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Reduction of Forward Bias Degradation in 4H-SiC PiN Diodes Fabricated on 4H-SiC Bonded Substrates

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Outline

- **Introduction**
  - What is a 4H-SiC bonded substrate?
  - Forward bias degradation in 4H-SiC bipolar devices

- **Experimental**
  - PiN diode employed in this study
  - Experimental procedure

- **Results and Discussion**
  - Forward current stress test for both bonded and conventional bulk substrates
  - Photoluminescence (PL) imaging
  - Investigation of number of the bar-shaped Shockley-type stacking faults (SSFs) after applying high forward current stress

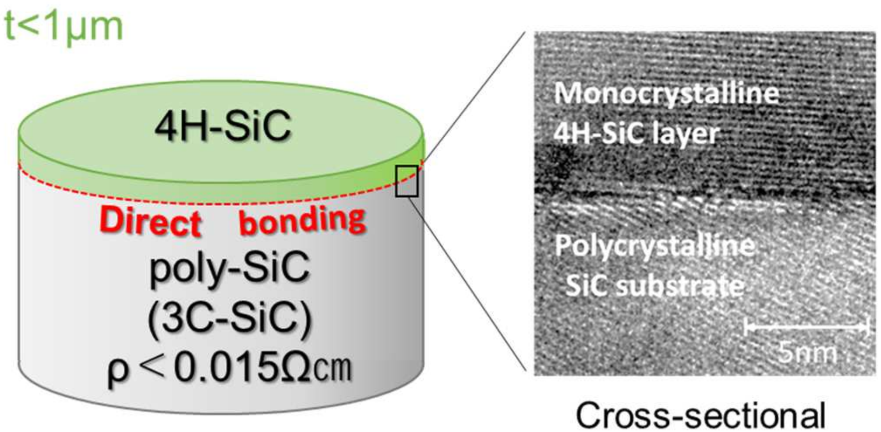
  - Prediction of a mechanism of basal-plane-dislocation(BPD) reduction in 4H-SiC bonded substrates with referring some prior studies.

- **Summary**

What is a 4H-SiC bonded substrate?

■ Structure

- A stacked substrate with two different SiC polytype using direct wafer bonding technologies



Cross-sectional TEM image

4H-SiC bonded substrate (SiCkrest®)

■ Features

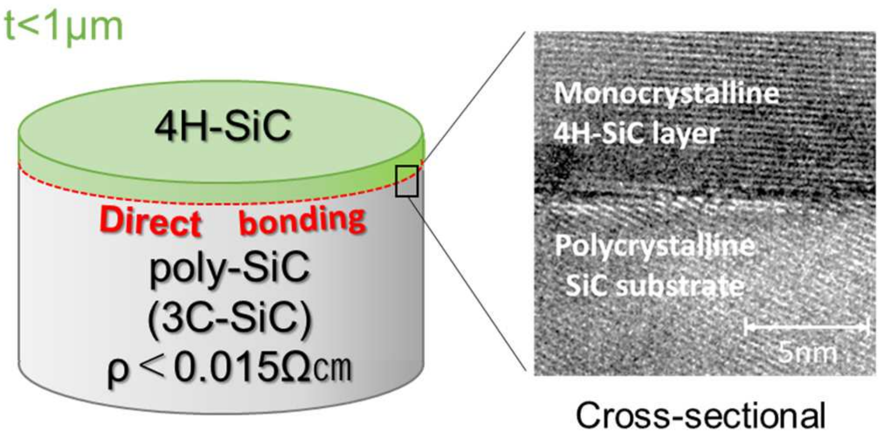
- No unstable interlayer at the bonded interface
  →Enable to apply various high temperature process of SiC

- Extremely thin (the order of submicrons) monocrystalline 4H-SiC layer
  → Minimize the volume of high-quality monocrystalline 4H-SiC portion

What is a 4H-SiC bonded substrate?

■ Benefits in characteristics

- Its unique structure is ***expected to bring some benefits that are not possible with a conventional 4H-SiC bulk substrate***.



Cross-sectional TEM image

4H-SiC bonded substrate (SiCkrest®)

■ Outcomes (Reported in Japan, 2020)

- Reduction of on-state resistance in 4H-SiC PiN diodes
- Backside ohmic contact formation requiring no thermal annealing process

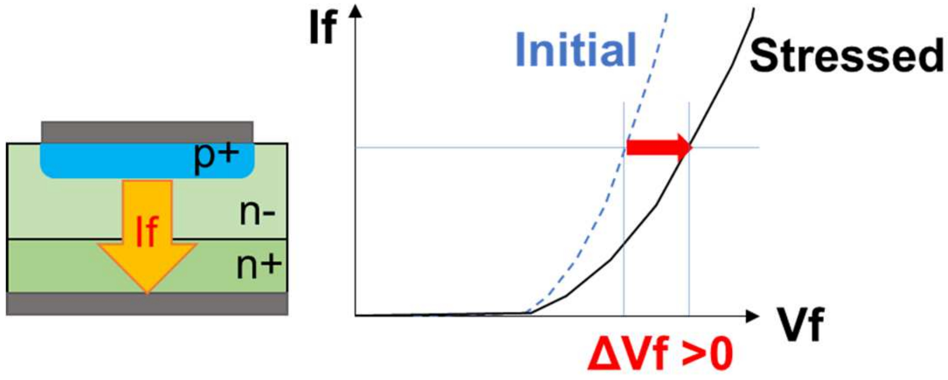
■ Outcomes (Report in Switzerland, 2022)

- ***"Reduction of Forward Bias Degradation in 4H-SiC PiN Diodes" will be demonstrated.***

Forward bias degradation in 4H-SiC bipolar devices

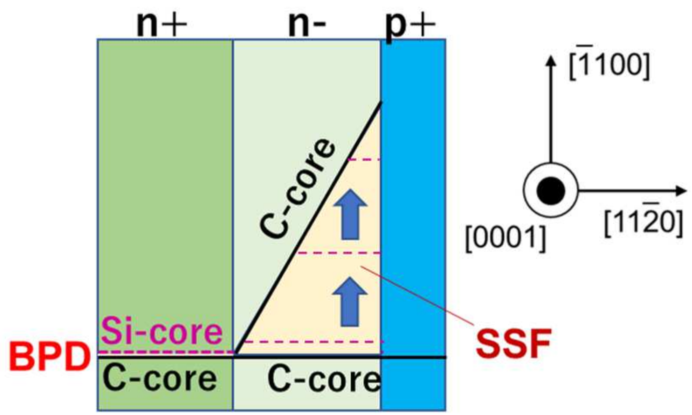
■ **Phenomenon**

- Forward voltage (Vf) increases with
  forward current stress through the pn junction.



■ **Cause**

- Due to the expansion of Shockley-type stacking faults (SSFs) from basal-plane dislocation (BPD) induced by electron-hole pair recombination

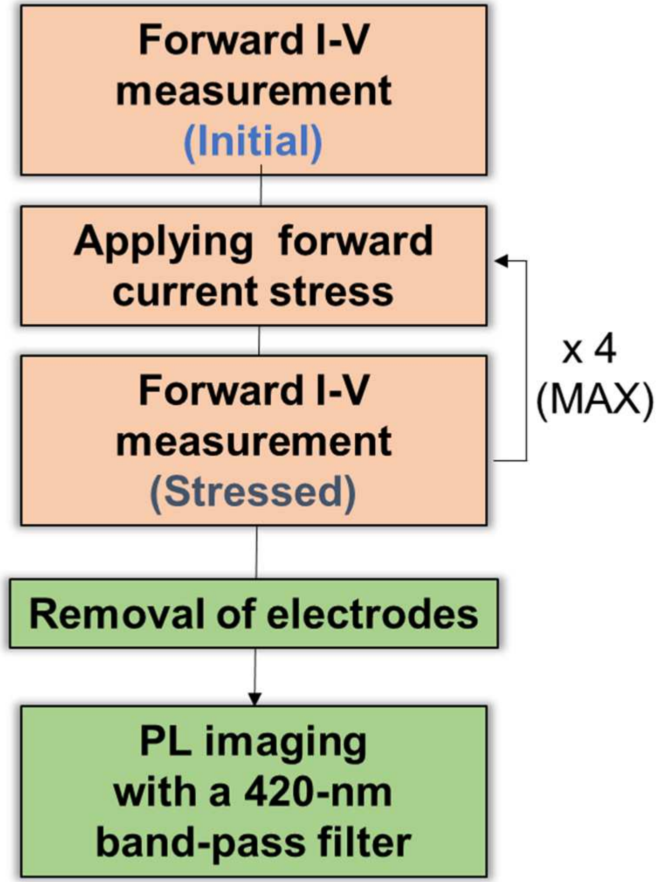


The electrical and optical observations of PiN diodes fabricated on both the substrates were performed.

Experimental
(Experimental procedure)

■ Flow chart

Forward current stress test on PiN diodes



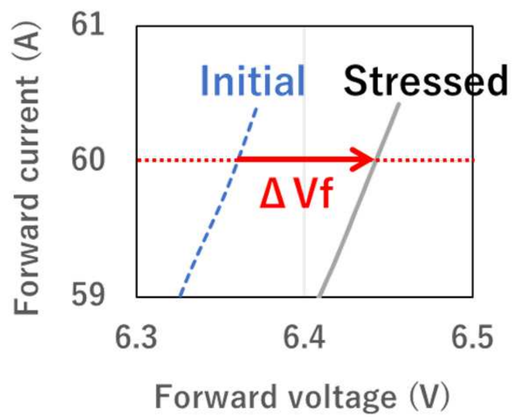
Photoluminescence (PL) imaging

Forward current stress conditions

- Temperature: 175 ℃
- Forward current density:

1st	100 A/cm^2	for 600 sec (DC)
2nd	500 A/cm^2	for 300 sec (Pulsed)
3rd	1000 A/cm^2	for 300 sec (Pulsed)
4th	1500 A/cm^2	for 300 sec (Pulsed)

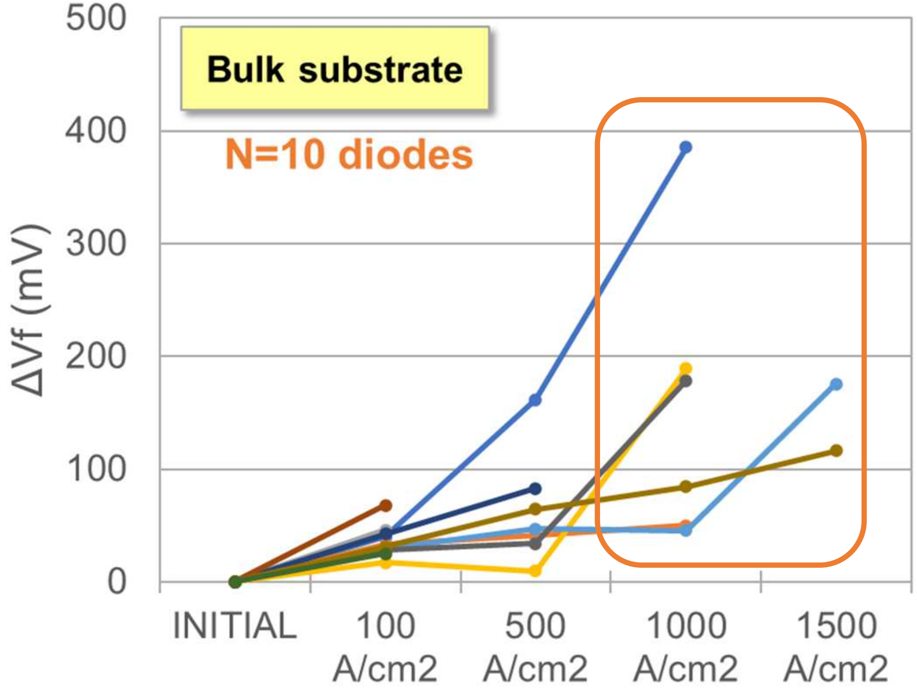
Definition of forward voltage shift (ΔVf)

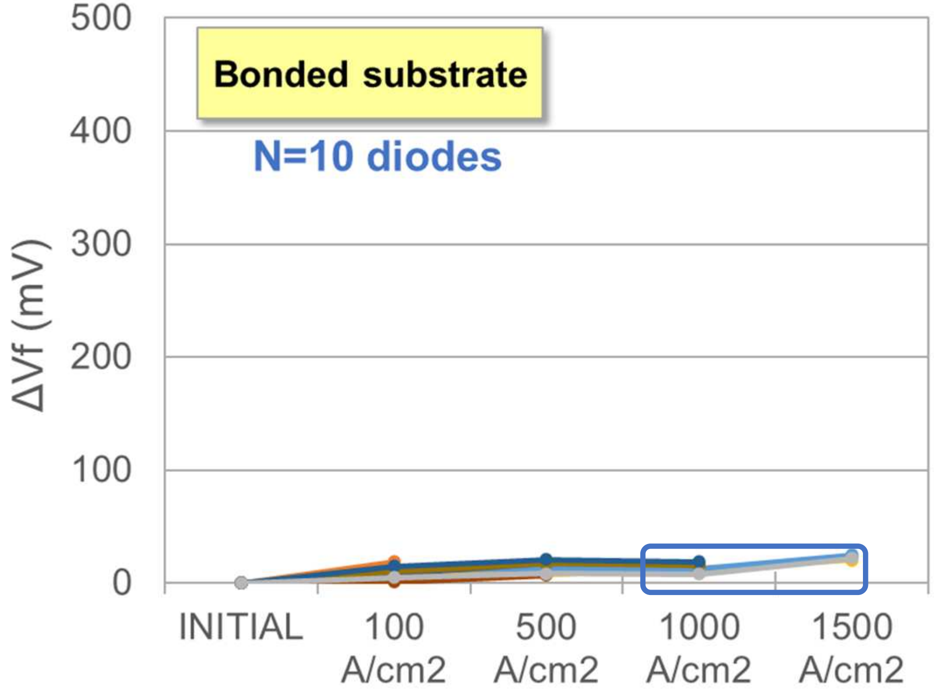


ΔVf：
Forward voltage shift from initial to stressed at the forward current of 60 A

Results and Discussion
(Forward current stress tests and PL imaging)

Changes in the ΔVf caused by forward current stress for both the substrates



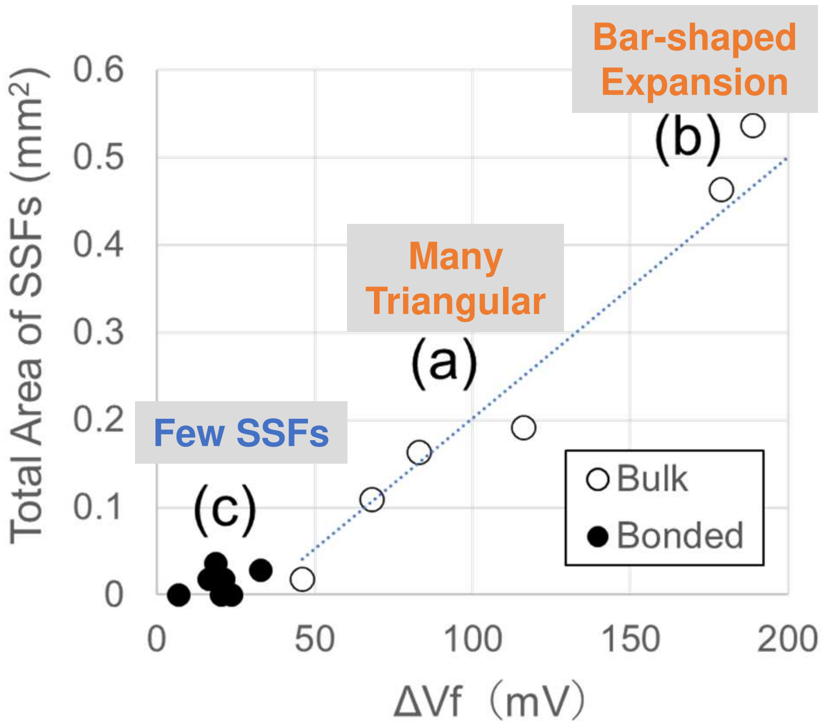


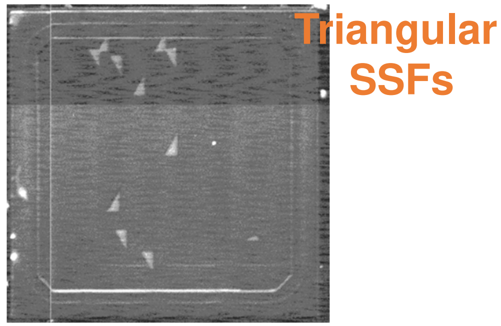
Increasing steeply at 1000 A/cm^2 or more

Remaining low even at 1500 A/cm^2

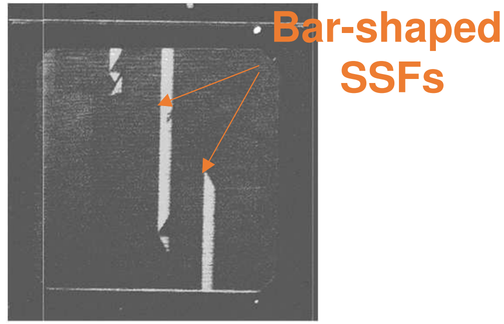
Results and Discussion
(Forward current stress tests and PL imaging)

Plot of correlation between ΔVf and total area of SSFs

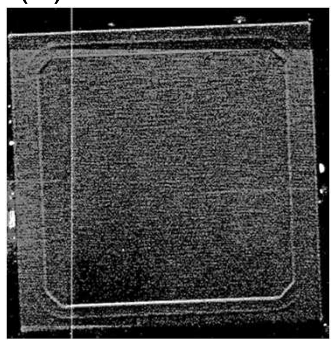




(a) ΔVf=83 mV



(b) ΔVf=178.6 mV

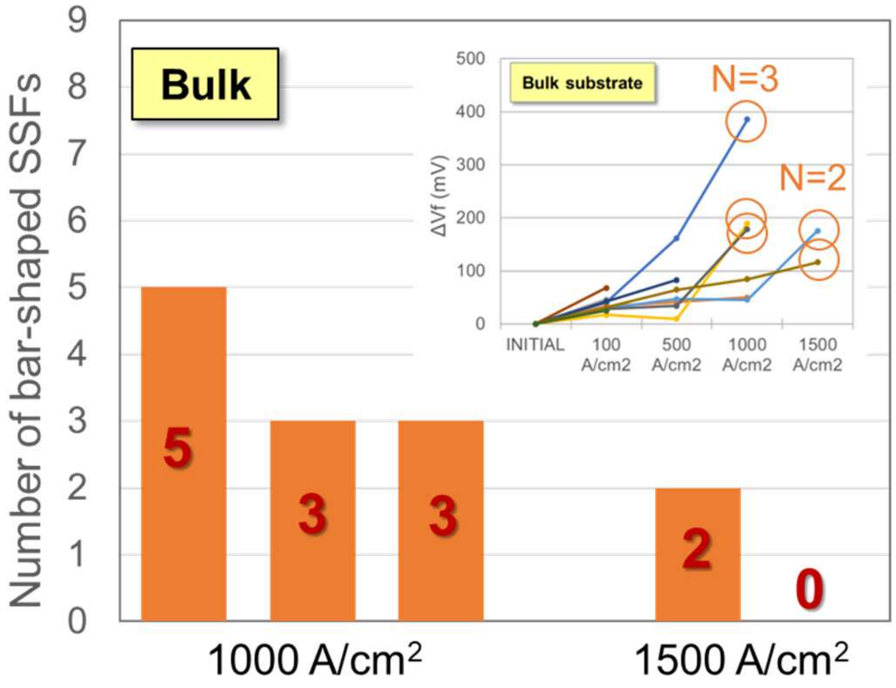


(c) ΔVf=20.1 mV

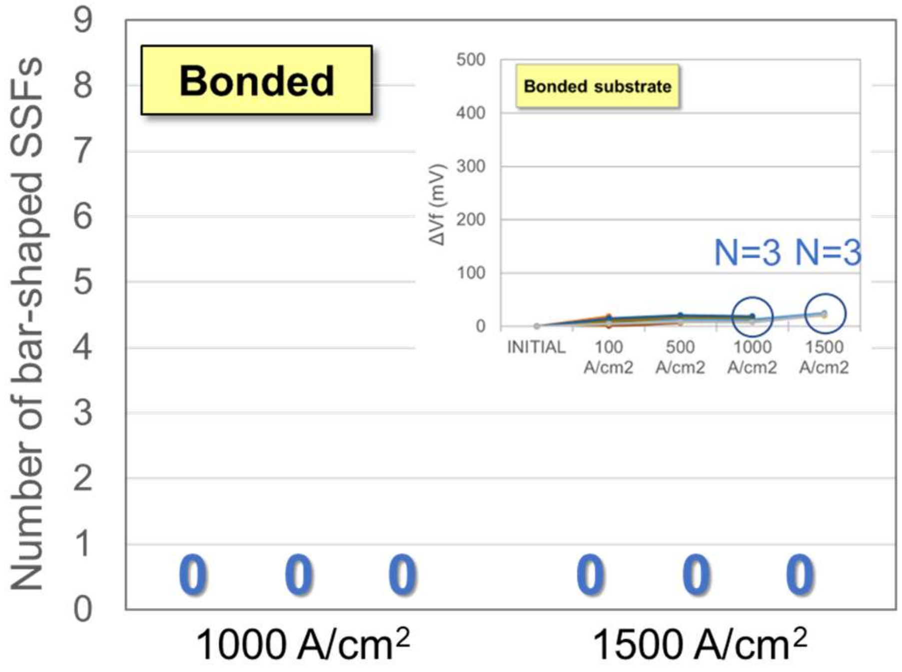
The ΔVf reflects the total area of the expanded SSFs, which depend on the forward current stress in the bulk substrate.

Results and Discussion
(Investigation of number of the bar-shaped SSFs)

Investigation of the number of bar-shaped SSFs within
the electrically stressed diodes with high forward current density



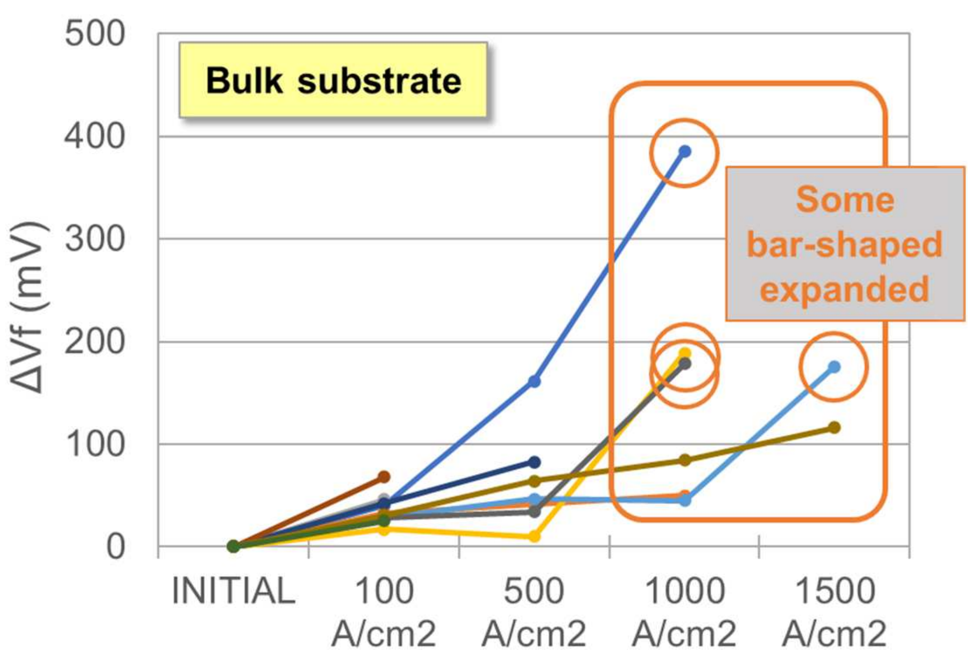
Some bar-shaped SSFs observed from almost all the investigated diodes

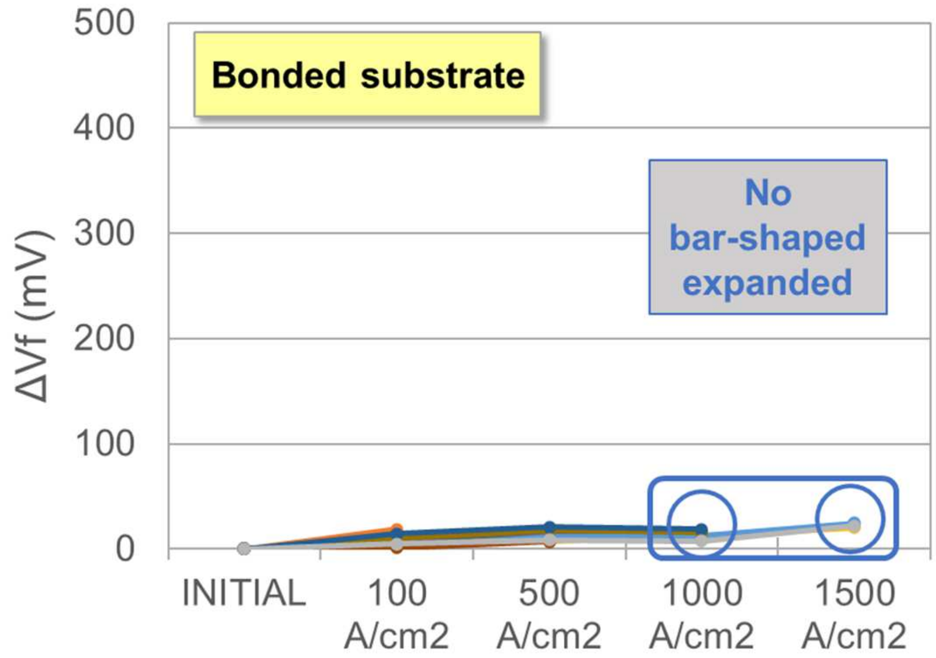


No bar-shaped SSFs observed from all the investigated diodes

Results and Discussion
(Forward current stress tests and PL imaging)

Difference in forward bias degradation for both the substrates



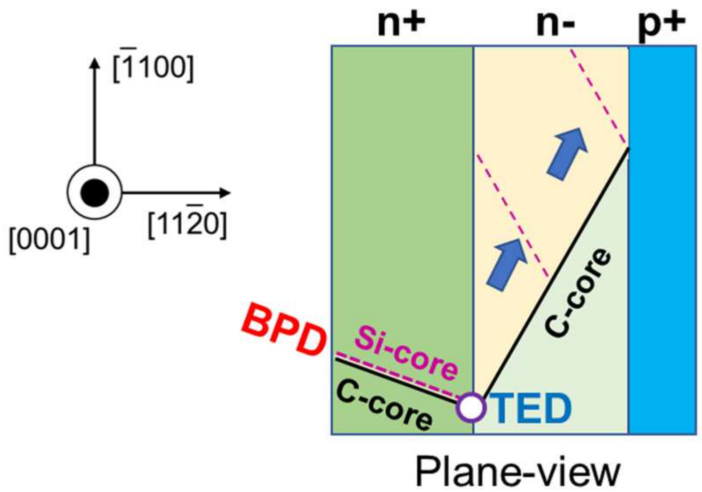


Under high-forward current density (1000 A/cm^2 or more),
- Bulk substrate: **Some bar-shaped SSFs expanded**.
- Bonded substrate: **No bar-shaped SSFs expanded**.

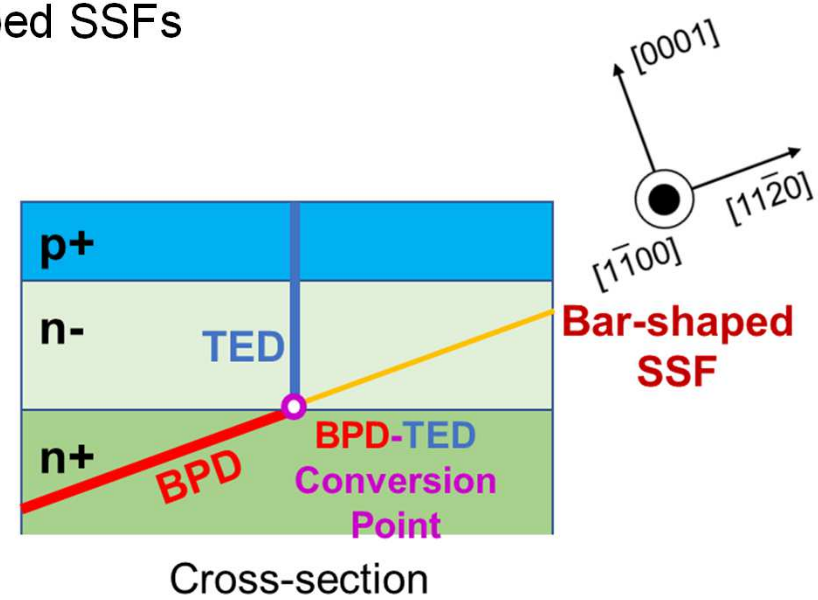
Results and Discussion

(Prediction of a mechanism of BPD reduction in 4H-SiC bonded substrates)

1. Origin of the bar-shaped SSFs



TED: threading edge dislocation



Origin (main): BPDs converted into TEDs in the early stage of epitaxial growth

Under high-forward current density (1000 A/cm^2 or more),

- Bulk substrate: **Some BPDs contributed to bar-shaped SSF expansion.**
- Bonded substrate: **No BPDs contributed to bar-shaped SSF expansion.**

Results and Discussion

(Prediction of a mechanism of BPD reduction in 4H-SiC bonded substrates)

2. Contribution of forward current density

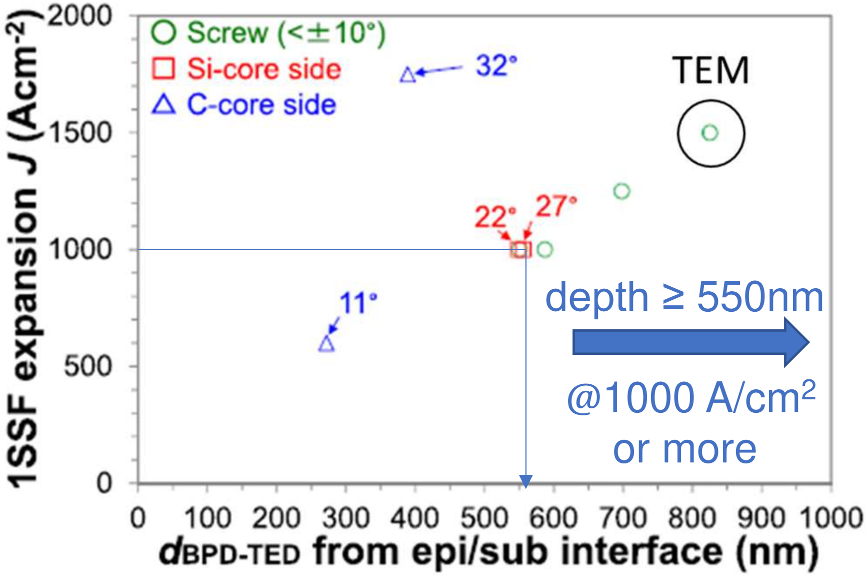
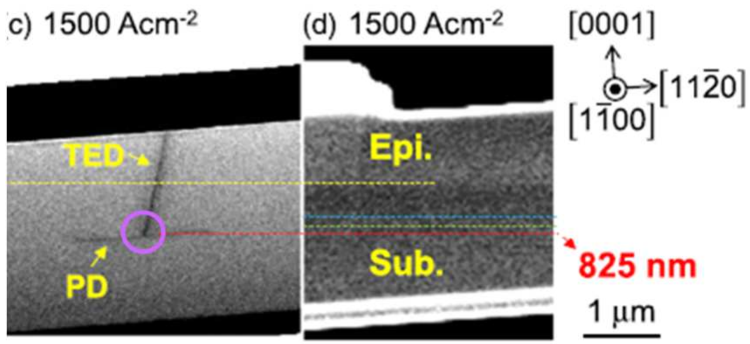


Fig. 4. (Color online) Dependence of the threshold J at which 1SSF expansion occurred at $d_{BPD\text{-}TED}$ from the epi/sub interface.

S. Hayashi et al., Appl. Phys. Express **12**, 051007 (2019)



Notice:
BPD-TED conversion point ◯ is located below the epilayer/substrate interface.

At the submicron depth below the epilayer/substrate interface,

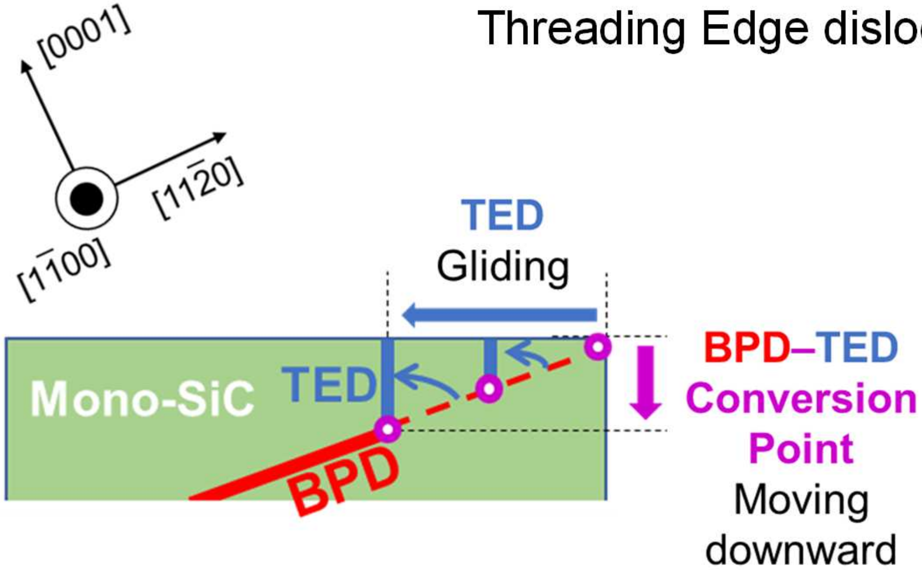
- Bulk substrate: **Some BPDs contributed to bar-shaped SSF expansion.**
- Bonded substrate: **No BPDs contributed to bar-shaped SSF expansion.**

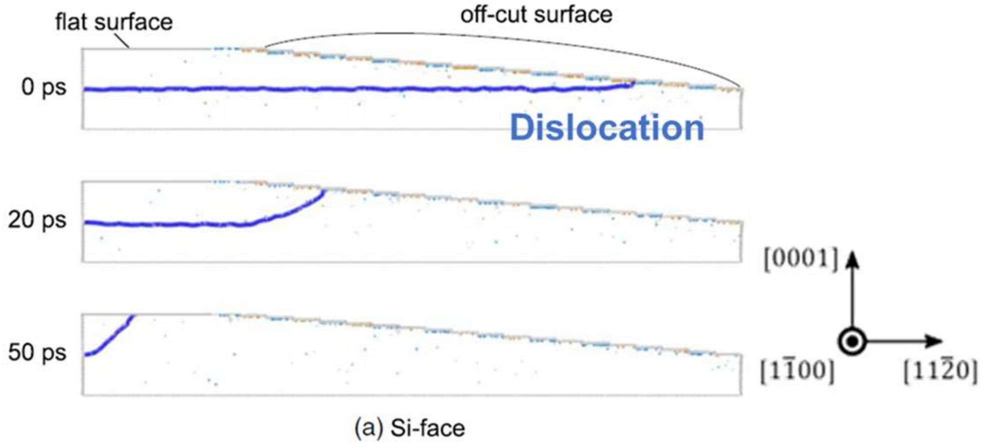
Results and Discussion

(Prediction of a mechanism of BPD reduction in 4H-SiC bonded substrates)

3. The reason that a BPD-TED conversion point can move to below the epilayer/substrate interface

Threading Edge dislocation Glide (TED glide)



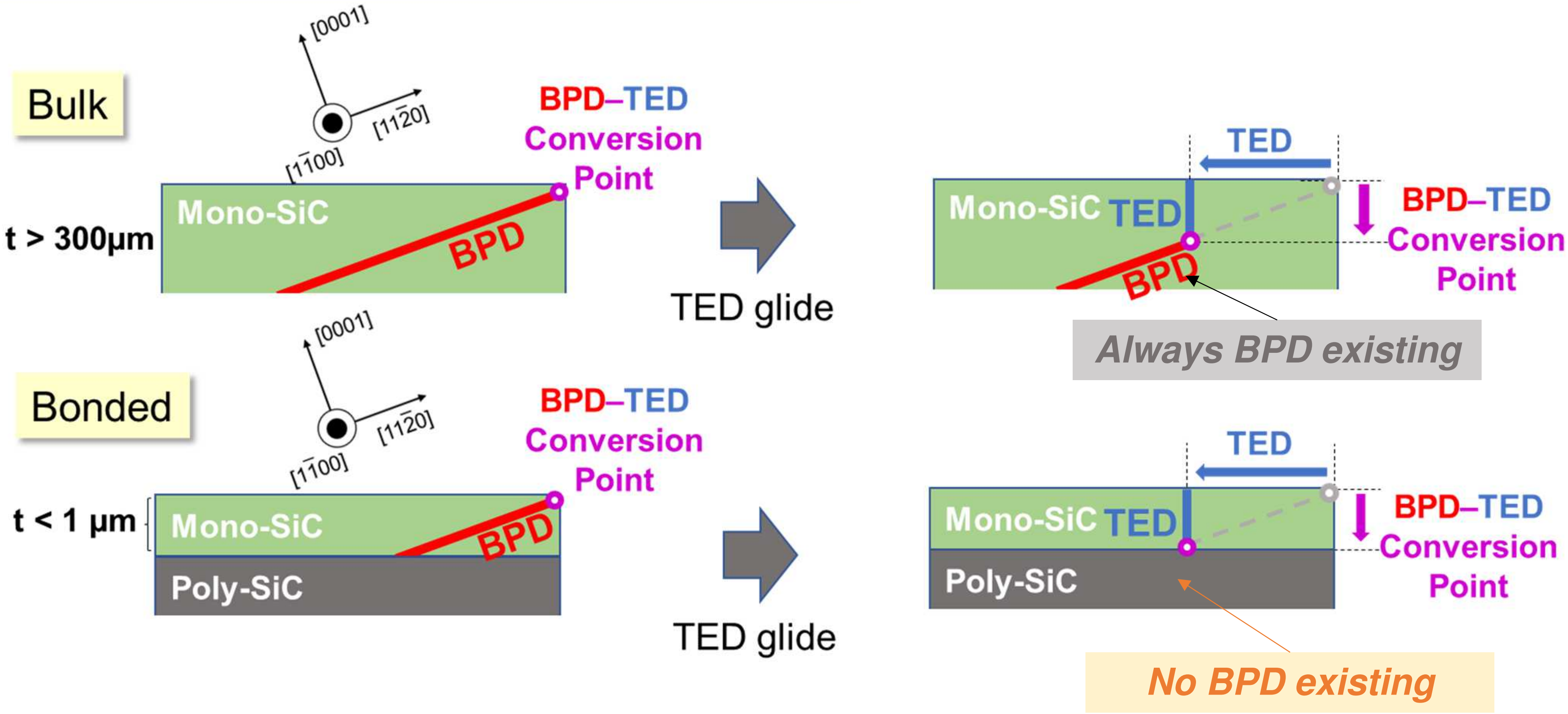


Molecular dynamics simulation of the BPD-TED conversion of perfect screw dislocation

Y. Tamura et al., Jpn. J. Appl. Phys. 58, 081005 (2019)

Results and Discussion

(Prediction of a mechanism of BPD reduction in 4H-SiC bonded substrates)



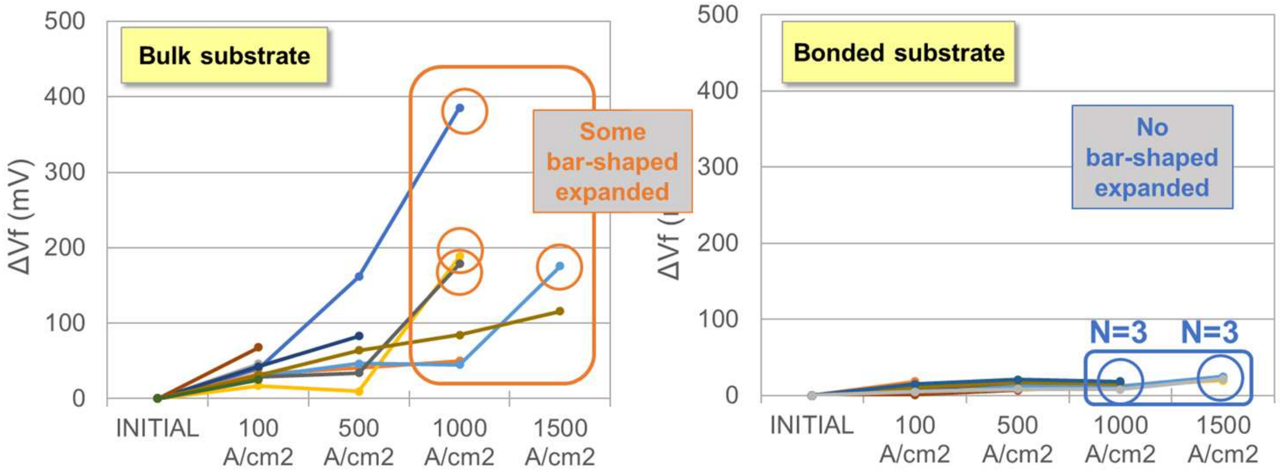
4H-SiC bonded substrates are highly advantageous
for reducing forward bias degradation in 4H-SiC bipolar devices,
especially under high-forward current stress.

Summary

The advantage in reducing forward bias degradation of
PiN diodes using a 4H-SiC bonded substrate is demonstrated.

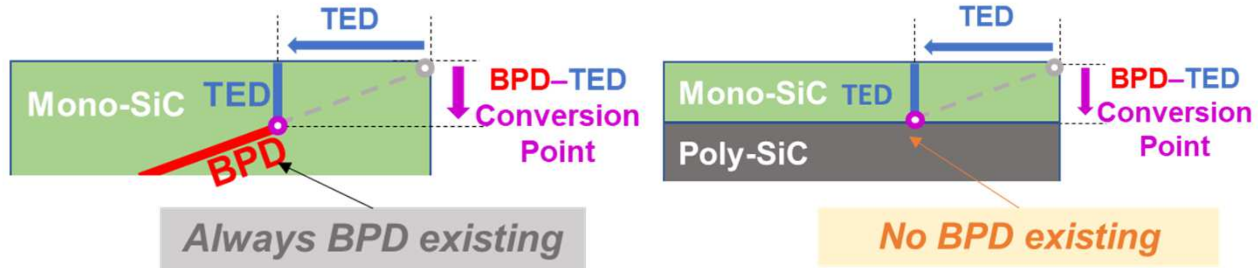
- Forward current stress test on the PiN diodes
- PL imaging

We found the distinct difference in the bar-shaped SSF expansion at high forward current density (1000 A/cm^2 or more).

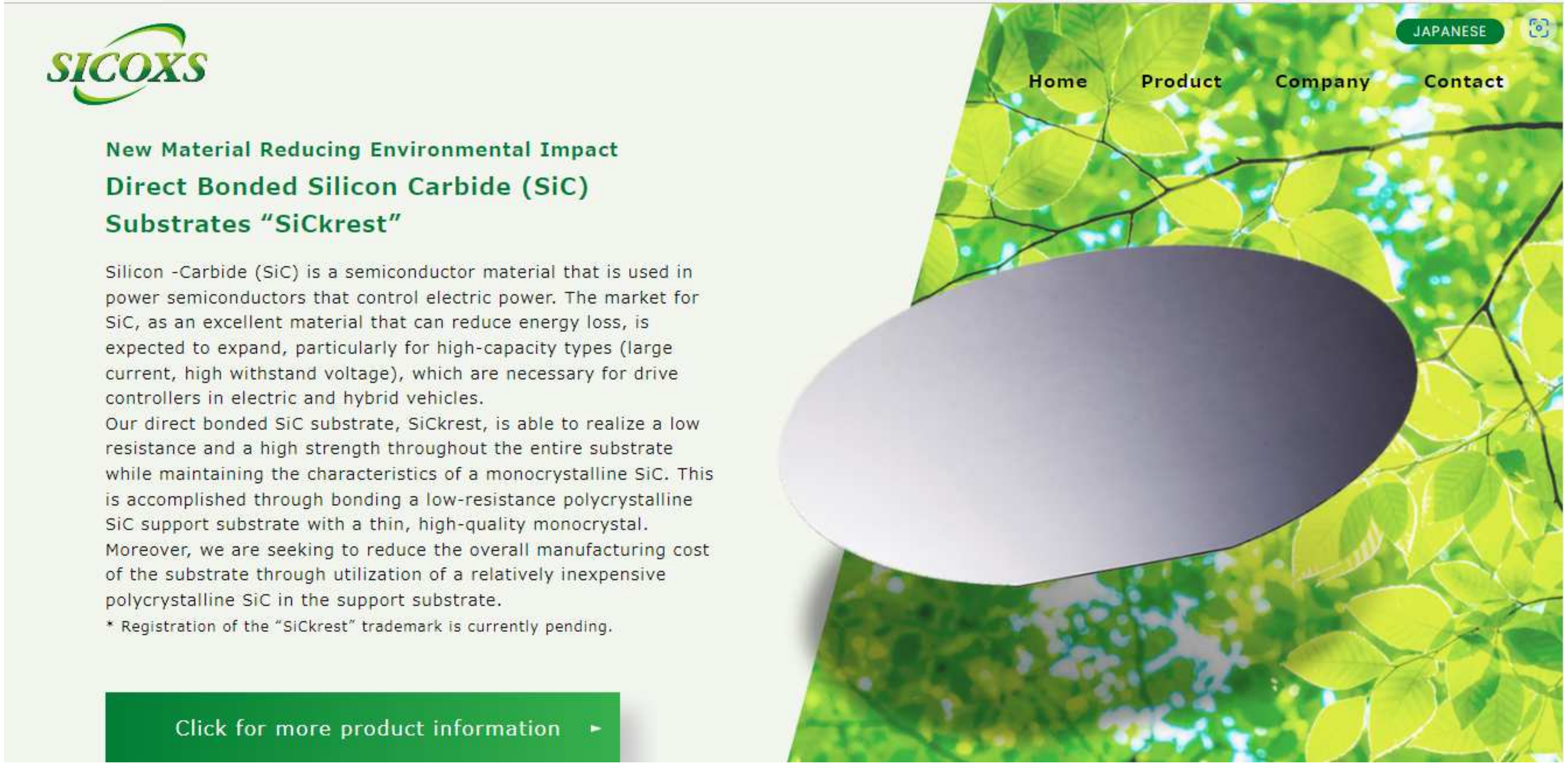


- Prediction with referring some previous studies

The mechanism of BPD reduction associated with a TED glide was predicted in the 4H-SiC bonded substrate.



About sample used in this study



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