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INTERNATIONAL STANDARD

**Semiconductor devices – Non-destructive recognition criteria of defects in silicon carbide homoepitaxial wafer for power devices –
Part 1: Classification of defects**

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Semiconductor devices – Non-destructive recognition criteria of defects in silicon carbide homoepitaxial wafer for power devices – Part 1: Classification of defects

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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SEMICONDUCTOR DEVICES – NON-DESTRUCTIVE RECOGNITION CRITERIA OF DEFECTS IN SILICON CARBIDE HOMOEPITAXIAL WAFER FOR POWER DEVICES –

Part 1: Classification of defects

FOREWORD

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International Standard IEC 63068-1 has been prepared by IEC technical committee 47: Semiconductor devices.

The text of this International Standard is based on the following documents:

CDV	Report on voting
47/2474/CDV	47/2521A/RVC

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 63068 series, published under the general title *Semiconductor devices – Non-destructive recognition criteria of defects in silicon carbide homoepitaxial wafer for power devices*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

Silicon carbide (SiC) is widely used as a semiconductor material for next-generation power semiconductor devices. SiC, as compared with silicon (Si), has superior physical properties such as a higher breakdown electric field, higher thermal conductivity, lower thermal generation rate, higher saturated electron drift velocity, and lower intrinsic carrier concentration. Their attributes realize SiC-based power semiconductor devices with faster switching speeds, lower losses, higher blocking voltages, and higher temperature operation relative to standard Si-based power semiconductor devices.

SiC-based power semiconductor devices are not fully realized due to high costs, low yield, and perceived reliability concerns. One of the serious issues lies in the defects existing in SiC homoepitaxial wafers. Although an effort of decreasing defects in the SiC homoepitaxial layer is actively implemented, there are a number of defects (approximately 1 000 defects/cm^2) in commercially available SiC homoepitaxial wafers. Therefore, it is indispensable to establish an international standard regarding the quality assessment of SiC homoepitaxial wafers.

The IEC 63068 series of standards is planned to comprise Part 1, Part 2, and Part 3, as detailed below. The outline of this Part 1 is to list, illustrate and provide reference for various characteristic features and defects that are observed on SiC homoepitaxial wafers of crystallographic polytype 4H used in high-power semiconductor device manufacturing.

Part 1: Classification of defects

Part 2: Test method for defects using optical inspection

Part 3: Test method for defects using photoluminescence

SEMICONDUCTOR DEVICES – NON-DESTRUCTIVE RECOGNITION CRITERIA OF DEFECTS IN SILICON CARBIDE HOMOEPITAXIAL WAFER FOR POWER DEVICES –

Part 1: Classification of defects

1 Scope

This part of IEC 63068 gives a classification of defects in as-grown 4H-SiC (Silicon Carbide) epitaxial layers. The defects are classified on the basis of their crystallographic structures and recognized by non-destructive detection methods including bright-field OM (optical microscopy), PL (photoluminescence), and XRT (X-ray topography) images.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
silicon carbide
SiC
semiconductor crystal composed of silicon and carbon, which exhibits a large number of polytypes such as 3C, 4H, and 6H

Note 1 to entry: A symbol like 4H gives the number of periodic stacking layers (2, 3, 4,…) and the crystal symmetry (H = hexagonal, C = cubic) of each polytype.

3.2
3C-SiC
SiC crystal with zinc blende structure, in which three Si-C layers are periodically arranged along the <111> direction

3.3
4H-SiC
SiC crystal showing a hexagonal symmetry, in which four Si-C layers are periodically arranged along the crystallographic c-axis

Note 1 to entry: The crystal structure of 4H-SiC is similar to wurtzite with a unit cell having four periodical occupied sites along the <0001> direction.

3.4
6H-SiC
SiC crystal showing a hexagonal symmetry, in which six Si-C layers are periodically arranged along the crystallographic c-axis

Note 1 to entry: The crystal structure of 6H-SiC is similar to wurtzite with a unit cell having six periodical occupied sites along the <0001> direction.

3.5
crystal plane
plane, usually denoted as (hkl), representing the intersection of a plane with the *a*-, *b*- and *c*-axes of the unit cell at distances of $1/h$, $1/k$ and $1/l$, where h, k and l are integers

Note 1 to entry: The integers h, k and l are usually referred to as the Miller indices of a crystal plane.

Note 2 to entry: In 4H-SiC showing a hexagonal symmetry, four-digit indices are frequently used for planes $(hkil)$.

[SOURCE: ISO 24173:2009, 3.2, modified – Note 2 to entry has been entirely redrafted.]

3.6
crystal direction
direction, denoted as $[uvw]$, representing a vector direction in multiples of the basis vectors describing the *a*–, *b*- and *c*-axes

Note 1 to entry: In 4H-SiC showing a hexagonal symmetry, four-digit indices $[uvtw]$ are frequently used for crystal directions.

Note 2 to entry: Families of symmetrically equivalent directions are written by $\langle uvw \rangle$ and $\langle uvtw \rangle$ for cubic and hexagonal symmetries, respectively.

[SOURCE: ISO 24173:2009, 3.3, modified – Note 1 to entry and Note 2 to entry have been added.]

3.7
polytypism
phenomenon where a material occurs in several structural modifications, each of which can be regarded as built up by stacking layers of identical structure and chemical composition

3.8
polytype
one of the modifications of monocrystalline material which shows polytypism

3.9
substrate
material on which homoepitaxial layer is deposited

3.10
homoepitaxial layer
thin monocrystalline film epitaxially-formed on a substrate of the same material and crystallographic orientation, inheriting the atomic order of the substrate

3.11
crystal
monocrystalline material

3.12
lattice site
arrangement position of the atoms in crystal

3.13
basal plane
plane perpendicular to the crystallographic c-axis in a hexagonal crystal

3.14
prism plane
plane parallel to the crystallographic c-axis in a hexagonal crystal

3.15
crystallographic c-axis
principal axis in a hexagonal crystal

3.16
defect
crystalline imperfection

Note 1 to entry: Defect of SiC homoepitaxial wafers including point defect, extended defects, surface defects, and others.

3.17
crystal defect
local alteration of crystal periodicity

Note 1 to entry: Crystal defect is generally classified into point and extended defects.

3.18
point defect
crystal defect that occurs at or around a single lattice site, such as a vacancy, interstitial, antisite, impurity and complex

3.19
vacancy
lattice site of a lack of atom in crystal

3.20
interstitial
atom that occupies a site in monocrystalline material, at which atoms usually do not exist

3.21
extended defect
crystal defect extended in space in one, two or three-dimension

3.22
dislocation
linear crystallographic defect in monocrystalline material

3.23
micropipe
hollow tube extending approximately normal to the basal plane

3.24
threading screw dislocation
TSD
screw dislocation penetrating through the crystal approximately normal to the basal plane

3.25
threading edge dislocation
TED
edge dislocation penetrating through the crystal approximately normal to the basal plane

3.26
basal plane dislocation
BPD
dislocation lying on the basal plane

3.27
partial dislocation
dislocation encompassing a stacking fault

3.28
Frank partial dislocation
dislocation encompassing a Frank-type stacking fault

3.29
Shockley partial dislocation
dislocation encompassing a Shockley-type stacking fault

3.30
Si-core partial dislocation
partial dislocation having Si-Si bonds at the dislocation core

3.31
C-core partial dislocation
partial dislocation having C-C bonds at the dislocation core

3.32
stacking fault
planar crystallographic defect in monocrystalline material, characterized by an error in the stacking sequence of crystallographic planes

3.33
basal plane stacking fault
stacking fault lying on the basal plane

3.34
prismatic fault
stacking fault lying on the prism plane

3.35
Frank-type stacking fault
stacking fault where atomic displacement occurs in the direction perpendicular to the plane on which the stacking fault lies

3.36
Shockley-type stacking fault
stacking fault where atomic displacement occurs in the direction parallel to the plane on which the stacking fault lies

3.37
surface defect
morphological irregularity on the homoepitaxial layer surface, not associated with extended defects in the underlying layer

3.38
bunched-step
surface steps of multiple height of unit steps, which are formed by coalescing unit steps into a large single step

Note 1 to entry: The height of the bunched-step ranges from a few nm to several tens nm.

3.39
inclusion
volume crystal defect in monocrystalline material, showing physical and/or chemical properties different from those of the monocrystalline material

3.40
pit
dimple existing on the homoepitaxial layer surface

3.41
scratch
surface roughness associated with mechanical damage

3.42
Burgers vector
vector representing the magnitude and direction of lattice distortion along a dislocation in monocrystalline material

3.43
off-cut angle
angle between the crystallographic c-axis and the substrate surface normal

3.44
off-cut direction
crystallographic direction projected on the basal plane of tilt of the crystallographic c-axis from the substrate surface normal

3.45
optical microscopy
OM
technique employed to observe morphological features of wafer surface through the magnification by lenses with visible light

3.46
photoluminescence
PL
emission of light by a substance as a result of absorption of optical radiation

3.47
x-ray topography
XRT
method of assessing extended defects in a crystal, where a two-dimensional intensity profile of x-rays diffracted by a crystal is recorded

Note 1 to entry: The diffraction condition in x-ray topography is characterized by the diffraction vector ***g***.

4 Classification of defects

4.1 General

The defects in SiC homoepitaxial wafers, which are based on the crystallographic type and structure, shall be categorized into fourteen classes of defects given in Table 1.

Table 1 – Classification of defects

<table>
<tr><th>No</th><th>Defect class</th><th>Type</th><th>Dimensionality</th><th>Structure</th><th>Figure</th></tr>
<tr><td>1</td><td>Point defect</td><td>Point defect</td><td>Point</td><td>Vacancy, Interstitial, etc.</td><td>None</td></tr>
<tr><td>2</td><td>Micropipe</td><td rowspan="10">Extended defect</td><td rowspan="5">Linear</td><td>Shallow hollow tube</td><td>1</td></tr>
<tr><td>3</td><td>TSD</td><td>Threading screw dislocation</td><td>2</td></tr>
<tr><td>4</td><td>TED</td><td>Threading edge dislocation</td><td>3</td></tr>
<tr><td>5</td><td>BPD</td><td>Basal plane dislocation</td><td>4</td></tr>
<tr><td>6</td><td>Scratch trace</td><td>Dense row of dislocations</td><td>5</td></tr>
<tr><td>7</td><td>Stacking fault</td><td rowspan="3">Planar</td><td>Stacking fault</td><td>6</td></tr>
<tr><td>8</td><td>Propagated stacking fault</td><td>Stacking fault</td><td>7</td></tr>
<tr><td>9</td><td>Stacking fault complex</td><td>Complex of prismatic and basal plane faults</td><td>8</td></tr>
<tr><td>10</td><td>Polytype inclusion</td><td rowspan="2">Volume</td><td>Foreign polytype</td><td>9</td></tr>
<tr><td>11</td><td>Particle inclusion</td><td>Particle</td><td>10</td></tr>
<tr><td>12</td><td>Bunched-step segment</td><td rowspan="2">Surface defect</td><td>Planar</td><td>Bunched-step</td><td>11</td></tr>
<tr><td>13</td><td>Surface particle</td><td>Volume</td><td>Particle</td><td>None</td></tr>
<tr><td>14</td><td>Others</td><td>Not specified</td><td>Not specified</td><td>Not specified</td><td>None</td></tr>
</table>

4.2 Description of the defect classes

4.2.1 Examples of defects

The terminology, schematic illustrations, plan-view observation images of each defect are shown in 4.2.2 to 4.2.15. All the figures show the following:

a) a schematic illustration of each defect in the homoepitaxial wafer;

b) a schematic illustration of the plan-view observation image of each defect;

c) a bright-field optical microscope image of each figure;

d) a photoluminescence mapping image of each figure;

e) an X-ray topographic image of each figure.

All the images are obtained from 4H-SiC homoepitaxial wafers with an off-cut direction of $[11\bar{2}0]$ and an off-cut angle of 4°. The photoluminescence mapping image was acquired with a 340 nm excitation at room temperature, and the luminescence wavelength detected to obtain the image is indicated in a note within each text describing the relevant defect. All the X-ray topographic images were taken under $\boldsymbol{g} = 11\bar{2}8$ diffraction condition.

4.2.2 Point defect

The class of point defect means a crystal defect that occurs at or around a single lattice site.

NOTE Point defects cannot be detected using optical inspection and photoluminescence methods, and thus they are not treated in this document.

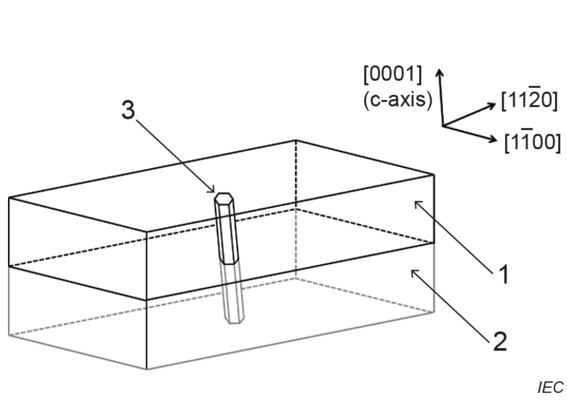
4.2.3 Micropipe

The class of micropipe means a hollow tube extending approximately along <0001> c-axis of 4H-SiC single crystal and can be described as coreless dislocations having a Burgers vector $\boldsymbol{b}$ with a c component, $\boldsymbol{b} = n\boldsymbol{c}$, $n \geqq 3$. Plan-view observation images of micropipe are shown in Figure 1.

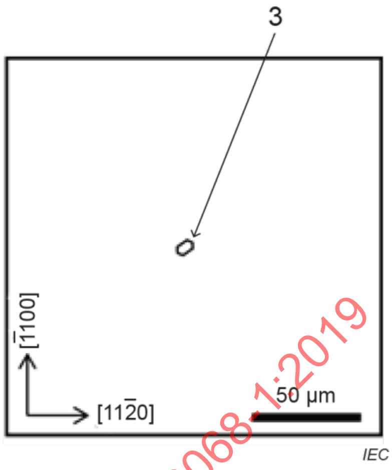
NOTE 1 This defect exhibits characteristic morphological features on the 4H-SiC homoepitaxial layer surface, that is, large dark pits.

NOTE 2 Micropipes can only be detected for large values of *n* using optical inspection.

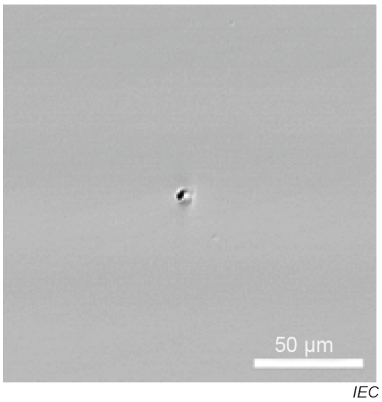
NOTE 3 Subfigure 1 d) was obtained in a wavelength range from 750 nm to 1 100 nm.



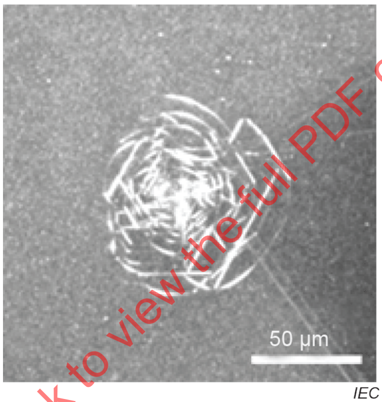
a) Schematic illustration of micropipe



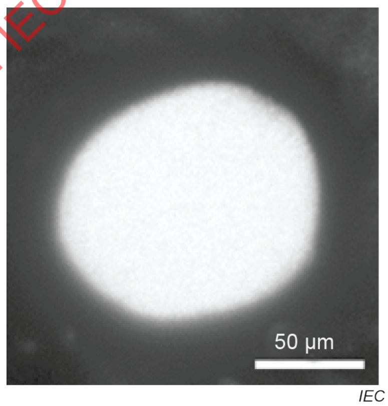
b) Plan-view observation image



c) Bright-field OM image



d) PL image



e) XRT image

Key

1 Epitaxial layer

2 Substrate

3 Micropipe

Figure 1 – Micropipe

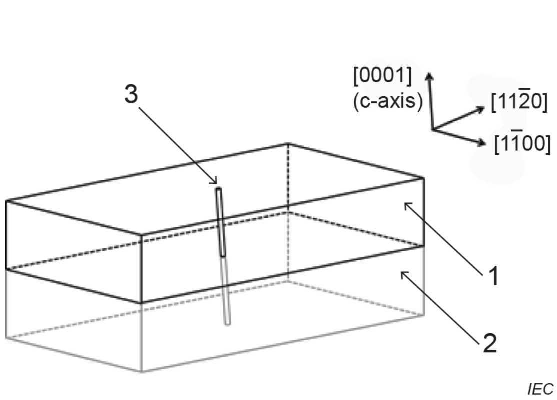
4.2.4 TSD

The class of TSD means a screw dislocation extending approximately parallel to the crystallographic c-axis. The Burgers vector of TSDs is either <0001> or <0001> plus *a* component perpendicular to the c-axis. Plan-view observation images of TSD are shown in Figure 2.

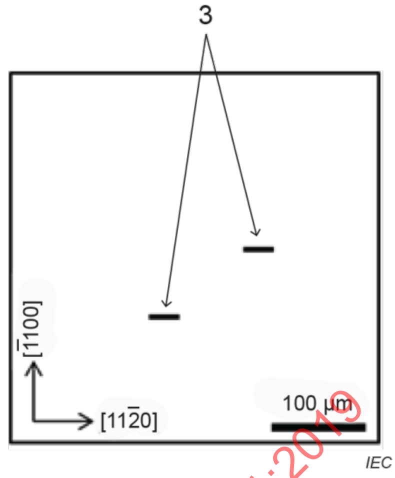
NOTE 1 This defect often exhibits characteristic morphological features on the 4H-SiC homoepitaxial layer surface, that is, so-called "shallow pits".

NOTE 2 Pit sizes of TSDs observed with optical inspection are larger than those of TEDs. Since TSDs and TEDs are observed simultaneously in almost all cases, the same subfigures c), d), and e) are used in Figure 2 and Figure 3.

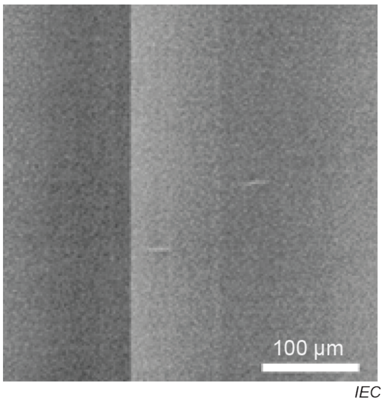
NOTE 3 Subfigure 2 d) was obtained in a wavelength range from 750 nm to 1 100 nm.



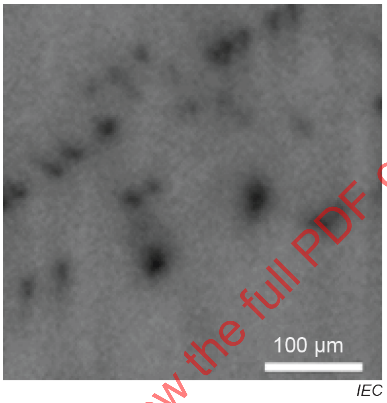
a) Schematic illustration of TSD



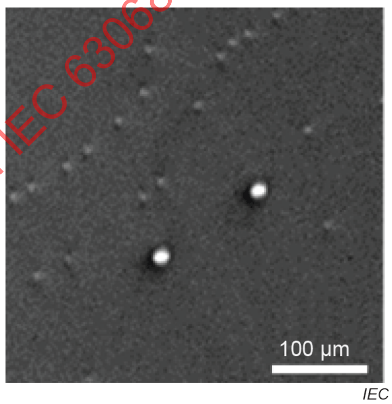
b) Plan-view observation image



c) Bright-field OM image



d) PL image



e) XRT image

Key

1 Epitaxial layer

2 Substrate

3 TSD

Figure 2 – TSD

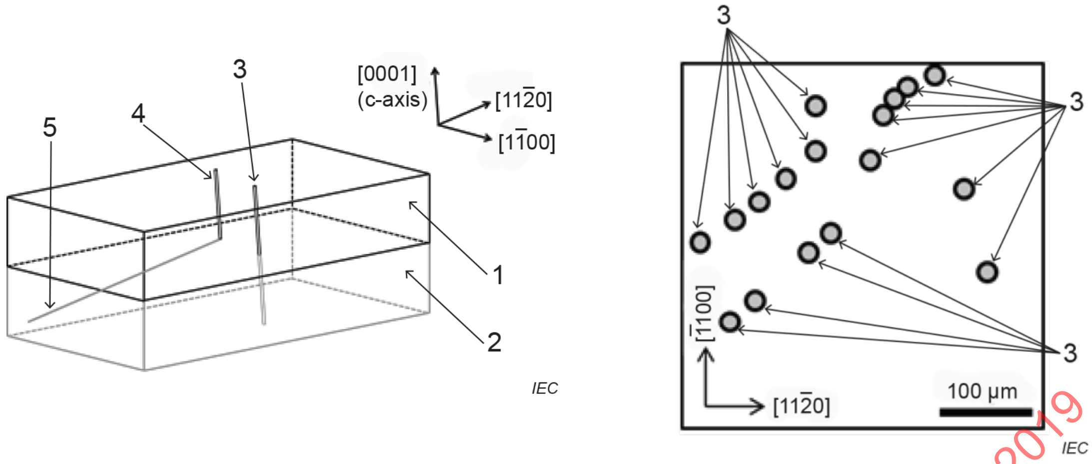
4.2.5 TED

The class of TED means an edge dislocation with a Burgers vector of 1/3<11$\bar{2}$0>, extending approximately parallel to the crystallographic c-axis. Plan-view observation images of TED are shown in Figure 3.

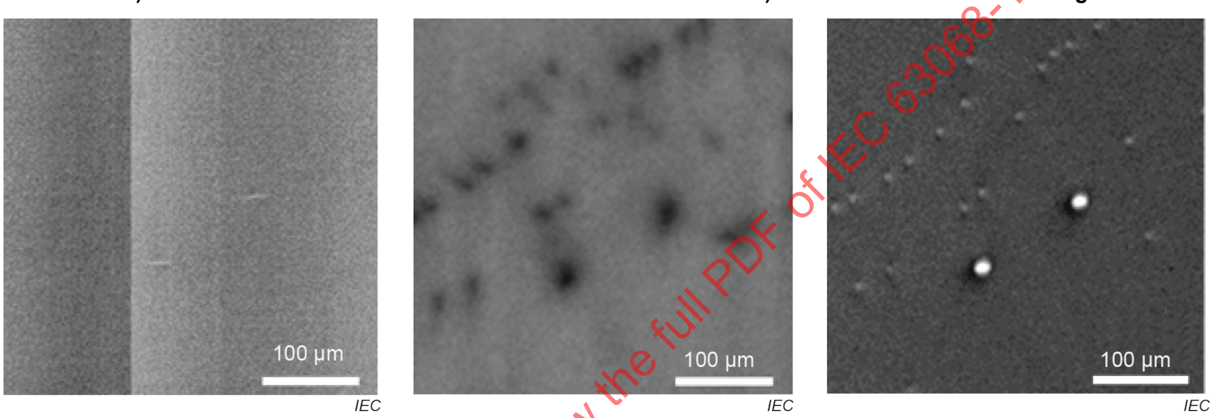
NOTE 1 This defect often exhibits characteristic morphological features on the 4H-SiC homoepitaxial layer surface, that is, so-called "shallow pits".

NOTE 2 Pit sizes of TEDs observed with optical inspection are smaller than those of TSDs. Since TSDs and TEDs are observed simultaneously in almost all cases, the same Subfigures c), d), and e) are used in Figure 2 and Figure 3.

NOTE 3 Subfigure 3 d) was obtained in a wavelength range from 750 nm to 1 100 nm.



a) Schematic illustration of TEDs   b) Plan-view observation image



c) Bright-field OM image   d) PL image   e) XRT image

Key

1 Epitaxial layer

2 Substrate

3 TED

4 TED in epitaxial layer

5 BPD in substrate

Figure 3 – TED

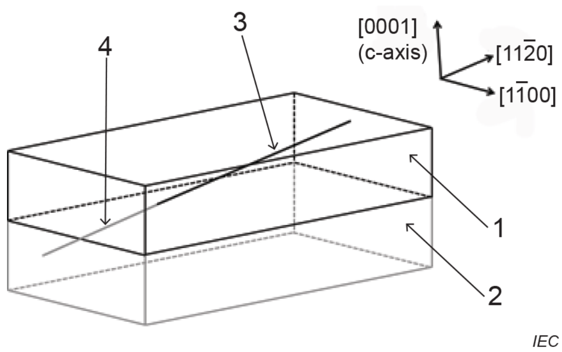
4.2.6 BPD

The class of BPD means a dislocation lying on the basal plane with a Burgers vector of 1/3<11-$\bar{2}$-0>. BPD is usually dissociated into two partial dislocations with different core structures: Si-core and C-core partial dislocations. Plan-view observation images of BPD are shown in Figure 4.

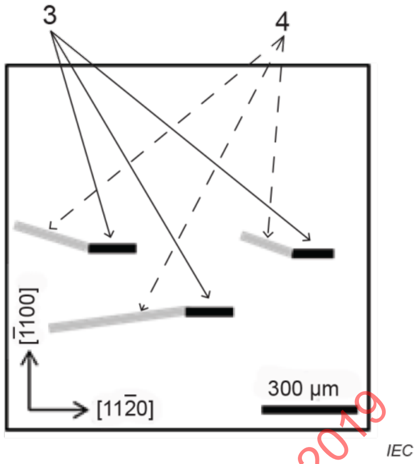
NOTE 1 This defect causes no morphological feature on the 4H-SiC homoepitaxial layer surface.

NOTE 2 The extension directions of BPD lines are predominantly parallel or nearly parallel to the step flow direction. However, other directions of BPD lines do occur. The BPD lines can also be curved.

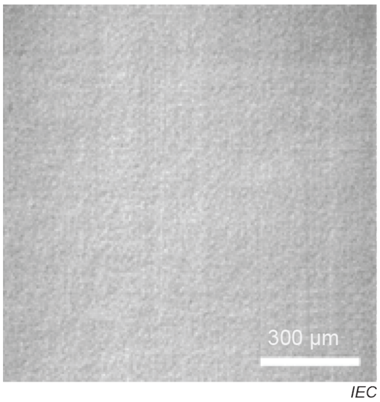
NOTE 3 Subfigure 4 d) was obtained in a wavelength range from 750 nm to 1 100 nm.



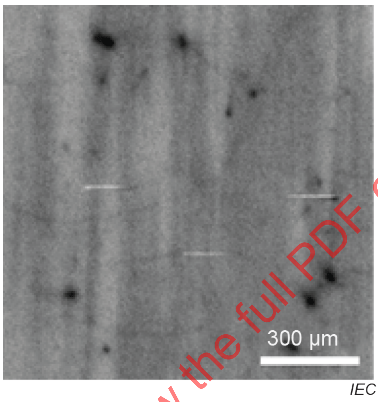
a) Schematic illustration of BPD



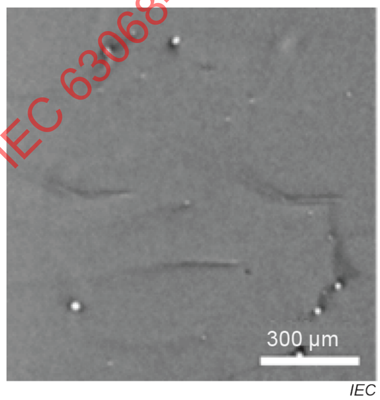
b) Plan-view observation image



c) Bright-field OM image



d) PL image



e) XRT image

Key

1 Epitaxial layer

2 Substrate

3 BPD in epitaxial layer

4 BPD in substrate

Figure 4 – BPD

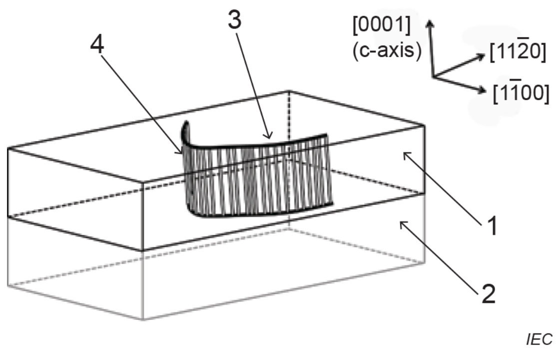
4.2.7 Scratch trace

The class of scratch trace means dense rows of dislocations caused by mechanical damage on the substrate surface. Plan-view observation images of scratch trace are shown in Figure 5.

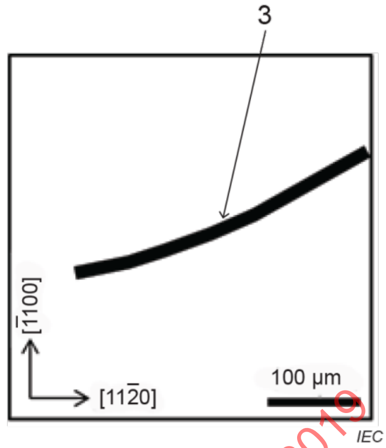
NOTE 1 This defect is usually caused by polishing scratches on the substrate surface.

NOTE 2 The defect exhibits characteristic morphological features on the 4H-SiC homoepitaxial layer surface, that is, scratch-like random line morphologies.

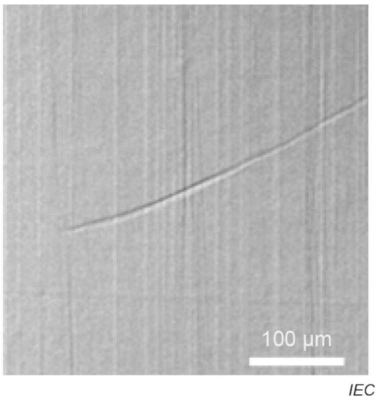
NOTE 3 Subfigure 5 d) was obtained in a wavelength range from 750 nm to 1 100 nm.



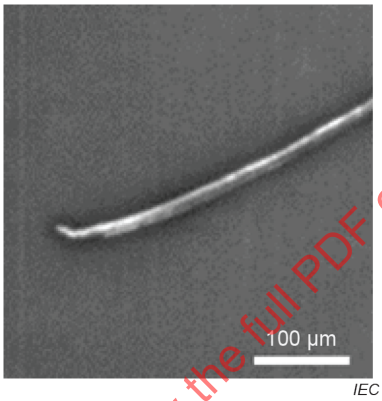
a) Schematic illustration of scratch trace



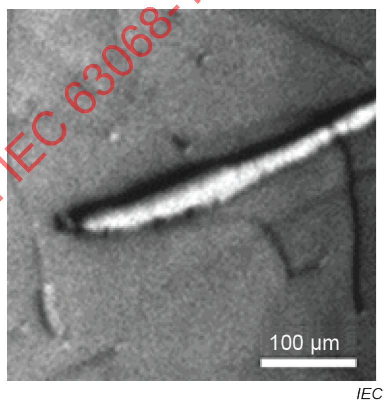
b) Plan-view observation image



c) Bright-field OM image



d) PL image



e) XRT image

Key

1 Epitaxial layer

2 Substrate

3 Scratch trace

4 Row of dislocations

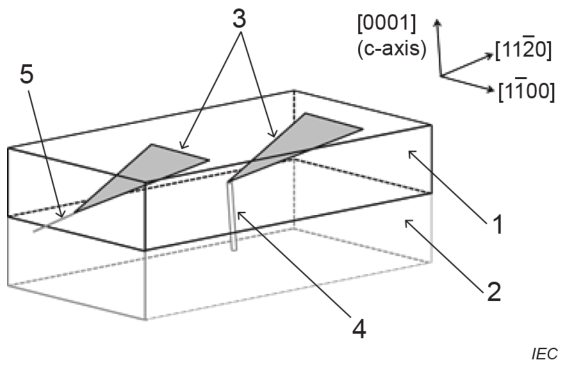
Figure 5 – Scratch trace

4.2.8 Stacking fault

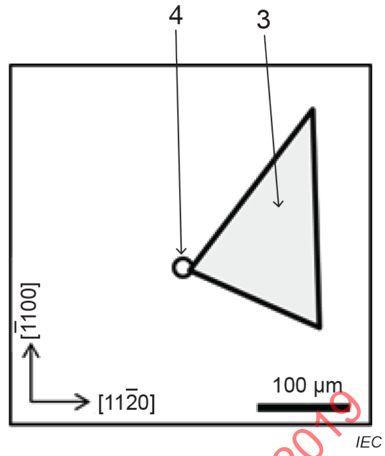
The class of stacking fault means a basal plane stacking fault with various types of stacking errors, each exhibiting photoluminescence with a characteristic spectrum. Plan-view observation images of stacking fault are shown in Figure 6.

NOTE 1 This defect often exhibits characteristic morphological features on the 4H-SiC homoepitaxial layer surface, that is, faintly-outlined triangle.

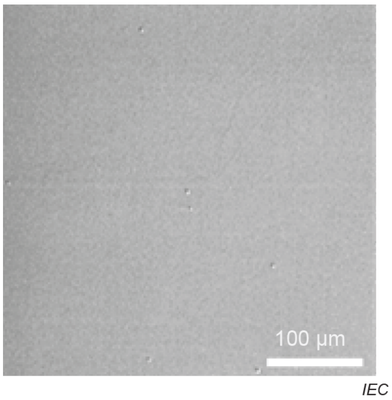
NOTE 2 Subfigure 6 d) was obtained at a wavelength of 460 nm.



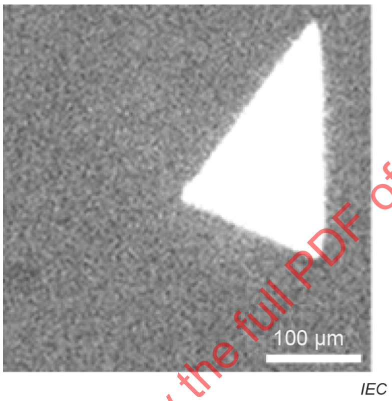
a) Schematic illustration of stacking faults



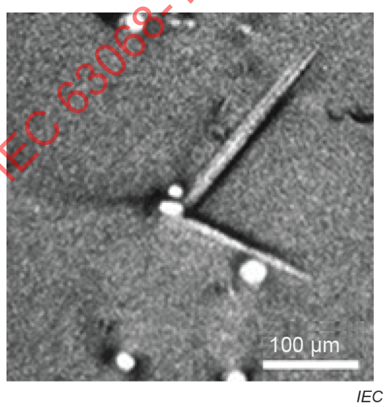
b) Plan-view observation image



c) Bright-field OM image



d) PL image



e) XRT image

Key

1 Epitaxial layer

2 Substrate

3 Stacking fault

4 TSD in substrate

5 BPD in substrate

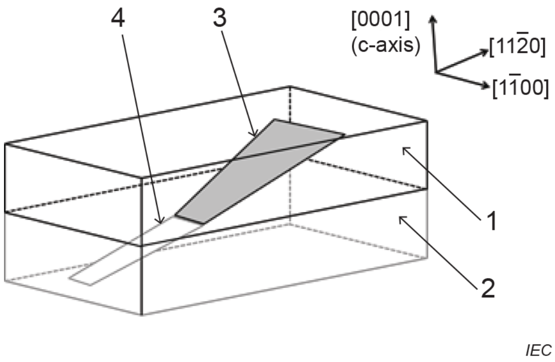
Figure 6 – Stacking fault

4.2.9 Propagated stacking fault

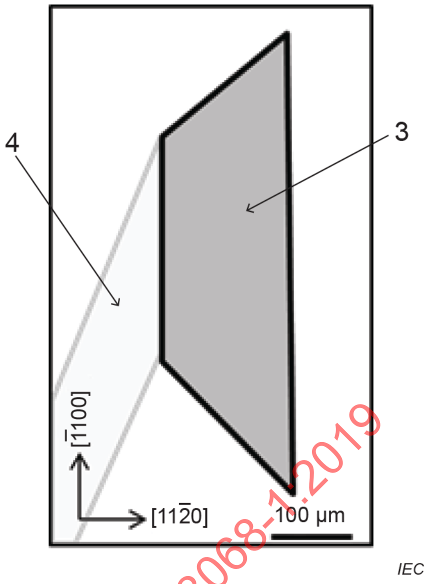
The class of propagated stacking fault means a stacking fault propagating from substrate toward the epitaxial layer surface. Plan-view observation images of propagated stacking fault are shown in Figure 7.

NOTE 1 This defect often exhibits characteristic morphological features on the 4H-SiC homoepitaxial layer surface, that is, trapezoid elongated along the direction perpendicular to the off-cut direction. It is also referred to as “bar-shaped stacking fault”.

NOTE 2 Subfigure 7 d) was obtained in a wavelength range from 750 nm to 1 100 nm.



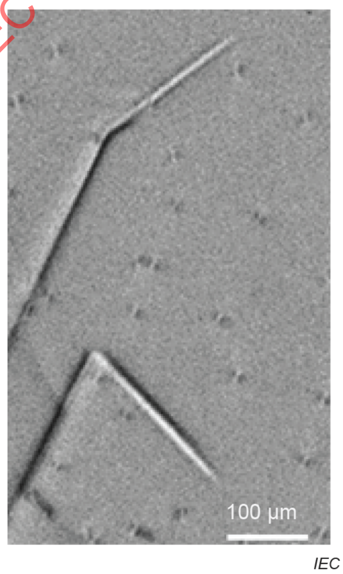
a) Schematic illustration of propagated stacking fault



b) Plan-view observation image

c) Bright-field OM image

d) PL image



e) XRT image

Key

1 Epitaxial layer

2 Substrate

3 Propagated stacking fault in epitaxial layer

4 Stacking fault in substrate

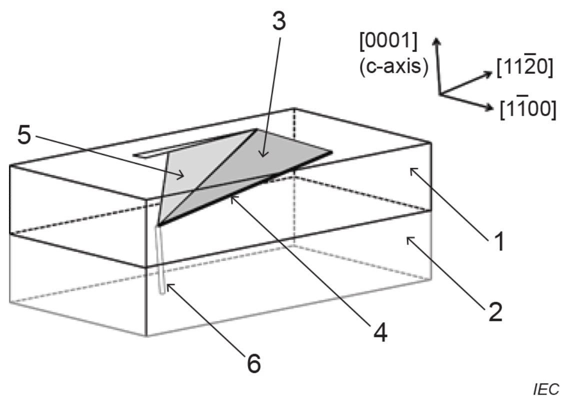
Figure 7 – Propagated stacking fault

4.2.10 Stacking fault complex

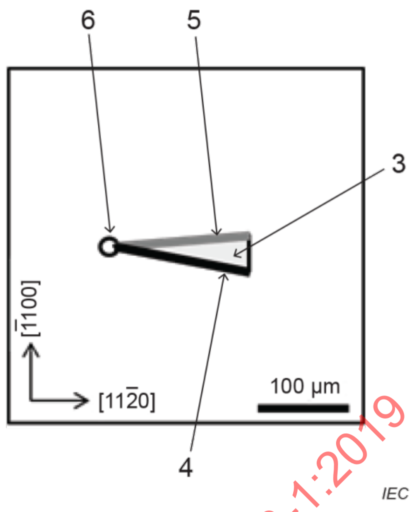
The class of stacking fault complex means a stacking fault complex consisting a basal plane stacking fault terminating at a Frank partial dislocation and a prismatic fault terminating at the homoepitaxial layer surface. Plan-view observation images of stacking fault complex are shown in Figure 8.

NOTE 1 This defect exhibits characteristic morphological features on the 4H-SiC homoepitaxial layer surface, that is, needle shaped features extending along the off-cut direction. It is also referred to as “carrot defect”.

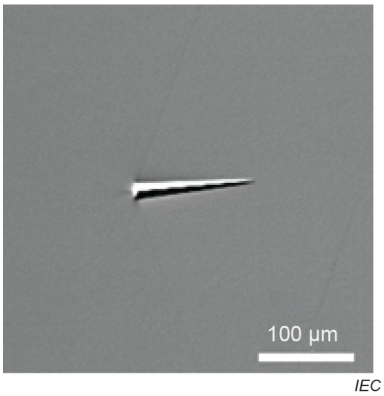
NOTE 2 Subfigure 8 d) was obtained at a wavelength of 420 nm.



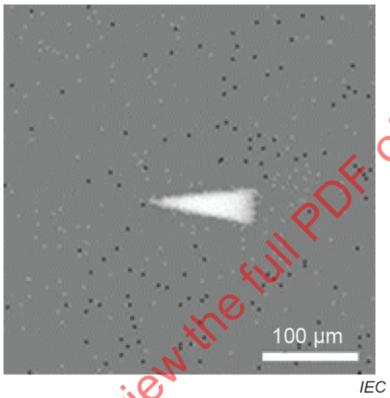
a) **Schematic illustration of stacking fault complex**



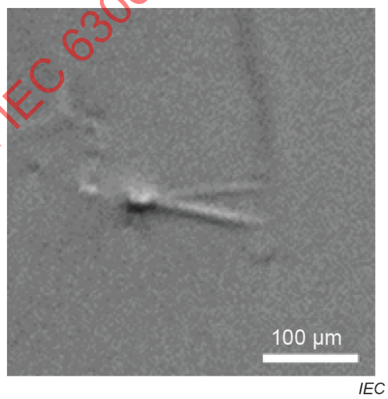
b) Plan-view observation image



c) Bright-field OM image



d) PL image



e) XRT image

Key

1 Epitaxial layer

2 Substrate

3 Basal plane stacking fault

4 Prismatic fault

5 Frank partial dislocation

6 TSD in substrate

Figure 8 – Stacking fault complex

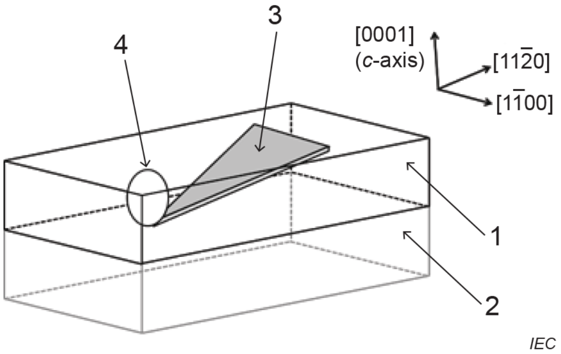
4.2.11 Polytype inclusion

The class of polytype inclusion means a lamellar inclusion with a cubic (3C) stacking sequence, so-called “3C inclusion”, extending toward the homoepitaxial layer surface. Plan-view observation images of polytype inclusion are shown in Figure 9.

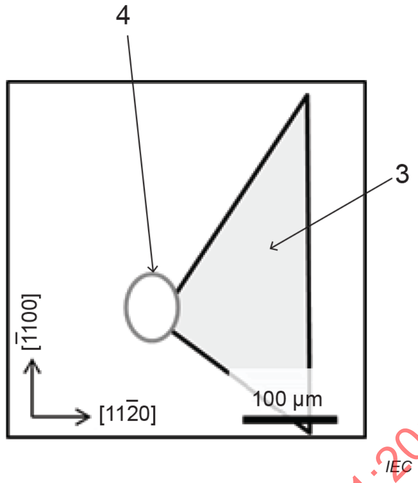
NOTE 1 This defect exhibits characteristic morphological features on the 4H-SiC homoepitaxial layer surface, that is, acute triangle or needle shaped features extending along the off-cut direction. It is also referred to as “triangular inclusion”, "triangular defect", or "comet tail defect".

NOTE 2 This defect is formed not only due to particles but also due to other causes such as mechanical surface damage as a result of the polishing process or uncontrolled nucleation and two-dimensional extension on the (0001) terrace during epitaxial growth.

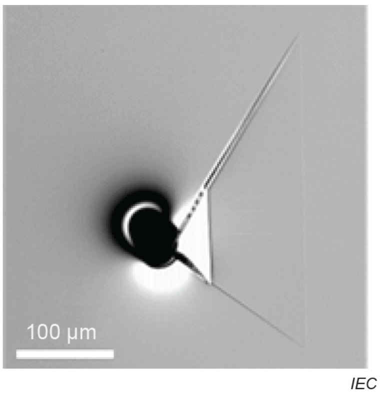
NOTE 3 Subfigure 9 d) was obtained in a wavelength range from 750 nm to 1 100 nm.



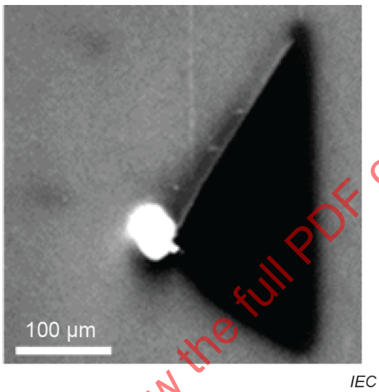
a) Schematic illustration of polytype inclusion



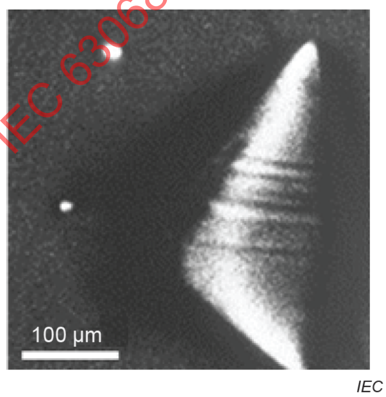
b) Plan-view observation image



c) Bright-field OM image



d) PL image



e) XRT image

Key

1 Epitaxial layer

2 Substrate

3 Lamellar inclusion

4 Particle

Figure 9 – Polytype inclusion

4.2.12 Particle inclusion

The class of particle inclusion means a macroscopic size particle existing within or extending beyond the homoepitaxial layer. The crystal structure of the particles is usually 3C. Plan-view observation images of particle inclusion are shown in Figure 10.

NOTE 1 This defect is often referred to as “down-fall”.

NOTE 2 Subfigure 10 d) was obtained in a wavelength range from 750 nm to 1 100 nm.