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Semiconductor devices – Non-destructive recognition criteria of defects in silicon carbide homoepitaxial wafer for power devices –
Part 3: Test method for defects using photoluminescence

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Dispositifs à semiconducteurs – Critères de reconnaissance non destructifs des défauts au sein d'une plaquette homoépitaxiale de carbure de silicium pour des dispositifs d'alimentation –
Partie 3: Méthode d'essai pour les défauts à l'aide de la photoluminescence

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

Part 3: Test method for defects using photoluminescence

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

FDIS	Report on voting
47/2628/FDIS	47/2638/RVD

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.

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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 photoluminescence 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

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

Part 3: Test method for defects using photoluminescence

1 Scope

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

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

3.1
photoluminescence
PL
emission of light from materials as a subsequence of electronic excitation by absorption of photons

3.2
photoluminescence imaging
PL imaging
technique for capturing, processing and analysing images of defects using light source for electronic excitation, focusing optics, optical filter, optical image sensor and computer systems

3.3
focusing optics
lens system used for magnifying and capturing optical images

3.4
optical filter
optical component designed to transmit only a specific wavelength region and to block other regions

3.5
optical image sensor
device to transform an optical image into digital data

3.6
image capturing
process of creating a two-dimensional original digital image of defects in the wafer

3.7
original digital image
digitized image acquired by an optical image sensor, without performing any image processing

Note 1 to entry: An original digital image consists of pixels divided by a grid, and each pixel has a grey level.

3.8
charge-coupled device image sensor
CCD image sensor
light-sensitive integrated circuit chip that converts detected optical information to electrical signals

Note 1 to entry: A CCD consists of fine elements, each of which corresponds to a pixel of original digital images.

3.9
pixel
smallest formative element of original digital images, to which a grey level is assigned

3.10
resolution
number of pixels per unit length (or area) of original digital images

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

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3.11
spatial resolution
ability to distinguish two closely spaced points as two independent points

3.12
grey level
degree of brightness defined in a greyscale

Note 1 to entry: Degree of brightness is usually represented as a positive integer taken from greyscale.

3.13
greyscale
range of grey shades from black to white

EXAMPLE 8-bit greyscale 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.

3.14
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.

3.15
binary image
image in which either 0 (black) or 1 (white) is assigned to each pixel

3.16
brightness
average grey level of a specified part of optical images

3.17
contrast
difference between the grey levels of two specified parts of optical images

3.18
shading correction
software method for correcting non-uniformity of the illumination over the wafer surface

3.19
thresholding
process of creating a binary image out of a greyscale 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, the grey level of each pixel in the original greyscale image is replaced with 0 (black) or 1 (white), depending on whether the grey level is greater than or less than or equal to a given threshold.

3.20
edge detection
method of isolating and locating edges of defects and surface features in a given digital image

3.21
image analysis
extraction of imaging information from processed digital images by software

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3.22
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

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3.23
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

3.24
test wafer
semiconductor wafer under test to evaluate defects

3.25
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 [1][1], 3.3, modified – The original note has been replaced by a new note to entry.]

3.26
defect
crystalline imperfection

1 Numbers in square brackets refer to the Bibliography.

3.27
micropipe
hollow tube extending approximately normal to the basal plane

3.28
threading screw dislocation
TSD
screw dislocation penetrating through the crystal approximately normal to the basal plane

3.29
threading edge dislocation
TED
edge dislocation penetrating through the crystal approximately normal to the basal plane

3.30
basal plane dislocation
BPD
dislocation lying on the basal plane

3.31
scratch trace
dense row of dislocations caused by mechanical damages on the substrate surface

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

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3.33
propagated stacking fault
stacking fault propagating from substrate toward the homoepitaxial layer surface

3.34
stacking fault complex
stacking fault complex consisting of a basal plane stacking fault and a prismatic fault

3.35
polytype inclusion
volume crystal defect showing different polytypes from that of the homoepitaxial layer

3.36
particle inclusion
macroscopic size particle existing in the homoepitaxial layer

3.37
bunched-step segment
surface morphological roughness consisting of bunched-steps

3.38
surface particle
particle deposited on the epitaxial layer surface after epitaxial growth

4 Photoluminescence method

4.1 General

Defects with characteristic PL features shall be evaluated by PL 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 $[11\bar{2}0]$, where their PL images are obtained by detecting emission wavelengths longer than 650 nm:

– individual linear defects exhibiting bright line images, e.g. BPDs;

– individual planar defects exhibiting dark contrast images, e.g. stacking faults, propagated stacking faults, stacking fault complexes, and polytype inclusions.

When emission wavelengths from 400 nm to 500 nm are used for the defect detection, stacking faults exhibit bright contrast images.

Defects without characteristic PL features or with weak PL contrasts against SiC area with no defects should be evaluated by other test methods such as optical inspection and X-ray topography. Those defects include micropipes, TSDs, TEDs, scratch traces, particle inclusions, bunched-step segments, and surface particles.

4.2 Principle

PL images of defects are captured and transformed into a digital format. In the course of this process, an SiC homoepitaxial wafer is irradiated with excitation light whose energy is greater than the bandgap of 4H-SiC crystals, and the resulting PL is collected and recorded as a PL image of a specified area of the wafer including defects. PL is detected using an optical image sensor such as a CCD image sensor, and PL image is usually acquired using an optical filter which transmits a specific range of PL appropriate for the detection of each type of defect. Then, the obtained PL image (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 detected defects.

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A greyscale image is produced from the original digital image of defects in the wafer. This image can be 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.

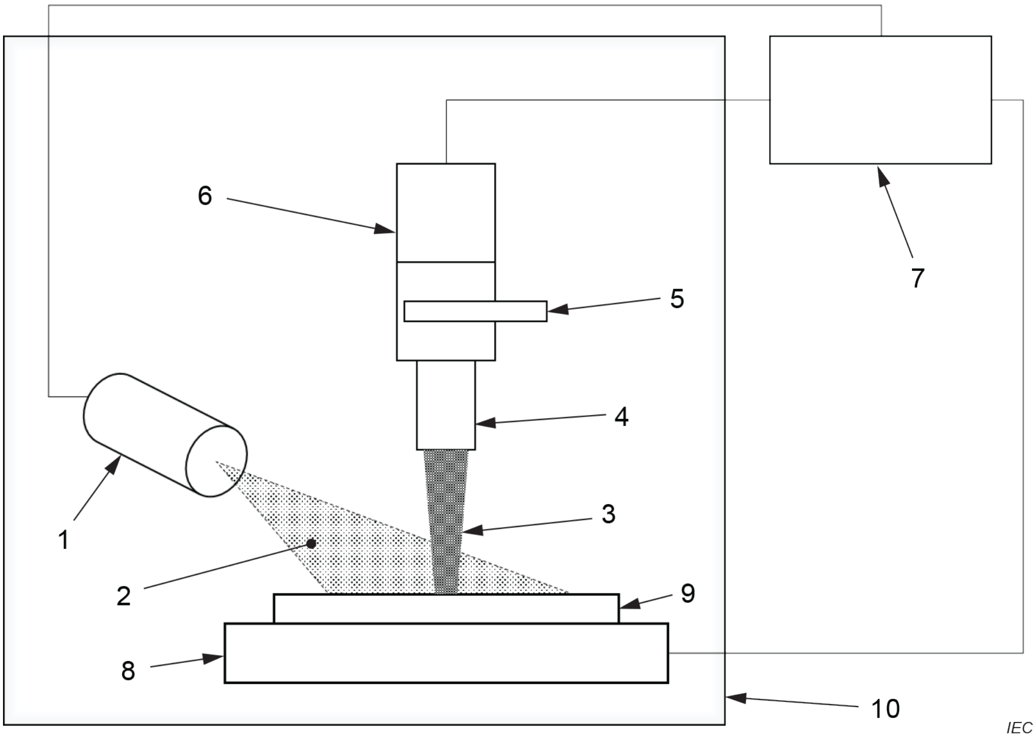
NOTE The size of planar and volume defects extending along the off-cut direction depends on the thickness of homoepitaxial layer. Details of such defects and the method of estimating the size of their PL images are described in Annex A and 4.6.2, respectively.

4.3 Requirements

4.3.1 Measuring equipment

4.3.1.1 PL imaging system

Measuring equipment for PL imaging of defects in 4H-SiC homoepitaxial wafers is shown in Figure 1. The measuring equipment consists of light source, focusing optics, optical filter, CCD, wafer stage, controller/processor, and dark box. Each component shall have the performance specified below. Different wafer specifications and defect types will require an optimum setup of light source, focusing optics and optical filter to acquire distinct PL features that are to be analysed. Therefore, a combination of light source, focusing optics and optical filter for a specific application needs to be prepared.



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Key

1 light source

2 excitation light

3 photoluminescence

4 focusing optics

5 optical filter

6 CCD

7 controller/processor

8 wafer stage

9 test wafer or reference wafer

10 dark box or rack housing

Figure 1 – Schematic diagram of PL imaging system

4.3.1.2 Light source

A gas discharge lamp, such as a mercury-xenon lamp, and diode lasers with a specific emission wavelength are used as a typical source of photons for electronic excitation. When a white light from a gas discharge lamp is used for electronic excitation, suitable optical filters for the light source shall be used to obtain excitation light with a suitable wavelength band for PL imaging. The suitable wavelength of excitation light shall be selected to be equal to or greater than the bandgap energy of 4H-SiC. For example, an emission line of 313 nm or 365 nm from a mercury-xenon lamp is suitable for electronic excitation of 4H-SiC.

4.3.1.3 Objective lens

Objective lens should be selected to adjust the inspection area and the depth of focus to eliminate the influence from wafer backside.

4.3.1.4 Optical filter

Optical filters shall be selected to suit the inspection for specified defects in homoepitaxial wafers.

NOTE Typical PL spectra of defects are described in Annex B.

4.3.1.5 Uniformity and constancy

A combination of light source and focusing optics should be optimized to achieve sufficient uniformity of the excitation light intensity on the wafer surface. The PL intensity at each point on the epitaxial layer is adjusted in an appropriate range so that defects are clearly detected. Uniformity of excitation light intensity can be achieved using hardware and/or software.

The spectral and power distributions of the excitation light are maintained constant during the whole measurement period.

4.3.2 Wafer positioning and focusing

Wafers shall be positioned in the plane of Cartesian coordinate system (X–Y) or cylindrical coordinate system (R–θ). The third axis (Z) is the optical axis of image capturing system. The Z-axis is perpendicular to the plane and its point of intersection with the plane 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 focusing and magnification are not mutually adversely affected.

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4.3.3 Image capturing

The PL imaging system is typically composed of a light source, focusing optics, CCD image sensor as an optical digital sensor, lighting-geometry adjustment system, wafer stage and light-tight enclosure. A dark box or a rack housing is often used to prevent the interference by external illumination. The spatial resolution of the PL imaging system shall be high enough to capture distinct features of small size defects. The image information is digitized directly within the optical image sensor unit.

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To ensure the repeatability and reproducibility of the image capturing procedure, parameter settings should 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 may employ different mathematical algorithms for similar operations, and images processed by different image-processing algorithms will not be identical. Parameter settings, e.g. using reference wafers, are 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, threshold procedure is used.

An appropriate algorithm should be used for image analysis to detect successfully defects in test wafers.