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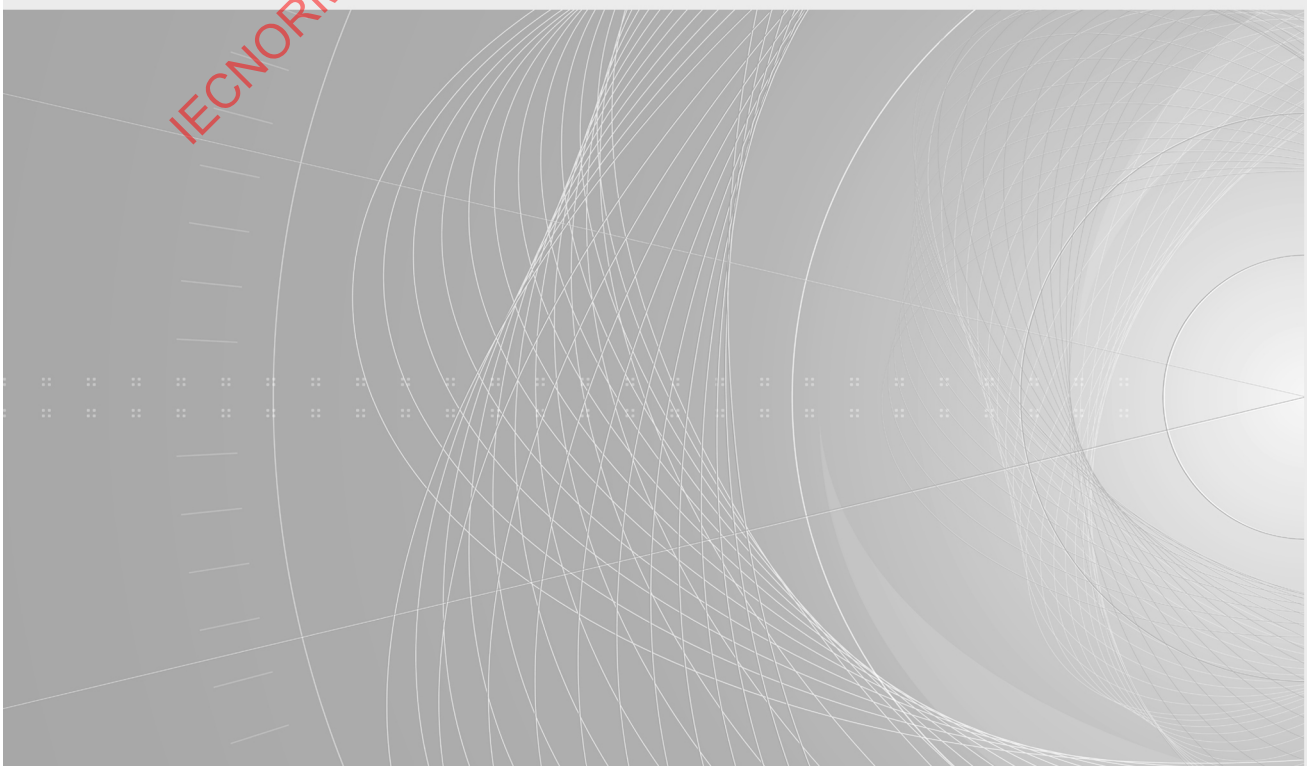
INTERNATIONAL STANDARD

Semiconductor devices – Non-destructive recognition criteria of defects in silicon carbide homoepitaxial wafer for power devices –
Part 2: Test method for defects using optical inspection



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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CONTENTS

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

Part 2: Test method for defects using optical inspection

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International Standard IEC 63068-2 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
47/2475/CDV	47/2522A/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- withdrawn,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. These 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 some issues including high costs, low yield, and low long-term reliability. In particular, one of the serious issues lies in the defects existing in SiC homoepitaxial wafers. Although efforts of decreasing defects in SiC homoepitaxial wafers are actively implemented, there are a number of defects 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. This document provides definitions and guidance in use of optical inspection for detecting defects in commercially available silicon carbide (SiC) homoepitaxial wafers.

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 2: Test method for defects using optical inspection

1 Scope

This part of IEC 63068 provides definitions and guidance in use of optical inspection for detecting as-grown defects in commercially available 4H-SiC (Silicon Carbide) epitaxial wafers. Additionally, this document exemplifies optical images to enable the detection and categorization of the defects for SiC homoepitaxial wafers.

This document deals with a non-destructive test method for the defects so that destructive methods such as preferential etching are out of scope in this document.

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
optical inspection
morphological inspection of wafers using optical imaging where an optical image sensor scans the wafer surface under a non-contact test method for obtaining features of defects, e.g. size and shape of defects

3.2
optical imaging
technique for capturing, processing and analysing images of defects using light source for illumination, optical components, optical image sensor and computer systems

3.3
illumination
application of light to defects and their surroundings so that they can be observed

3.4
reflective illumination
illumination for observing the reflected light from defects by irradiating light onto the wafer surface

3.5
directional lighting
lighting in which the light to the wafer is incident from a particular direction

3.6
diffused lighting
lighting in which the irradiation direction of the light to the wafer is random

3.7
bright-field observation
method of image capturing in which an optical image sensor detects both lights reflected and scattered from defects

3.8
dark-field observation
method of image capturing in which an optical image sensor detects only light scattered from defects

3.9
differential interference contrast observation
method of image capturing in which contrast derives from the difference in optical path between adjacent points on the wafer surface by irradiating two orthogonal polarized lights which are spatially displaced

3.10
polarized light observation
method of image capturing in which an optical image sensor detects a polarized light using polarizing plates in a path from defects by irradiating polarized light

3.11
optical image sensor
device to transform an optical image into digital data

3.12
optical component
lenses, mirrors, filters and other components, which comprise an optical system and are used to capture optical images

3.13
image capturing
process of creating a two-dimensional original digital image of defects on the wafer surface

3.14
original digital image
digitized image taken by an optical image sensor, without performing any image processing

Note 1 to entry: Original digital images are divided into pixels by a grid, and one grey level is assigned to each pixel.

3.15
charge-coupled device
CCD
light-sensitive integrated circuit that stores and displays the data for optical images

Note 1 to entry: CCD chips are subdivided into fine elements, each of which corresponds to a pixel of original digital images.

3.16
pixel
smallest formative element of original digital images, to which a grey level is assigned

3.17
resolution
number of pixels per unit length (or area) of original digital images

Note 1 to entry: If resolutions in the X- and Y- directions are different, both values have to be recorded.

3.18
grey level
shade of grey assigned to each pixel

Note 1 to entry: Shade of grey is usually a positive integer taken from grey scale.

3.19
grey scale
range of grey shades from black to white

EXAMPLE: 8-bit grey scale has two-to-the-eighth-power (= 256) grey levels. Grey level 0 (the 1st level) corresponds to black, grey level 255 (the 256th level) to white.

3.20
image processing
software manipulation of original digital images to prepare for subsequent image analysis

Note 1 to entry: For example, image processing can be used to eliminate mistakes generated during image capturing or to reduce image information to the essential.

3.21
binary image
image in which either 0 (black) or 1 (white) is assigned to each pixel

3.22
brightness
average grey level of a specified part of optical images

3.23
contrast
difference between the grey levels of two specified parts of optical images

3.24
shading correction
software method for correcting non-uniformity of the illumination over the wafer surface

3.25
thresholding
process of creating a binary image out of a grey scale image by setting exactly those pixels whose value is greater than a given threshold to white and setting the other pixels to black.

Note 1 to entry: To make a binary image, grey level 0 (black) or 1 (white) is assigned to each pixel in the grey-scale image, depending on whether the pixel indicates a grey level greater than or less than or equal to a given threshold.

3.25.1
edge detection
method of isolating and locating edges of defects and surface features in a given digital image

3.26
image analysis
extraction of imaging information from processed digital images by software

3.27
image evaluation
process of relating a series of values resulting from image analysis of one or more characteristic images via a classification scheme of defects

3.28
reference wafer
specified wafer used for parameter settings, which has already been evaluated for checking the reproducibility and repeatability of optical inspection process for defects

3.29
test wafer
SiC homoepitaxial wafers provided to evaluate defects

3.30
crystal direction
direction, usually denoted as [*uvw*], representing a vector direction in multiples of the basis vectors describing the *a*, *b* and *c* crystal axes

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

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

3.31
defect
crystalline imperfection

3.32
micropipe
hollow tube extending approximately normal to the basal plane

3.33
threading screw dislocation
TSD
screw dislocation penetrating through the crystal approximately normal to the basal plane

3.34
threading edge dislocation
TED
edge dislocation penetrating through the crystal approximately normal to the basal plane

3.35
basal plane dislocation
BPD
dislocation lying on the basal plane

3.36
scratch trace
dense low of dislocations caused by mechanical damages on the substrate surface

3.37
stacking fault
planar crystallographic defect in monocrystalline material, characterized by an error in the stacking sequence of crystallographic planes

3.38
propagated stacking fault
stacking fault propagating from substrate toward the homoepitaxial layer surface

3.39
stacking fault complex
stacking fault complex consisting of a basal plane stacking fault and a prismatic fault

3.40
polytype inclusion
volume crystal defect showing different polytypes from that of the homoepitaxial layer

3.41
particle inclusion
macroscopic size particle existing in the homoepitaxial layer

3.42
bunched-step segment
surface morphological roughness consisting of bunched-steps

3.43
surface particle
particle deposited on the epitaxial layer surface after epitaxial growth

4 Optical inspection method

4.1 General

Defects with surface morphological features shall be detected by optical inspection method. The following descriptions concern such defects in n/n+-type 4H-SiC homoepitaxial wafers with an off-cut angle of 4° along the direction of [11$\bar{2}$0]:

– individual defects exhibiting hexagonal-shaped or round-shaped large holes on the wafer surface, e.g. micropipe (Figure A.1);
– individual minute defects giving rise to a pit less than 50 µm in diameter on the wafer surface, e.g. TSD (Figure A.2), TED (Figure A.3);
– individual linear defects extending in various directions, e.g. scratch trace (Figure A.4);
– individual planar defects providing needle-shaped features on the wafer surface, which extend along the off-cut direction, e.g. stacking fault complex (Figure A.7);
– individual planar defects providing faintly-outlined features on the wafer surface, which extend diagonally to the off-cut direction, e.g. stacking fault (Figure A.5), propagated stacking fault (Figure A.6);
– individual volume defects giving rise to triangle-shaped features on the wafer surface, which extend along the off-cut direction, e.g. polytype inclusion (Figure A.8);
– individual volume defects, e.g. particle inclusions (Figure A.9), surface particle;
– individual surface defects exhibiting obtuse triangle-shaped or trapezoid-shaped features on the wafer surface, e.g. bunched-step segment (Figure A.10).

Defects without surface morphological features should be evaluated by other test methods such as photoluminescence and X-ray topography. Those defects include BPDs, TSDs

without surface morphological features, TEDs without surface morphological features, stacking faults without surface morphological features, and propagated stacking faults without surface morphological features.

4.2 Principle

A grey scale image (or colour image) is produced from the original digital image of defects on the wafer surface. This image is converted into a binary image (thresholding). The size and shape of defects are measured, and the distribution and number of defects within a specified area of wafer are calculated.

First, an optical image of defects has to be captured and transformed into a digital format. An optical image is captured via an optical image sensor such as a charge-coupled device. Then, the obtained digital image is processed by manipulating the grey levels of the image. Through a specified scheme of image analysis, the image information is reduced to a set of values which are specific to the application.

NOTE The size of planar and volume defects extending along the off-cut direction depends on the thickness of homoepitaxial layer. Details of such defects and the method of estimating the size of their optical images are described in 4.6.2 and Annex A, respectively.

4.3 Requirements

4.3.1 Illumination

4.3.1.1 Types of observations

Different wafer surface conditions and defect types will require an optimum setup of optics and illumination to acquire distinct surface features in an image that are to be analysed. Therefore, a combination of optics and illumination for a specific application has to be prepared. Generally, the following types of lightings and observations are used.

a) Types of lightings are:
   1) directional lighting;
   2) diffused lighting;
   3) mixture of directional and diffused lightings.
b) Types of observations are:
   1) bright-field observation;
   2) dark-field observation;
   3) differential interference contrast observation;
   4) polarized light observation.

All the types of observations can be done under reflective illumination. Influences from wafer backsides shall be eliminated in any observations.

4.3.1.2 Uniformity and constancy

A combination of light source and optical components is used to achieve sufficient uniformity of the illuminance on the wafer surface. The illuminance at each point to be inspected on the wafer surface is adjusted in an appropriate range so that defects are clearly detected. Illumination uniformity can be achieved using hardware and/or software.

The illuminance and spectral – power distribution are kept constant during the whole measurement period.

4.3.2 Wafer positioning and focusing

Wafers shall be positioned in the plane of two mutually perpendicular axes X and Y. The third axis (Z) is the optical axis of image capturing system. The Z-axis is perpendicular to the X-Y plane and its point of intersection with the wafer surface shall be the point of focus. The distance between the front-end portion of image-capturing optics and the wafer surface shall be constant, independent of the thickness of the wafers, so that focussing and magnification are not mutually adversely affected.

4.3.3 Image capturing

The optical system is typically composed of a light source, focussing optics, optical digital sensor, lighting-geometry adjustment system, wafer support and light-tight enclosure. The resolution of the optical system shall be much smaller than the sizes of defects for capturing of distinct defect images. The recommended range of grey scale for an original digital image is 256 grey levels (8-bit) for each pixel. The image information is digitized directly within the optical digital sensor unit. The system shall also be protected against interference by external illumination using a dark box or a rack housing.

To ensure the repeatability and reproducibility of the image capturing procedure, parameter settings shall be carried out at a regular interval. This can be performed using specified reference wafers, for example, silicon or silicon carbide wafers.

4.3.4 Image processing

The image processing covers numerous features such as brightness, contrast, edge detection, shading correction, and inversion.

– Different software solutions should employ different mathematical algorithms for similar operations, and processed images produced by different image-processing algorithms will not be identical. Parameter settings, e.g. using reference wafers, is performed to ensure that results are comparable.

4.3.5 Image analysis

Two different methods are used for image analysis: binary (black / white) analysis and grey-level analysis. To obtain a binary image from a grey-level image, the threshold procedure is used.

As in image processing, an automatic image analysis requires a number of sequential steps for defect analysis. An algorithm is selected for each specific application.

4.3.6 Image evaluation

The result of image analysis is a set of values which are pertinent to a specific application. This set of values is transformed into one or more characteristic values via a classification scheme of defects.

4.3.7 Documentation

Relevant parameters for illumination, image capturing, image processing and image analysis should be documented. These comprise:

a) for the illumination: light source used and lighting geometry;

b) for the image capturing: original digital image and details of the image capturing system (manufacturer, product name, optical components, resolution), image size, range of grey levels;

c) for the image processing and image analysis: procedures used (including details of filters) and details of the software used (manufacturer and product name).

4.4 Parameter settings

4.4.1 General

Test wafers shall be compared with reference wafers.

The purpose of parameter settings is to fix the image capturing parameters in such a way that image analysis will be possible to identify the surface features of defects in test wafers by using reference wafers. A visual comparison is performed to confirm the correspondence between the reference wafers and test wafers with regard to the detected defect.

The reference wafers should be as similar as possible to the test wafers on the structure and specification; thus it is desirable to prepare both the reference wafers and the test wafers in the same laboratory or factory, using the same equipment and process.

4.4.2 Parameter setting process

Execute the parameter settings as described below using a set of reference wafers.

Take an image of each defect on the test wafer using a selected optical imaging system. The images of defects on the test wafer shall be visually compared with those of reference wafers.

4.5 Procedure

Prepare test wafers for optical imaging as follows.

Create images of test wafers using a parameter-optimised optical imaging system. Once suitable threshold values are established, digitized image provides, on analysis, contrasts pertinent to the surface features of defects.

4.6 Evaluation

4.6.1 General

In contrast to manual assessment of defects, optical inspection can determine directly the size and shape of any defects (see in Annex A).

The result of the image analysis is recorded data to which defects are assigned. The edge exclusion of test wafers should be less than 5 mm.

4.6.2 Mean width of planar and volume defects

With the known thickness of homoepitaxial layer d, in micrometres, and an off-cut angle of 4°, calculate the mean width l, in micrometres, parallel to the off-cut direction, of planar and volume defects except particle inclusions and surface particles using the following formula:

$$l = \frac{d}{\tan(4°)}$$

For example, values of the mean width l of defects for 10 μm and 30 μm thickness homoepitaxial layers are approximately 145 μm and 430 μm, respectively.

When planar and volume defects are formed in the middle of epitaxial growth, the defect width is less than given by the above formula.

4.6.3 Evaluation process

If recognized objects are extended defects or surface defects, a number of all such defects shall be counted with respect to each one in the evaluation.

Defect maps, which indicate the positions of detected defects across the entire wafer surface, shall be formed. In the maps, the position of the orientation flat or notch of the wafer should also be indicated. The coordinate origin of the map should be the centre of the wafer.

4.7 Precision

Information on the precision of this test method is currently not available.

4.8 Test report

A test report should contain at least the following information:

a) inspection results:
   1) defect maps;
   2) total number of each detected defect;
   3) positions of all detected defects;
b) all information necessary for identification of test wafers (manufacturer, trade name, batch number, wafer specification, etc.);
c) reference to this part of IEC 63068;
d) image capturing system (manufacturer, trade name, etc.);
e) illumination type (type and configuration of light source);
f) image capturing setup used, including details of the:
   1) original digital image;
   2) image capturing system;
   3) resolution, image size;
   4) grey scale,
g) details of the image processing and analysis, including all the processing procedures used, if available;
h) result of the test, as specified in 4.6 (“Evaluation”);
i) any deviations from the procedure specified;
j) any unusual features (anomalies) observed during the test;
k) date and time of the test;
l) name of the person who carried out the test.

Annex A
(informative)

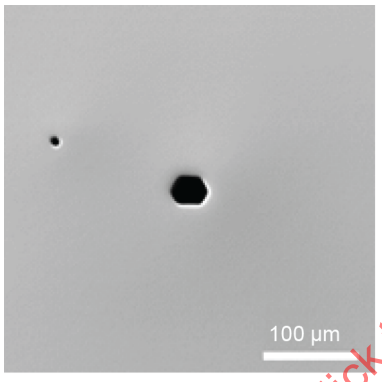
Optical inspection images of defects

A.1 General

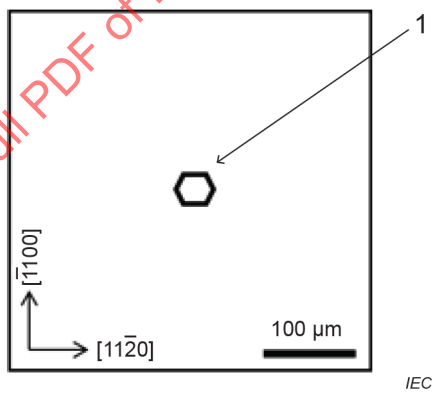
Annex A shows typical images and features of defects in 4H-SiC homoepitaxial wafers (epitaxial layer thickness: 10 μm) acquired by means of bright-field differential interference contrast observation under reflective illumination (light source: Hg-Xe lamp). The pixel resolution of the images is 2 μm. In Figures A.1 to A.10, the subfigures in the left and right columns denote a bright-field optical microscope (OM) image and a schematic illustration of the plan-view observation image of defect, respectively.

A.2 Micropipe

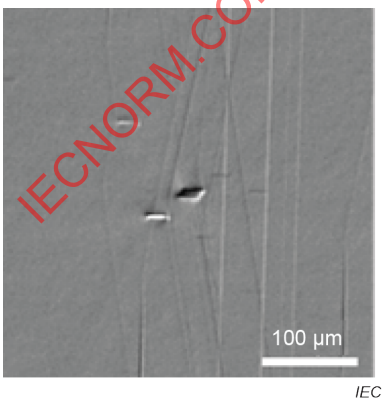
Micropipes exhibit characteristic morphological features on the 4H-SiC homoepitaxial layer surface: for example, holes and/or pits of various shapes.



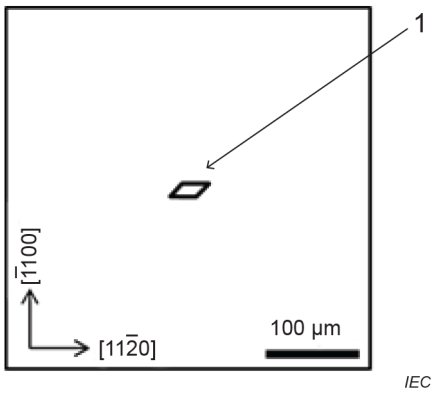
a) Example 1 of micropipe: Bright-field OM image



b) Example 1 of micropipe: Plan-view observation image



c) Example 2 of micropipe: Bright-field OM image



d) Example 2 of micropipe: Plan-view observation image

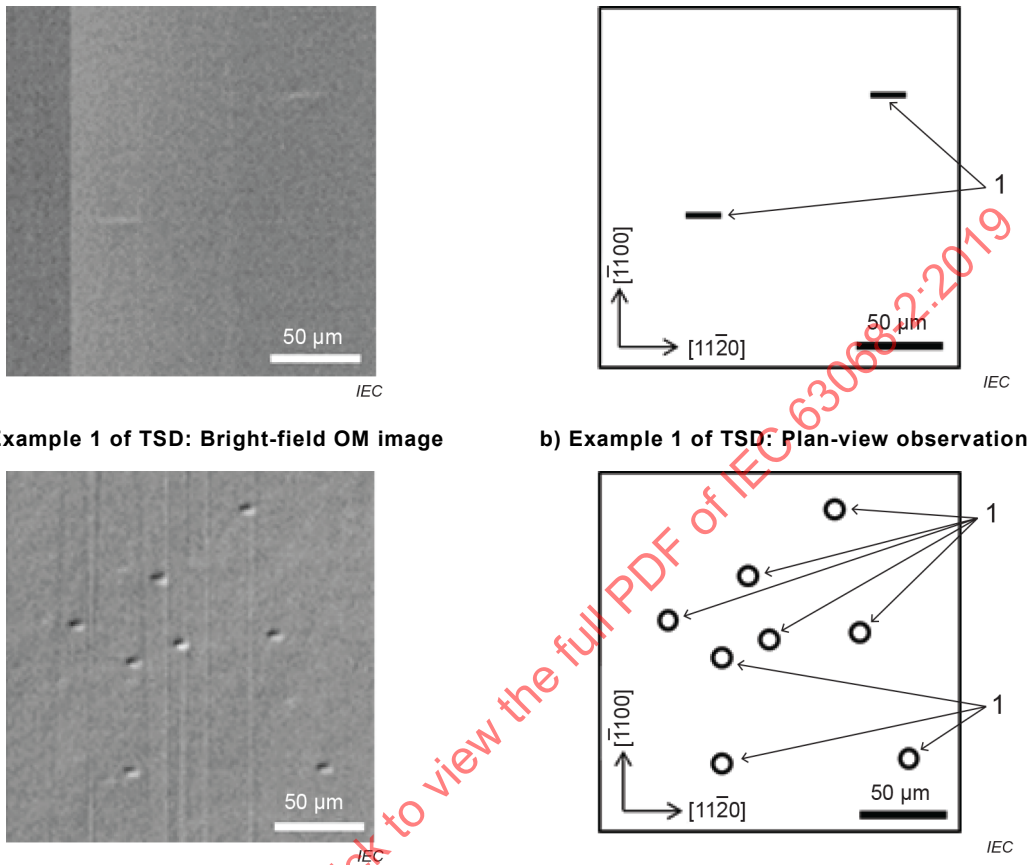
Key

1 Micropipe

Figure A.1 – Micropipe

A.3 TSD

TSDs often exhibit characteristic morphological features on the 4H-SiC homoepitaxial layer surface: for example, pits of various shapes. TSDs without surface features should be evaluated by a test method using photoluminescence.



a) Example 1 of TSD: Bright-field OM image

b) Example 1 of TSD: Plan-view observation image

c) Example 2 of TSD: Bright-field OM image

d) Example 2 of TSD: Plan-view observation image

Key

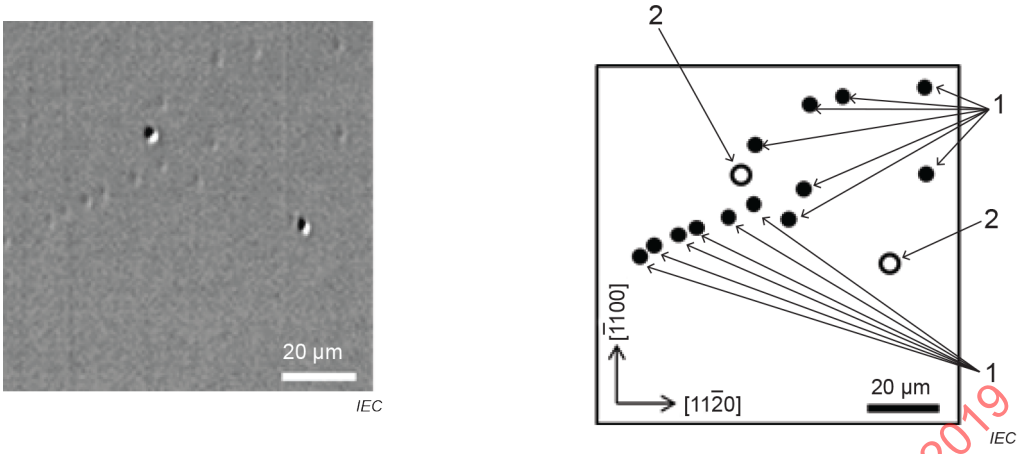
1 TSD

Figure A.2 – TSD

A.4 TED

TEDs occasionally exhibit characteristic morphological features on the 4H-SiC homoepitaxial layer surface: for example, pits of various shapes. TEDs without surface features should be evaluated by a test method using photoluminescence.

NOTE Since TEDs and TSDs are observed simultaneously in most cases, subfigures A.3 a) and b) include both TEDs and TSDs.



a) Bright-field OM image **b) Plan-view observation image**

Key

1 TED

2 TSD

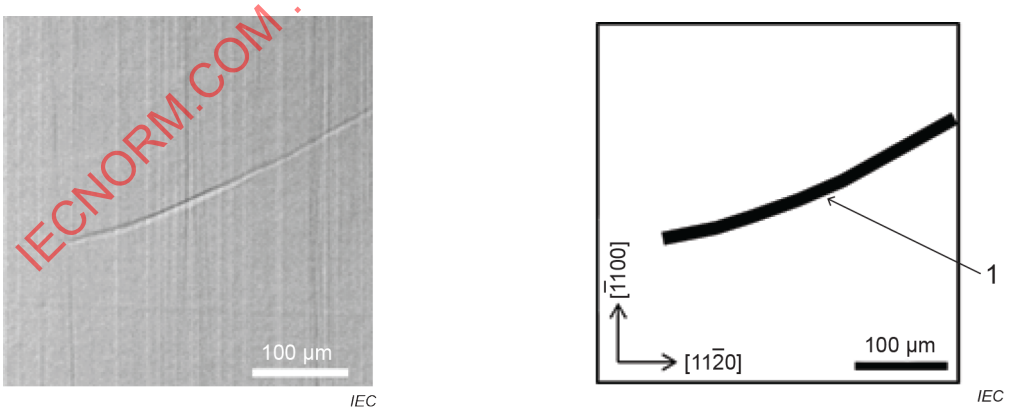
Figure A.3 – TED

A.5 BPD

BPDs cause no morphological features on the 4H-SiC homoepitaxial layer surface. BPDs should be evaluated by a test method using photoluminescence.

A.6 Scratch trace

Scratch traces exhibit characteristic morphological features on the 4H-SiC homoepitaxial layer surface: for example, scratch-like random line morphologies.



a) Bright-field OM image **b) Plan-view observation image**

Key

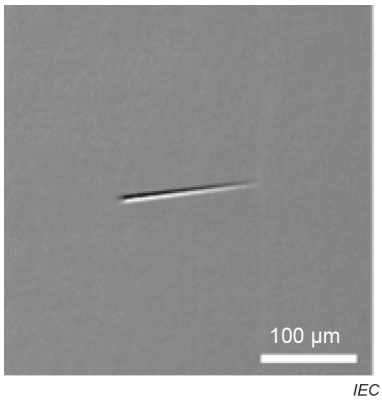
1 Scratch

Figure A.4 – Scratch trace

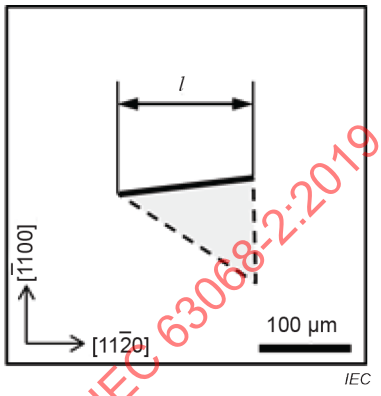
A.7 Stacking fault

Stacking faults often exhibit characteristic morphological features on the 4H-SiC homoepitaxial layer surface: for example, faintly-outlined triangles. Stacking faults without surface features should be evaluated by a test method using photoluminescence.

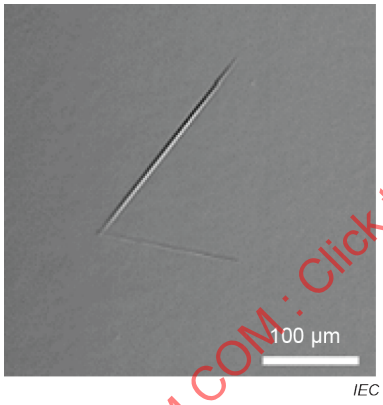
NOTE The mean width l, in micrometres, of this type of defects depends on the thickness d, in micrometres, of homoepitaxial layer (see 4.6.2).



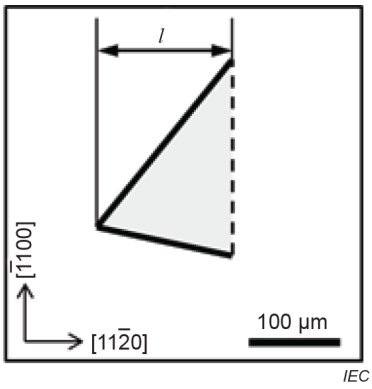
a) Example 1 of stacking fault: Bright-field OM image



b) Example 1 of stacking fault: Plan-view observation image



c) Example 2 of stacking fault: Bright-field OM image



d) Example 2 of stacking fault: Plan-view observation image

Figure A.5 – Stacking fault

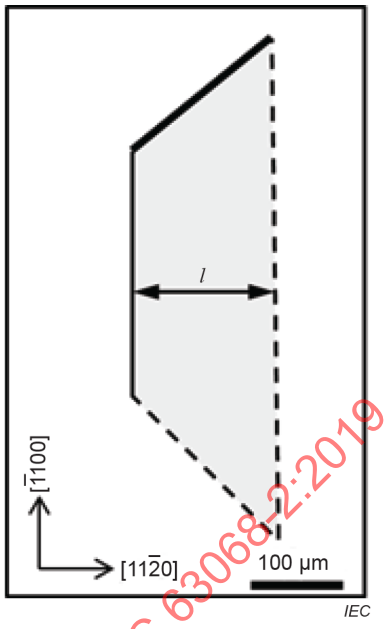
A.8 Propagated stacking fault

Propagated stacking faults often exhibit characteristic morphological features on the 4H-SiC homoepitaxial layer surface: for example, faintly-outlined trapezoids elongated along the direction perpendicular to the off-cut direction. Propagated stacking faults without surface features should be evaluated by a test method using photoluminescence.

NOTE 1 The mean width l, in micrometres, of this type of defects depends on the thickness d, in micrometres, of homoepitaxial layer (see 4.6.2).

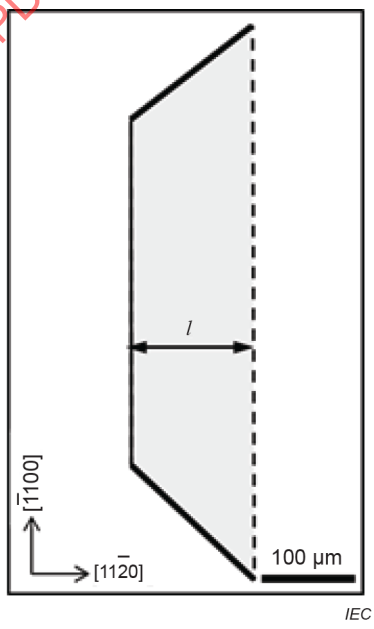
NOTE 2 These defects are often referred to as “bar-shaped stacking fault”.

a) Example 1 of propagated stacking fault: Bright-field OM image



b) Example 1 of propagated stacking fault: Plan-view observation image

c) Example 2 of propagated stacking fault: Bright-field OM image



d) Example 2 of propagated stacking fault: Plan-view observation image

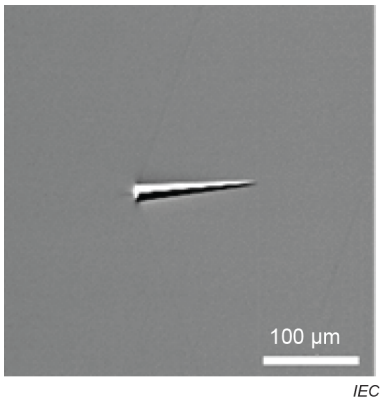
Figure A.6 – Propagated stacking fault

A.9 Stacking fault complex

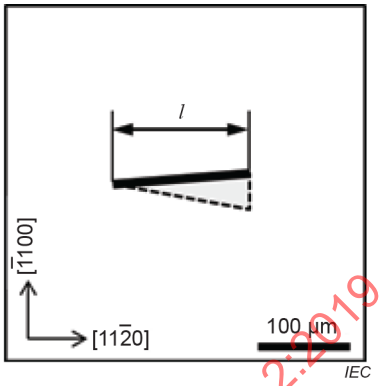
Stacking fault complexes exhibit characteristic morphological features on the 4H-SiC homoepitaxial layer surface: for example, needle-shaped features extending along the off-cut direction. Stacking faults complexes without surface features should be evaluated by a test method using photoluminescence.

NOTE 1 The mean width l, in micrometres, of this type of defects depends on the thickness d, in micrometres, of homoepitaxial layer (see 4.6.2).

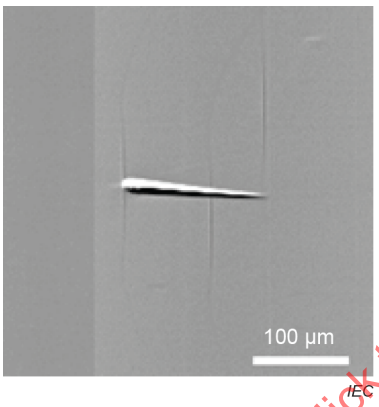
NOTE 2 These defects are often referred to as “carrot defect”.



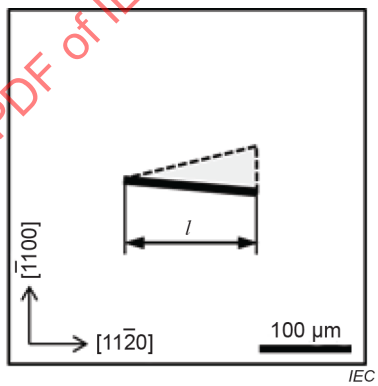
a) Example 1 of stacking fault complex: Bright-field OM image



b) Example 1 of stacking fault complex: Plan-view observation image



c) Example 2 of stacking fault complex: Bright-field OM image



d) Example 2 of stacking fault complex: Plan-view observation image

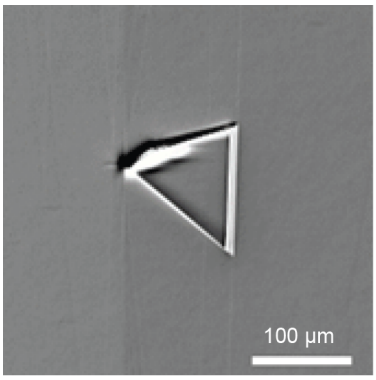
Figure A.7 – Stacking fault complex

A.10 Polytype inclusion

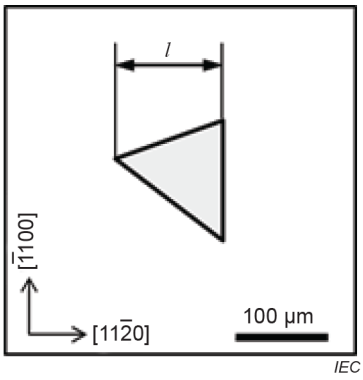
Polytype inclusions exhibit characteristic morphological features on the 4H-SiC homoepitaxial layer surface: for example, triangles of various shapes extending along the off-cut direction.

NOTE 1 The mean width l, in micrometres, of this type of defects depends on the thickness d, in micrometres, of homoepitaxial layer (see 4.6.2).

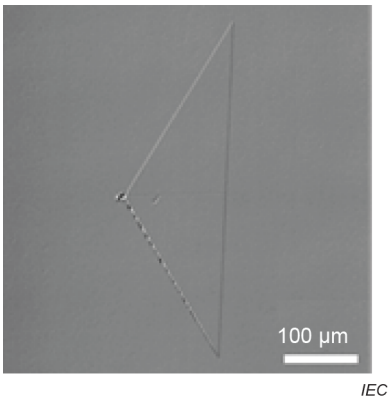
NOTE 2 These defects are often referred to as “triangular inclusion”, “triangular defect”, or “comet tail defect”.



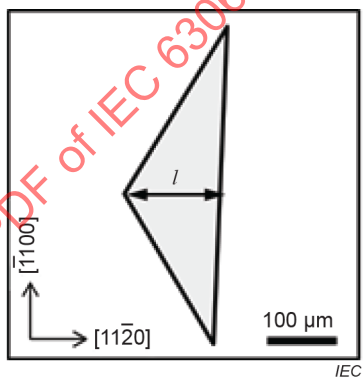
a) Example 1 of polytype inclusion: Bright-field OM image



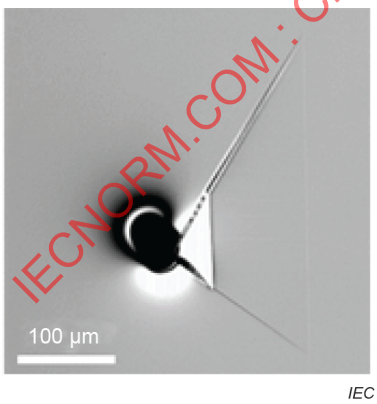
b) Example 1 of polytype inclusion: Plan-view observation image



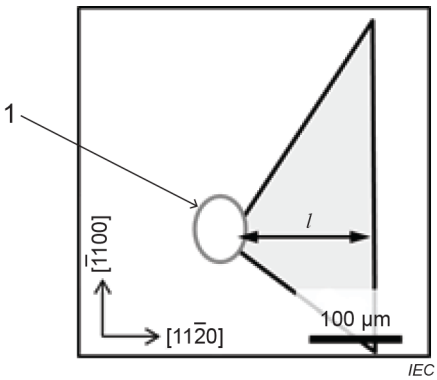
c) Example 2 of polytype inclusion: Bright-field OM image



d) Example 2 of polytype inclusion: Plan-view observation image



e) Example 3 of polytype inclusion: Bright-field OM image



f) Example 3 of polytype inclusion: Plan-view observation image

Key

1 Particle

Figure A.8 – Polytype inclusion