Defect Spectroscopy on Proton Irradiated 4H Silicon Carbide Sensors

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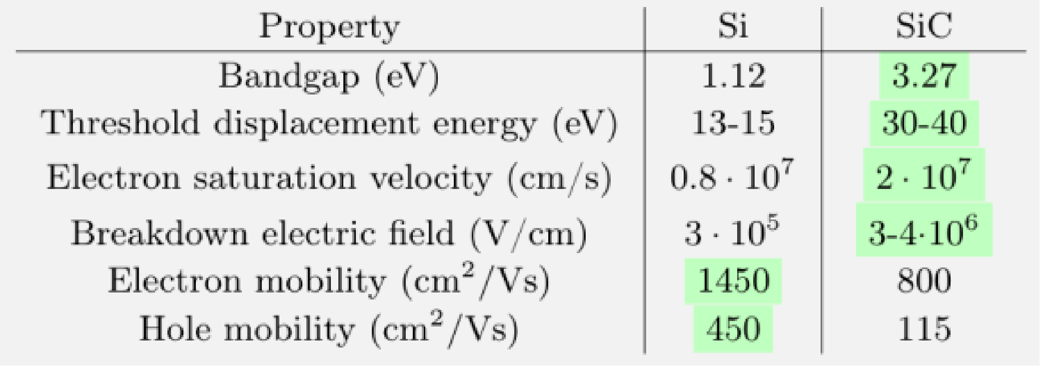
20.02.2024

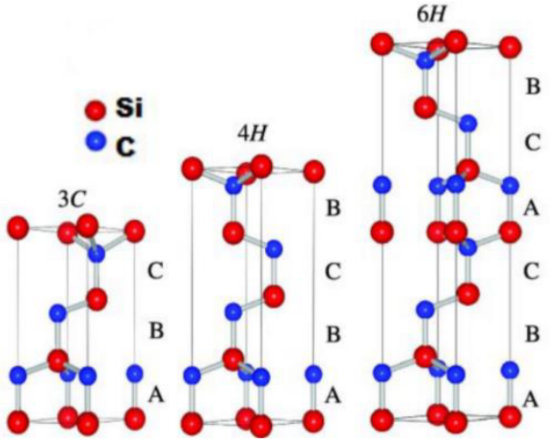
Outline

- Intro to SiC / samples
- Results
  - Electrical characterization (IV / CV)
  - TCT
  - Defect characterization
- Summary

Silicon Carbide



Property	Si	SiC
Bandgap (eV)	1.12	3.27
Threshold displacement energy (eV)	13-15	30-40
Electron saturation velocity (cm/s)	$0.8 \cdot 10^7$	$2 \cdot 10^7$
Breakdown electric field (V/cm)	$3 \cdot 10^5$	$3\text{-}4 \cdot 10^6$
Electron mobility (cm^2/Vs)	1450	800
Hole mobility (cm^2/Vs)	450	115



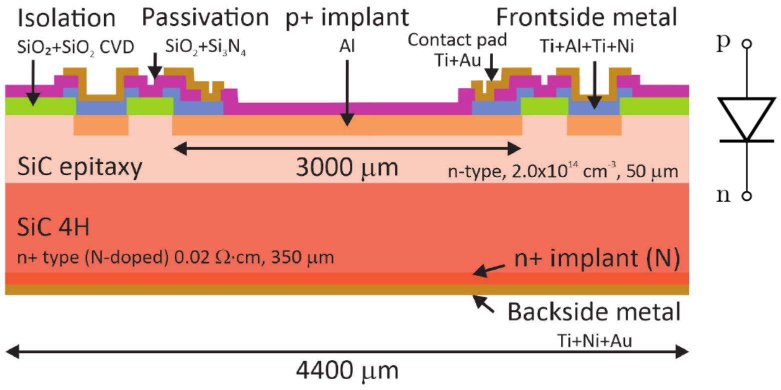
Interesting properties for particle detection:

- Very low leakage current even after irradiation
- Can be operated at high temperatures, no cooling required
- Can be operated under ambient light
- High break down electric field and high electron saturation velocity
- High quality 4” and 6” wafers commercially available

Drawbacks:

- Active layer thickness (epi-layer) currently with limited thickness
- Higher Ionization energy compared to silicon: ~ 50 $^{\text{eh-pairs}}/_{\mu m}$ (SiC) vs. 80 $^{\text{eh-pairs}}/_{\mu m}$ (Si)
- Anisotropy

CNM SiC samples

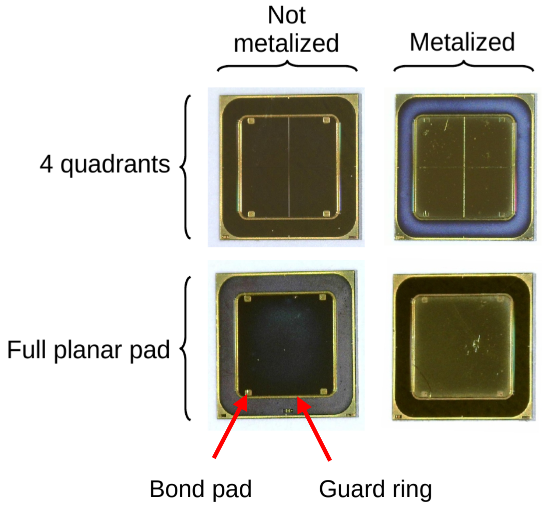


Measurements performed at the
Solid State Detectors (SSD) lab of the CERN EP-DT group

- Sensors used were manufactured by IMB-CNM, Spain

Centro Nacional de Microelectrónica IMB

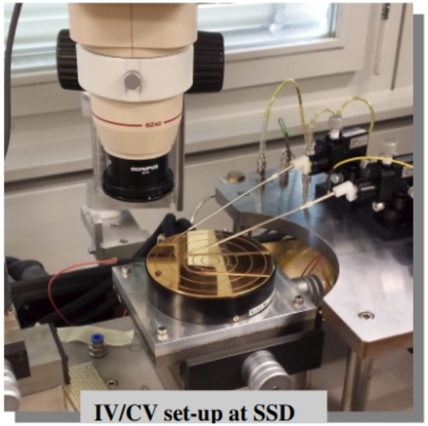
Proton Fluence [p/cm^2]	Samples	Nominal Thickness
0	CNM_SiC_14171-1_50_D7_4QMG	50µm
1E11	CNM_SiC_14171-1_50_D12_4QM	
1E12	CNM_SiC_14171-1_50_D11_4QMG	
1E13	CNM_SiC_14171-1_50_D20_1M	
1E14	CNM_SiC_14171-1_50_D18_1M	
0	CNM_SiC_14171-2_5_D7_4QMG	5µm
1E12	CNM_SiC_14171-2_5_D3_4QMG	
1E14	CNM_SiC_14171-2_5_D14_1M	

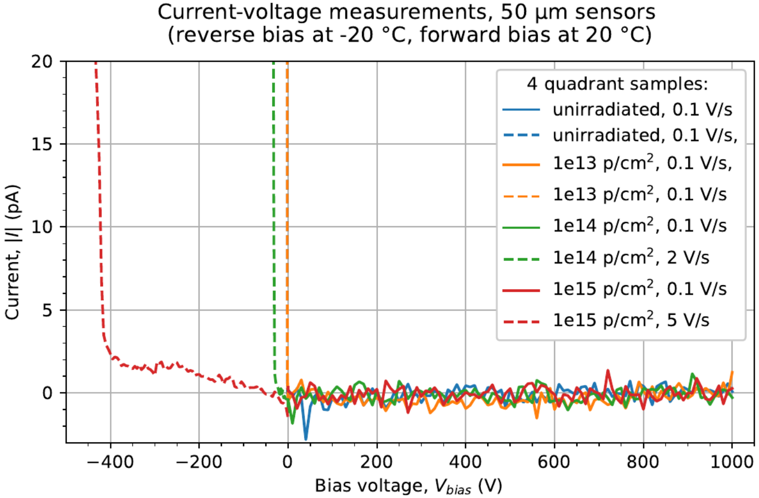


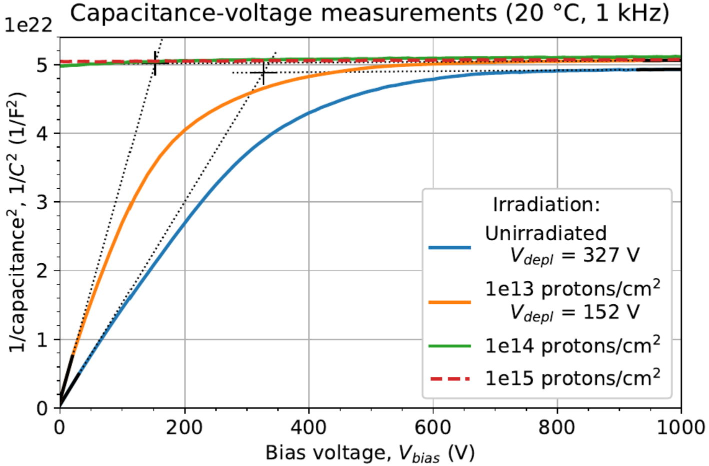
- n-type epi 4H-SiC
- 5µm thick (10 samples) or 50µm thick (14 samples)
- Full planar pad or divided into 4 quadrants
- Full surface metalization or non-metalized
- Vanadium doping for 5µm devices to form semi-insulating layer
- Proton irradiation (IRRAD) to max. 10^{15} p/cm²

Rafí, 2020, https://doi.org/10.1109/TNS.2020.3029730

Electrical Characterization





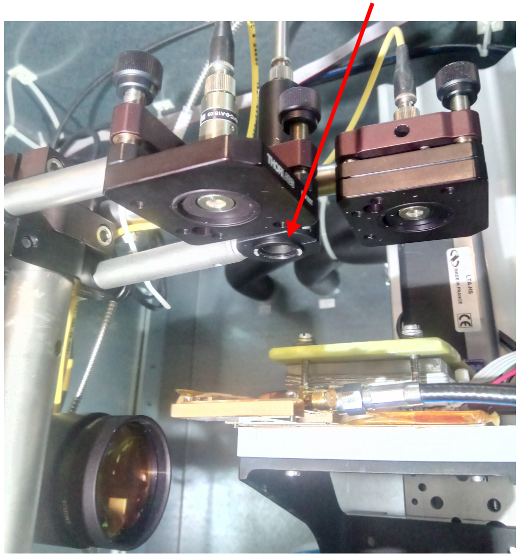


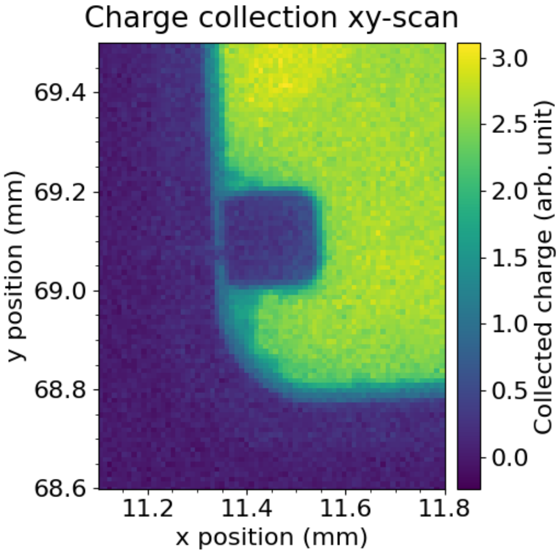
- Silicon carbide sensors show a very low leakage current at elevated temperatures and irradiation levels
- The threshold voltage for forward conductivity increases significantly with irradiation
- Effective doping concentration / depletion voltage decrease after irradiation
- CV can not be measured above a fluence of 10^{14} p/cm^2
- Irradiation leads to a reduction of the effective doping concentration through compensation by defects

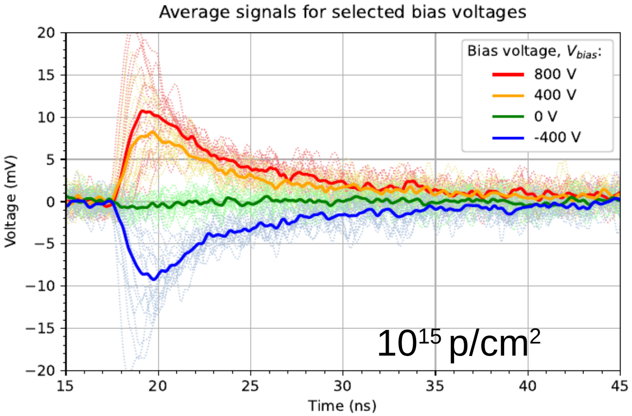
Elias Arnqvist (SSD summer student), https://cds.cern.ch/record/2868507/files/CERN_Report.pdf

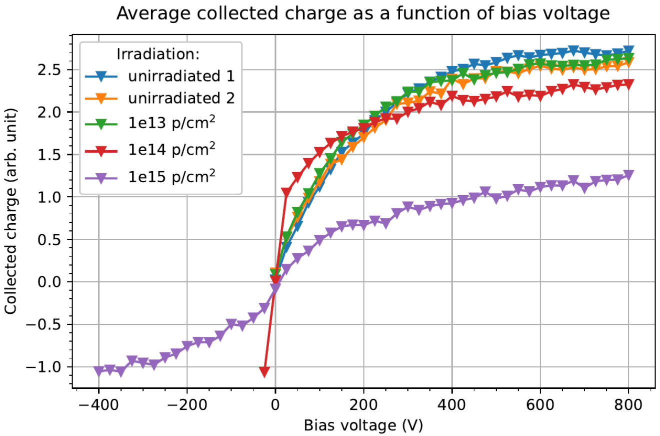
Charge collection with TCT

The existing TCT-setup (Transient Current Technique) in the SSD lab was extended by a 375nm UV-laser for the use with SiC sensors.







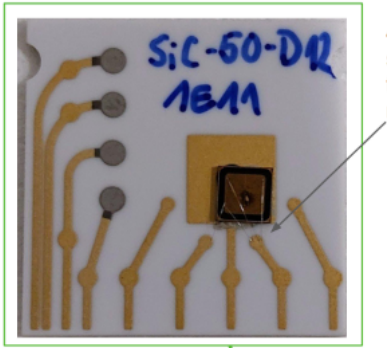


- Inhomogeneous charge collection over the opening area, strongest near bondpads
- Charge collection decreased to about 50% after 10^{15} p/cm^2
- Identical charge collection under forward and reverse bias after heavy irradiation
- No charge multiplication under forward bias observed below the threshold voltage

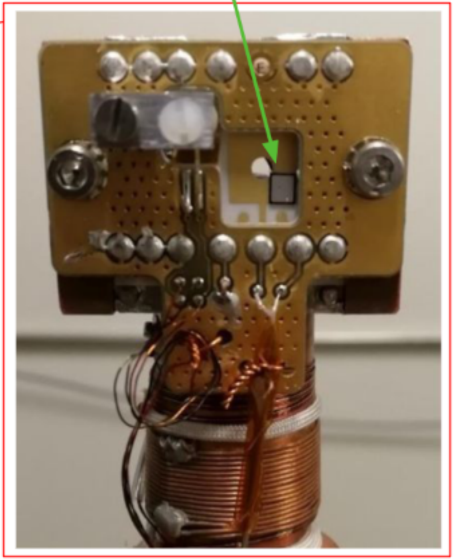
Defect characterization

TSC and DLTS setup

- Closed Cycle Liquid Helium Cryocooler from ARS, down to <20 K
- Vacuum ~ 10^{-6} mbar
- Heating coil for controlled warm-up (up to 350 K)
- TSC: Keithley + Custom LabView DAQ
- DLTS: Phystech commercial system (hardware, DAQ, analysis)



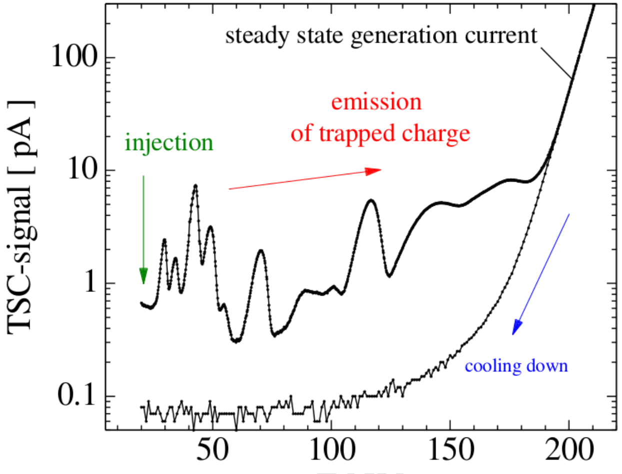
4 quadrants shorted together to one readout/bias



Defect characterization performed by Yana Gurimskaya and Niels Sorgenfrei, presented in Niels Sorgenfrei, Defect Spectroscopy on Proton Irradiated 4H-Silicon Carbide Devices, 43rd RD50 workshop, Nov. 2023

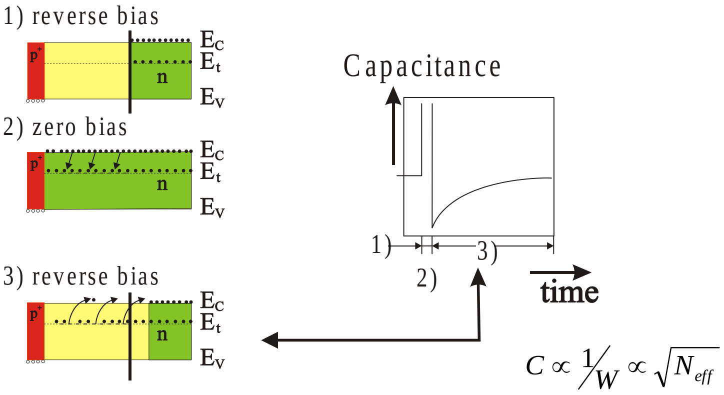
1) TSC – Working Principle

- Cooling
  - Under bias or without
- Filling (charge injection)
  - Forward bias, zero bias or light injection
- Recording
  - Measure current while ramping up the temperature



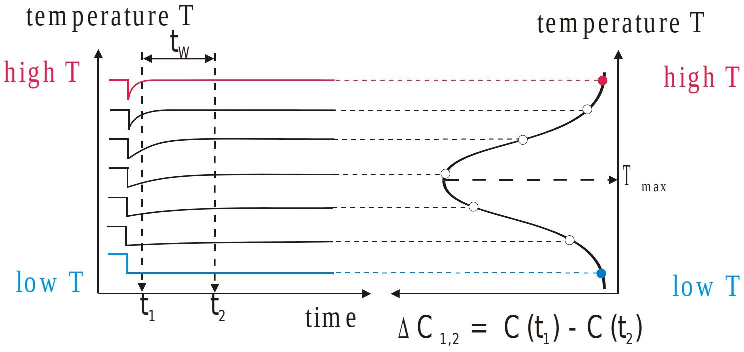
[M.Moll - PhD thesis 1999]

2) DLTS – Working Principle



$$C \propto 1/W \propto \sqrt{N_{eff}}$$

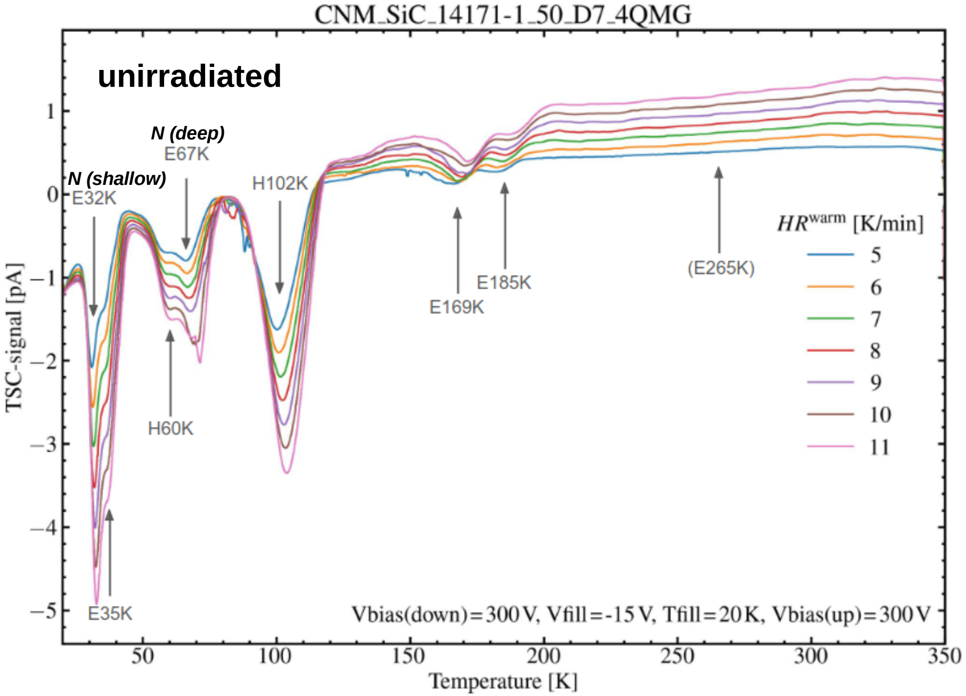
Variation of voltage (zero bias pulse)
- measurement of capacitance transient

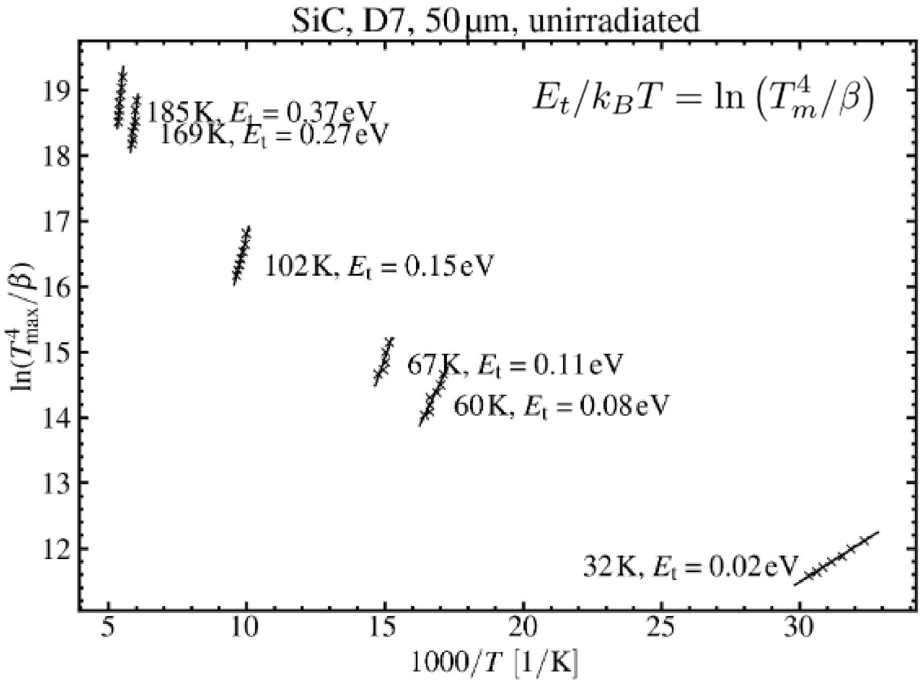


Measure capacitance transients at many temperatures to obtain a DLTS - spectrum

Defect characterization

TSC - unirradiated

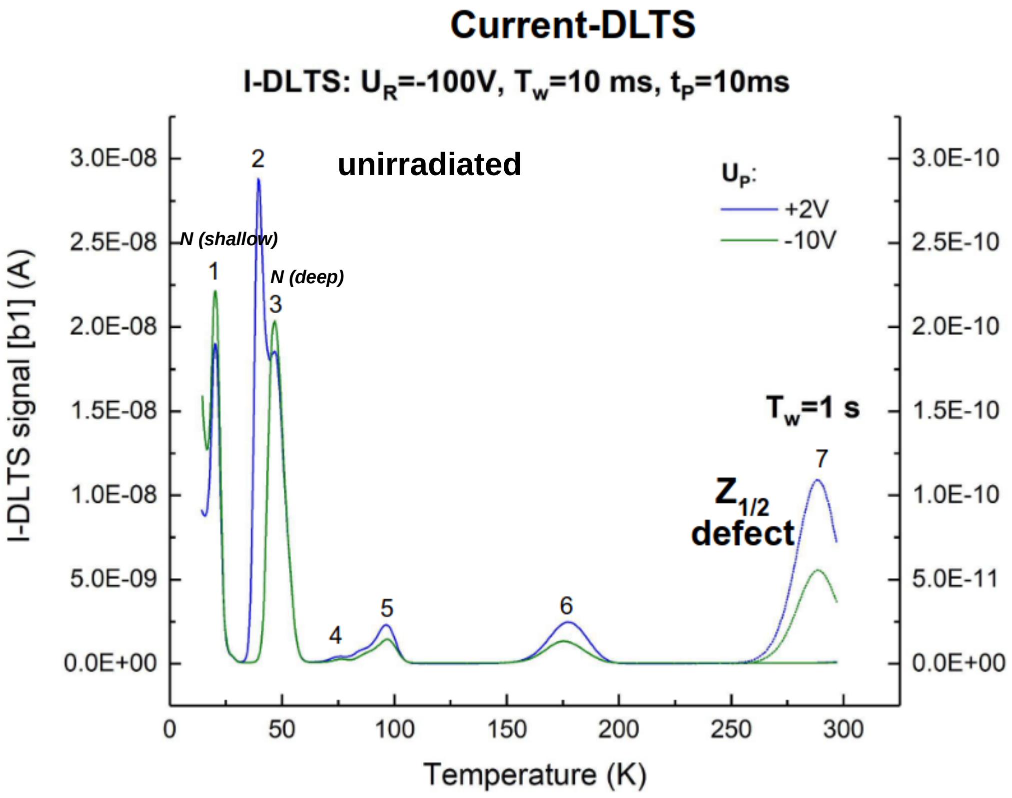


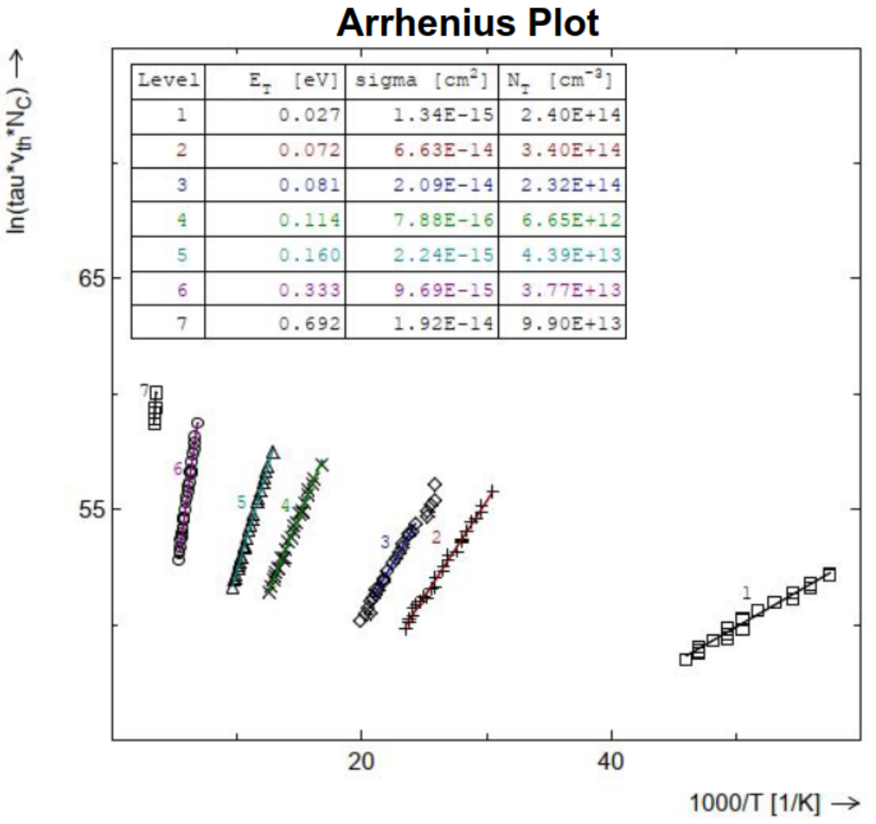


- Intrinsic (vacancies, interstitials, antisites) or impurity (boron, aluminium, …) related defects
- Defect at ~ 265 K (not visible here) only filled for Tfill > 50 K
- Much less peaks observed in unirradiated Silicon

Defect characterization

I-DLTS - unirradiated



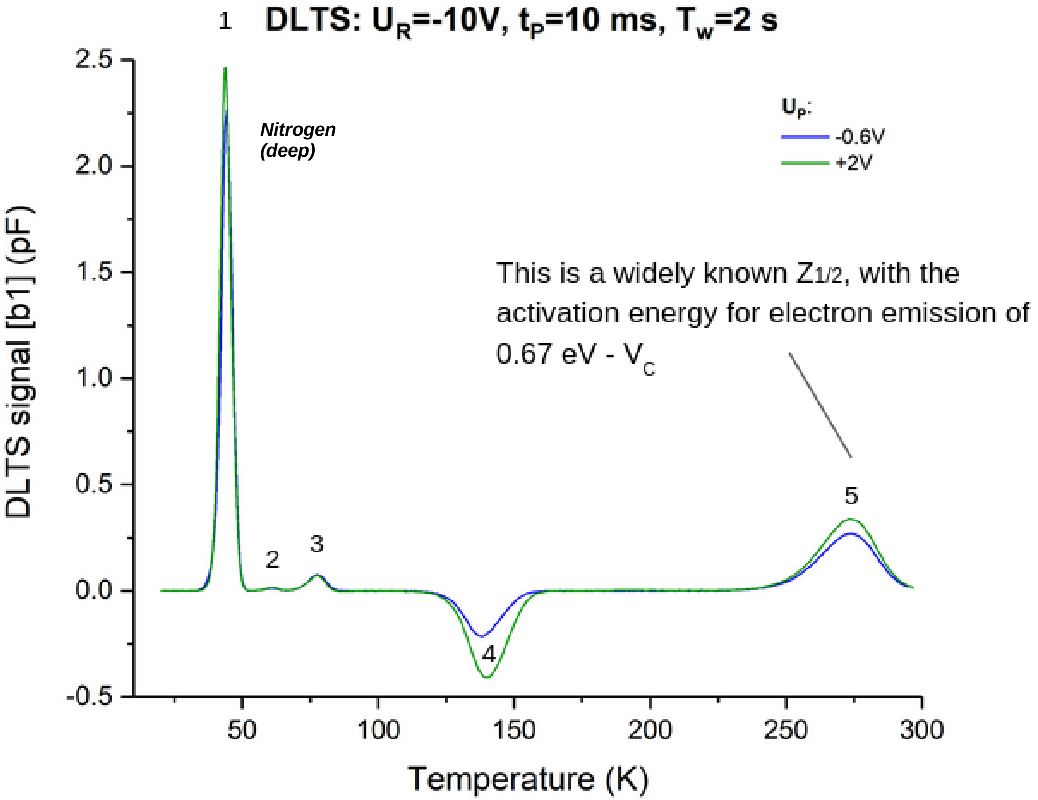


Level	E_T [eV]	sigma [cm^2]	N_T [cm^{-3}]
1	0.027	1.34E-15	2.40E+14
2	0.072	6.63E-14	3.40E+14
3	0.081	2.09E-14	2.32E+14
4	0.114	7.88E-16	6.65E+12
5	0.160	2.24E-15	4.39E+13
6	0.333	9.69E-15	3.77E+13
7	0.692	1.92E-14	9.90E+13

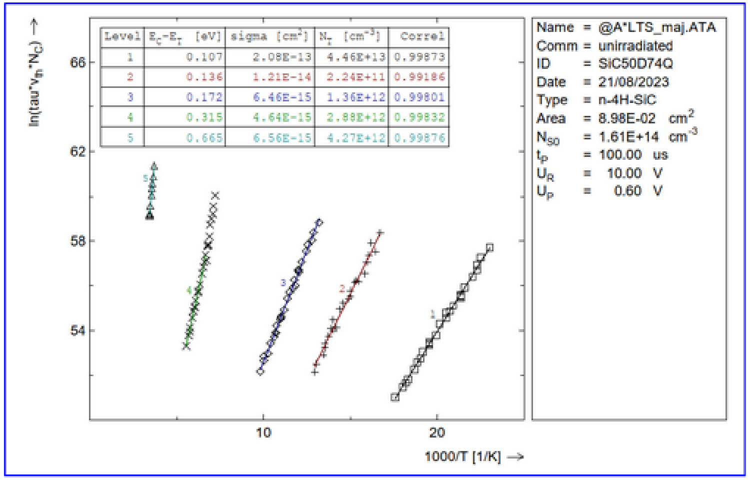
$Z_{1/2}$: two overlapping defect states, important for carrier lifetime reduction

Defect characterization

DLTS - unirradiated

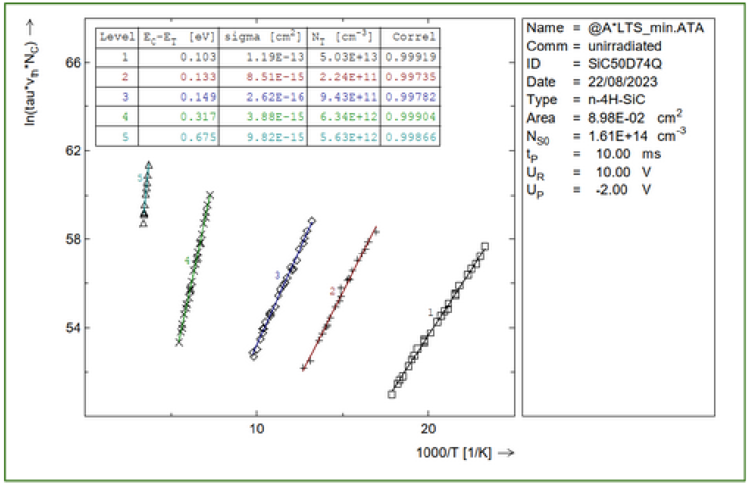

DLTS: U_R=-10V, t_P=10 ms, T_W=2 s

This is a widely known $Z_{1/2}$, with the activation energy for electron emission of 0.67 eV - V_C



Level	E_C-E_T [eV]	sigma [cm^2]	N_T [cm^{-3}]	Correl
1	0.107	2.08E-13	4.46E+13	0.99873
2	0.136	1.21E-14	2.24E+11	0.99186
3	0.172	6.46E-15	1.36E+12	0.99801
4	0.315	4.64E-15	2.88E+12	0.99832
5	0.665	6.56E-15	4.27E+12	0.99876

Name = @A*LTS_maj.ATA
Comm = unirradiated
ID = SiC50D74Q
Date = 21/08/2023
Type = n-4H-SiC
Area = 8.98E-02 cm^2
N_{S0} = 1.61E+14 cm^{-3}
t_P = 100.00 us
U_R = 10.00 V
U_P = 0.60 V



Level	E_C-E_T [eV]	sigma [cm^2]	N_T [cm^{-3}]	Correl
1	0.103	1.19E-13	5.03E+13	0.99919
2	0.133	8.51E-15	2.24E+11	0.99735
3	0.149	2.62E-16	9.43E+11	0.99782
4	0.317	3.88E-15	6.34E+12	0.99904
5	0.675	9.82E-15	5.63E+12	0.99866

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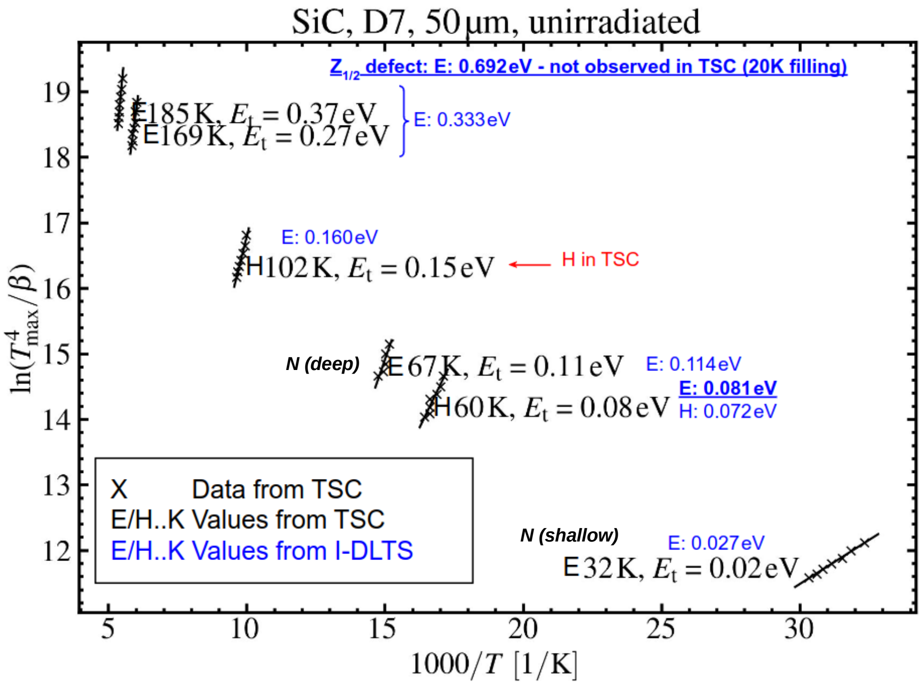
Date = 22/08/2023
Type = n-4H-SiC
Area = 8.98E-02 cm^2
N_{S0} = 1.61E+14 cm^{-3}
t_P = 10.00 ms
U_R = 10.00 V
U_P = -2.00 V

Defect characterization

I-DLTS and TSC

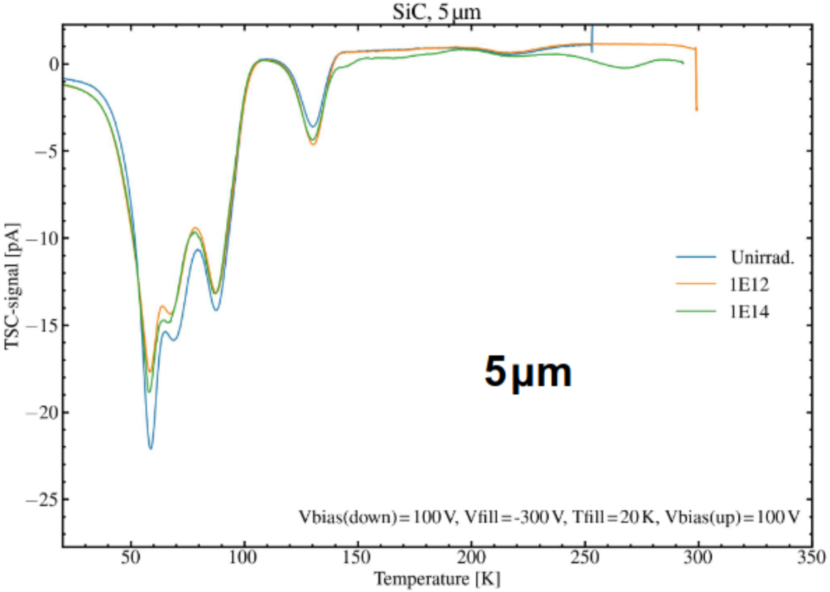


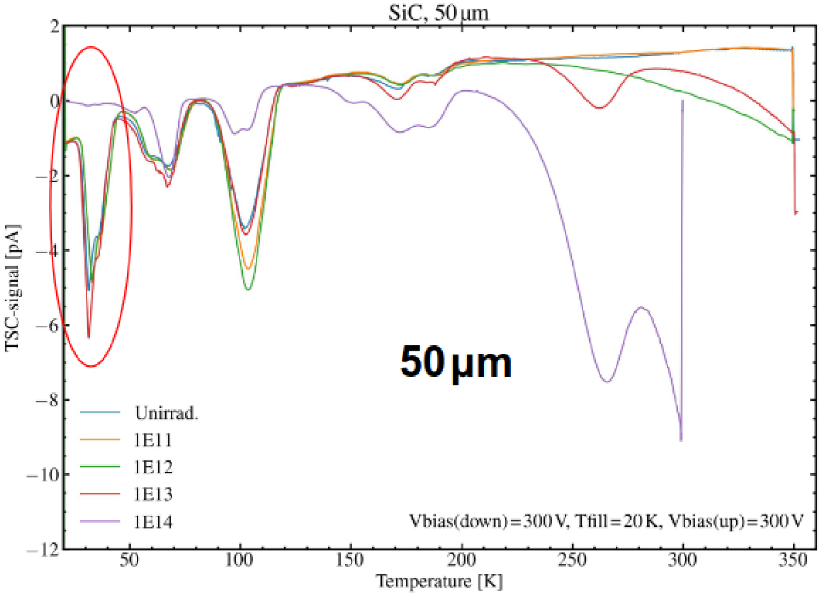
- TSC and I-DLTS measurements carried out to identify defects and observe changes with irradiation
- Multiple intrinsic or impurity related defects found in unirradiated sensors
- No strong change with irradiation observed
  Many radiation induced defects expected at T>250 K
- Currently the measurement range is limited to ~350K
  ➔ higher temperature cryostat purchased

Defect characterization

TSC - irradiated

24 GeV/c proton irradiation





- Limited change with irradiation for 5µm
- Different electric field leads to different peak positions compared to 50µm sensor
- Vanadium co-doping can lead to changed spectrum

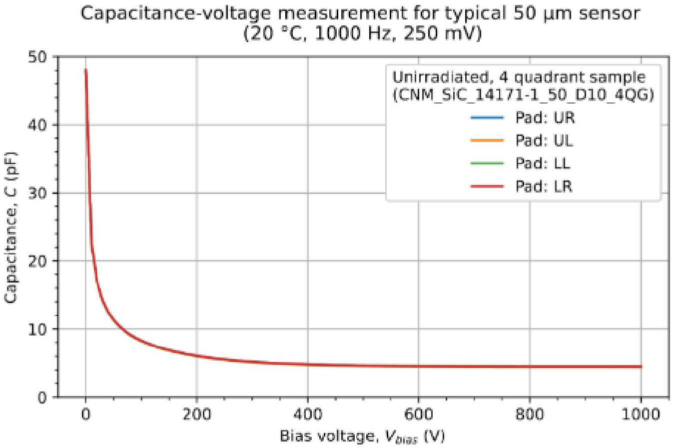
- $Z_{1/2}$ (@265 K) concentration increases
- H102K first increases, then decreases
  - Introduction rates only decrease
- E32K peak vanishes at highest fluence, highest V_{bias}
  - Trapped charges de-trap with longer wait times: *Field enhanced tunneling*

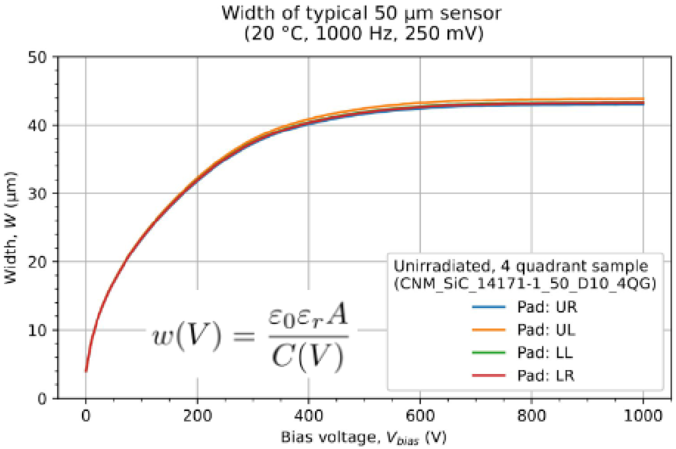
Conclusions

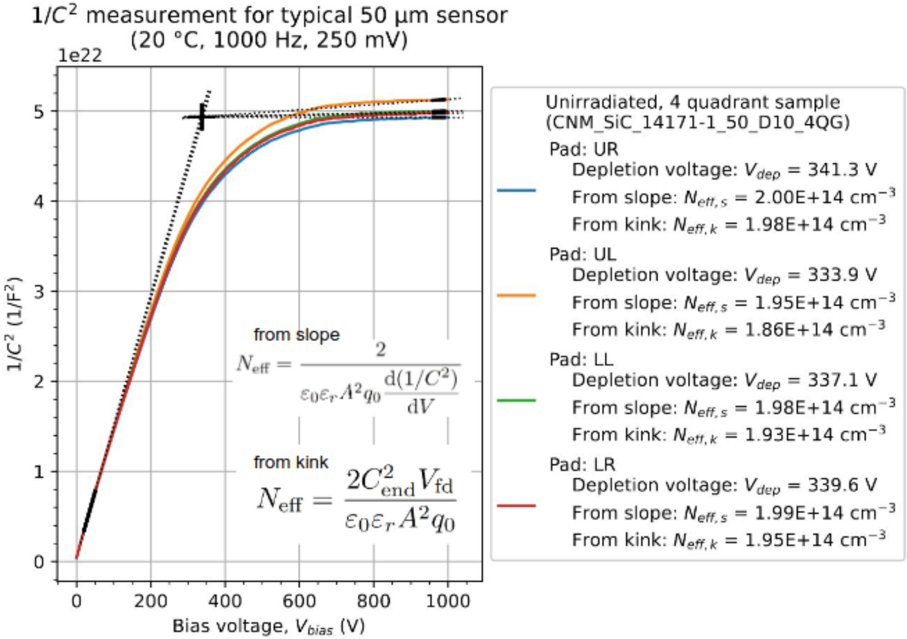
- 5µm and 50µm CNM SiC samples were irradiated with 24GeV/c protons and measured with IV/CV, TCT, DLTS and TSC
- IVCV:
  - Very limited increase of the leakage current with irradiation
  - Devices become intrinsic, increased forward threshold voltage, diode properties after 10^{14} p/cm^2
- TCT:
  - Charge collection decreases down to 50% after 10^{15} p/cm^2
  - Charge collection identical under forward and reverse bias after irradiation (no charge multiplication observed below the threshold voltage)
- TSC and DLTS:
  - Multiple defects before irradiation, some with increased concentration after irradiation
  - Most interesting defects ($Z_{1/2}$, EH6/EH7) are located at higher temperatures than currently achievable
- Cryostat with extended temperature range will be delivered mid-2024

CNM SiC samples tested at CERN

Electrical characterization, unirradiated







- End capacitance of 3.9pF (single pad) and 38.6pF (full area) reached at around 600V
- Vdep ≈ 340 V, Neff ≈ 1.95 x 10^{14} cm^{-3}
- Results are consistent with nominal Neff = 2 x 10^{14} cm^{-3}

Defect characterization
Nitrogen donor

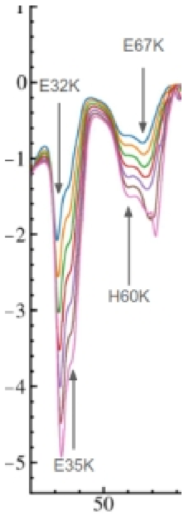
Identification of the deep nitrogen donor state:
- **TSC**:
  - E_t = 0.1eV (67K), electron trap
  - Poole-Frenkel effect observed
- **DLTS (Level 1),** :
  - E_t = 0.1eV
  - σ = 1 – 2e-13 cm^2
  - N_t = 4.5 – 5e+13 cm^{-3}
  - observed under majority (minority + majority) injection
- **I-DLTS (Level 2/3)**:
  - E_t = 0.08eV
  - σ = 1 – 10e-14 cm^2
  - N_t = 2 - 2.5e+14 cm^{-3}
  - observed under majority (minority + majority) injection

From literature:
- **Deep nitrogen level** (quasi-cubic carbon site)
  - E_t = 0.1 eV
  - σ = 1 – 20e-14 cm^2
  - Shows Poole-Frenkel effect

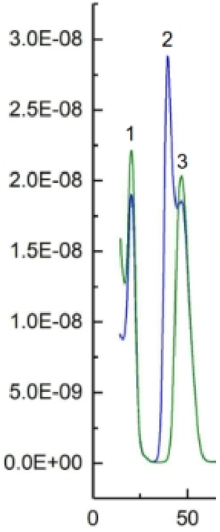
Identification of the shallow nitrogen donor state:
- **TSC**:
  - E_t = 0.02eV (32K), electron trap
  - Poole-Frenkel effect observed
- **I-DLTS (Level 1)**:
  - E_t = 0.027eV
  - σ = 1.34e-15 cm^2
  - N_t = 2.4e+14 cm^{-3}
  - observed under majority (minority + majority) injection

From literature:
- **Shallow nitrogen level** (quasi-hexagonal carbon site)
  - E_t = 0.05 eV
  - Can not be observed in capacitance measurements
  - because of carrier freeze-out

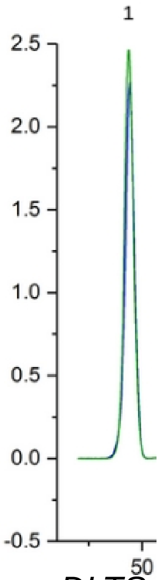
Menichelli et al., 2007, https://doi.org/10.1016/j.diamond.2006.03.008
Assmann et al., 2021, https://doi.org/10.1063/5.0074046



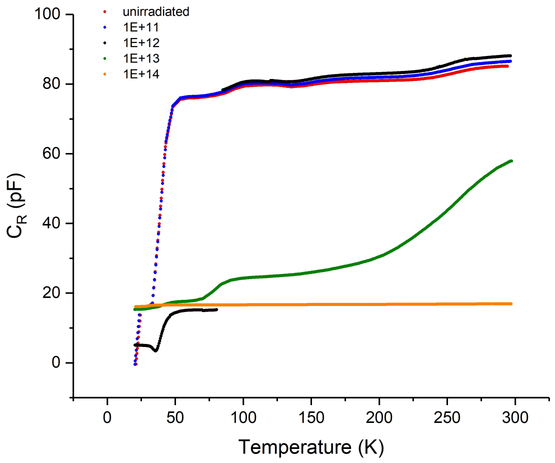
TSC



I-DLTS

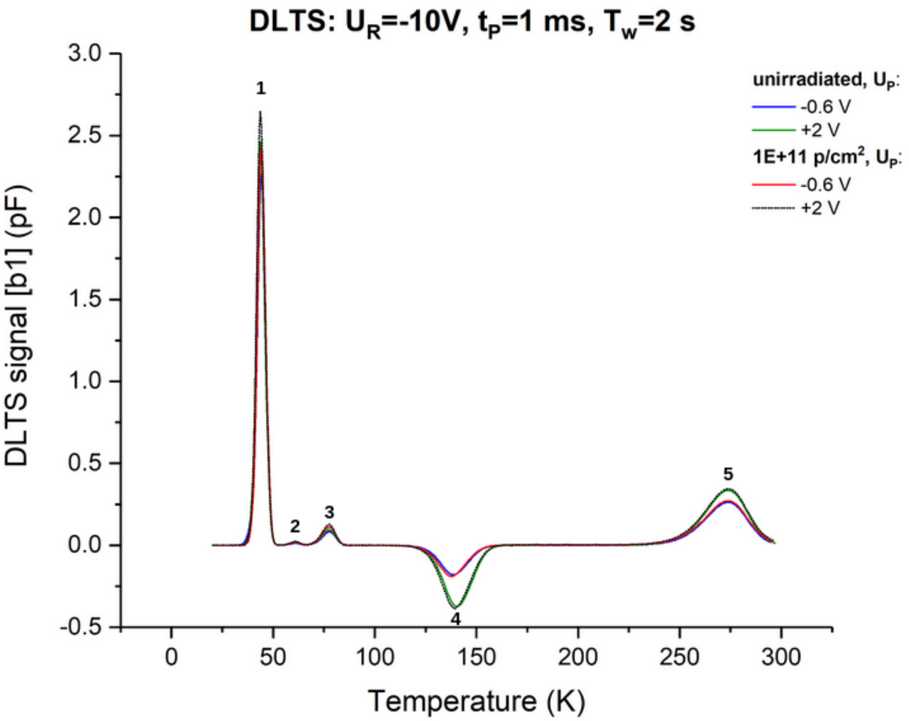


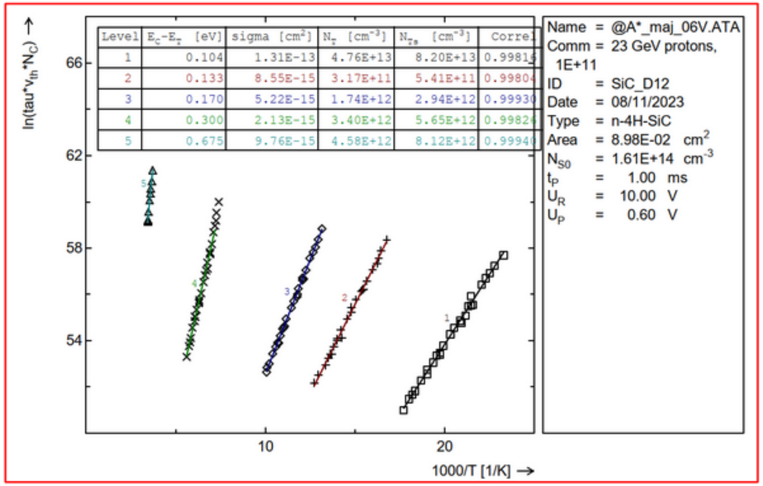
DLTS



Reverse capacitance as a function of temperature. Carrier freeze-out in the nitrogen state at 40-50K.

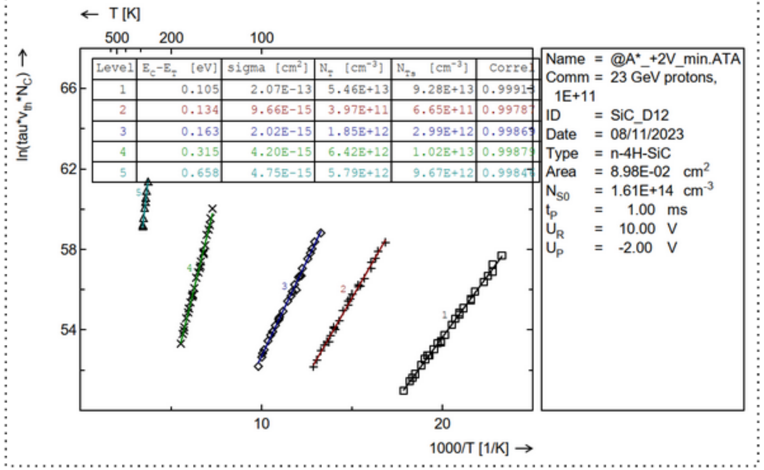
DLTS: SiC unirradiated and 1E+11 p/cm^2





Level	E_C-E_T [eV]	sigma [cm^2]	N_T [cm^{-3}]	N_{Ts} [cm^{-3}]	Correl
1	0.104	1.31E-13	4.76E+13	8.20E+13	0.99816
2	0.133	8.55E-15	3.17E+11	5.41E+11	0.99804
3	0.170	5.22E-15	1.74E+12	2.94E+12	0.99930
4	0.300	2.13E-15	3.40E+12	5.65E+12	0.99826
5	0.675	9.76E-15	4.58E+12	8.12E+12	0.99940

Name = @A*_maj_06V.ATA
Comm = 23 GeV protons,
1E+11
ID = SiC_D12
Date = 08/11/2023
Type = n-4H-SiC
Area = 8.98E-02 cm^2
N_{S0} = 1.61E+14 cm^{-3}
t_P = 1.00 ms
U_R = 10.00 V
U_P = 0.60 V



Level	E_C-E_T [eV]	sigma [cm^2]	N_T [cm^{-3}]	N_{Ts} [cm^{-3}]	Correl
1	0.105	2.07E-13	5.46E+13	9.28E+13	0.99913
2	0.134	9.66E-15	3.97E+11	6.65E+11	0.99787
3	0.163	2.02E-15	1.85E+12	2.99E+12	0.99869
4	0.315	4.20E-15	6.42E+12	1.02E+13	0.99879
5	0.658	4.75E-15	5.79E+12	9.67E+12	0.99846

Name = @A*_+2V_min.ATA
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1E+11
ID = SiC_D12
Date = 08/11/2023
Type = n-4H-SiC
Area = 8.98E-02 cm^2
N_{S0} = 1.61E+14 cm^{-3}
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U_R = 10.00 V
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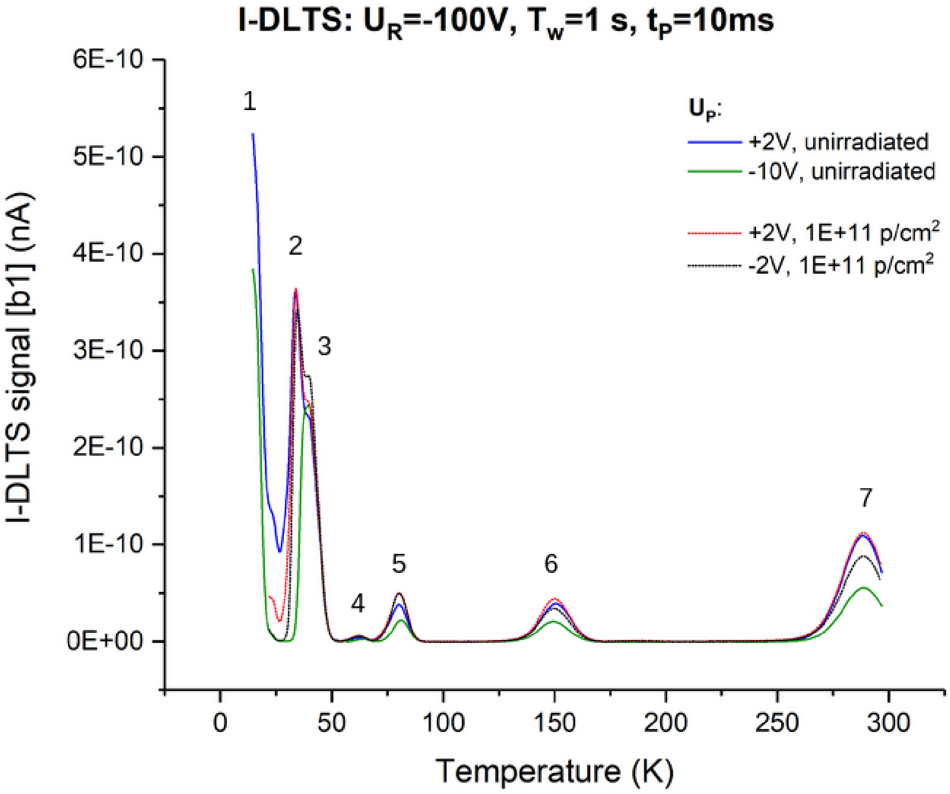

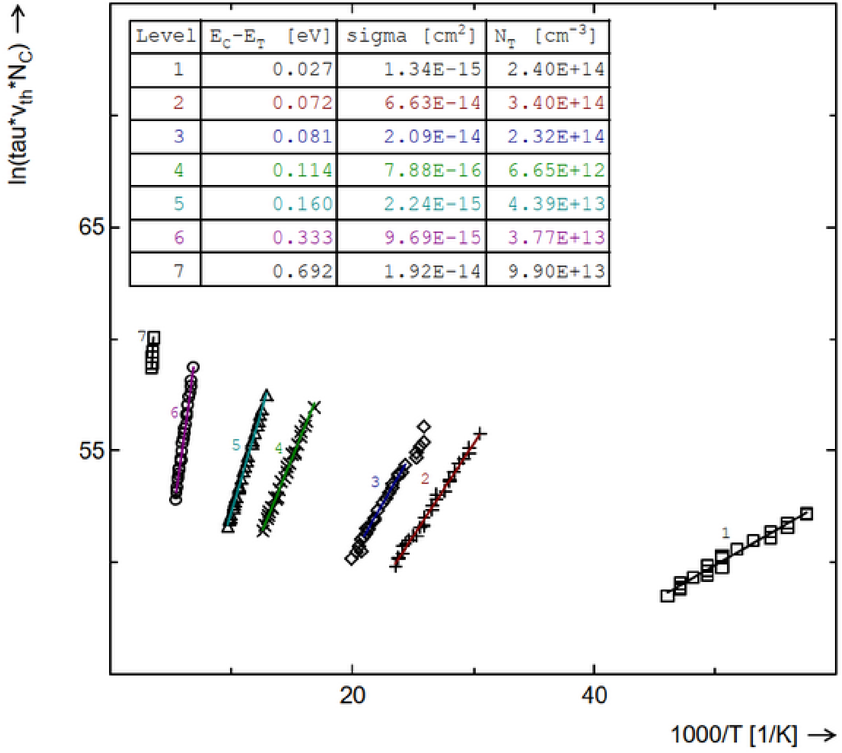

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3	0.081	2.09E-14	2.32E+14
4	0.114	7.88E-16	6.65E+12
5	0.160	2.24E-15	4.39E+13
6	0.333	9.69E-15	3.77E+13
7	0.692	1.92E-14	9.90E+13