42nd RD50 Workshop on Radiation Hard Semiconductor Devices for Very High Luminosity Colliders
20-23 June 2023, Tivat, Montenegro

Exploring boron-induced defects in n-type 4H-SiC Schottky barrier diodes

Tihomir Knezevic[(1)], Eva Jelavić[(2)], Yuichi Yamazaki[(3)], Takeshi Ohshima[(3)], Takahiro Makino[(3)], *Ivana Capan*[(1)]

[(1)] **Laboratory for semiconductors** | Division of Materials Physics | **Ruder Boskovic Institute** | Zagreb | Croatia

[(2)] **Faculty of Science** | **University of Zagreb** | Zagreb | Croatia

[(3)] **National Institutes for Quantum Science and Technology** | Takasaki | Japan

tihomir.knezevic@irb.hr; ivana.capan@irb.hr

Institut Ruđer Bošković

PMF

University of Zagreb

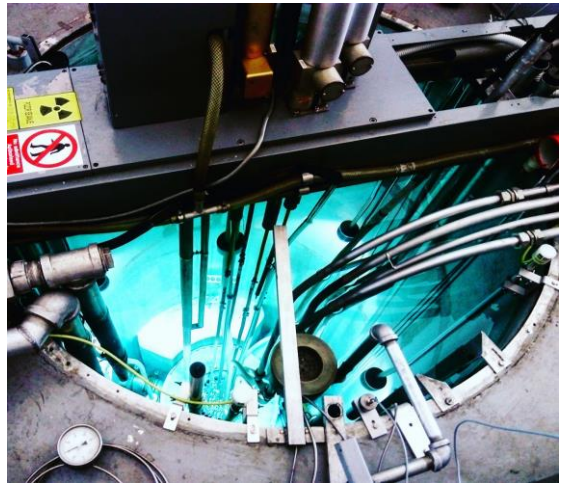
QST

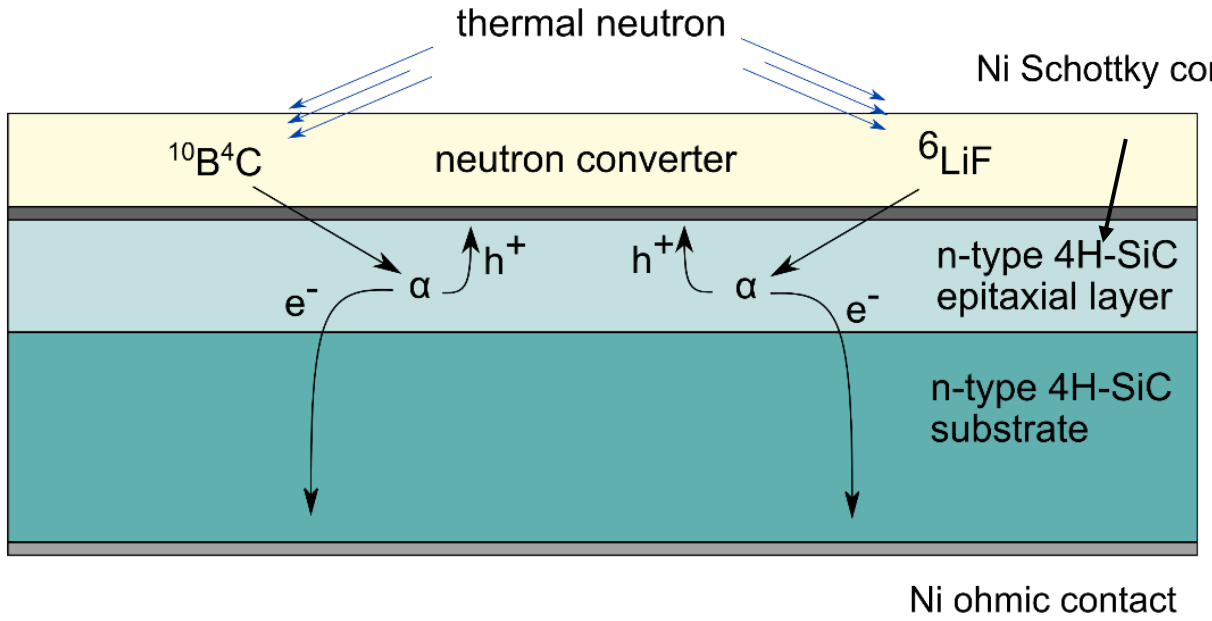
Outline

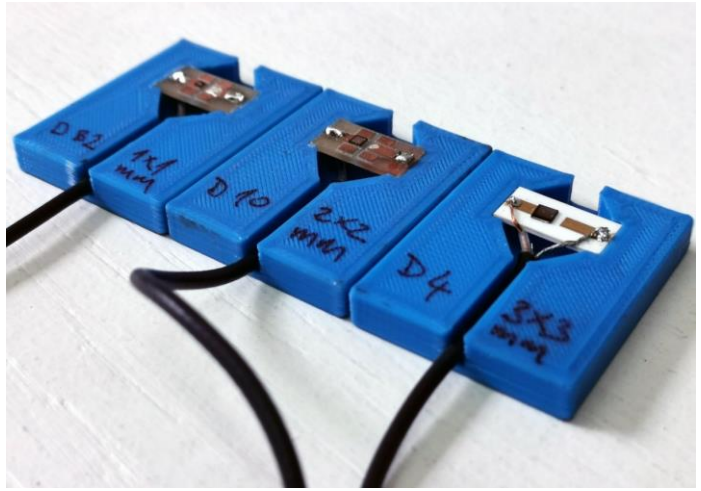
- Introduction
- Defects in 4H-SiC
- Deep-level transient spectroscopy
- Minority carrier transient spectroscopy
- Device fabrication and measurement setup
- Electrical characterization
- Conclusions

Introduction

- **4H-SiC Schottky barrier diode**
  - 4H-SiC: wide bandgap material
  - Applications in harsh environments – high temperature, high voltage, radiation
  - Neutron detection
    - Border security
    - Nuclear material detection



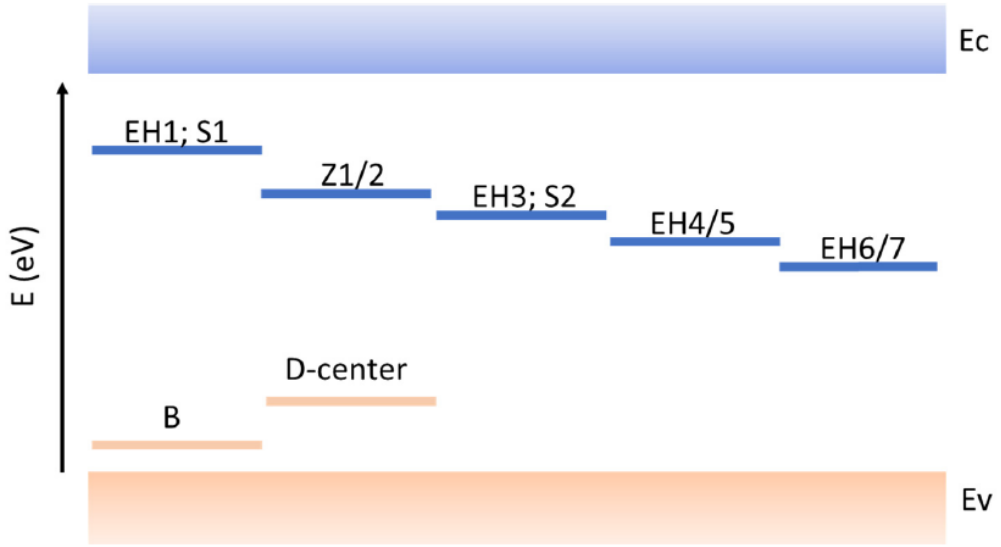




Defects in 4H-SiC

- Defects can be introduced
  - Unintentionally – during growth process
  - Intentionally – radiation, particles
- Electrically active defect can degrade the performance of the device
- Some defects considered “lifetime killers”

Trap Label	Identification	Activation Energy (eV)
EH_1	C_i	Ec – 0.40
EH_3	C_i	Ec – 0.70
S_1	V_{Si} (−3/−)	Ec – 0.40
S_2	V_{Si} (=/−)	Ec – 0.70
Z_1	V_c (=/0)	Ec – 0.59
Z_2	V_c (=/0)	Ec – 0.67
$EH_{4/5}$	C_{si}-V_c (+/0)	Ec – 1.10
EH_6	V_c (0/++)	Ec – 1.30
EH_7	V_c (0/++)	Ec – 1.40
B	B_{si}	Ev + 0.28
D-center	B_c	Ev + 0.54

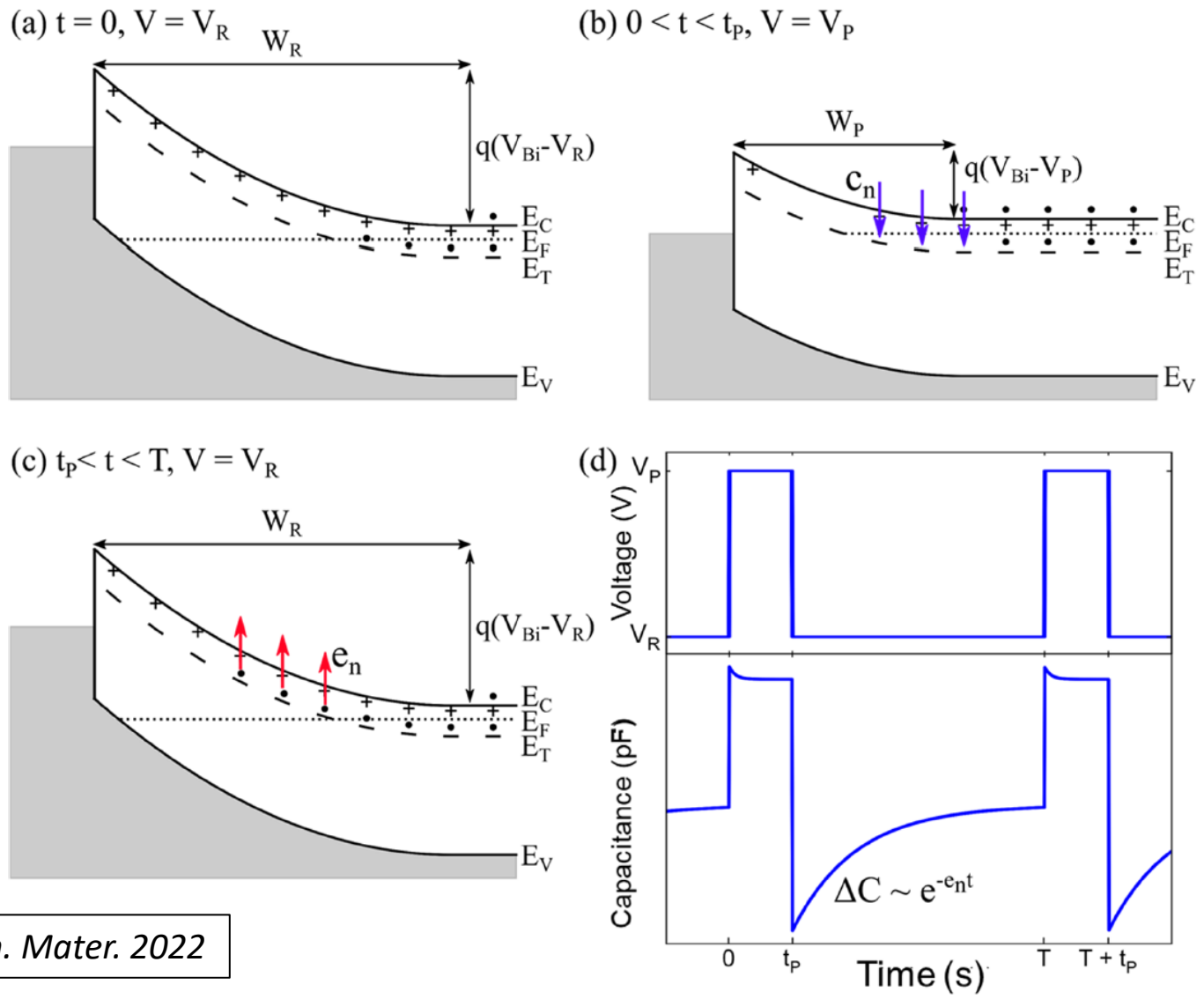


Graphical representation of energy levels based on DLTS studies

I. Capan, T. Brodar, Electron. Mater. 2022

Deep-level transient spectroscopy (DLTS)

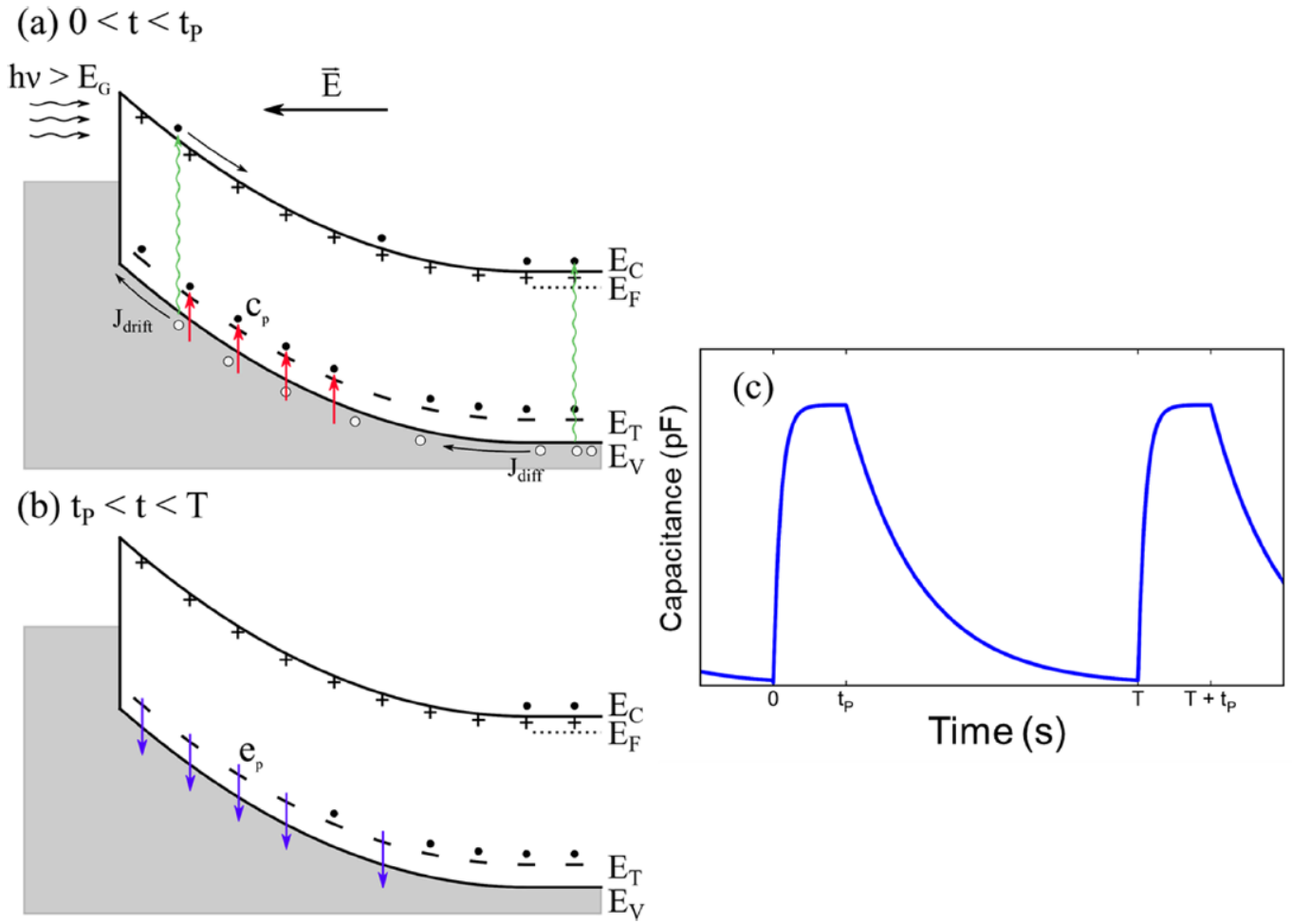
- **Detection of electrically active traps for majority charge carriers:**
  - Diode voltage pulsed – transient capacitance measured
  - Detection limit: ~ 10^9 – 10^{10} cm^{-3}
  - Parameters: V_R, t_p, V_p
    - e_n electron emission rate
    - c_n electron capture rate



I. Capan, T. Brodar, Electron. Mater. 2022

Minority carrier transient spectroscopy (MCTS)

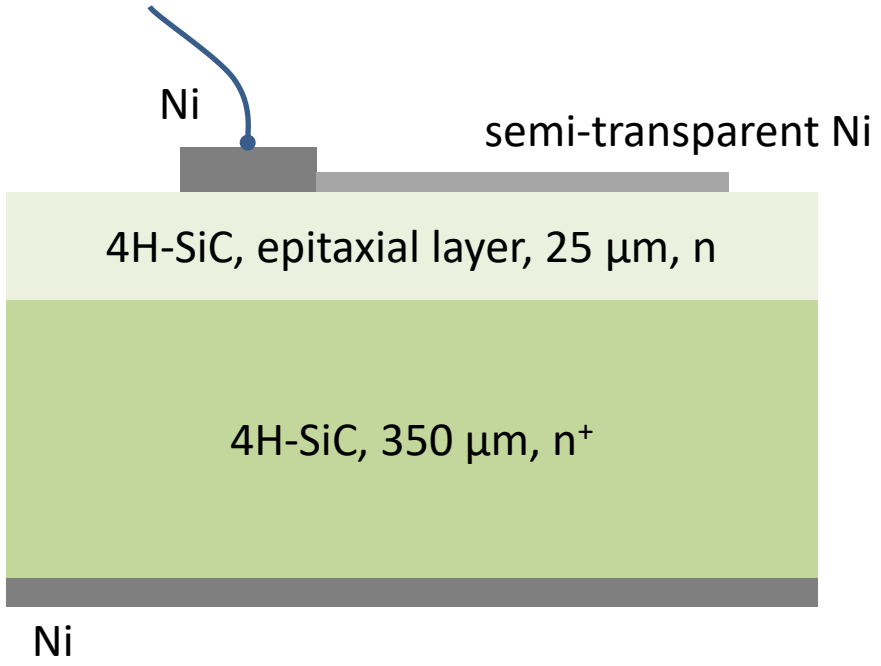
- **Detection of electrically active traps for minority charge carriers:**
  - Fixed reverse bias → optical excitation pulsed → transient capacitance measured
    - e_p hole emission rate
    - c_p hole capture rate



I. Capan, T. Brodar, Electron. Mater. 2022

Device fabrication

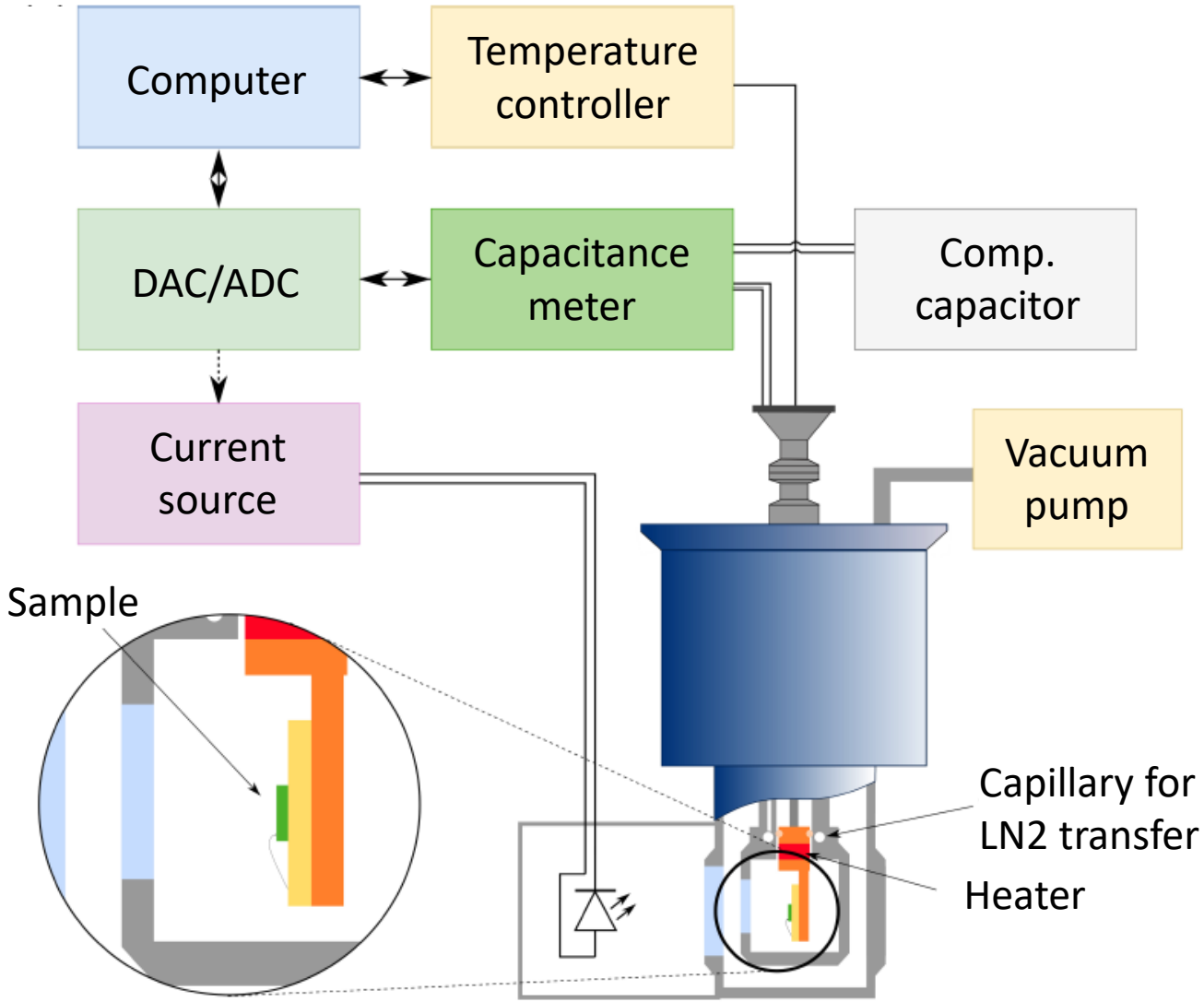
- Starting substrate: 4H-SiC 350 µm
- Epitaxial layer: 25 µm chemical vapor deposition, no buffer layer: n-type nitrogen doped
- Ohmic contact – sintered at 950 °C in an Ar atmosphere
- Schottky barrier – hard mask – Ni thermal evaporation
  - 2 × 2 mm^2 area
  - Semi transparent: 15 nm
  - Thick film for bonding: 100 nm



Measurement setup

- Deep-level transient spectroscopy
  - For MCTS: 365 nm LED
- Cryostat: ~77 K to 450 K

- Electrical characterization:
  - Current-voltage (*I-V*)
  - Capacitance-voltage (*C-V*)

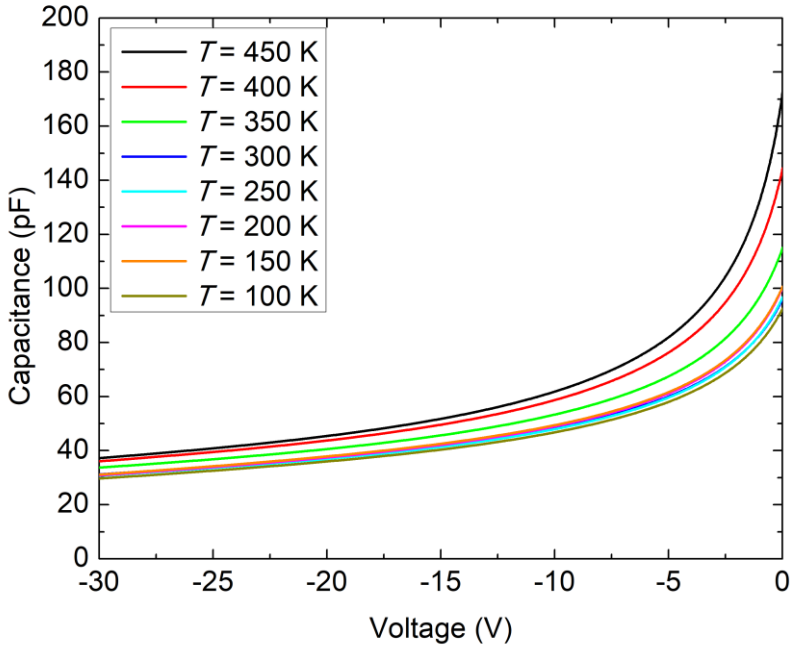


T. Brodar,PhD thesis, Zagreb, 2021

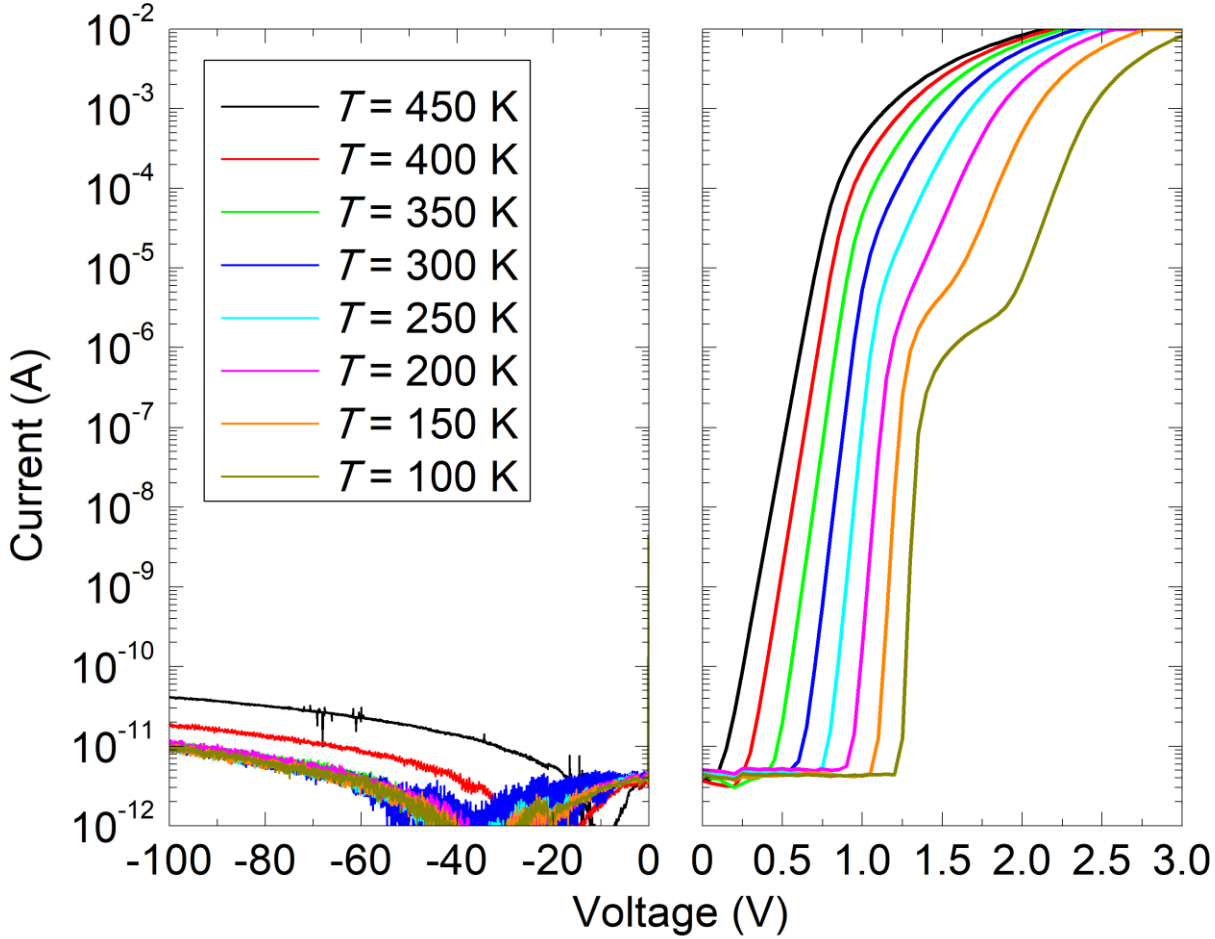
Electrical characterization – *I-V*, *C-V*

- *I-V* and *C-V* measurements – performed at temperatures from 100 K to 450 K
- 'Kinks' observed in *I-V*s at low temperatures → barrier height inhomogeneities

Capacitance-voltage (*C-V*)



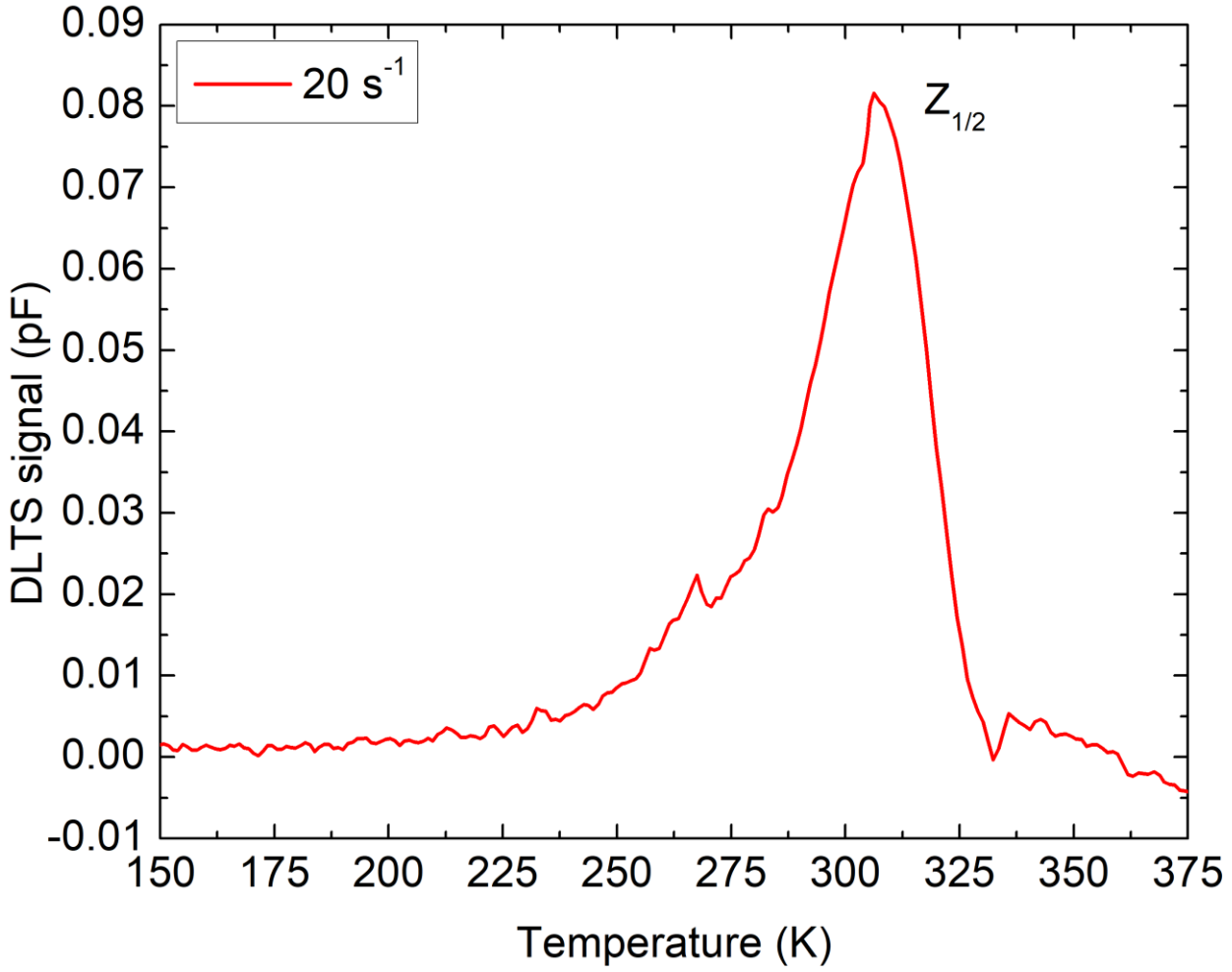
Current-voltage (*I-V*)



T. Knezevic, E. Jelavić, Y. Yamazaki, T. Ohshima, T. Makino, and I. Capan, Materials, Apr. 2023, doi: 10.3390/ma16093347.

Deep-level transient spectroscopy (DLTS)

- V_R = -10 V, V_p = -0.1 V, t_p = 10 ms
- Only $Z_{1/2}$ peak – carbon vacancy V_C(=/0)
  - "lifetime killer"
- Activation energy: E_C – 0.65 eV
- Trap concentration: 3×10^{12} cm^{-3}



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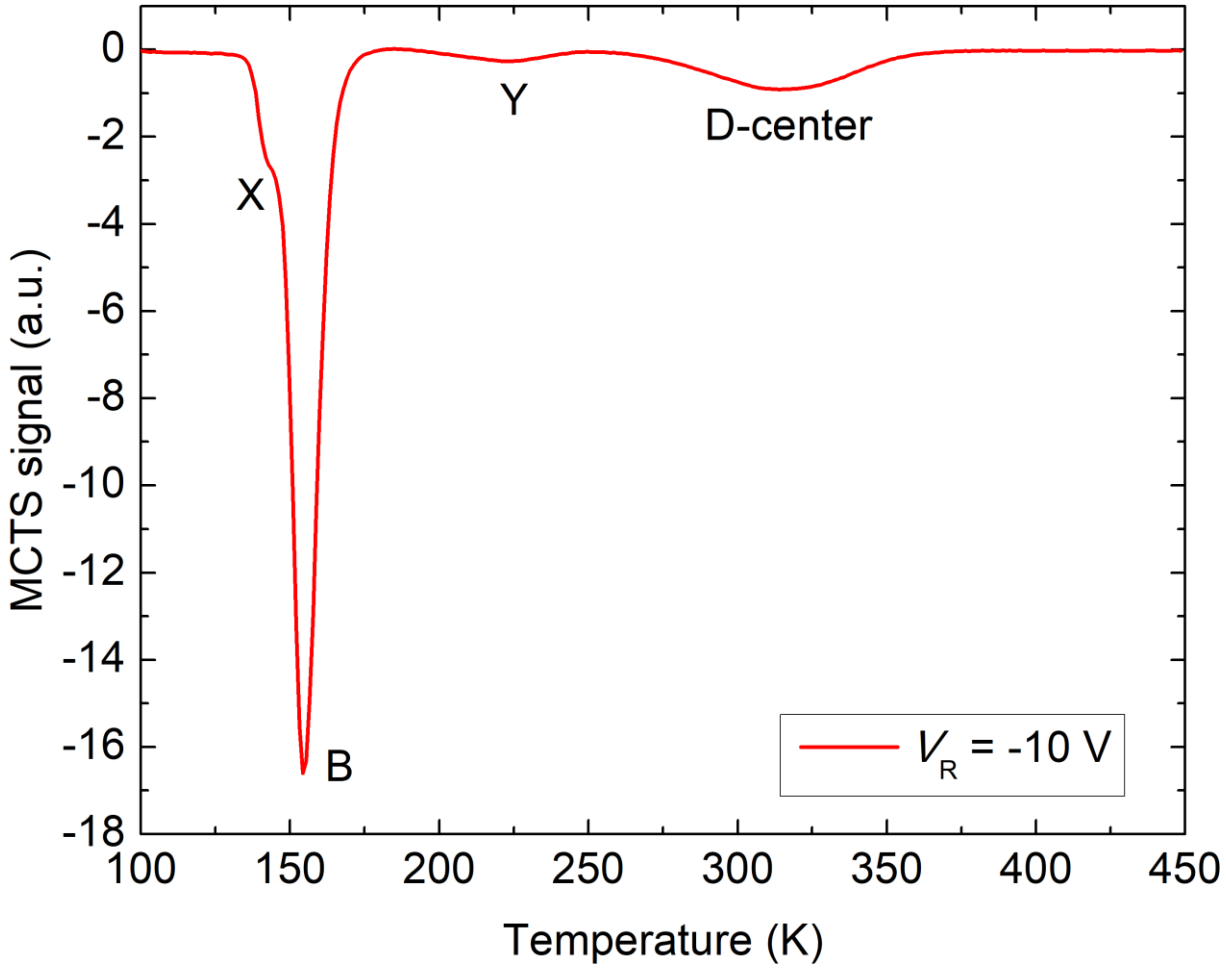
Minority carrier transient spectroscopy (MCTS)

- Well known defects: B and D-center
  - B:
    - E_V + 0.21 eV
  - D-center:
    - E_V + 0.65 eV

- B peak > D-center peak
  - C-rich growth conditions



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Depth profile of B-center and D-center

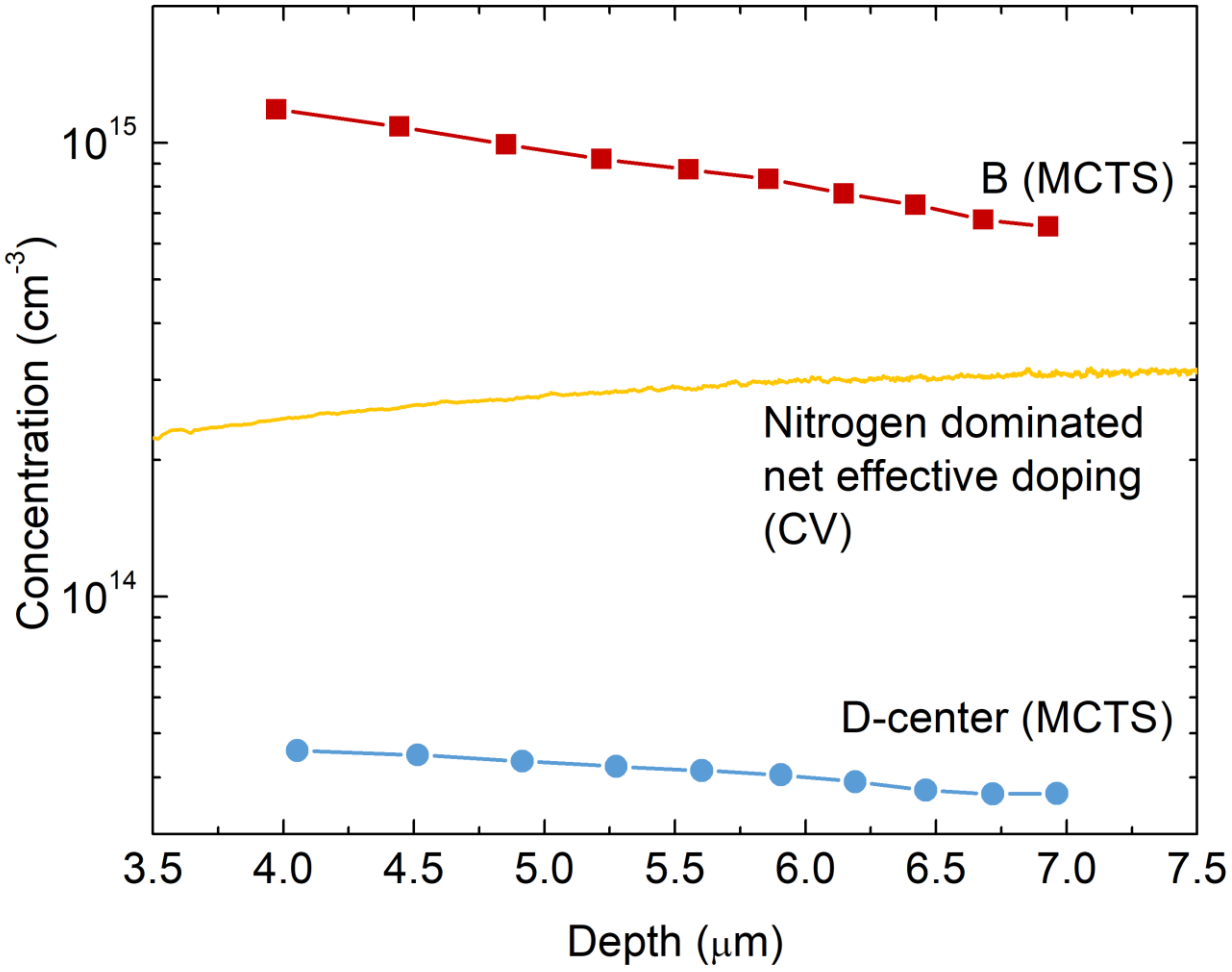
- Net effective doping – extracted from *C-V* measurements:

$$N_{TOT}(W) = \frac{2}{2\varepsilon_{SiC}\varepsilon_0 A^2 d\,(1/C^2)/d\,V}$$

- B and D-center concentration extracted from MCTS :

$$N_T = \frac{\delta C_{max}}{C_0}\frac{2r^{r/(r-1)}}{1-r}N_{TOT}$$

- Difference in the slope of extracted B and D-center depth profile



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Conclusions

- MCTS measurements performed on 4H-SiC Schottky barrier diodes
- Unintentional boron incorporation during CVD growth
  - Two boron-related deep-level defects: **B** and **D-center**
- Estimated boron concentration (MCTS) exceeds the nitrogen doping concentration determined from CV measurements
- Steady-state electrical performance of the 4H-SiC SBD is preserved

Acknowledgment

- This work was supported by the North Atlantic Treaty Organization Science for Peace and Security Program through Project No. G5674.

Thank you for your attention