys.: Condens. Matter 13 6203, N. T. Son et al, Appl. Phys. Lett. 81, 3945–3947 (2002)*
  - *Laplace DLTS shows* EH_7 is related to the $Z_{1,2}$ level with which shares the same elementary nature (V_C), while EH_6 may be related to a complex involving V_C. *G. Alfieri; T. Kimoto, Appl. Phys. Lett. 102, 152108 (2013)*

Inconsistencies in the V_C assignment of $Z_{1,2}$ and $EH_{6,7}$

- These centers are sometimes observed even under **C-rich growth conditions**, where the formation of V_C should be strongly suppressed

- Their **thermal stability varies inconsistently** in irradiated samples; in some studies the centers anneal already at relatively low temperatures, although isolated V_C should remain stable up to growth temperatures (~1400 °C)

- $Z_{1,2}$ and $EH_{6,7}$ **exhibit imperfect correlation** — their concentrations do not maintain the expected 1:1 ratio if they originate from the same defect.



DLTS spectra obtained on samples grown with different C/Si ratios but having similar Nd : (a) during the first heating ; (b) during the first cooling; *I. Pintilie et al, Appl. Phys. Lett.* 90, 062113 (2007)

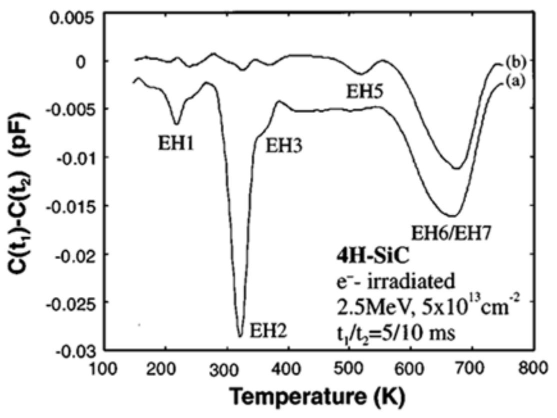


FIG. 2. DLTS spectrum measured with $t_1/t_2=5/10$ ms, a reverse bias of −6 V, and a pulse height of 5 V in 4*H* SiC irradiated by 2.5 MeV electrons with a dose of 5×10^{13} cm^{-2}. (a) Before annealing and (b) after annealing at 750 °C for 10 min. *J. Appl. Phys. 81, 6155–6159 (1997)*

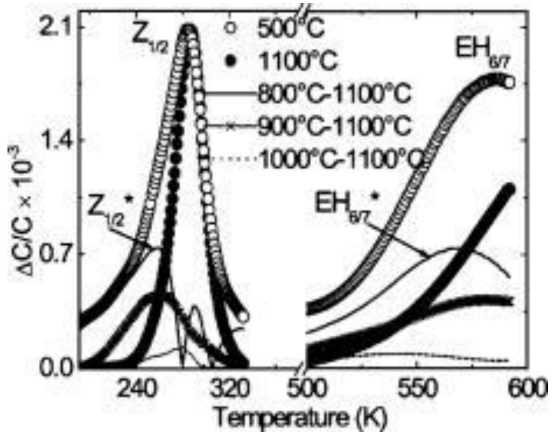


FIG. 6.DLTS spectra after 20 min at 500 and 1100 °C. The presence of two minor contributions called $Z_{1,2}$ and $EH_{6,7}$*, respectively, is revealed by subtracting the 1100 °C spectrum from one of the previous ones G.Alfieri et all., J. Appl. Phys. 98, 043518 (2005)*

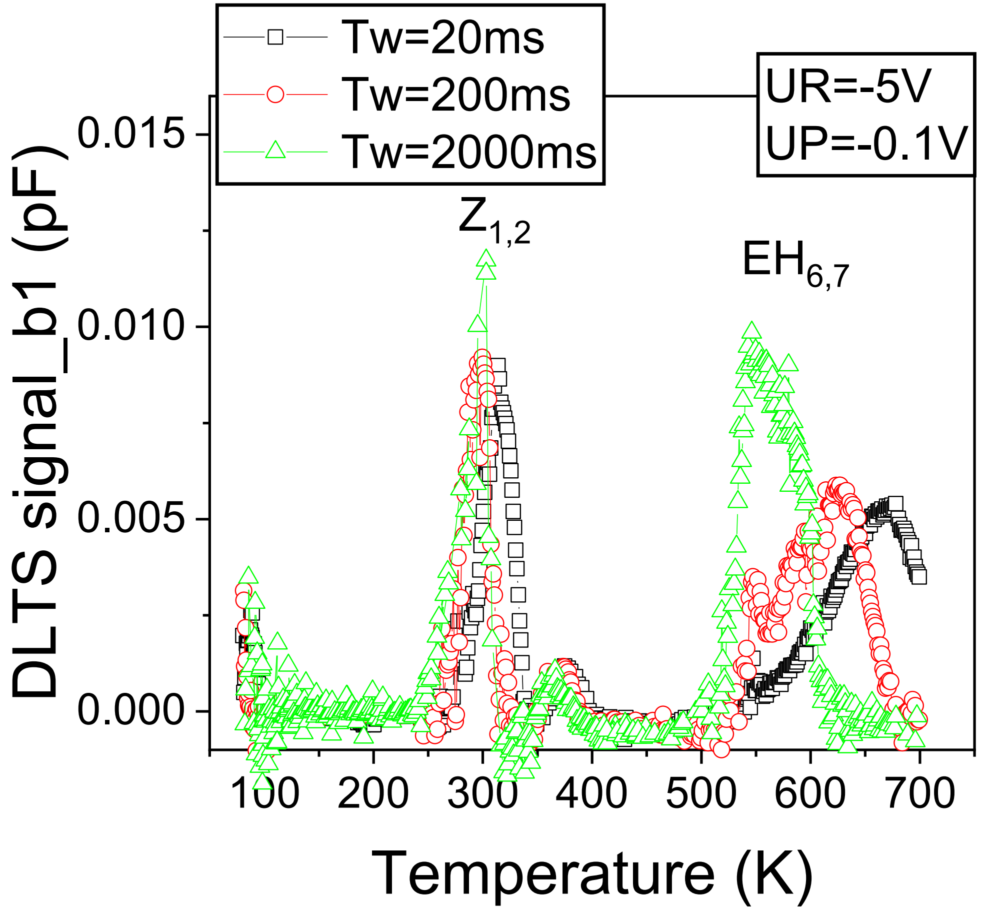
Samples and Irradiation Parameters

Sample Details – Growth and Device Parameters
Material: n-type 4H-SiC Schottky diodes
C/Si ratio: 1
Precursors: propane = 90 sccm, silane = 675 sccm
Doping concentration: 4.9×10^{15} cm^{-3}
Growth pressure: 250 mbar
Diode area: 5.87×10^{-3} cm^2

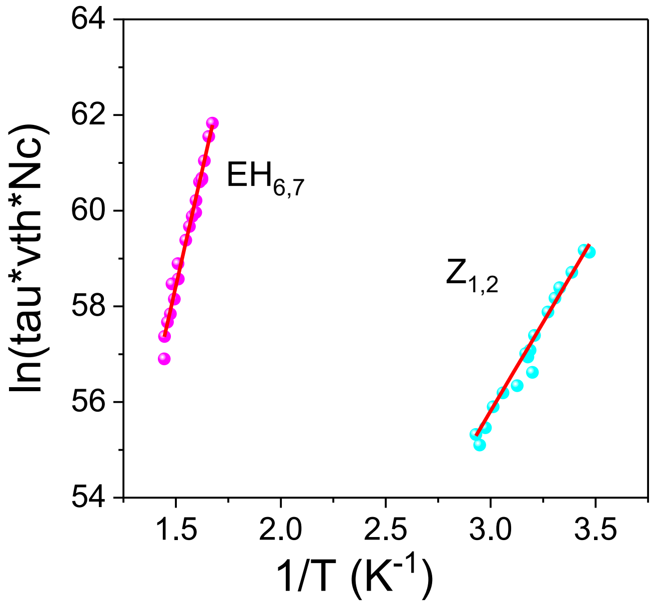
Irradiation Conditions
Samples analyzed: 3
1 unirradiated sample
several irradiated samples with 6 MeV electrons
Fluences: 1.5×10^{14} and 6×10^{14} e/cm^2

Majority carrier DLTS spectra measured in the *n*-type 4H-SiC epitaxial layer- ***unirradiated***

- $\boldsymbol{Z_{1,2}}$: Deep electron trap at $E_C \sim 0.63\ eV$, emitting 2 electrons and exhibiting negative-U behavior - is either a double acceptor (=/0) or a donor (-/+).
- $\boldsymbol{EH_{6,7}}$: Deep electron trap at $E_C \sim 1.5\ eV$, proposed to be the donor state of $\boldsymbol{Z_{1,2}}^{=/0}$, with transitions between 0/+ charge states.

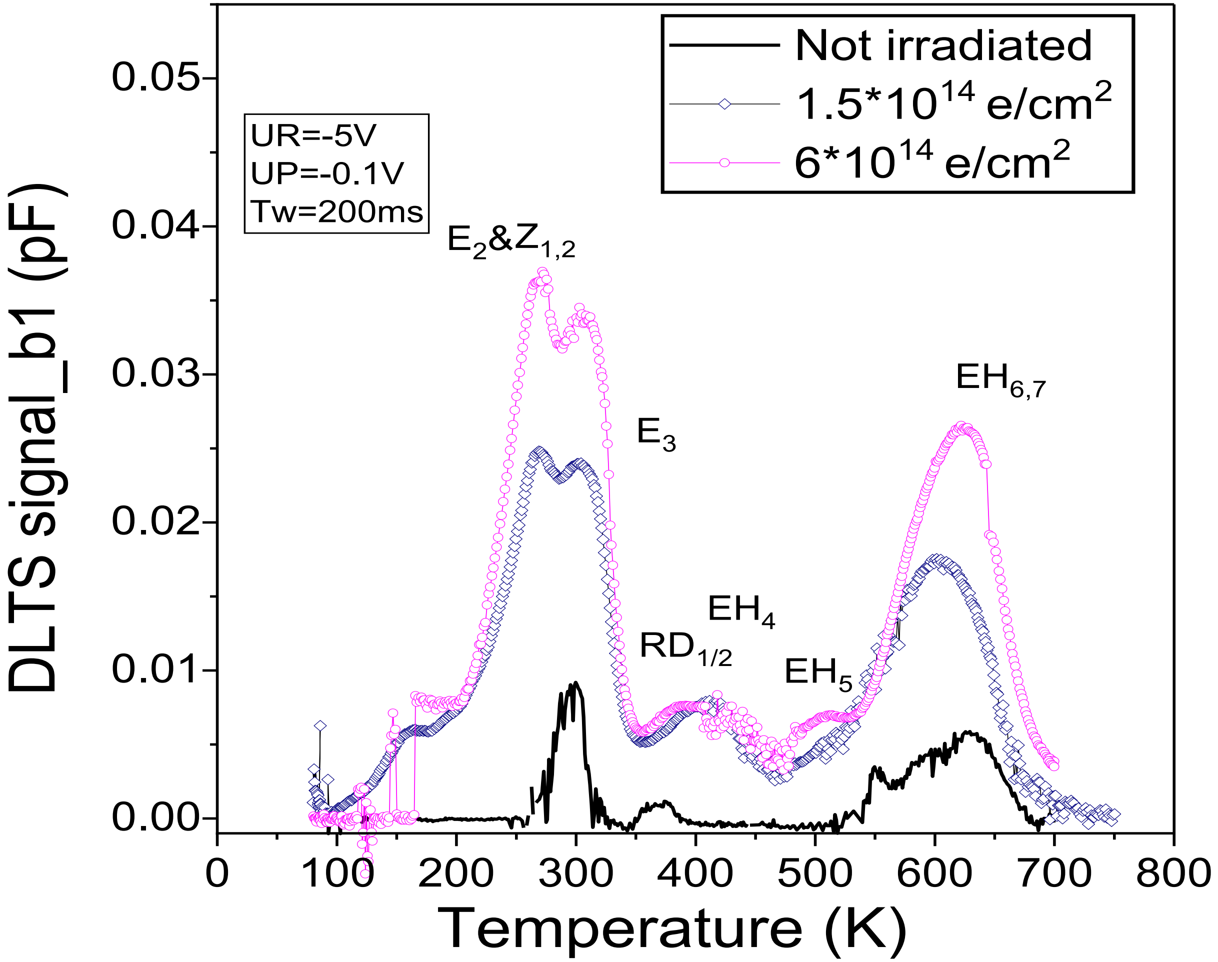


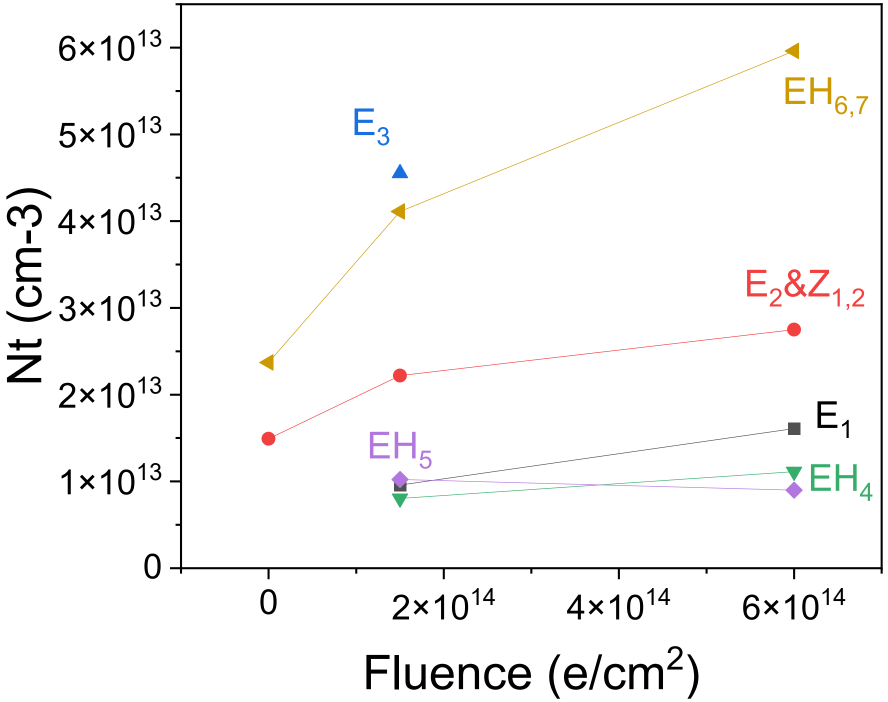
Defect	$E_c - E_t\ (eV)$	$\sigma\ (cm^2)$	$N_t\ (cm^{-3})$ (Defect concentration)
$Z_{1,2}$	0.665	$7.813 * 10^{-15}$	$1.492 * 10^{13}$
$EH_{6,7}$	1.667	$1.75 * 10^{-13}$	$2.37 * 10^{13}$



Maxima analyses

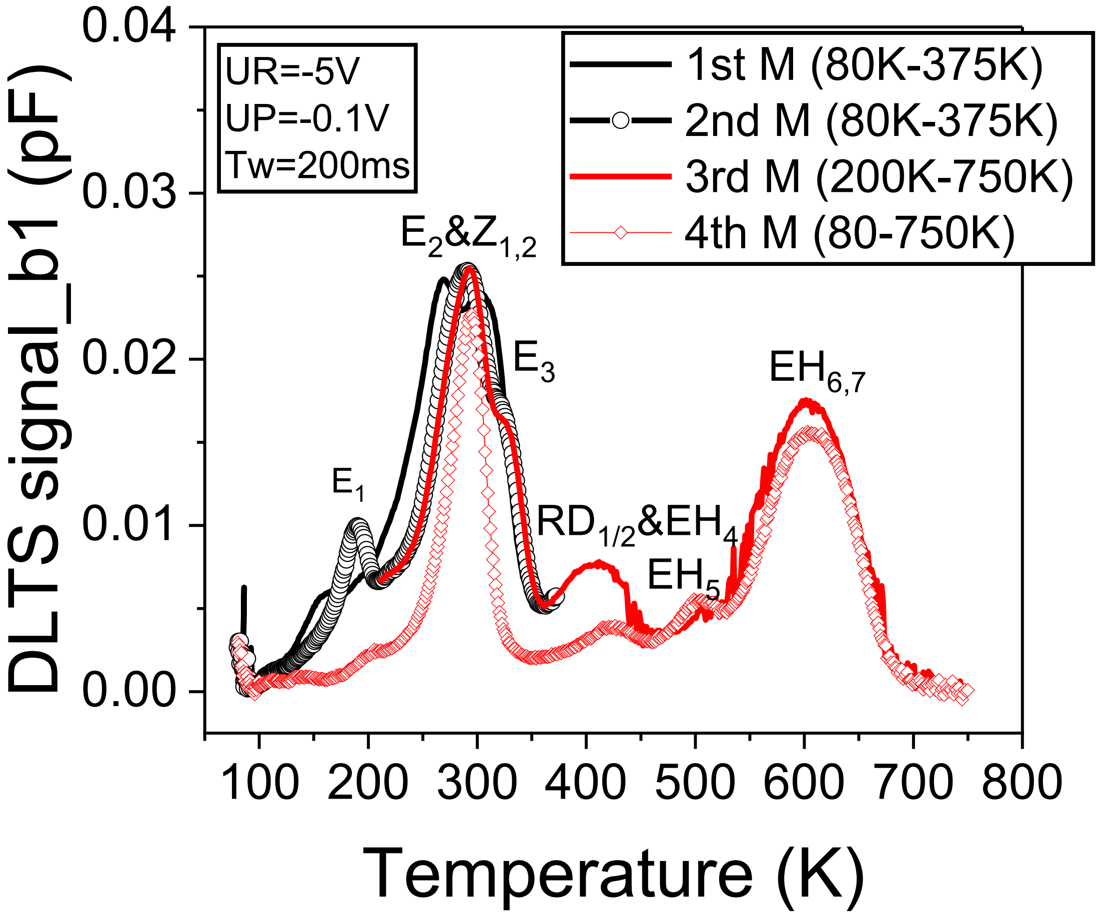
Measurements on **as irradiated** samples (6 MeV electrons)



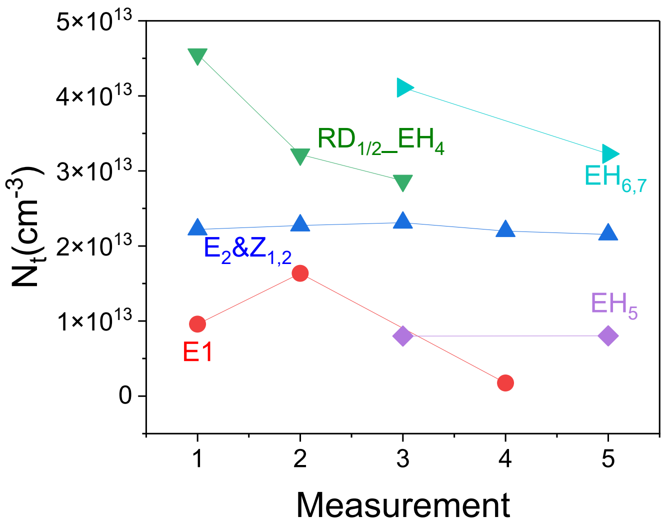


Continuous measurements 80K-750K

DLTS results after irradiation with $1.5 * 10^{14} e/cm^2$ (6 MeV) - annealing effects



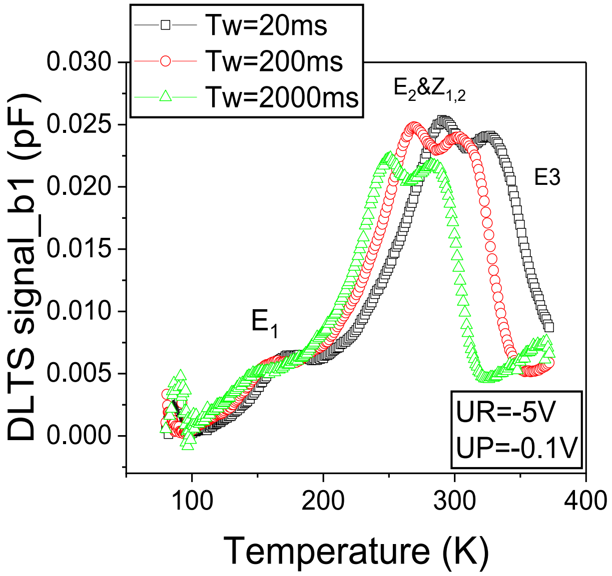
1st measurement (80K-375K)
2nd measurement (80K-375K)
3rd measurement (200K-750K)
4th measurement (80K-750K)

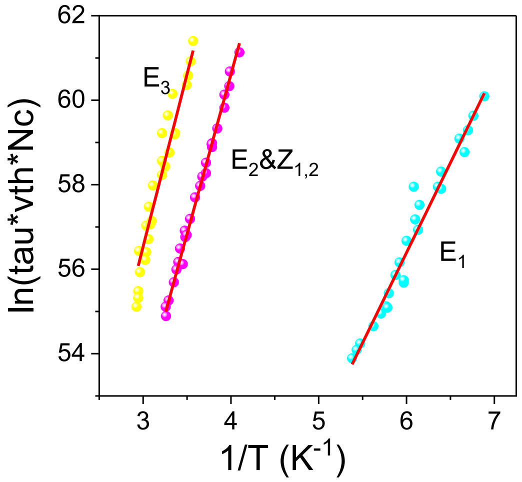


- E_1 is initially annealing in after the 1st heating at 375K and then anneals out after the heating at 750K.
- All other defects except $Z_{1,2}$ and $EH_{6,7}$ are annealing out during the measurements as the temperature is increased.

DLTS results after irradiation with $1.5 * 10^{14} e/cm^2$ (6 MeV)

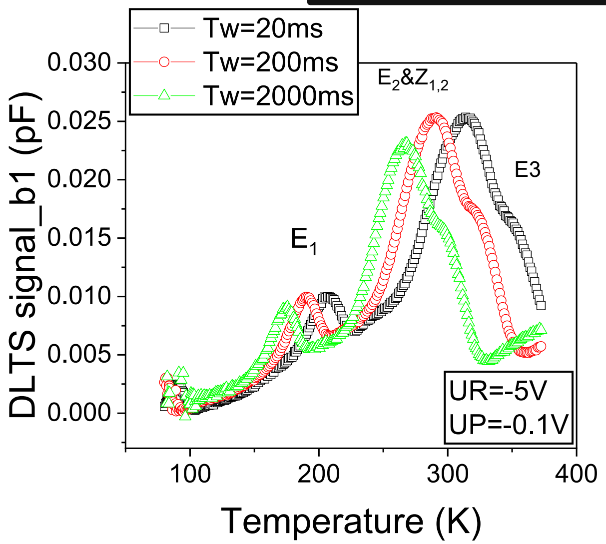
1st measurement (80K-375K)

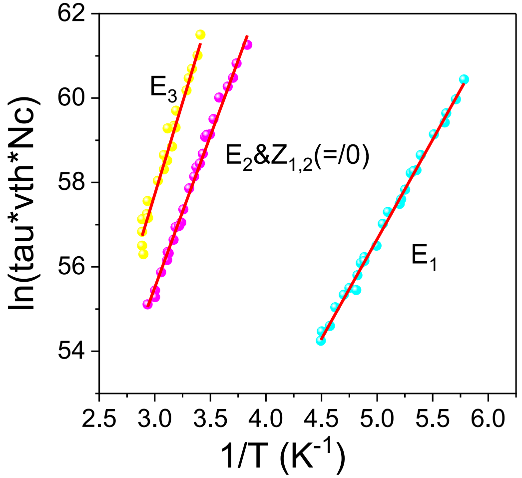




	$E_c - E_t\ (eV)$	$\sigma\ (cm^2)$	$N_t\ (cm^{-3})$
E_1	0.367	$3.889 * 10^{-14}$	$9.586 * 10^{12}$
E_2&$Z_{1,2}$	0.635	$3.24 * 10^{-14}$	$2.22 * 10^{13}$
E_3	0.765	$1.202 * 10^{-13}$	$4.552 * 10^{13}$

2nd measurement (80K-375K



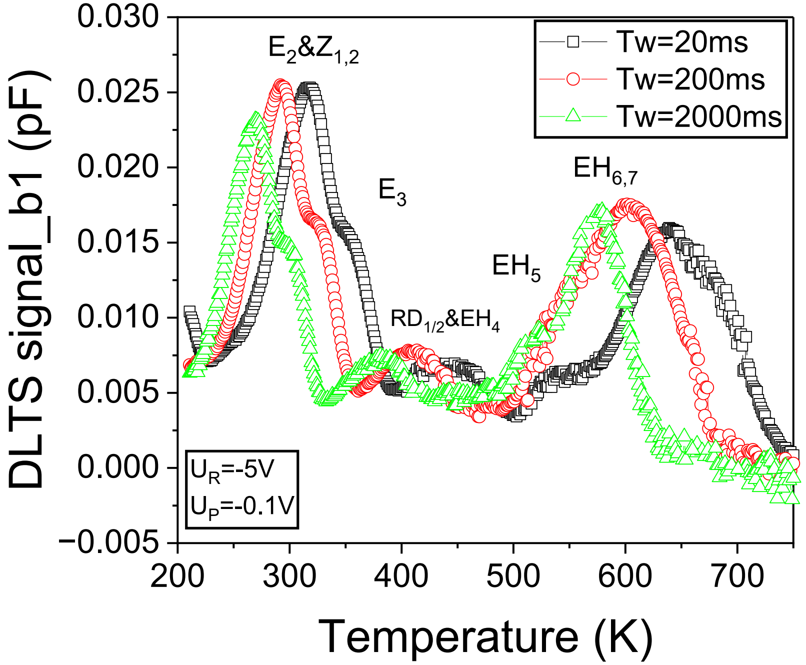


	$E_c - E_t\ (eV)$	$\sigma\ (cm^2)$	$N_t\ (cm^{-3})$
E_1	0.406	$4.04 * 10^{-14}$	$1.653 * 10^{13}$
E_2&$Z_{1,2}$	0.647	$5.14 * 10^{-14}$	$2.273 * 10^{13}$
E_3	0.758	$2.35 * 10^{-13}$	$3.221 * 10^{13}$

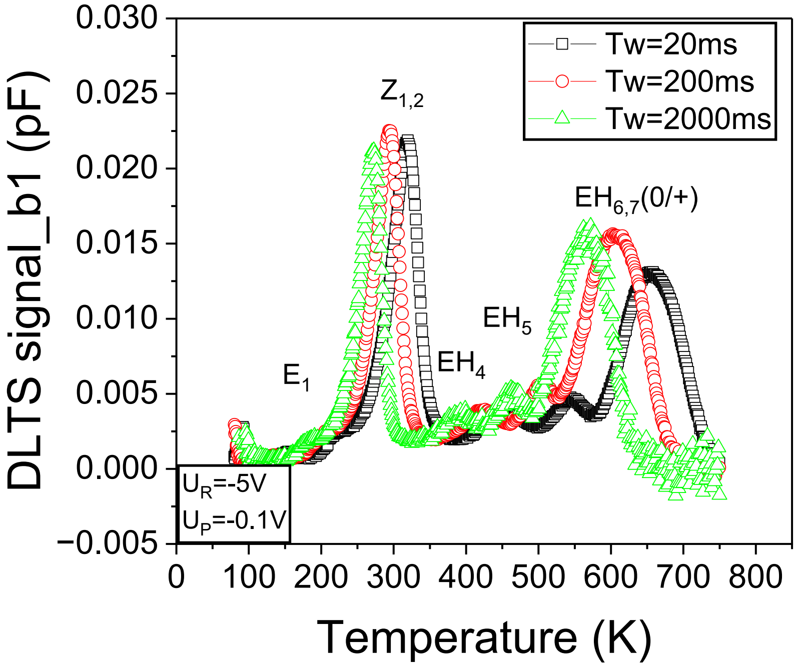
After the 1st measurement up to 375K, **E_1** anneals-in, **E_2&E_3** start to anneal-out

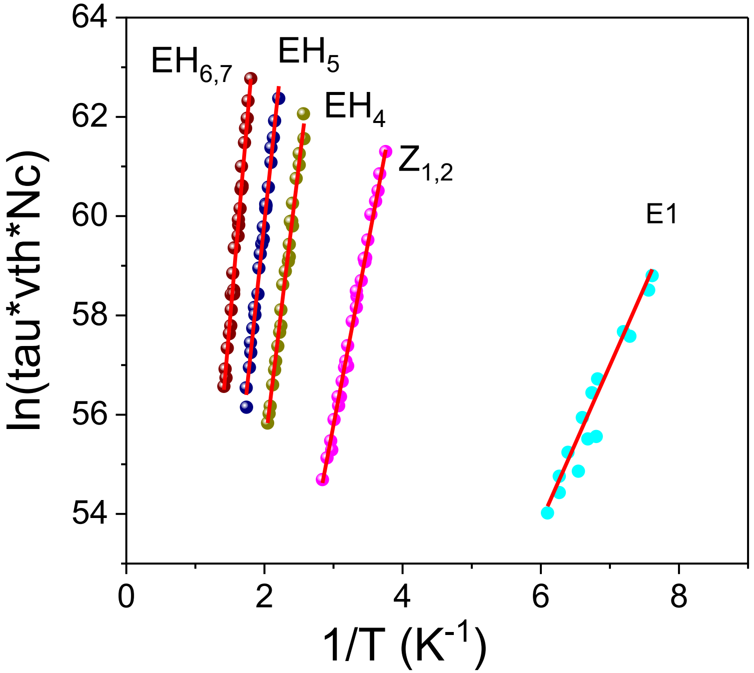
DLTS results after irradiation with $1.5 * 10^{14} e/cm^2$ (6 MeV)

3rd measurement (200K-750K)



4th measurement (80K-750K)



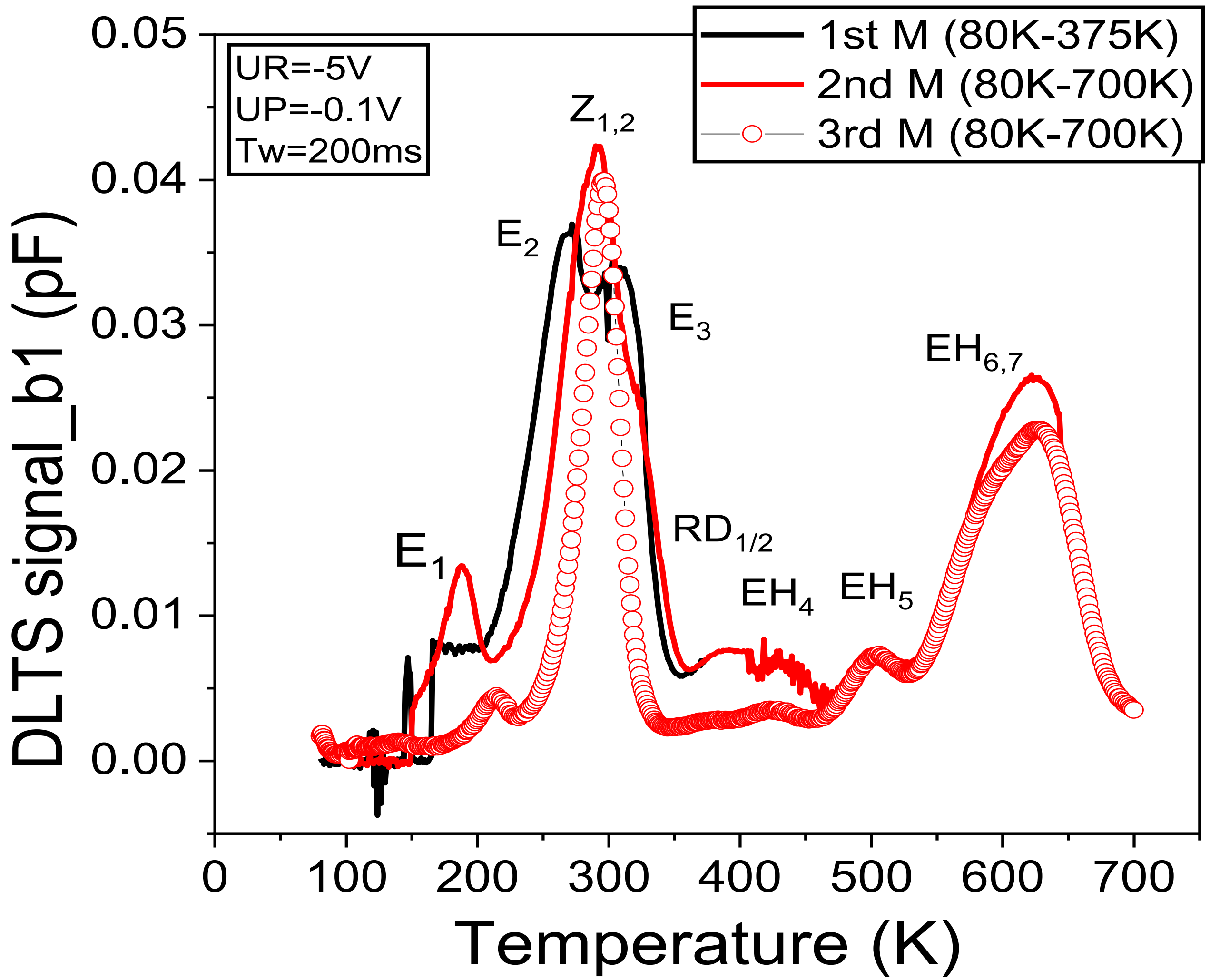


After the first heating at 750K (3rd measurement)

- $RD_{1,2}$ and E_2 anneals-out
- ~ $EH_{6,7}$ signal is reduced with ~20%

	$E_c - E_t\ (eV)$	$\sigma\ (cm^2)$	$N_t\ (cm^{-3})$
E_1	0.267	$5.371 * 10^{-16}$	$1.744 * 10^{12}$
$Z_{1,2}$	0.647	$3.689 * 10^{-15}$	$2.153 * 10^{13}$
EH_4	1.032	$2.821 * 10^{-14}$	$8.031 * 10^{12}$
EH_5	1.131	$2.46 * 10^{-15}$	$1.022 * 10^{13}$
$EH_{6,7}$	1.420	$4.032 * 10^{-15}$	$3.227 * 10^{13}$

DLTS results after irradiation with $6 * 10^{14} e/cm^2$ (6 MeV)



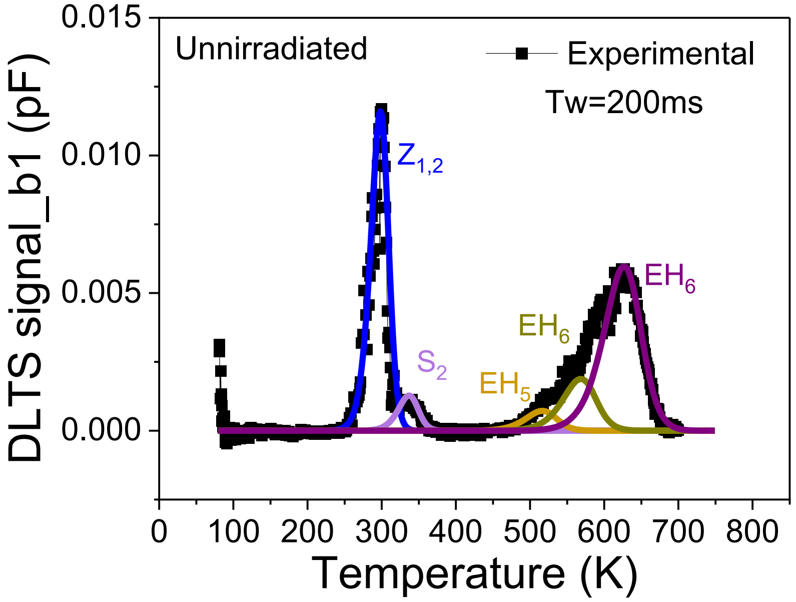
Same radiation induced defects are detected and **with similar annealing behaviour** as for irradiation with lower fluence

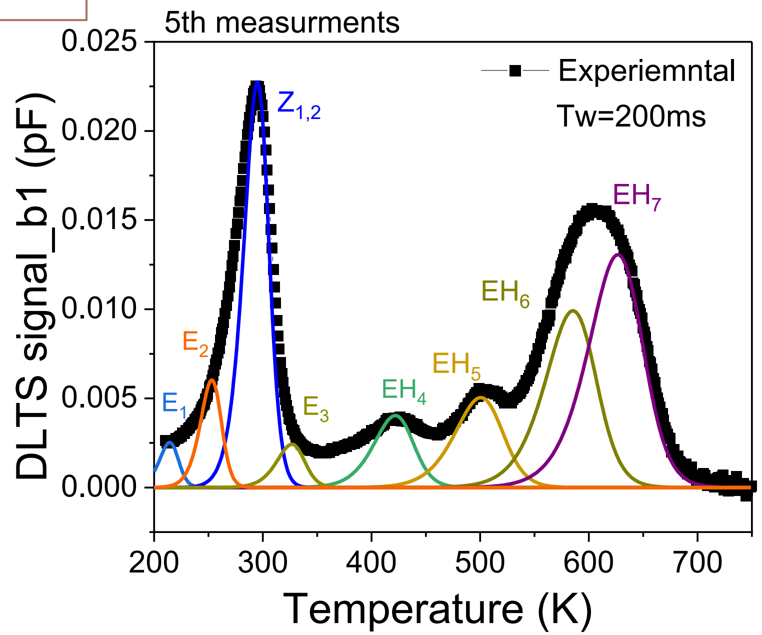
- **E_1** is initially annealing in after the 1st heating at 375K and then anneals out after the heating at 750K
- ***E_2* and *E_3*** – annealed out after heating up to **375 K**
- ***EH_4* and *$RD_{1/2}$*** – significantly reduced after heating up to **750 K**
- ***EH_5*** – remained unchanged within this temperature range

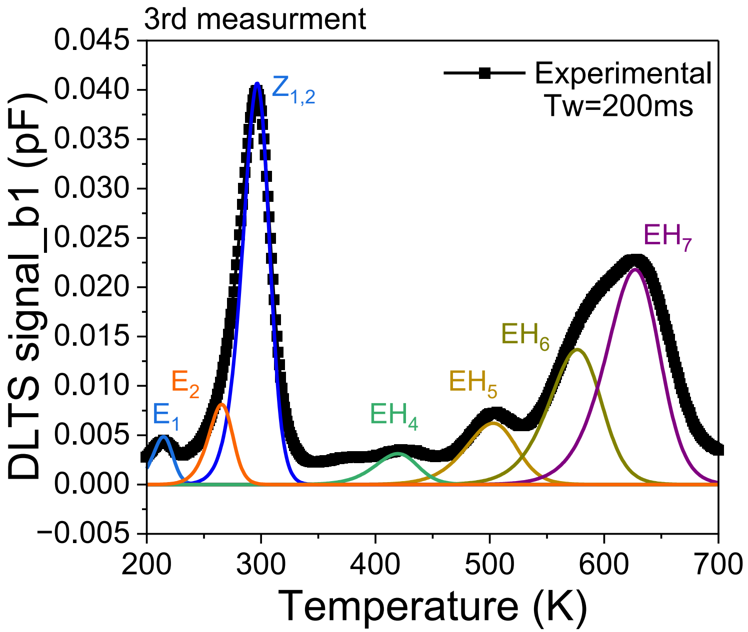
Simulation of DLTS Data
(better than maxima analyses when defect signals overlap)

$1.5 * 10^{14} e/cm^2$ (6 MeV)

$6 * 10^{14} e/cm^2$ (6 MeV)







$$\frac{N_{Z_{1,2}}}{N_{EH_7}} = 0.43$$

$$\frac{N_{Z_{1,2}}}{N_{EH_7}} = 1.16$$

$$\frac{N_{Z_{1,2}}}{N_{EH_7}} = 1.01$$

	$E_c - E_t\ (eV)$	$\sigma\ (cm^2)$	$N_t\ (cm^{-3})$
$Z_{1,2}$	0.68	$2 * 10^{-14}$	$1.8 * 10^{12}$
EH_6	1.3	$3 * 10^{-15}$	$1.25 * 10^{12}$
EH_7	1.422	$3 * 10^{-15}$	$4.1 * 10^{12}$

	$E_c - E_t\ (eV)$	$\sigma\ (cm^2)$	$N_t\ (cm^{-3})$
$Z_{1,2}$	0.687	$1.6 * 10^{-14}$	$1 * 10^{13}$
EH_6	1.35	$1.5 * 10^{-15}$	$7.4 * 10^{12}$
EH_7	1.4	$1 * 10^{-15}$	$8.6 * 10^{12}$

	$E_c - E_t\ (eV)$	$\sigma\ (cm^2)$	$N_t\ (cm^{-3})$
$Z_{1,2}$	0.682	$1.27 * 10^{-14}$	$1.32 * 10^{13}$
EH_6	1.3	$2 * 10^{-15}$	$9.2 * 10^{12}$
EH_7	1.51	$1 * 10^{-14}$	$1.3 * 10^{13}$

Summary and Conclusion

- n-type 4H-SiC Schottky diodes were investigated before and after irradiation with 6 MeV electrons, fluences of $1.5 * 10^{14} e/cm^2$ and $6 * 10^{14} e/cm^2$.
- The study aimed to investigate the correlation between the $\boldsymbol{Z_{1,2}}$ and $\boldsymbol{EH_{6,7}}$ centers and their possible assignment to V_C.
- DLTS measurements showed that the concentration of these defects increases after irradiation; additional, less stable centers also appear but anneal out after heating at 375 K or 750 K.
- Due to multiple overlapping peaks with close activation energies, the evaluation of individual defect parameters is difficult; after the final annealing step, when adjacent defects are removed, clearer extraction of activation energies and concentrations becomes possible.

- DLTS spectrum simulation provides a more reliable approach — using simulated defect levels to estimate concentrations and the $\boldsymbol{Z_{1,2}}$: $\boldsymbol{EH_7}$ ratio, which approaches **≈ 1** after annealing-out of other radiation induced defects.
- However, in non-irradiated samples or others grown in C-rich conditions, $\boldsymbol{Z_{1,2}}$: $\boldsymbol{EH_7}$ ratio is far away from 1, indicating that these centers do not belong to the same defect (V_C)
- Only EH_7 could be assigned to V_C in agreement with *L Torpo et al 2001 J. Phys.: Condens. Matter 13 6203, N. T. Son et al, Appl. Phys. Lett. 81, 3945–3947 (2002),* but this requires further investigations&comparison with results on samples grown in Carbon-rich conditions (C/Si >1)

Thank you for your attention!