Defects and carrier lifetime in 4H-Silicon Carbide

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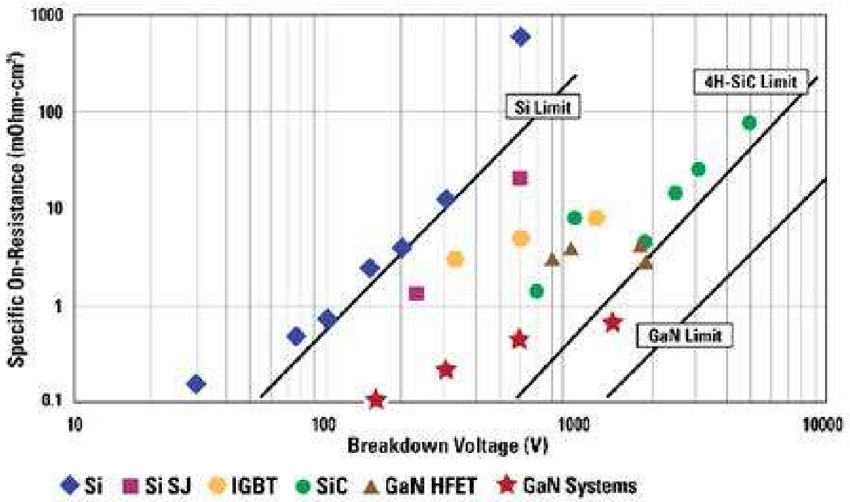
Advantages of SiC power electronics

Shifting device limitations

- Wide band gap (3x Si)
  - Intrinsic carrier conc. (10^{-8} cm^{-3} @ RT)
- Large breakdown field (10x Si)
  - Thinner drift regions
- Saturated drift velocity (2x Si)
- High thermal conductivity (3x Si)
  - Less cooling needed
  - Smaller and lighter systems possible

SiC material properties



$$R_{on} = \frac{4 \cdot (U_{BD})^2}{\varepsilon \cdot \mu \cdot (E_{crit})^3}$$

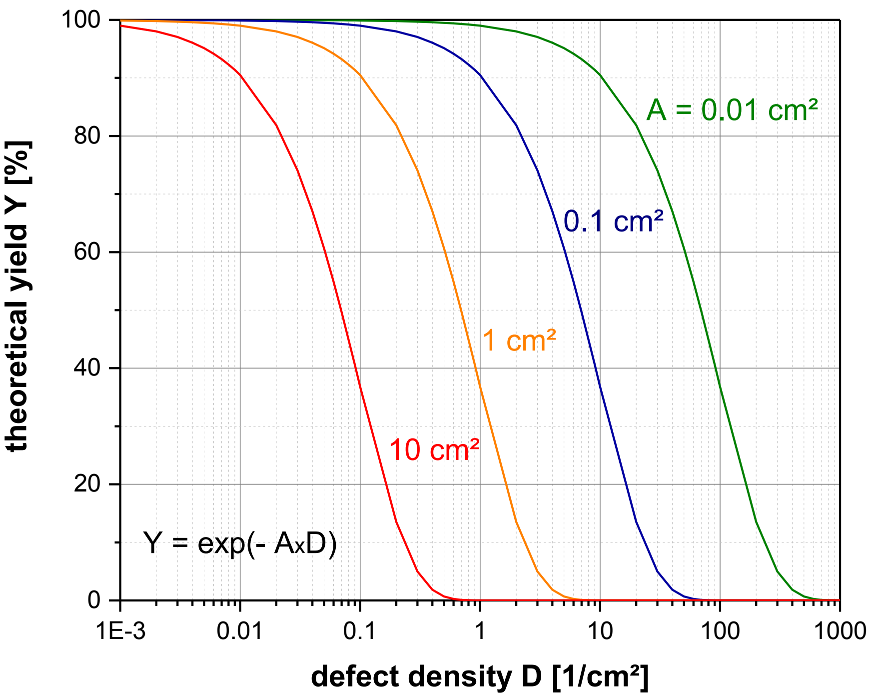
Graph: N. Ikeda et al., ISPSD 2008, p.289ff
Equation: B. J. Baliga, IEEE Electron Device Letters 10 (1989) 455-457.

Defects limit the device production yield

Large area devices

- Material quality crucial for
  - Device production yield / wafer
  - Performance and reliability of devices
- Control and uniformity regarding:
  - Thickness, doping concentration
  - Defect density
  - Carrier lifetime
- Large current → large area devices

SiC material properties



Simple yield model after Poisson

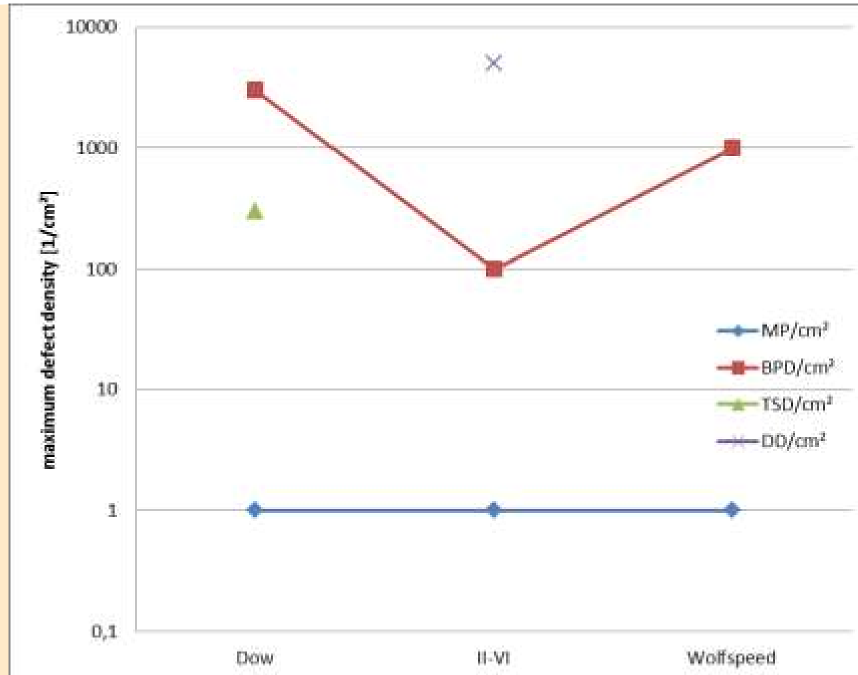
State of the art in 4H-SiC materials

Substrates

- Several suppliers worldwide
- Large diameter
  - 100 mm: from 2007 to 2018
  - 150 mm: industrial standard
  - 200 mm: demonstrated

- "Free" of micropipes (< 1 MP/cm²)
- Dislocation density decreasing
  - BPD < 3.000 /cm²
  - TD < 20.000 /cm²

substrate quality and supply



Graph: based on data from suppliers' homepages, September 2018

State of the art in 4H-SiC materials

Epitaxial wafers (epiwafers)

- Chemical vapor deposition process (CVD)
  - Temperature ~ 1600°C
  - Silane / Trichlorosilane and propane
- AIXTRON reactors at Fraunhofer IISB
  - R & D reactor VP508 (1 x 100 mm)
  - Production reactors G5WW (8 x 150 mm)
- Wafer diameters
  - 100 mm: still present in R & D
  - 150 mm: industrial standard

Homoepitaxial growth on vicinal substrates

Aixtron G5 – planetary reactor


R & D reactor - VP508GFR

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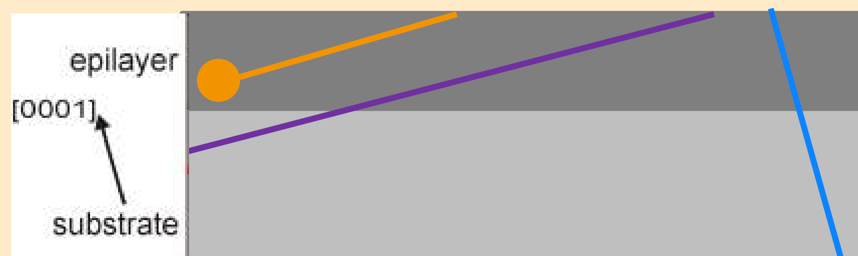
State of the art in 4H-SiC materials

Extended defects in epiwafers

- Dislocations from substrate propagate
  - BPDs convert to TEDs (> 95 %)
  - TEDs, TSDs propagate

  → Dislocation density constant

- Stacking faults in epilayers
  - Propagate from substrate
  - Originate from BPDs, TSDs
  - Originate at downfalls



Epiwafer quality

Downfall

BPD or bar-shaped SF

TSD

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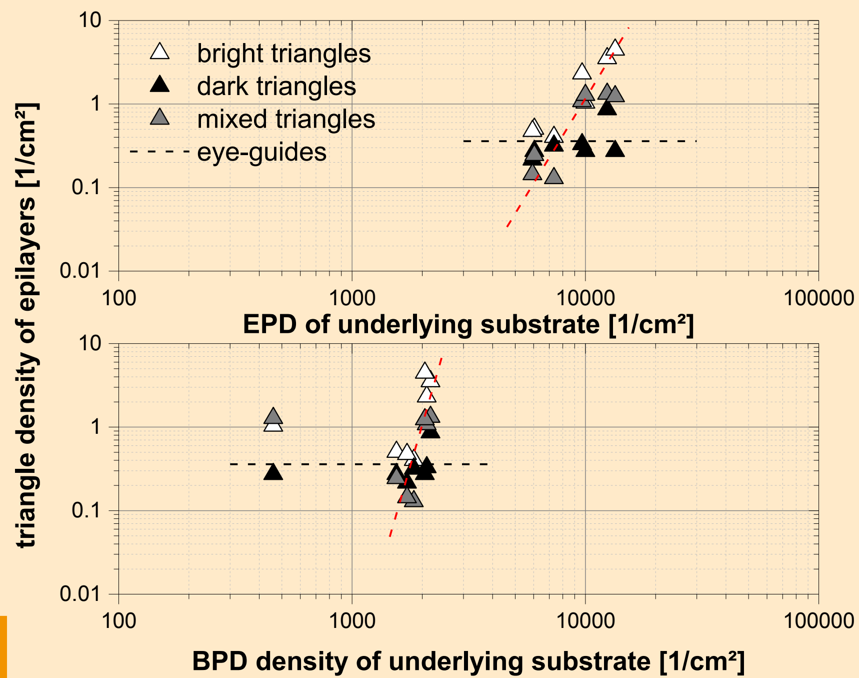
Extended defects in epiwafers
Origins of stacking faults (triangular defects)

- **EPD, BPD densities of substrates**
  - KOH etching of reference wafers
  - Interpolation for substrates used in this study
- **Defect densities of epilayers**
  - By UVPL imaging (Intego)
  - Dark triangles originate mainly at particles → epidefect
  - Bright and mixed triangles at dislocations[1] → substrate

Origin of epilayer defects



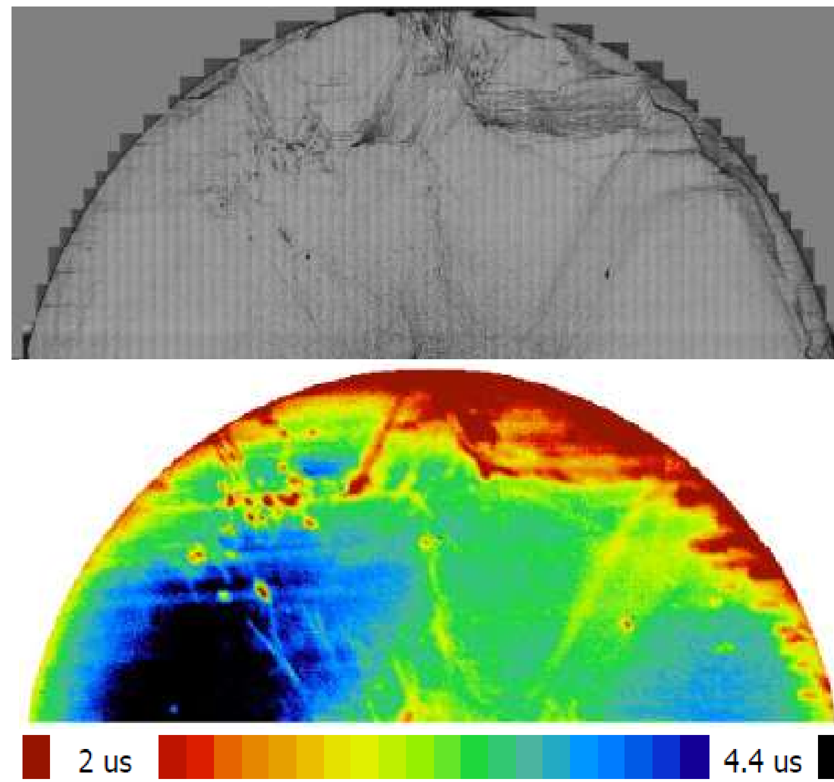
B. Kallinger et al., presented at ECSCRM 2018 in Birmingham
1 T. Okada et al., Mat. Sci Eng. A 361 (2003) p. 67-74.

Extended defects in epiwafers

Impact on minority carrier lifetime

- Extended defects present in epilayers:
  - By defect selective etching (KOH melt)
  - Dislocations: BPDs, TEDs, TSDs
  - Stacking faults
  - Downfalls, in-grown particles
- Minority carrier lifetime:
  - By µ-PCD method
  - Effective lifetime (surface, epilayer, substrate)
  - Lifetime locally reduced by defects

Dislocations limit the carrier lifetime



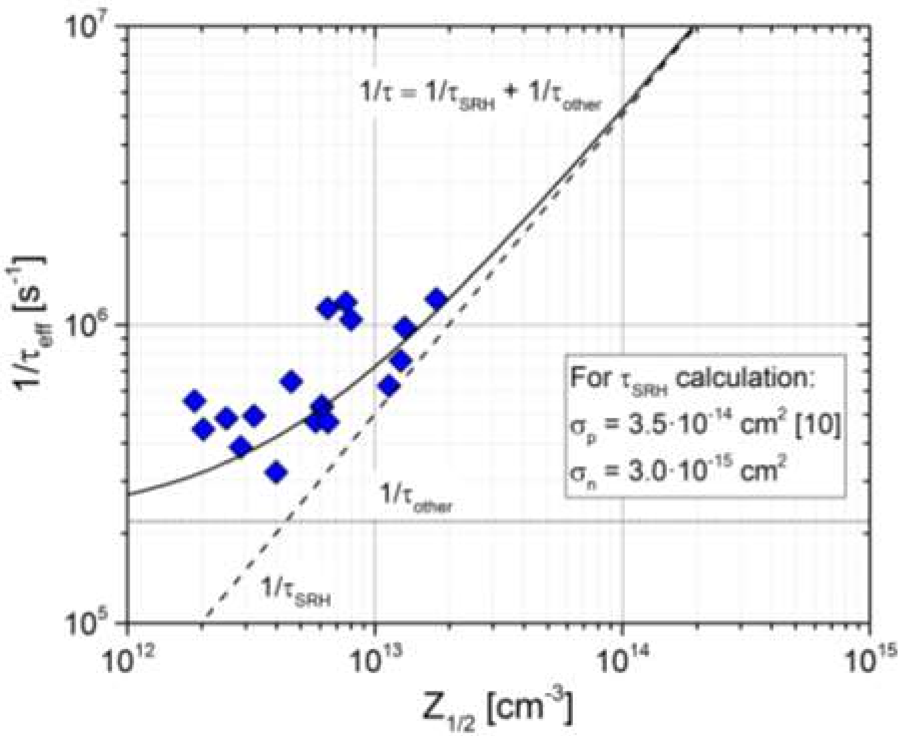
B. Kallinger et al., Materials Science Forum 740-742 (2013) p. 633-636.

Point defects in epilayers

Relation between [$Z_{1/2}$] and effective lifetime

- Effective minority carrier lifetime:
  - Shockley-Read-Hall lifetime, i.e. [$Z_{1/2}$]
  - Other effect, probably surface recombination
- Shockley-Read-Hall (SRH) lifetime in n-type SiC:
  - $EH_{6/7}$: minor player
  - **$Z_{1/2}$: lifetime killer**
  - Ti peak: minor player

Lifetime limited by SRH / [$Z_{1/2}$]



J. Erlekampf et al., Materials Science Forum 924 (2018).
[10] P. B. Klein et al., Appl. Phys. Lett. 88 (2006) 052110.

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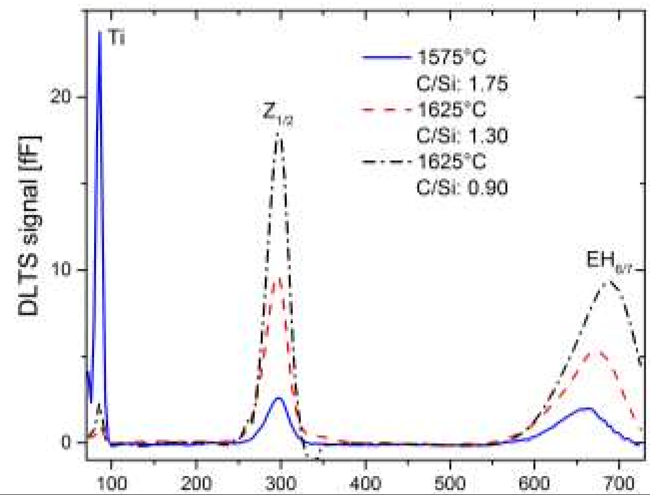
Point defects in epilayers

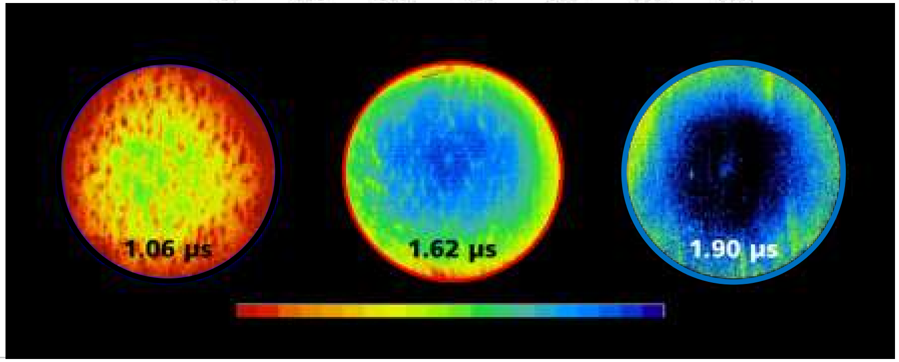
Impact of temperature and C/Si ratio on $[Z_{1/2}]$

- Point defects in epilayers:
  - By deep level transient spectroscopy
  - $Z_{1/2}$, $EH_{6/7}$: related to V_C
  - Ti peak
  - No other defects (upper half of E_G)

- Minority carrier lifetime:
  - Lifetime decreases with increasing $[Z_{1/2}]$
  - Lifetime locally reduced by defects

DLTS and µ-PCD on epilayers





J. Erlekampf et al., Materials Science Forum 924 (2018).

Point defects in epilayers

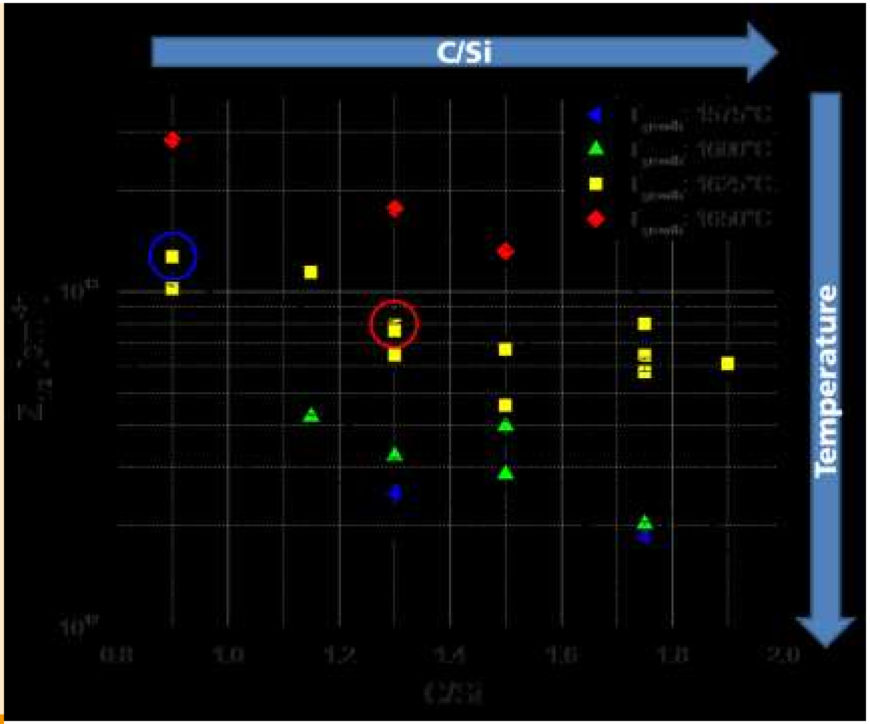
Impact of temperature and C/Si ratio on [$Z_{1/2}$]

- Reduction of [$Z_{1/2}$] by:
  - Large C/Si ratio → C rich
  - Low growth temperature

  → $Z_{1/2}$ is signature of carbon vacancy

- Minimum [$Z_{1/2}$] of 1.9 x 10^{12} cm^{-3}
  - Comparable to literature data[2,3] for epitaxial growth

Growth on 3“ substrates in R&D reactor



J. Erlekampf et al., Materials Science Forum 924 (2018).
2 L. Lilja et al., Journal of Crystal Growth 381 (2013) 43-50.
3 T. Kimoto, K. Danno, J. Suda, Phys. Stat. Sol. (B) 245, 1327–1336 (2008).

Point defects in epilayers

Control and uniformity of $[Z_{1/2}]$ in epigrowth

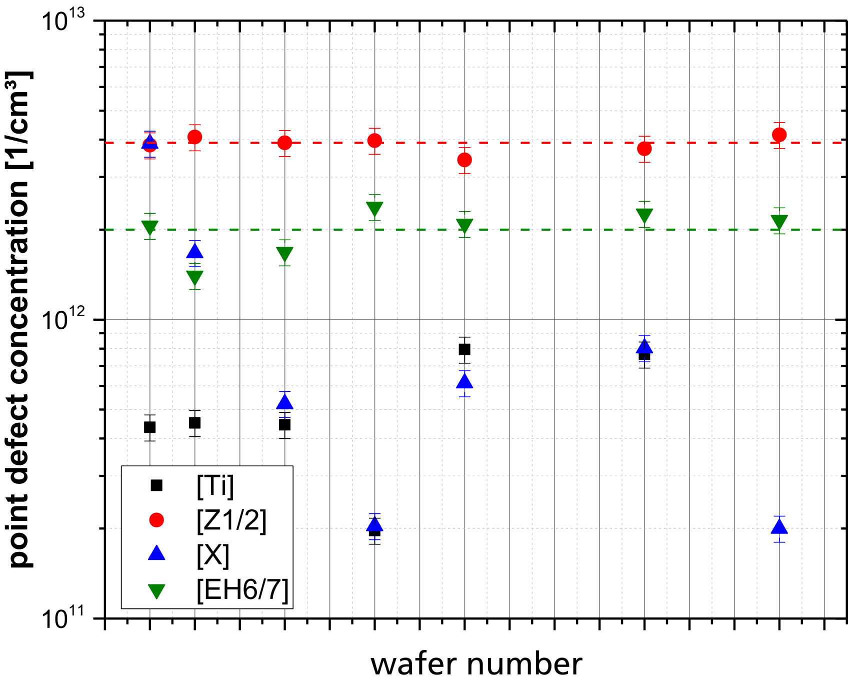
- Multi-wafer experiment:
  - 16 x 100 mm substrates (2 runs)
  - C/Si ratio and growth temperature kept constant
  - $[Z_{1/2}] = 3.9 \times 10^{12}$ cm^{-3} ± 10 %
  - $[EH_{6/7}] = 2.0 \times 10^{12}$ cm^{-3} ± 20 %

  → $C(Z_{1/2}):C(EH_{6/7}) \approx 2:1$[2]

  → Controllable by epigrowth conditions

- Expected SRH-lifetime[3] for $Z_{1/2}$ ~ 7 µs (with $\Delta p = 2 \times 10^{-14}$ cm^{-2}; $\Delta n = 3 \times 10^{16}$ cm^{-3})

Growth on 100 mm substrates in G5WW reactor (8 x 150 mm)



B. Kallinger et al., presented at ECSCRM 2018, Birmingham.

2 $Z_{1/2}$ has 2 electron transitions, 1 electron transition at $EH_{6/7}$

3 Dieter K. Schroder, Semiconductor Material and Device Characterization, 3rd edition, Wiley, 2006.

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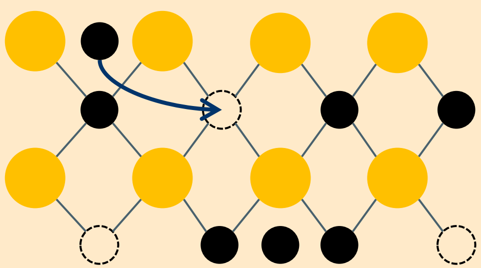
Reduction of carbon vacancies (V_C)

Main principles for V_C elimination

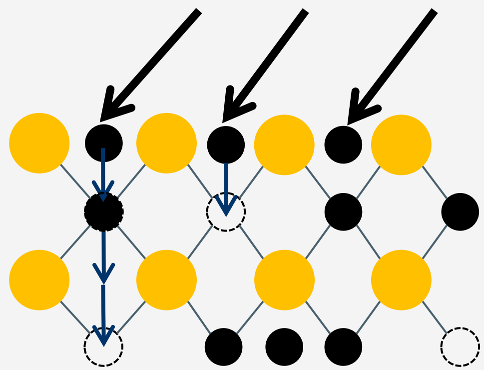
Annealing



Frenkel pairs: V_C and C_i

- Annihilation or generation
- Thermal process

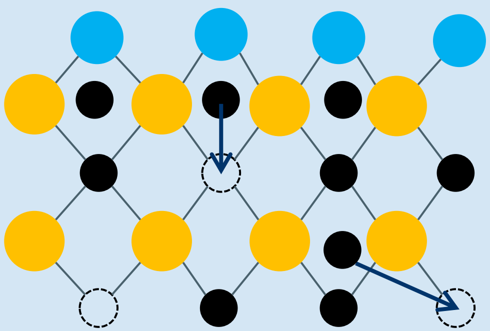
C^+ Implantation



Excess C_i by C implantation & subsequent annealing

- $[C_i]$ peak close to surface
- Diffusion of C_i

Oxidation



Excess C_i by oxidation (& annealing)

- $[C_i]$ peak close to surface
- Diffusion of C_i

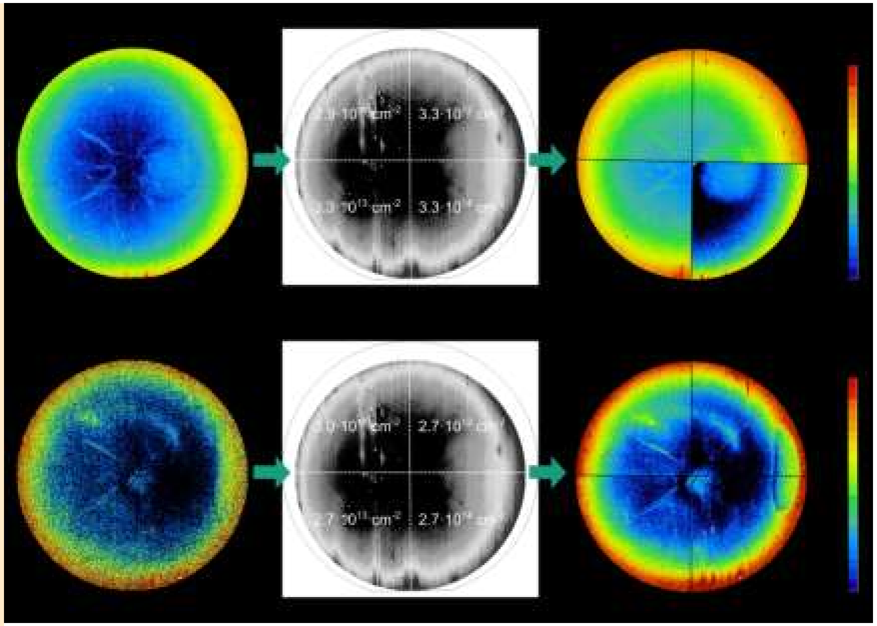
Reduction of carbon vacancies (V_C)

By Ion Implantion

- Ion implantation study on epiwafers
  - 65 µm thick, n = 1 x 10^{15} cm^{-3}
- Implantation of box profiles
  - N, Al, C, B, As
  - Conc.: 1 x 10^{16} to 1x 10^{20} cm^{-3}
  - Depth: 300 nm
  - Annealing (Ar, 1700°C, 30 min)
  - Removal of implanted layer (500 nm)

→ Lifetime changes

Lifetime engineering



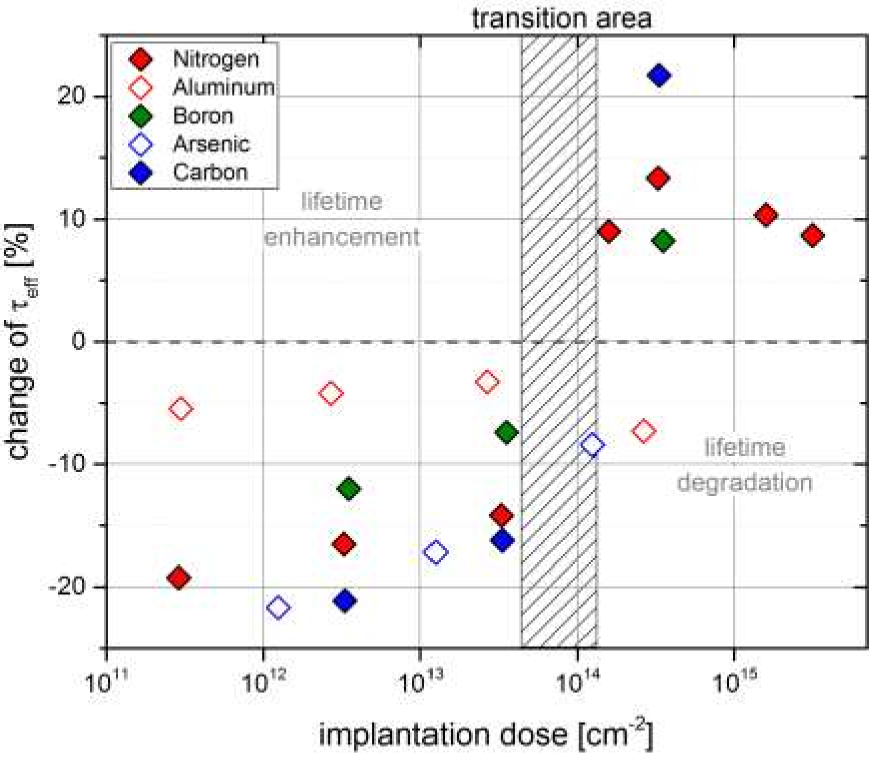
J. Erlekampf et al., presented at ECSCRM 2018, Birmingham.

Reduction of carbon vacancies (V_C)

By Ion Implantion

- Impact of concentration
  - Lifetime decreases for implantation doses < 10^{14} cm^{-2}
  - Lifetime enhanced for doses > 10^{14} cm^{-2}
- Impact of implanted element
  - Lifetime increases with N, C, B
  - Lifetime degrades with Al, As
  - → Incorporation on C lattice site

Lifetime engineering



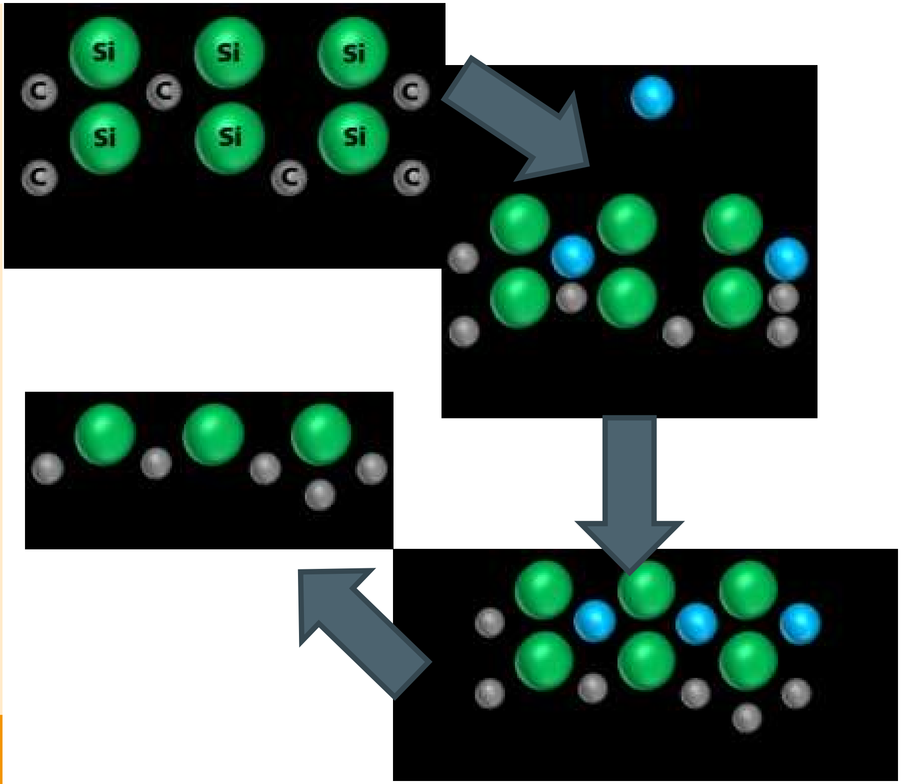
J. Erlekampf et al., presented at ECSCRM 2018, Birmingham.

Reduction of carbon vacancies (V_C)

By Ion Implantion

- Explanatory model:
  - Carbon vacancies present in as-grown epilayers
  - Implantation of N, C, B replaces C host atoms
  - Generation of excess C (interstitials)
  - Annihilation of C interstitials and vacancies
  - Effect remains even after annealing / RIE

Lifetime engineering



J. Erlekampf et al., presented at ECSCRM 2018, Birmingham.

Defects and carrier lifetime in 4H-SiC

Reasonable material quality available

- Dislocations propagate from substrate to epilayer
- Stacking faults can either originate in the substrate or originate during epigrowth
- Defect densities acceptable for device production

Defects and carrier lifetime

- Extended defects limit the (effective) carrier lifetime locally
- Point defects limit the SRH-lifetime, especially $Z_{1/2}$
- $[Z_{1/2}] < 4 \times 10^{12}$ cm^{-3} in as-grown epilayers corresponds to > 7 µs SRH-lifetime
- Further reduction of $Z_{1/2}$ by post-epi processes possible, e.g. by ion implantation

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THANK YOU FOR YOUR ATTENTION!

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