Fraunhofer IISB

INFLUENCE AND MUTUAL INTERACTION OF PROCESS PARAMETERS ON THE $Z_{1/2}$ DEFECT CONCENTRATION DURING EPITAXY OF 4H-SiC

J. Erlekampf, D. Kaminzky, K. Rosshirt, B. Kallinger, M. Rommel, P. Berwian, J. Friedrich, L. Frey

Fraunhofer Institute for Integrated Systems and Device Technology (IISB), Schottkystrasse 10, 91058 Erlangen, Germany

ICSCRM 2017 International Conference on Silicon Carbide and Related Materials, Washington, DC | September 17–22, 2017

Motivation

Bipolar 4H-SiC devices for high blocking voltages (> 10 kV) are gaining in importance

- Efficient carrier injection and conductivity modulation require high charge carrier lifetimes
- Carrier lifetimes currently limited by Shockley-Read-Hall (SRH) recombination at point defects ($Z_{1/2}$, $EH_{6/7}$)
- Carbon vacancies (V_C) found as origin of $Z_{1/2}$ and $EH_{6/7}$ [1]
- Epitaxial growth of 4H-SiC layer determines the as-grown $Z_{1/2}$ concentration [2, 3]

Aim of this work

- Comprehensive analysis of the influence of epitaxial growth parameters on $Z_{1/2}$ defect concentration and minority carrier lifetime τ_{eff}
- Comparison of experimental data to thermodynamic models of point defect generation (entropy ΔS, formation enthalpy ΔH_F) during epitaxial growth
- Revealing the relationship between minority carrier lifetime τ_{eff} and $Z_{1/2}$ concentration

Experimental details

Epitaxial 4H-SiC layers grown by CVD in an Epigress VP508 reactor [4]

- 25x commercial 3" 4H-SiC substrates
- Constant growth conditions: 11 µm thick, R_{growth}: 15 µm/h, N_D: $5\cdot10^{14}$ – $1\cdot10^{15}$ cm^{-3}
- Varied growth conditions: T_{growth}: 1575°C – 1650°C, C/Si ratio: 0.9 – 1.9

Minority carrier lifetime by microwave detected photoconductivity decay method (µ-PCD)

- Effective minority carrier lifetime τ_{eff} on full wafer area (5 mm edge exclusion, 250 µm raster)
- Extraction of τ_{eff} at DLTS location from µ-PCD mapping

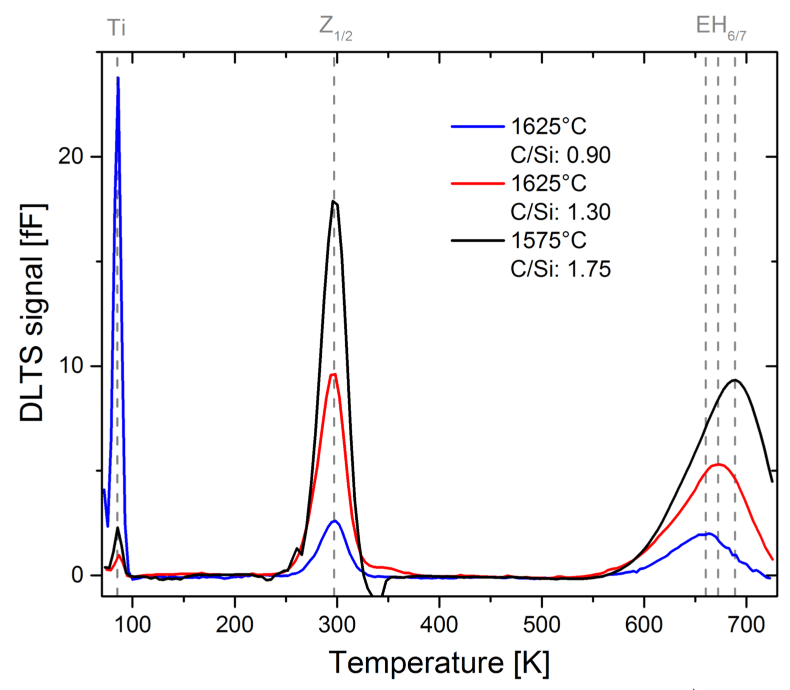
Point defect characterization by deep level transient spectroscopy (DLTS)

- DLTS samples with 10x10 mm² were cut out from wafer center
- Front side contact: Ni Schottky contact, 1 mm in diameter
- Back side contact: all-over ohmic Ni contact
- High accuracy measurement through different time windows (64, 128, 256, 512 ms) and pulse voltages (-0.2, -0.5, -0.8 V) at blocking voltage of -5 V

Influence of epitaxial parameters

Results of DLTS measurements

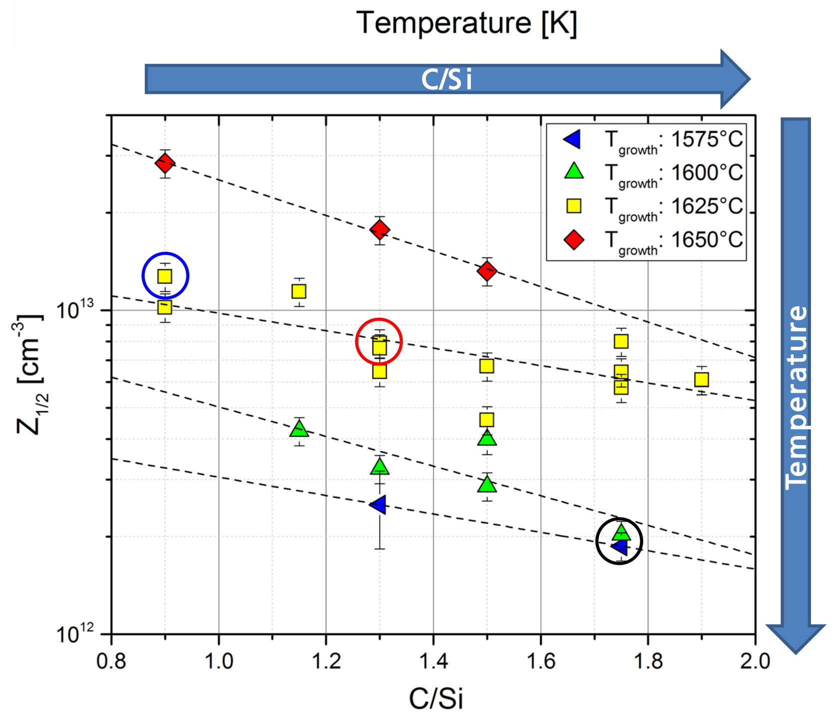
- No other point defects besides Ti (E_C-0.18 eV), $Z_{1/2}$ (E_C-0.66 eV), and $EH_{6/7}$ (E_C-1.5 eV) found
- DLTS reveals presence of $Z_{1/2}$ and $EH_{6/7}$ with constant ratio of $[Z_{1/2}]$:$[EH_{6/7}]$ = 2:1
- Peak height of $Z_{1/2}$ and $EH_{6/7}$ reduced with lower T_{growth} and higher C/Si ratio
- **Focusing on $Z_{1/2}$ as the lifetime-limiting defect**



Comparison of DLTS results to growth conditions

- Exponential decrease of $[Z_{1/2}]$ with increasing C/Si
- Increasing $[Z_{1/2}]$ with increasing growth temperature
- **Minimum $[Z_{1/2}]$ of $1.9\cdot10^{12}$ cm^{-3} (same range as comparable literature data [2, 5]) after epitaxial growth achieved**

µ-PCD mappings and mean τ_{eff} of blue, red, black circular marked points found below

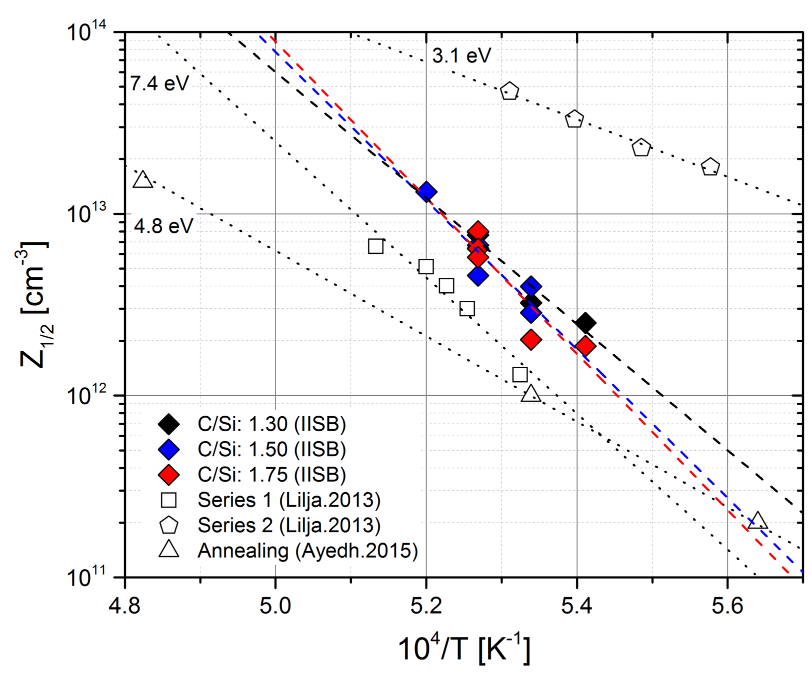


Thermodynamic consideration

Arrhenius plots of annealing and epitaxy experiments

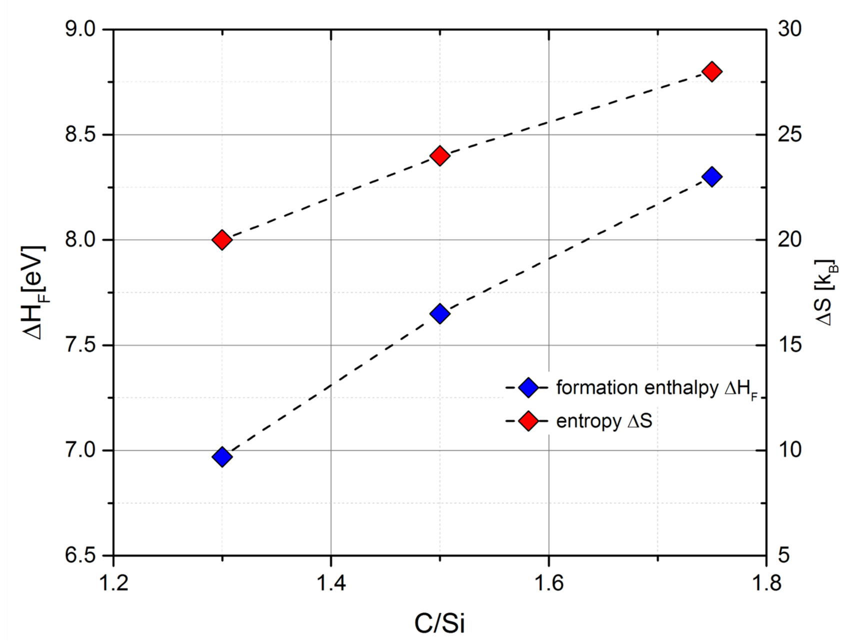
$$[Z_{1/2}] = N_C \cdot exp\left(\frac{\Delta S}{k_B}\right) \cdot \exp\left(-\frac{\Delta H_F}{k_B \cdot T}\right)$$

- Large differences of ΔH_F and ΔS found by comparing different thermal processes [2, 6]
- ΔH_F and ΔS during epitaxy seem significantly higher than during annealing [6]
- **ΔH_F and ΔS specific for each thermal process**

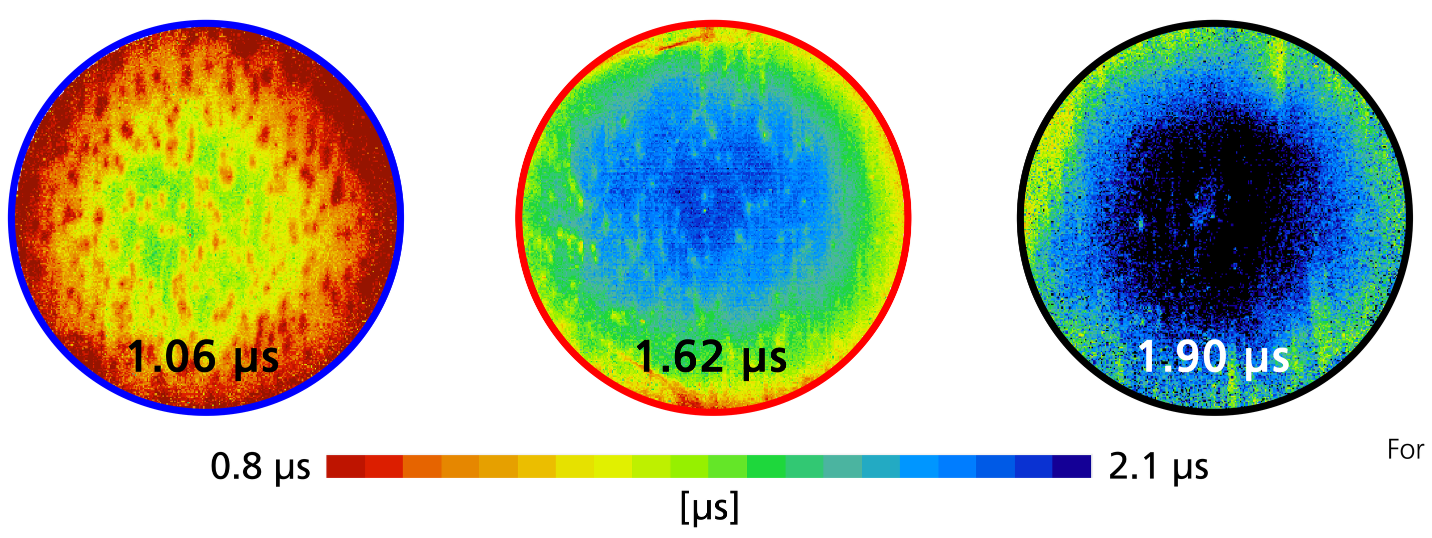


Formation of $Z_{1/2}$ over C/Si

- Increasing formation enthalpy ΔH_F and entropy ΔS found with increasing C/Si ratio
- **ΔH_F and ΔS depend on epitaxial growth parameters**
- **Change of chemical potential by surrounding crystal lattice properties, e.g. deviation from stoichiometry?**



Correlation between $Z_{1/2}$ and τ_{eff}



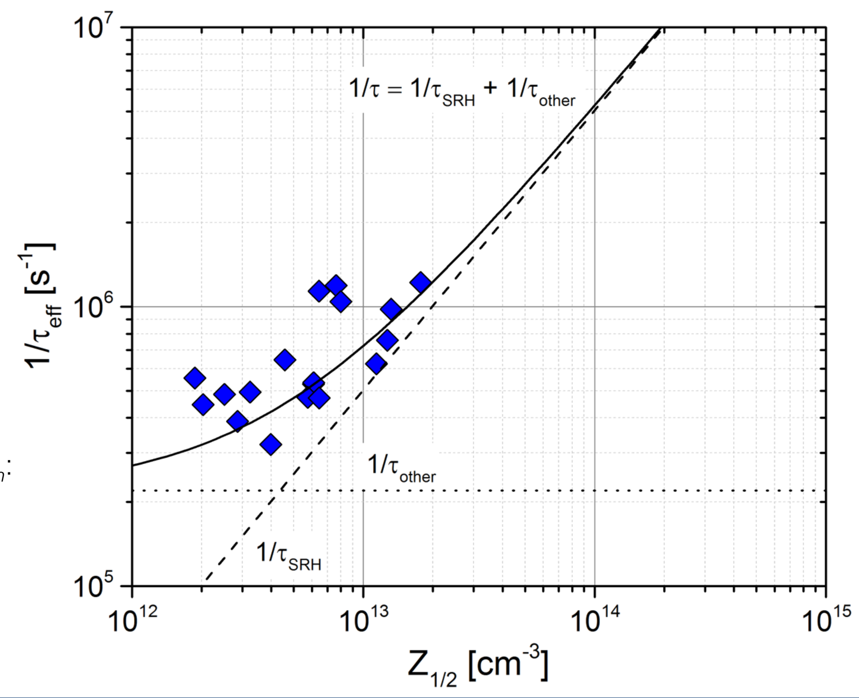
- Radially symmetric lifetime distribution following doping / thickness profiles
- **Minority carrier lifetime (τ_{eff}) increased from 1.06 to 1.90 µs**

For calculation of τ_p and τ_n:

$$\tau_{p/n} = \frac{1}{\sigma_{p/n} v_{th} N_T}$$

$\sigma_p = 3.5\cdot10^{-14}$ cm² [7]

$\sigma_n = 3.0\cdot10^{-15}$ cm²



Relationship between $1/\tau_{eff}$ and $Z_{1/2}$ modeled

$$\tau_{SRH} = \frac{\tau_p(n_0 + n_1 + \Delta n) + \tau_n(p_0 + p_1 + \Delta p)}{p_0 + n_0 + \Delta n}$$

$$\tau_{other} = 4.5\ \mu s$$

- **τ_{eff} of some samples limited by different surface recombination velocities**
- **At lower $[Z_{1/2}]$ another recombination mechanism (τ_{other}) dominates over SRH**

Conclusions

- Variation of $[Z_{1/2}]$ between $3.0\cdot10^{13}$ cm^{-3} and $1.9\cdot10^{12}$ cm^{-3} and increase of τ_{eff} achieved by adjusting the growth parameters (temperature and C/Si ratio).
- ΔH_F and ΔS of $Z_{1/2}$ strongly depend on the specific thermal process and the epitaxial growth parameters.
- Second dominant recombination mechanism (τ_{other}) beside SRH found under $[Z_{1/2}]$ of $4.5\cdot10^{12}$ cm^{-3}

References

[1] N. T. Son, X. T. Trinh, L. S. Løvlie et al., Phys. Rev. Lett. 109, 187603 (2012).
[2] L. Lilja, I. D. Booker, J. Hassan et al., J. Cryst. Growth 381, 43–50 (2013).
[3] I. Pintilie, L. Pintilie, K. Irmscher et al., Appl. Phys. Lett. 81, 4841 (2002).
[4] B. Kallinger, P. Berwian, J. Friedrich et al., J. Cryst. Growth 381, 127-133 (2013).
[5] T. Kimoto, K. Danno, J. Suda, phys. stat. sol. (b) 245, 1327–1336 (2008).
[6] H. M. Ayedh, V. Bobal, R. Nipoti et al., J. Appl. Phys. 115, 012005 (2014).
[7] P. B. Klein, B. V. Shanabrook, S. W. Huh et al., Appl. Phys. Letters 88, 052110 (2006).