*Defect and Diffusion Forum*
*ISSN: 1662-9507, Vol. 426, pp 29-33*
*doi:10.4028/p-0yob2s*

*Submitted: 2022-09-05*
*Revised: 2022-12-12*
*Accepted: 2022-12-13*
*Online: 2023-06-06*

# Stacking Faults Originating from Star-defects in 4H-SiC

S.A. El Hageali[1,2,a*] and N. Mahadik[3,b*], R. Stahlbush[3,c], H. Guthrey[2,d],
S. Johnston[2,e], Jake Soto[4,f], Bruce Odekirk[4,g], Brian P. Gorman[1,h],
Mowafak Al-Jassim[2,i]

[1]Colorado School of Mines, 1500 Illinois Street, Golden, Colorado 80401, USA

[2]National Renewable Energy Laboratory, 15013 Denver West Parkway,
Golden, Colorado 80401, USA

[3]Naval Research Laboratory, 4555 Overlook Ave SW, Washington, DC 20375, USA

[4]Microchip Technology Inc., 405 SW Columbia Street, Bend, Oregon 97702, USA

[a]elhageali@mines, [b]nadeem.mahadik@nrl.navy.mil, [c]stahlbush@nrl.navy.mil,
[d]harvey.guthrey@nrel.gov, [e]steve.johnston@nrel.gov, [f]jake.soto@microchip.com,
[g]bruce.odekirk@microchip.com, [h]bgorman@mines.edu, [i]mowafak.aljassim@nrel.gov

**Keywords:** Star-defect, stacking faults, MOSFETs, degradation, luminescence.

**Abstract.** Intense efforts are currently in progress to study various sources of basal plane dislocations (BPDs) in SiC epitaxial layers. BPDs can generate Shockley-type stacking faults (SSFs) in SiC epitaxial layers, which have been shown to be associated with the degradation of power devices. This study shows that the star-shaped defect can be a source of several BPDs in the epitaxial layer. We investigate the complex microstructure of the star defect, the generation of BPDs, and expansion of SSFs using various complementary microscopy and optical techniques. We show direct evidence that star-defects can be a nucleation point of single-SSFs that can expand at the core of the defect. Newly found secondary dislocation arrays extending over a few centimeters away are found to be emanating from the primary arms of the star defect. The presence of such dislocation walls and the expansion of single-SSFs will affect the yield of numerous die on a wafer. Further understanding of the formation mechanism of stacking faults generated from star-defects as provided in this study helps understand their effect on SiC-based devices, which is crucial to assess device reliability.

## Introduction

Degradation caused by stacking faults (SFs), expansion from pre-existing basal plane dislocations (BPDs) or post-induced BPDs (conversion points) continues to be a key issue in 4H-SiC devices. The generation and expansion of recombination-induced stacking faults (SFs) or BPDs in 4H-SiC devices results in various forms of electrical degradation which have been widely discussed in the literature [1]. In the active area of the device, Shockley-type stacking faults (SSFs) can impede current flow and, as a result, increase the forward voltage drop, reverse leakage and on-state resistance [2]. The elimination of defects causing such degradation needs to be taken into account and have to be erased in order to enhance the performance and improve reliability of SiC-based power devices.

Several growth and processing techniques have successfully converted almost all individual substrate BPDs to benign threading edge dislocations in the epitaxial layers. In fact, high quality epilayers up to 6 inches can now be grown almost BPD-free. The growth of 4H-SiC has advanced to a stage where most stacking faults and dislocations observed in the epilayer come from the substrate and that is why bulk 4H-SiC growth has gained some attention recently. The star-shaped defect that was previously reported by Lee and Skowronski [3] to originate from the substrate can be a source of several BPDs in the epitaxial layer. Fig. 1 is a UV-PL image acquired using a long-pass filter > 700 nm showing the fine structure of the star-defect as commonly found in state-of-the-art commercial wafers. Star-defects are formed in on-axis grown 4H-SiC boule and consist of a highly-deformed center region with high densities of threading dislocations (edge, mixed, screw types and micropipes) and six arms of dislocation arrays extending along <11-20> directions that are consistent with the slip bands generated by the prismatic slip: a/3<11-20>{1-100}. All six <11-20> arms consist of two threading edge dislocation arrays (upper array and bottom array) with a-components differing by 180°. There has been no report on how the star defects may affect SiC-based-devices.

In this study, we investigate the possibility of BPDs generation, and expansion of SSFs from the star-defect using various complementary microscopy and optical techniques, such as cathodoluminescence (CL) spectrum imaging, ultraviolet photoluminescence (UV-PL) imaging and X-ray topography (XRT) imaging.

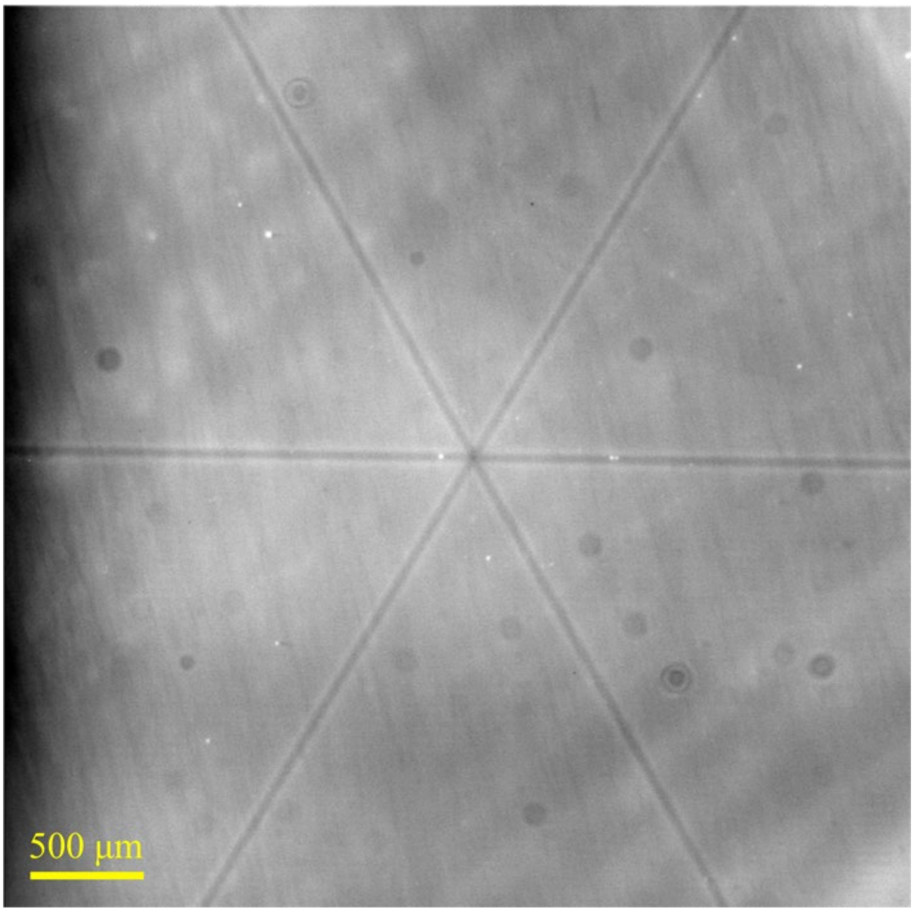

Fig. 1 UV-PL image acquired using a long-pass filter > 700 nm showing the fine structure of a star-defect as commonly found in state-of-the-art commercial wafers.

## Experimental

The 150 mm diameter SiC wafer used in this study was commercially obtained and had a 30 µm thick n-type epitaxial layer. High resolution ultraviolet photoluminescence (UV-PL) imaging was done at the core and the extended dislocation arrays of the star-defect to observe the expansion of SSFs from BPDs. The detection system is equipped with a cooled Si-CCD camera and the excitation was provided by a 360 nm laser diode. Adequate output filters were used for identification of the faults and visualization of dislocation expansion. Cathodoluminescence (CL) spectrum imaging was performed at 15 kV in a JEOL 7600F Schottky Field-Emission SEM with a Horiba H-CLUE CL system with samples cryogenically cooled to 6 K. X-ray topography (XRT) imaging was performed using Rigaku XRTMicron system with 70 µm microfocus Cu/Mo rotating anode, collimating mirror, reflection/transmission sample stage and a high-resolution x-ray camera.

## Results and Discussion

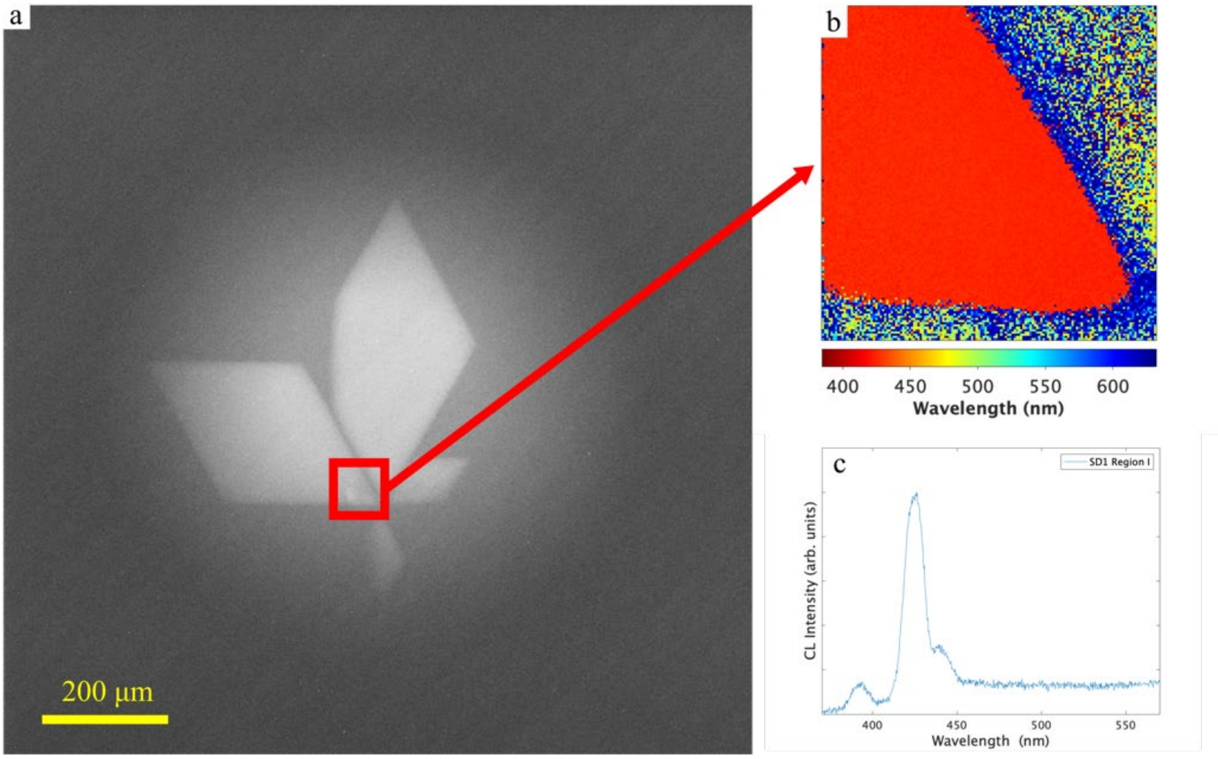

Fig. 2 (a) UV-PL image of a star-defect using a 420 ± 10 nm band-pass filter with expanded stacking faults after short time UV-exposure; (b) 80×80 µm cathodoluminescence hyper-spectral map of an area containing Shockley stacking faults; (c) global average spectrum of (b) showing peak wavelength emission at ~420 nm.

The understanding of the behavior of the star-defect during device operation is experimentally simulated by excess carrier introduction in the SiC epilayer using high intensity UV-PL exposure. In-situ imaging shows that SSFs form in response to a locally applied irradiated stress in the crystal. Above a certain concentration of excess carriers generated by ultra-high intensity UV exposure, SSF are generated preferentially from higher strain regions such as, in this case, the defect center. The high intensity UV exposure is similar to current injection at ~200 A/cm$^2$ which is comparable to current density during MOSFET switching. Already existing BPDs that are too small to be observed at the highest available magnification can also expand. Fig. 2(a) is a UV-PL image acquired with a bandpass filter 420 ± 10 nm after short-time UV exposure. Fig. 2(b) is a peak photon energy map where each pixel shows the maximum photon emission intensity. It is clear from this hyper-spectral map that the SSFs emit in the 420 nm range and that the core of the star-defect is closer in emission to the 700 nm (blue color) range corresponding to the characteristic emission of BPDs or threading dislocations [4, 5]. Fig. 2(c) is a global spectrum of this hyper-spectral map showing strong peak emission wavelength at ~425 nm. According to the literature [6], this SSF corresponds to a Single-Shockley stacking fault (single-SSF). It is postulated that the dislocation reaction that generates Single-SSFs occurs more specifically from TSDs and TMDs with burger vector components parallel to dislocation lines that can cross slip from prismatic plane to basal plane. The morphology of the single-SSF responsible for the device degradation is found to have a rhombus shape with the sides along <11-20> directions and bounded by 30° partial dislocations. The fault expands through electrically active Si-core partials via the recombination-induced dislocation glide (REDG) mechanism [7] in all six slip directions from the defect center, at the substrate/epilayer interface, to the surface of the epilayer.

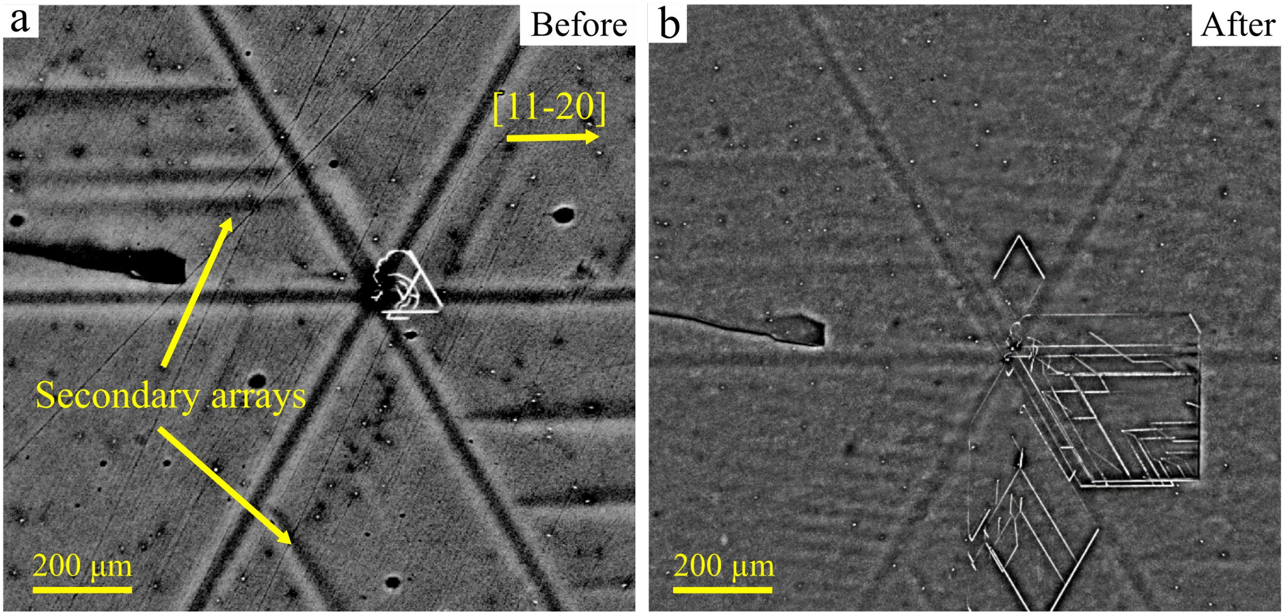

Fig. 3 UV-PL images using a long-pass filter > 700 nm showing a star-defect with secondary arrays before (a) and after (b) long-time UV-exposure.

Fig. 3(a) and (b) show UV-PL images using a long-pass filter > 700 nm of a star-defect found in a wafer before and after long time UV-exposure, respectively. Fig. 3(a) shows that a BPD network is already present at the center of the star-defect prior to UV-exposure. After long-time high intensity UV-exposure Fig. 3(b), UV-PL imaging shows that multiple overlapping single-SSFs (various depths) form and expand via the REDG mechanism in all six slip directions from the defect center at the substrate/epilayer interface toward the surface of the epilayer. Single-SSFs expanding in a perpendicular direction to the step-flow growth direction are longer in length due to the bounding star-defect arms that delay their reach to the top surface of the epitaxial layer. BPDs that expand from the core gliding in the opposite direction of the growth are hardly visible due to high level of impurities in the substrate. Furthermore, newly observed secondary dislocation arrays were found to be emanating at 60° from the primary arrays of the star-defect, Fig. 3(a). The arms of a star-defect can be centimeters in length and the presence of such arrays could be detrimental for several die on a wafer.

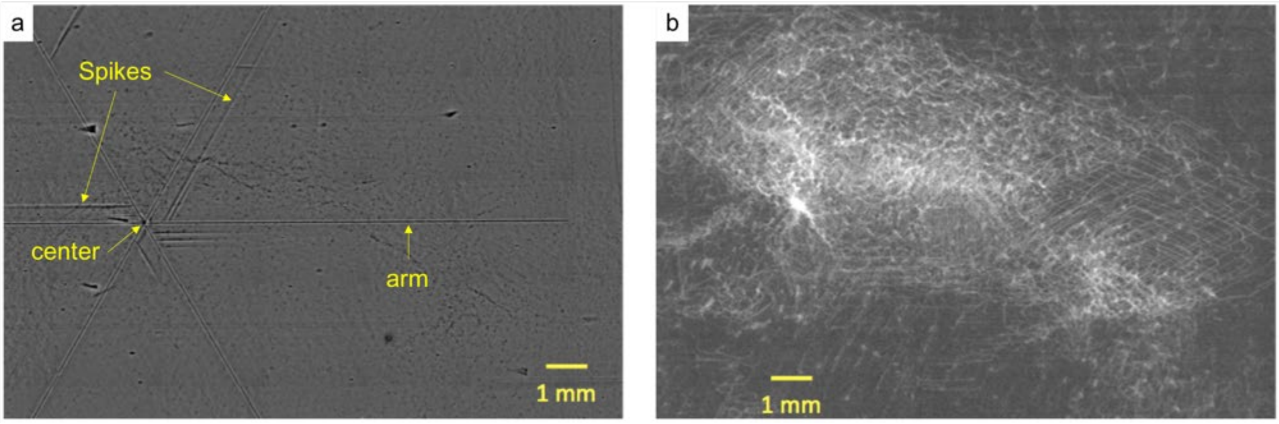

Fig. 4 (a) UV-PL image showing the fine structure of a star-defect with secondary spikes using a 655 nm longpass filter; (b) X-ray transmission topograph on the same area than (a) recorded using g = [11-20] reflection.

Fig. 4 shows a correlation between a UV-PL image Fig. 4(a) and an X-ray transmission topograph Fig. 4(b) with g = [11-20]. The bright short segments and curved lines randomly distributed in the topograph correspond to BPDs generated by lattice distortion. The lattice strain related to BPDs is observed to be distributed over a large region from the defect center to the end of the primary dislocation array. Since the corresponding UV-PL image does not show any BPDs, these are in the substrate around the star defect area.

## Summary

This study provides direct evidence that star-defects can be massive nucleation points of single-SSFs to expand from the core of the defect**.** A wafer having multiple star-defects will eventually pass the MOSFESTs characteristics screening-tests making the devices available on the market. However, the results presented in the study clearly suggest a rapid electrical degradation of the body diode as the single-SSFs expand. Furthermore, one star-defect was found to have secondary dislocation arrays emanating from primary arms which could be detrimental to several devices on a wafer. Additional XRT and UV-PL experiments are needed to further investigate the origin and effect of secondary arrays on SiC-based devices. The complete understanding of star-defect behavior under device operation, as presented in this study, is crucial to assess device reliability and robustness of SiC-based devices.

## References

[1] R.E. Stahlbush, K.N.A. Mahakik, A.J. Lelis, and R. Green, Effects of basal plane dislocations on SiC power device reliability, in Technical Digest - International Electron Devices Meeting, IEDM. (2019) 19.4.1-19.4.4.

[2] J.D. Caldwell et al., Influence of shockley stacking fault propagation and contraction on electrical behavior of 4H-SiC pin diodes and DMOSFETs, 2007 International Semiconductor Device Research Symposium, IEEE. (2007) 1-2.

[3] J.W. Lee and M. Skowronski, Structure of ‘Star’ Defect in 4H-SiC Substrates and Epilayers, Mater. Sci. Forum. 527 (2006) 403–406.

[4] J. Nishio, A. Okada, C. Ota, and M. Kushibe, Photoluminescence analysis of individual partial dislocations in 4h-sic epilayers, Mater. Sci. Forum. 1004 (2020) 376–386.

[5] M. Nagano, I. Kamata, and H. Tsuchida, Photoluminescence imaging and discrimination of threading dislocations in 4H-SiC epilayers, Mater. Sci. Forum. 778 (2014) 313–318.

[6] N. Thierry-Jebali, C. Kawahara, T. Miyazawa, H. Tsuchida, and T. Kimoto, Application of UV photoluminescence imaging spectroscopy for stacking faults identification on thick, lightly n-type doped, 4°-off 4H-SiC epilayers, AIP Adv. 5 (2015) 037121.

[7] J.D. Caldwell, R. E. Stahlbush, M.G. Ancona, O.J. Glembocki, and K.D. Hobart, On the driving force for recombination-induced stacking fault motion in 4H-SiC, J. Appl. Phys. 108 (2010) 044503.