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Fine ceramics (advanced ceramics, advanced technical ceramics) — Ultraviolet photoluminescence image test method for analysing polytypes of boron- and nitrogen-doped SiC crystals

Céramiques techniques — Méthode d'imagerie de photoluminescence ultraviolette pour l'analyse des polytypes dans les cristaux de SiC dopés à l'azote et au bore

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 206, *Fine ceramics*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Silicon carbide (SiC), which has a close-packed crystal structure, is a promising wide-bandgap (WBG) material applicable to laser diodes (LDs), light-emitting diodes (LEDs) and electronic power devices.

Polytype inclusion generated during SiC growth is a common problem. During crystal growth, many types of SiC-stacking can occur within the bulk of a single sample. These different stacking-order types are called “polytypes.” Polytypes have identical close-packed planes but differ in the stacking sequence on the axis that is perpendicular to these planes.

SiC has more than 200 known polytypes, but most polytypes are rare, except types 2H, 4H, 6H, 15R and 3C. For example, 4H-SiC is the material used for power production in devices because of its excellent physical properties. These SiC polytypes have the same density and Gibbs-free energy but different electronic band structures. The different band structures cause different wavelengths of luminescence induced by incident ultraviolet (UV) light.

SiC can be grown using several crystal-growth techniques, such as physical vapor transport (PVT), chemical vapor deposition (CVD) and top-seeded solution growth (TSSG). Polytype inclusion in bulk SiC is one of the drawbacks during production.

Therefore, a rapid test method to discriminate between polytypes would be useful for the development and mass production of SiC crystals.

This document specifies a test method to evaluate the polytypes and their SiC ratios by UV-induced photoluminescence using non-contact and full-field measurement techniques.

Fine ceramics (advanced ceramics, advanced technical ceramics) — Ultraviolet photoluminescence image test method for analysing polytypes of boron- and nitrogen-doped SiC crystals

1 Scope

This document specifies a test method for determining the polytypes and their ratios in silicon carbide (SiC) wafers or bulk crystals using ultraviolet photoluminescence (UVPL) imaging. The range of SiC is limited to semiconductor SiC doped with nitrogen and boron to have a deep acceptor level and a shallow donor level, respectively. The SiC wafers or bulk crystals discussed in this document typically show electrical resistivities ranging from 10^{-3} ohm · cm to 10^{-2} ohm · cm, applicable to power electronic devices.

This method is applicable to the SiC-crystal 4H, 6H and 15R polytypes that contain boron and nitrogen as acceptor and donor, respectively, at concentrations that produce donor-acceptor pairs (DAPs) to generate UVPL. In 4H-SiC the boron and nitrogen concentrations typically range from 10^{16} cm^{-3} to 10^{18} cm^{-3}. Semi-insulating SiC is not of concern because it usually contains minimal boron and nitrogen; therefore deep level cannot be achieved.

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.

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

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:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
ultraviolet photoluminescence
UVPL
wavelength shifting to a longer wavelength by the interaction of photons with matter

3.2
donor-acceptor pair
DAP
state of a solid in which an electron-hole is created when a photon or other energy is absorbed

3.3
DAP recombination energy
photon energy emitted by the recombination of the *donor-acceptor pair* (3.2)

3.4
ultraviolet photoluminescence image test method
method to identify the polytypes and their ratios using the *donor-acceptor pair recombination energy* (3.3) of materials as the *ultraviolet photoluminescence* (3.1) colour

4 Symbols

Symbol	Designation	Unit
C	velocity of light	299 792 458 m/s
E	bandgap energy (or DAP recombination energy)	eV
H	Planck's constant	$6{,}626\ 070\ 04 \times 10^{-34}$ J·s
I	intensity of the light source	W/cm^2
T	temperature	K
λ	wavelength	nm
ρ	resistivity	Ω.cm
ω	angular velocity	radian/s

5 Principle

When UV light illuminates a material having DAP recombination energy in the visible-light range, the material will emit a specific colour depending on the DAP recombination energy. Thus, the polytypes of SiC can be identified by their luminescence colour because different SiC polytypes have their own DAP recombination energy. The polytype area in CIE 1931 colour space is mapped and transformed from the UVPL image; subsequently, the polytype ratios are calculated.

6 Apparatus

6.1 Stage. The experiment should be performed in a non-vibrational state or on an anti-vibration table to prevent noise caused by vibration.

6.2 Digital camera. This should be a charge-coupled device (CCD) camera with an ISO rating of (500 ± 100), (f/#) of f/1,8–f/3,2 and zero exposure compensation. The shutter speed should be 1/30 to 1/50 and the white balance should be 6 500 K. These are the standard conditions for the UVPL image test, but they can be varied.

The purpose and function of a CCD camera is to produce an image similar to the object recognized by the human eye. This is achieved by synthesizing the image consisting of the artificial fine shapes and colours. It should be noted that the CCD camera is neither a spectra analyser nor a spectra recorder.

Before evaluating the polytype, the CCD camera should be calibrated. The UVPL image captured by the CCD camera should be significantly expanded and carefully checked. If any artificial pattern is observed, the CCD camera should be replaced with another.

6.3 Lens. This is used to focus the incident UV beam onto the specimens. The position and focal length of the lens should be selected for the beam to spread over every sample with uniform intensity.

6.4 Light source. The wavelength (λ) of the UV light source (UVLS) should be 180 nm to 365 nm in the nonvisible range and monochromatic range. The intensity of the light source should be 600 mW/cm^2 or above. The working distance between the sample and the light source should be approximately (10~30) cm. In reflectance mode, adjust the angle (0~360)° between the direction of the light source and the direction normal to the sample to prevent the UV source from being incident directly on the CCD camera and measure only the luminescence beam. In transmission mode, the luminescence beam produced by the sample should be measured using the CCD camera after having been transmitted through the sample.

6.5 Filter. UVLSs can emit a visible beam as well as a UV beam. If the visible beam is incident on the CCD camera, it can disturb the data measurements. Therefore, a bandpass filter that passes only UV beams should be positioned in front of the UVLS.

7 Sampling

7.1 The UVPL technique can be applied to SiC samples grown by various techniques. The necessary condition is to have boron and nitrogen dopant at concentrations that are sufficient to emit the luminescence of the DA pair at an effectively high intensity.

7.2 The flat surface of a sample should be polished finely to improve the measurement accuracy by preventing the UV beam from being scattered for the beam to remain incident directly on the digital camera.

7.3 Should there be any treatment (e.g. polishing) before the test, it shall be recorded in the test report.

8 Procedure

8.1 Cleaning of SiC wafer surface

The samples should be handled in a clean environment, such as a clean-booth or clean-room. The clean surface of a wafer should be maintained. Wiping with a soft tissue soaked with a volatile solvent, such as acetone or ethanol, can render the sample surface free of foreign contaminations, such as dust, other particles, metals, organic compounds, inorganic compounds or moisture. However, if the surface contamination remains and thereby influences the measurements, the sample surface should be wet cleaned in a clean environment, using ultra-high-purity water and chemicals, such as H_2SO_4: H_2O_2: H_2O, NH_4OH: H_2O_2: H_2O, HCl: H_2O_2: H_2O or other suitable chemicals.

Figure 1 shows examples of polytype shapes. Typically, they have clear and sharp lines revealing the grain boundaries.

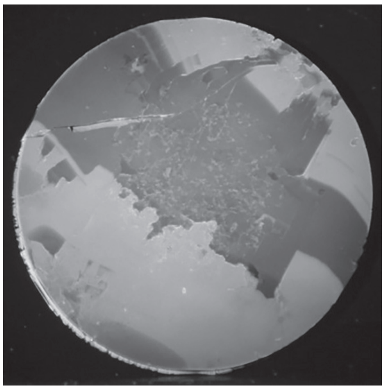


Figure 1 — Crystal grains in UVPL image (clear lines of grain boundary expressing crystal shapes)

8.2 Optical setup

8.2.1 The optical setup should be constructed as shown in Figure 2 a).

8.2.2 The experiment should be performed in a darkroom or with a blackout curtain to prevent extraneous light, which can disturb the UVPL beam.

8.2.3 The experiment should be performed in a non-vibrational state or on an anti-vibration table to prevent noise caused by vibration.

8.2.4 Beam expanders (BEs) should be positioned adjacent to the UVLS to expand the beam.

8.2.5 Optical bandpass filters (BF_1) are positioned after the BE to filter light except in the UV range. The transmittance distribution along the wavelength of BF_1 when it passes only the intended UV light is shown in Figure 2 b).

8.2.6 Support for the sample (SiC) should be positioned such that the UV beam is not incident directly on the CCD camera.

8.2.7 The normal axes of the CCD camera and the SiC sample should coincide to maximize the UVPL intensity.

8.2.8 The photoluminescent beam emitted from the SiC sample incident on the CCD camera should be filtered by a bandpass filter (BF_2) to filter the reflected or scattered UV beam from the SiC sample for only PL light to be incident on the CCD camera. The transmittance distribution along the wavelength when it filters UV-range light is shown in Figure 2 c).

8.2.9 The image taken by the CCD camera should be transformed into colour space.

8.3 Measurement

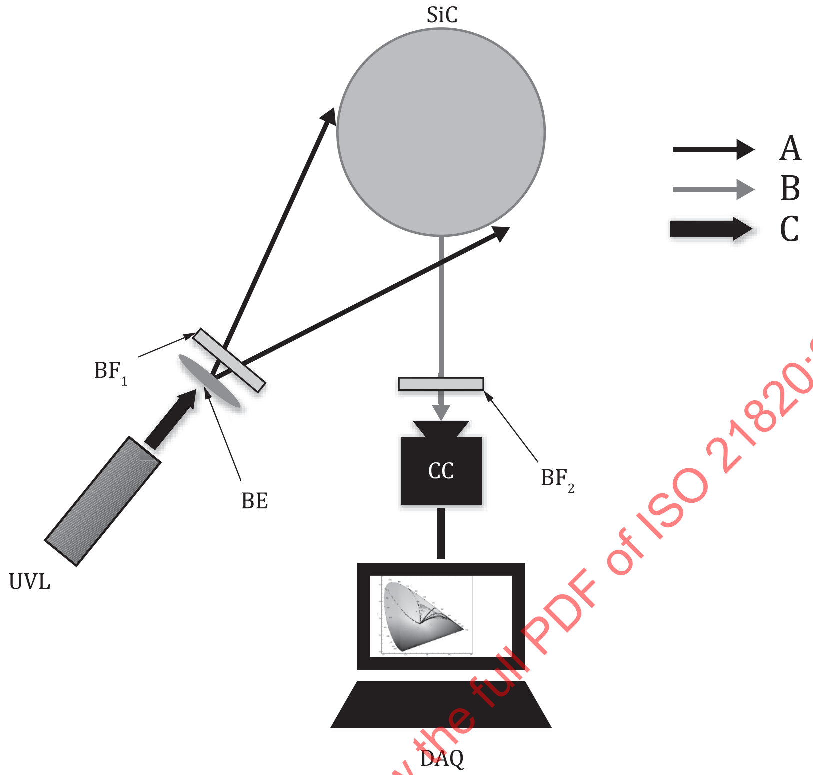
8.3.1 Calibration is necessary before measurement. See Annex D.

8.3.2 The UV beam emitted by the UVLS passing through BE and BF_1 then irradiates the SiC sample.

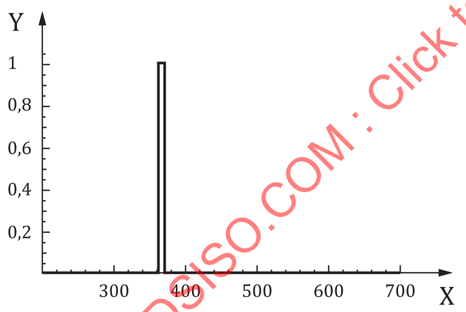
8.3.3 Take pictures of the UVPL image using the CCD camera and save the images in RGB format.

8.3.4 Transform the RGB images to the CIE 1931 colour space.

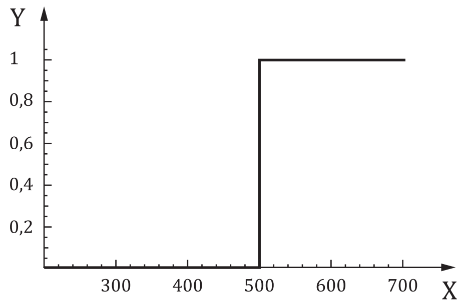
8.3.5 The polytype can be determined by the position of the colour point when it is plotted on the colour space.



a) Schematic of a UVPL imaging system



b) Transmittance distribution of BF_1



c) Transmittance distribution of BF_2

Key

A	expanded UV beam
B	UV induced PL beam
C	UV LED
UVL	ultraviolet light source
BF	bandpass filter
BE	beam expander
SiC	silicon carbide
CC	CCD camera
DAQ	data acquisition
X	wavelength, nm
Y	transmittance

Figure 2 — Optical setup for UVPL measurement

9 Expression of results

9.1 Expression of boundaries of polytypes in CIE 1931 colour space

The polytype boundaries are defined in the CIE 1931 colour space as shown in Figure 3. The dotted lines are the polytype lines. When the temperature of a SiC sample is near 0 K, the transformed points from the UVPL image are positioned near the edge of the colour space; as the temperature increases, the colour points approach the centre of the colour space (1/3,1/3,1/3). The black lines in Figure 3 represent the boundary lines, which are between polytype lines and help to determine the major polytypes.

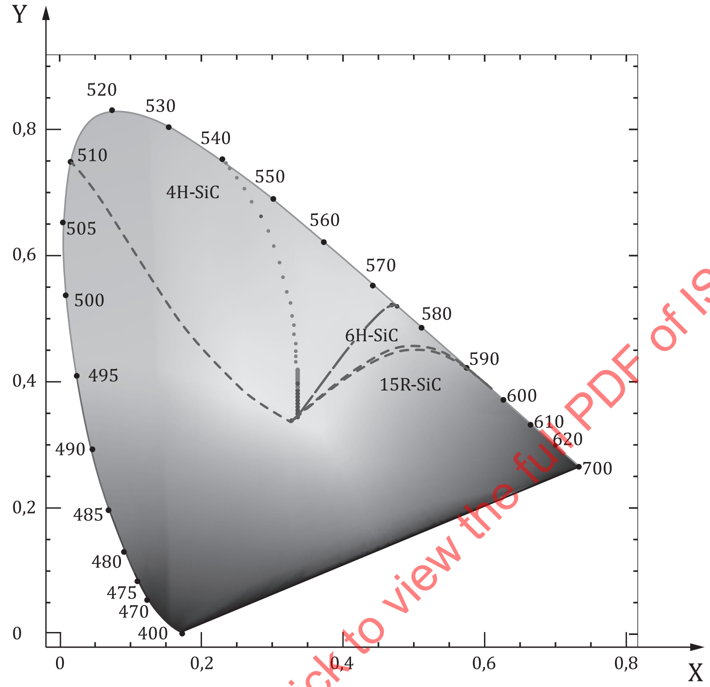


Figure 3 — Polytype lines (dotted lines) and boundary lines (dashed lines) of polytypes in CIE 1913 colour space

The detailed procedure for producing the polytype lines and boundaries is described in Annex A.

Annex B shows the boundary points table of each polytype in the CIE 1931 colour space. The specific polytype regions are defined as the inner regions of polygons made by connecting these boundary points, as shown in Figures B.1 to B.3.

9.2 Transformation of the UVPL image to CIE 1931 colour space with polytype boundaries

The UVPL colour data should be transformed to the CIE 1931 colour space using the polytype boundaries to identify the polytype.

Each polytype has a different DAP recombination energy, which indicates that each polytype has a different colour. Therefore, when a UVPL image is transformed into the CIE 1931 colour space, each polytype colour has a different position in the colour space.

9.3 Determination of polytype

9.3.1 After the transformation of the UVPL image to the colour space, the SiC polytype should be determined.

If the SiC sample is a perfect single crystal, colour points transformed from the image to colour space should be on one of the red lines only, thus allowing the polytype to be easily determined. However, there can be a mixture of polytypes in the sample. In that case, colour points can be distributed around the polytype line.

9.3.2 The polytype can be determined quantitatively. That is, if the colour points are distributed on only one polytype region, that would be the desired polytype.

9.3.3 If the colour points are distributed widely across several polytype regions, the number of colour points on each polytype region should be counted and the ratio of polytype region should be calculated as follows:

$$100\ \% = 4H\ (\%) + 6H\ (\%) + 15R\ (\%) + \text{other polytypes}\ (\%)$$

If the 4H (6H, 15R) SiC surface is significantly contaminated, the UVPL image of the contaminated region can exhibit a different colour from those of the 4H (6H, 15R) SiC. It may then be identified as one of the other polytypes. Therefore, the measured ratio of 4H, 6H and 15R is the minimum value.

When the total ratio of the 4H, 6H and 15R polytype is less than 100 %, the following issues should be taken into account.

If a UVPL image has ambiguous shapes accompanied by an unclear boundary or if a region with characteristic patterns changes its position and area for each measurement, then the sample surface may be significantly contaminated.

The sample surface should be cleaned following a wet cleaning process using H_2SO_4: H_2O_2: H_2O, NH_4OH: H_2O_2: H_2O, HCl: H_2O_2: H_2O or other suitable chemicals.

10 Test report

The test report shall be in accordance with the reporting provisions of ISO/IEC 17025 and shall contain the following information, if available:

a) the name of the testing establishment;

b) the date of the test, report identification and number, operator, signatory;

c) a description of the SiC wafers (material manufacturer, growth method, and conditions);

d) the results obtained, including the UVPL images:

   1) image of SiC under illumination in the visible range;

   2) UVPL image, image size and format;

   3) CIE 1931 colour space and range;

   4) penetration depth (see Annex C);

   5) CCD camera name;

e) the polytype results determined according to the ranges in colour space;

f) comments about the test or test results;

g) a reference to this document (i.e. ISO 21820:2021).

Annex A
(informative)

Determination of polytypes

A.1 Determination of coordinates of each polytype at 0 K in colour space

Each polytype has an intrinsic DAP recombination energy so that it emits a monochromatic photoluminescent beam at zero Kelvin when it is illuminated by UV light. The DAP recombination energy of each polytype is different; this can be used as a criterion for polytype determination.

Table A.1 shows the wavelength of the polytypes measured by a PL spectrometer and the corresponding DAP recombination energy calculated by applying Planck's relation (Formula A.1).

Table A.1 — Relation between polytype, DAP recombination energy and wavelength.

Polytype	DAP recombination energy eV	Wavelength nm
4H-SiC	2,295 9	540
6H-SiC	2,032 5	610
15R-SiC	2,006 2	618

$$E = h\nu = \frac{hc}{\lambda} \tag{A.1}$$

where

E is the energy;

h is Planck's constant;

ν is the frequency of light;

c is the velocity of light;

λ is the wavelength of light.

These DAP recombination energies or wavelengths can be converted into colour space as one-colour points.

The total intensities of red, green and blue are denoted as X, Y and Z and can be calculated using Formulae (A.2) to (A.4). Figure A.1 depicts the conversion of monochromatic light into colour space as colour points. Figure A.1 a) shows the normalized spectral density distribution of the tristimuli, $M(\lambda)$, defined in CIE 1931 and ISO/CIE 11664-3. Figure A.1 b) depicts the monochromatic light intensity distribution, $\overline{x}(\lambda)$, that has the form of a delta function for each polytype as shown in the last row of Table A.1. Figure A.1 c) depicts the final intensities of X, Y and Z calculated with Formulae (A.2) to (A.4). The normalized X, Y and Z coordinates are denoted as x, y and z and can be calculated using Formulae (A.5) to (A.7).

$$X = \int_{450}^{850} M(\lambda)\overline{x}(\lambda)d\lambda \tag{A.2}$$

$$Y = \int_{450}^{850} M(\lambda)\bar{y}(\lambda)d\lambda \tag{A.3}$$

$$Z = \int_{450}^{850} M(\lambda)\bar{z}(\lambda)d\lambda \tag{A.4}$$

$$x = \frac{X}{X+Y+Z} \tag{A.5}$$

$$y = \frac{Y}{X+Y+Z} \tag{A.6}$$

$$z = \frac{Z}{X+Y+Z} = 1 - x - y \tag{A.7}$$

where

λ is the wavelength of light;

$\bar{x}(\lambda)$ is the monochromatic light intensity distribution of red light where the wavelength is λ;

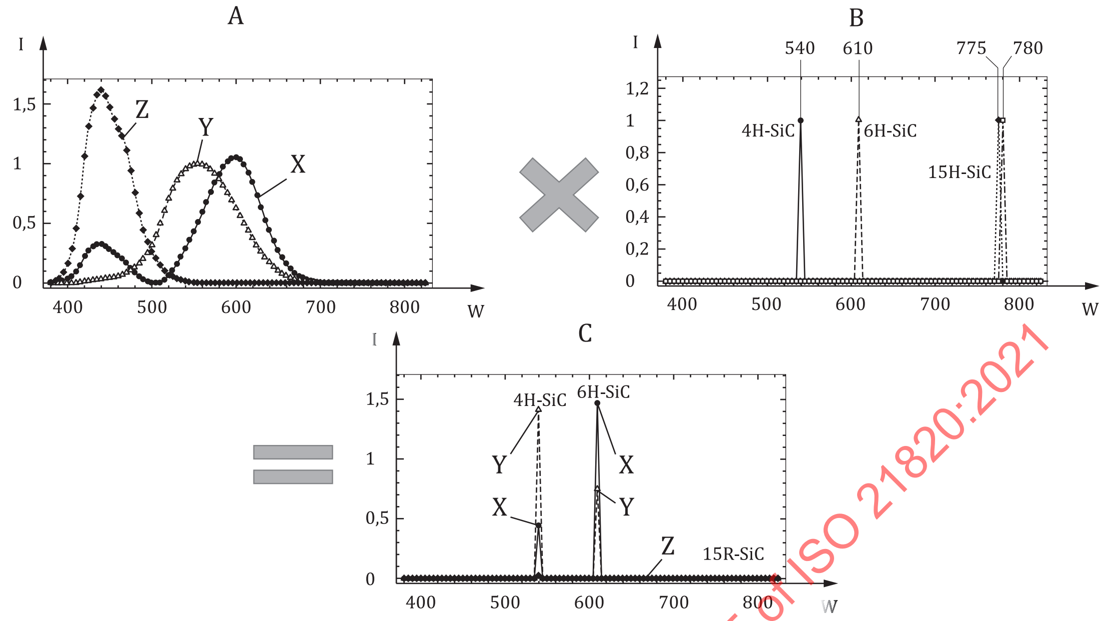
$\bar{y}(\lambda)$ is the monochromatic light intensity distribution of green light where the wavelength is λ;

$\bar{z}(\lambda)$ is the monochromatic light intensity distribution of blue light where the wavelength is λ;

X is the normalized total intensity of red light;

Y is the normalized total intensity of green light;

Z is the normalized total intensity of blue light.



Key

I intensity

W wavelength (nm)

A normalized spectral distribution of tristimulus

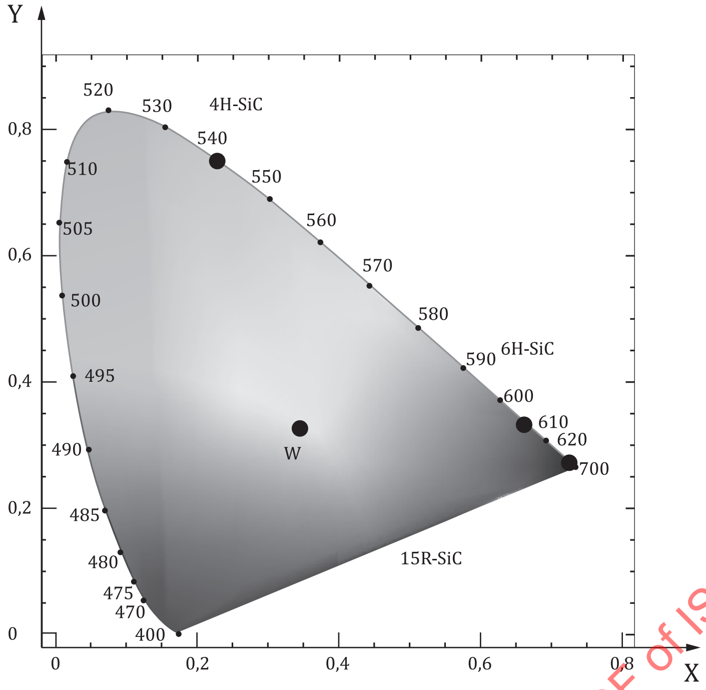
B delta functional distribution of photoluminescence

C intensities of XYZ

Figure A.1 — Conversion from monochromatic light to RGB

4H-SiC, 6H-SiC, 15R-SiC and 3C-SiC are plotted as dots at the edge of the colour space. The monochromatic light is always placed at the edge of the colour space. The dot at the centre corresponds to the white point because the RGB coordinates of white are (1/3,1/3,1/3).

The monochromatic wavelengths of 15R-SiC and 3C-SiC are closely adjacent to 770 nm and 780 nm when they are converted into the colour space wherein they overlap, as can be seen in Figure A.2.



Key

W white

Figure A.2 — Polytype colour points in colour space

A.2 Determination of lines of each polytype at various temperatures

At extremely low temperatures, the PL beam is so monochromatic that it has the form of a delta function.

However, as the temperature increases, it assumes the form of a Gaussian distribution.

This property of the PL beam enables it to be modelled as the Gaussian function M(λ) in Formula (A.8), in which its shape changes as the shape parameter β changes.

When β in Formula (A.8) decreases to zero, M(λ) becomes a delta function, as in Formula (A.9), and the maximum value and full width half maximum (FWHM) of M(λ) are as shown in Formulae (A.10) and (A.11).

$$\mathrm{M}(\lambda)=\frac{1}{\beta\sqrt{\pi}}e^{-(\frac{\lambda-\lambda_0}{\beta})^2} \tag{A.8}$$

$$\lim_{\beta\to 0}\mathrm{M}(\lambda)=\delta(\lambda-\lambda_0) \tag{A.9}$$

$$\mathrm{M}(\lambda_0)=\frac{1}{\beta\sqrt{\pi}}e^{-(\frac{\lambda_0-\lambda_0}{\beta})^2}=\frac{1}{\beta\sqrt{\pi}}e^0=\frac{1}{\beta\sqrt{\pi}} \tag{A.10}$$

$$\lambda_{\mathrm{FWHM}}=2\sqrt{2ln2}\beta \tag{A.11}$$

where

λ_0 is the centre point of the Gaussian function;

λ_{FWHM} is the FWHM of function $M(\lambda)$;

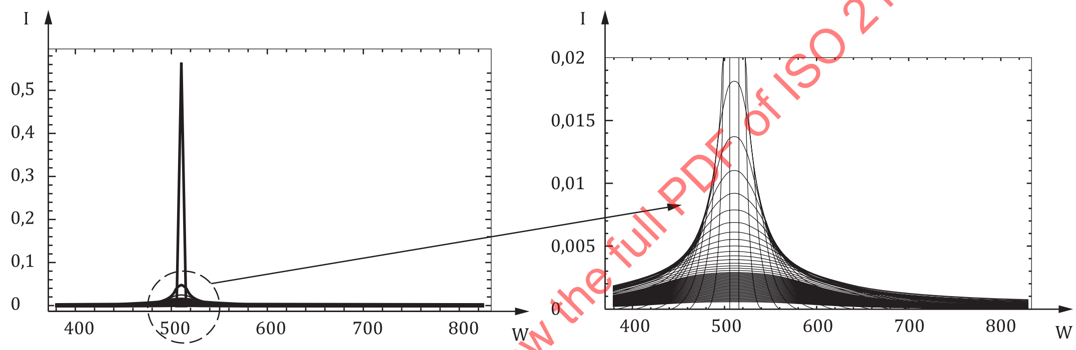
e is exponential function;

ln is natural logarithm function.

β in Formula (A.8) increases as temperature increases, though the relation between them differs depending on the material. Using this characteristic, the polytype lines are calculated as follows.

The coordinate in the colour space of each polytype at 0 K is calculated and plotted first. These colour points are all plotted at the edge of the colour space. As the temperature increases, β increases so that the maximum height of the PL distribution decreases, as in Formula (A.10), and its width increases, according to Formula (A.11).

Finally, the distribution becomes uniform as β goes to infinity, as shown in Figure A.3.



Key

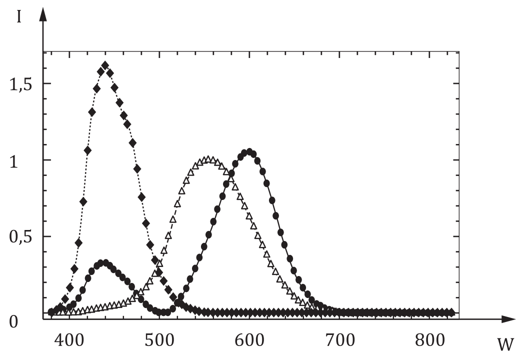
W wavelength (nm)

I intensity

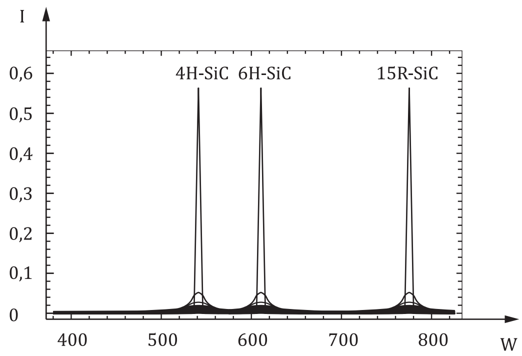
Figure A.3 — Gaussian distribution depending on temperature

The polytype lines can be calculated using a Gaussian distribution at various temperatures in Formula (A.8). Figure A.4 shows the procedure, which almost replicates that in Figure A.1, except for Figure A.4 b), which is extended to various shape parameter β values as in Figure A.3. Figure A.4 c) shows the results. Although Figure A.3 c) plots only every individual point at the edge of the colour space, every point becomes a line as it follows the temperature change in Figure A.4 c). These lines finally converge to (1/3, 1/3, 1/3), because if the temperature goes to infinity, the PL beam becomes a uniform distribution such that the intensity of the RGB colours becomes equal, i.e. white. In Figure A.4 c), every line converges to white.

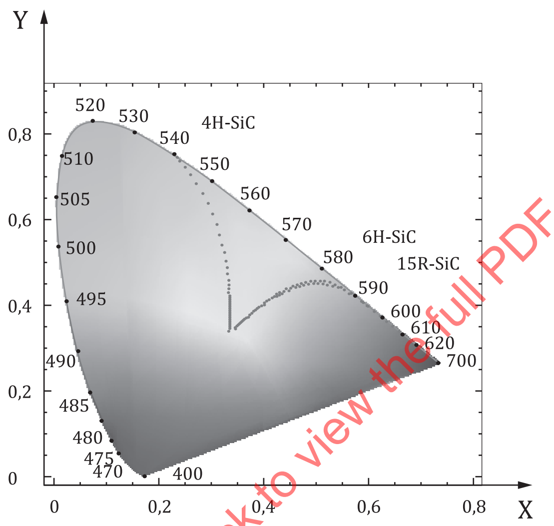
The polytype lines in Figure A.4 c) are not straight because the CIE 1931 distribution in Figure A.4 a) is not uniform or symmetric. In addition, the lines of 15R-SiC and 3C-SiC are so close that it is difficult to distinguish them. If there is only one polytype, the points from the SiC UVPL image converted to colour space should be located on one of these lines.



a) Normalized spectral distribution of tristimulus



b) Gaussian distribution of photoluminescence



c) Transformation to colour space of XYZ

Key

W wavelength (nm)

I intensity

—●— X

---∆--- Y

......◆...... Z

NOTE a) × b) = c)

Figure A.4 — Determination of polytype lines in colour at various temperatures

Even if it were attempted to grow a single crystalline SiC it may contain other polytypes. In this case, the colour points converted into colour space are not placed on one polytype line but are distributed around the line. Therefore, the boundaries that define the domain of a specific polytype are required.

Table A.2 shows the arithmetic mean of DAP recombination energy between adjacent polytypes added to the values in Table A.1.

Table A.2 — DAP recombination energy and wavelengths of polytypes and their boundaries

Polytype	DAP recombination energy eV	Wavelength nm
Upper boundary	**2,427 6**	**510**
4H-SiC	2,295 9	540
Boundary between 4H and 6H-SiC	**2,164 2**	**575**
6H-SiC	2,032 5	610
Boundary between 6H and 15R-SiC	**2,019 4**	**614**
15R-SiC	2,006 2	618
Lower boundary	**1,993 1**	**622**

From Formula (A.1), the DAP recombination energy (E) and wavelength (λ) are inversely proportional; therefore, the arithmetic mean was calculated not in the wavelength domain but in the DAP recombination energy domain and was converted to the wavelength domain using Formula (A.1).

The procedure to obtain the polytype boundary lines is the same as in A.2.

Figure A.5 shows the boundary of each polytype. The area of 3C-SiC is excluded because it is outside the colour space.

These boundaries can be used as a benchmark to determine the polytype or can be the criteria for failure. Figure A.6, which includes boundaries and polytype lines, can also be used to determine the polytype.

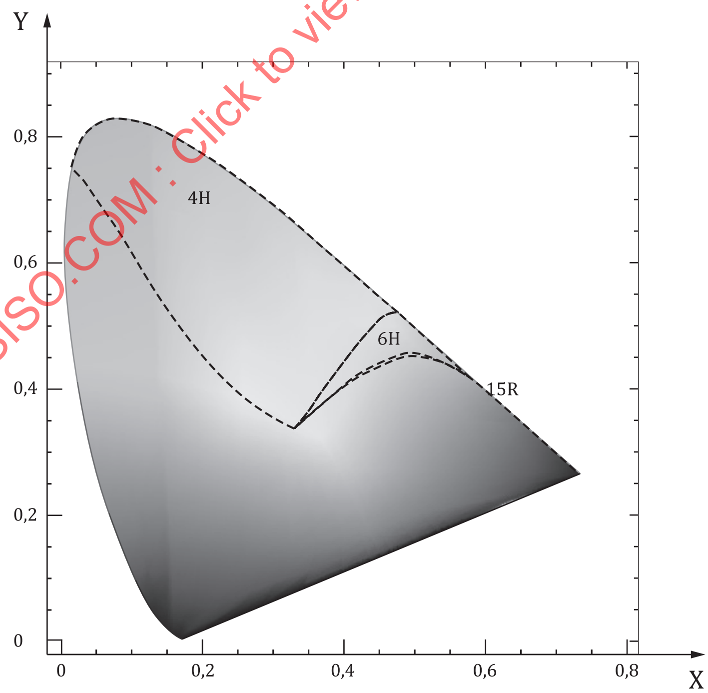


Figure A.5 — Polytype boundaries

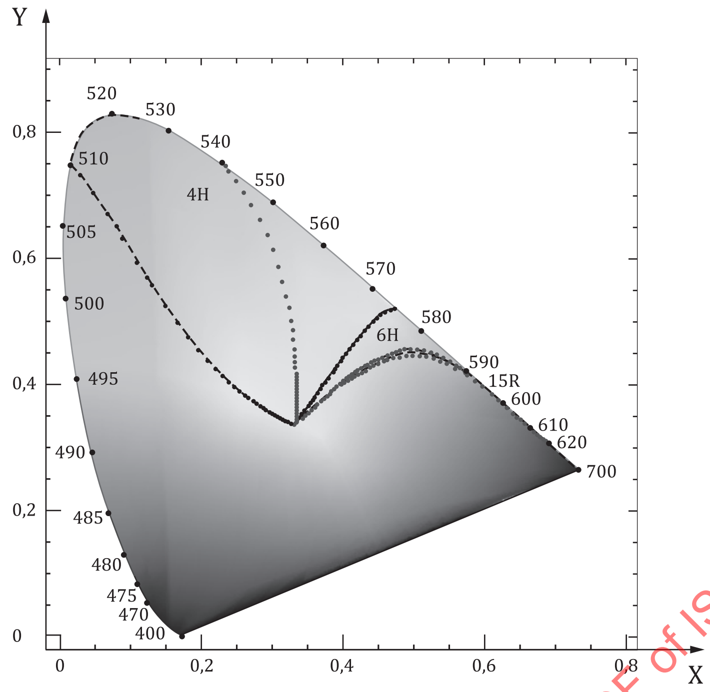


Figure A.6 — Polytype boundaries and lines

Annex B
(informative)

Determination of polytypes

B.1 Region of 4H-SiC in CIE 1931 colour space

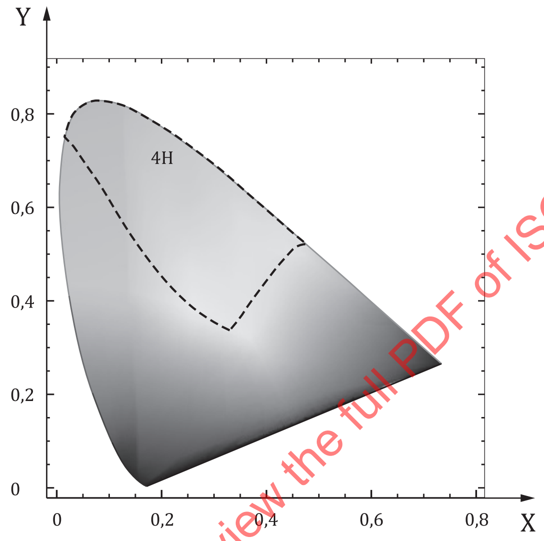


Figure B.1 — Area of 4H-SiC in CIE 1931 colour space

Region 4H-SiC								
No.	**CIE X**	**CIE Y**	**No.**	**CIE X**	**CIE Y**	**No.**	**CIE X**	**CIE Y**
1	0,331 6	0,338 0	**82**	0,260 7	0,386 6	**163**	0,407 0	0,453 6
2	0,331 5	0,338 0	**83**	0,254 3	0,392 4	**164**	0,402 5	0,446 9
3	0,331 5	0,338 1	**84**	0,247 1	0,399 3	**165**	0,398 3	0,440 5
4	0,331 4	0,338 1	**85**	0,239 1	0,407 5	**166**	0,394 4	0,434 5
5	0,331 3	0,338 1	**86**	0,230 1	0,417 1	**167**	0,390 8	0,428 9
6	0,331 3	0,338 2	**87**	0,220 0	0,428 6	**168**	0,387 4	0,423 6
7	0,331 2	0,338 2	**88**	0,208 8	0,442 4	**169**	0,384 3	0,418 7
8	0,331 1	0,338 3	**89**	0,196 2	0,459 0	**170**	0,381 4	0,414 1
9	0,331 0	0,338 3	**90**	0,182 3	0,478 7	**171**	0,378 8	0,409 8
10	0,330 9	0,338 3	**91**	0,166 8	0,502 2	**173**	0,376 3	0,405 8
11	0,330 8	0,338 4	**92**	0,149 8	0,529 7	**173**	0,374 0	0,402 1
12	0,330 7	0,338 4	**93**	0,131 3	0,561 3	**174**	0,371 9	0,398 7
13	0,330 7	0,338 5	**94**	0,111 4	0,596 6	**175**	0,370 0	0,395 5
14	0,330 6	0,338 5	**95**	0,090 5	0,634 5	**176**	0,368 1	0,392 5
15	0,330 5	0,338 6	**96**	0,069 2	0,672 8	**177**	0,366 5	0,389 7
16	0,330 3	0,338 6	**97**	0,048 9	0,707 5	**178**	0,364 9	0,387 1
17	0,330 2	0,338 7	**98**	0,031 2	0,734 1	**179**	0,363 4	0,384 7
18	0,330 1	0,338 8	**99**	0,013 9	0,754 4	**180**	0,362 1	0,382 5

Region 4H-SiC								
No.	**CIE X**	**CIE Y**	**No.**	**CIE X**	**CIE Y**	**No.**	**CIE X**	**CIE Y**
19	0,330 0	0,338 8	**100**	0,013 9	0,754 4	**181**	0,360 8	0,380 3
20	0,329 9	0,338 9	**101**	0,014 1	0,754 9	**182**	0,359 6	0,378 4
21	0,329 8	0,338 9	**102**	0,039 1	0,814 2	**183**	0,358 5	0,376 5
22	0,329 6	0,339 0	**103**	0,039 2	0,814 5	**184**	0,357 4	0,374 8
23	0,329 5	0,339 1	**104**	0,039 2	0,814 5	**185**	0,356 5	0,373 1
24	0,329 4	0,339 2	**105**	0,039 2	0,814 5	**186**	0,355 6	0,371 6
25	0,329 2	0,339 2	**106**	0,039 5	0,814 7	**187**	0,354 7	0,370 2
26	0,329 1	0,339 3	**107**	0,074 8	0,834 8	**188**	0,353 9	0,368 8
27	0,328 9	0,339 4	**108**	0,075 0	0,834 9	**189**	0,353 1	0,367 5
28	0,328 7	0,339 5	**109**	0,075 0	0,834 9	**190**	0,352 4	0,366 3
29	0,328 6	0,339 6	**110**	0,075 0	0,834 9	**191**	0,351 7	0,365 2
30	0,328 4	0,339 7	**111**	0,075 3	0,834 9	**192**	0,351 1	0,364 1
31	0,328 2	0,339 8	**112**	0,114 9	0,826 4	**193**	0,350 5	0,363 1
32	0,328 0	0,339 9	**113**	0,115 2	0,826 4	**194**	0,349 9	0,362 1
33	0,327 8	0,340 0	**114**	0,115 2	0,826 4	**195**	0,349 4	0,361 2
34	0,327 6	0,340 1	**115**	0,267 5	0,722 7	**196**	0,348 9	0,360 3
35	0,327 4	0,340 2	**116**	0,302 8	0,691 1	**197**	0,348 4	0,359 5
36	0,327 2	0,340 3	**117**	0,303 0	0,690 9	**198**	0,347 9	0,358 7
37	0,326 9	0,340 4	**118**	0,303 0	0,690 9	**199**	0,347 5	0,357 9
38	0,326 7	0,340 6	**119**	0,303 0	0,690 9	**200**	0,347 1	0,357 2
39	0,326 4	0,340 7	**120**	0,303 3	0,690 7	**201**	0,346 7	0,356 6
40	0,326 1	0,340 9	**121**	0,338 4	0,657 7	**202**	0,346 3	0,355 9
41	0,325 8	0,341 0	**122**	0,338 7	0,657 5	**203**	0,345 9	0,355 3
42	0,325 5	0,341 2	**123**	0,338 7	0,657 5	**204**	0,345 6	0,354 7
43	0,325 2	0,341 4	**124**	0,338 7	0,657 5	**205**	0,345 3	0,354 2
44	0,324 9	0,341 5	**125**	0,338 9	0,657 2	**206**	0,344 9	0,353 6
45	0,324 5	0,341 7	**126**	0,374 0	0,623 4	**207**	0,344 6	0,353 1
46	0,324 1	0,341 9	**127**	0,374 2	0,623 2	**208**	0,344 4	0,352 6
47	0,323 8	0,342 2	**128**	0,374 2	0,623 2	**209**	0,344 1	0,352 1
48	0,323 3	0,342 4	**129**	0,374 2	0,623 2	**210**	0,343 8	0,351 7
49	0,322 9	0,342 6	**130**	0,374 5	0,623 0	**211**	0,343 6	0,351 3
50	0,322 4	0,342 9	**131**	0,409 4	0,588 8	**212**	0,343 3	0,350 9
51	0,321 9	0,343 1	**132**	0,409 7	0,588 6	**213**	0,343 1	0,350 5
52	0,321 4	0,343 4	**133**	0,409 7	0,588 6	**214**	0,342 9	0,350 1
53	0,320 9	0,343 7	**134**	0,409 7	0,588 6	**215**	0,342 7	0,349 7
54	0,320 3	0,344 1	**135**	0,409 9	0,588 3	**216**	0,342 5	0,349 4
55	0,319 7	0,344 4	**136**	0,444 5	0,554 2	**217**	0,342 3	0,349 0
56	0,319 0	0,344 8	**137**	0,444 7	0,554 0	**218**	0,342 1	0,348 7
57	0,318 3	0,345 2	**138**	0,444 7	0,554 0	**219**	0,341 9	0,348 4
58	0,317 6	0,345 6	**139**	0,444 7	0,554 0	**220**	0,341 7	0,348 1
59	0,316 8	0,346 1	**140**	0,444 9	0,553 7	**221**	0,341 5	0,347 8
60	0,315 9	0,346 6	**141**	0,478 9	0,520 0	**222**	0,341 4	0,347 5
61	0,315 0	0,347 1	**142**	0,479 1	0,519 8	**223**	0,341 2	0,347 2
62	0,314 0	0,347 7	**143**	0,479 1	0,519 8	**224**	0,341 1	0,347 0

Region 4H-SiC								
No.	**CIE X**	**CIE Y**	**No.**	**CIE X**	**CIE Y**	**No.**	**CIE X**	**CIE Y**
63	0,312 9	0,348 3	**144**	0,479 3	0,519 5	**225**	0,340 9	0,346 7
64	0,311 8	0,349 0	**145**	0,479 3	0,519 4	**226**	0,340 8	0,346 5
65	0,310 6	0,349 7	**146**	0,478 8	0,519 5	**227**	0,340 6	0,346 3
66	0,309 3	0,350 5	**147**	0,477 7	0,520 1	**228**	0,340 5	0,346 0
67	0,307 8	0,351 4	**148**	0,476 0	0,520 9	**229**	0,340 4	0,345 8
68	0,306 3	0,352 4	**149**	0,473 7	0,521 6	**230**	0,340 3	0,345 6
69	0,304 6	0,353 4	**150**	0,471 0	0,522 0	**231**	0,340 1	0,345 4
70	0,302 8	0,354 6	**151**	0,467 8	0,521 7	**231**	0,340 0	0,345 2
71	0,300 8	0,355 9	**152**	0,464 1	0,520 4	**233**	0,339 9	0,345 0
72	0,298 7	0,357 3	**153**	0,459 9	0,518 0	**234**	0,339 8	0,344 8
73	0,296 3	0,358 9	**154**	0,455 2	0,514 4	**235**	0,339 7	0,344 6
74	0,293 7	0,360 6	**155**	0,450 1	0,509 7	**236**	0,339 6	0,344 5
75	0,290 9	0,362 6	**156**	0,444 7	0,504 0	**237**	0,339 5	0,344 3
76	0,287 8	0,364 8	**157**	0,439 1	0,497 4	**238**	0,339 4	0,344 1
77	0,284 3	0,367 4	**158**	0,433 4	0,490 4	**239**	0,339 3	0,344 0
78	0,280 5	0,370 2	**159**	0,427 7	0,483 0	**240**	0,339 2	0,343 8
79	0,276 3	0,373 5	**160**	0,422 2	0,475 5	**241**	0,339 1	0,343 7
80	0,271 7	0,377 2	**161**	0,416 9	0,468 0			
81	0,266 5	0,381 6	**162**	0,411 8	0,460 7			

B.2 Region of 6H-SiC in CIE 1931 colour space

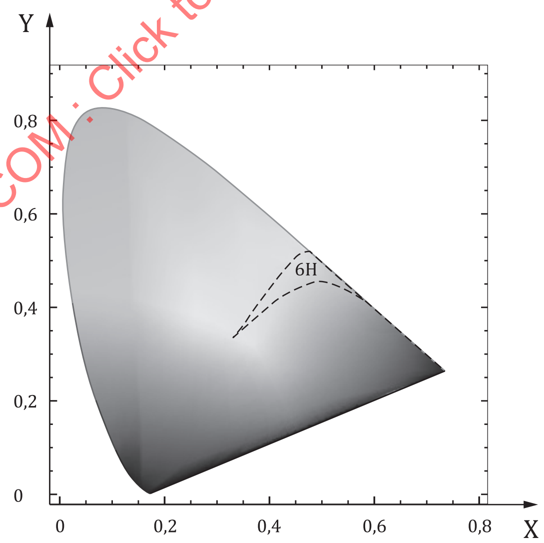


Figure B.2 — Area of 6H-SiC in CIE 1931 colour space

Region 6H-SiC								
No.	**CIE X**	**CIE Y**	**No.**	**CIE X**	**CIE Y**	**No.**	**CIE X**	**CIE Y**
1	0,339 1	0,343 7	**102**	0,498 8	0,500 1	**203**	0,728 8	0,271 2
2	0,339 2	0,343 8	**103**	0,505 2	0,493 7	**204**	0,728 9	0,271 0
3	0,339 3	0,344 0	**104**	0,511 5	0,487 4	**205**	0,669 6	0,330 1
4	0,339 4	0,344 1	**105**	0,517 8	0,481 2	**206**	0,663 2	0,336 4

Region 6H-SiC								
No.	**CIE X**	**CIE Y**	**No.**	**CIE X**	**CIE Y**	**No.**	**CIE X**	**CIE Y**
5	0,339 5	0,344 3	**106**	0,524 0	0,475 0	**207**	0,654 9	0,344 7
6	0,339 6	0,344 5	**107**	0,530 2	0,468 9	**208**	0,645 1	0,354 5
7	0,339 7	0,344 6	**108**	0,536 3	0,462 8	**209**	0,634 2	0,365 3
8	0,339 8	0,344 8	**109**	0,542 3	0,456 9	**210**	0,622 7	0,376 7
9	0,339 9	0,345 0	**110**	0,548 2	0,451 0	**211**	0,610 9	0,388 3
10	0,340 0	0,345 2	**111**	0,553 9	0,445 2	**212**	0,599 1	0,399 7
11	0,340 1	0,345 4	**112**	0,559 7	0,439 5	**213**	0,587 5	0,410 5
12	0,340 3	0,345 6	**113**	0,565 4	0,433 8	**214**	0,576 2	0,420 6
13	0,340 4	0,345 8	**114**	0,570 9	0,428 3	**215**	0,565 2	0,429 7
14	0,340 5	0,346 0	**115**	0,576 4	0,422 9	**216**	0,554 5	0,437 5
15	0,340 6	0,346 3	**116**	0,581 7	0,417 6	**217**	0,544 2	0,444 0
16	0,340 8	0,346 5	**117**	0,587 0	0,412 3	**218**	0,534 0	0,449 0
17	0,340 9	0,346 7	**118**	0,592 1	0,407 2	**219**	0,524 1	0,452 7
18	0,341 1	0,347 0	**119**	0,597 1	0,402 2	**220**	0,514 5	0,454 9
19	0,341 2	0,347 2	**120**	0,602 0	0,397 4	**221**	0,505 0	0,455 9
20	0,341 4	0,347 5	**121**	0,606 8	0,392 6	**222**	0,495 9	0,455 8
21	0,341 5	0,347 8	**122**	0,611 5	0,387 9	**223**	0,487 1	0,454 7
22	0,341 7	0,348 1	**123**	0,616 0	0,383 4	**224**	0,478 6	0,452 8
23	0,341 9	0,348 4	**124**	0,620 4	0,379 0	**225**	0,470 6	0,450 4
24	0,342 1	0,348 7	**125**	0,624 7	0,374 7	**226**	0,462 9	0,447 4
25	0,342 3	0,349 0	**126**	0,628 9	0,370 6	**227**	0,455 6	0,444 1
26	0,342 5	0,349 4	**127**	0,633 0	0,366 5	**228**	0,448 8	0,440 6
27	0,342 7	0,349 7	**128**	0,636 9	0,362 6	**229**	0,442 4	0,437 0
28	0,342 9	0,350 1	**129**	0,640 7	0,358 8	**230**	0,436 3	0,433 2
29	0,343 1	0,350 5	**130**	0,644 4	0,355 2	**231**	0,430 7	0,429 5
30	0,343 3	0,350 9	**131**	0,648 0	0,351 6	**232**	0,425 4	0,425 8
31	0,343 6	0,351 3	**132**	0,651 4	0,348 2	**233**	0,420 5	0,422 2
32	0,343 8	0,351 7	**133**	0,654 7	0,344 9	**234**	0,416 0	0,418 7
33	0,344 1	0,352 1	**134**	0,657 9	0,341 7	**235**	0,411 7	0,415 3
34	0,344 4	0,352 6	**135**	0,660 9	0,338 7	**236**	0,407 7	0,412 1
35	0,344 6	0,353 1	**136**	0,664 0	0,335 7	**237**	0,403 9	0,408 9
36	0,344 9	0,353 6	**137**	0,666 8	0,332 9	**238**	0,400 6	0,405 9
37	0,345 3	0,354 2	**138**	0,669 6	0,330 1	**239**	0,397 3	0,403 1
38	0,345 6	0,354 7	**139**	0,672 2	0,327 5	**240**	0,394 3	0,400 3
39	0,345 9	0,355 3	**140**	0,674 8	0,325 0	**241**	0,391 5	0,397 7
40	0,346 3	0,355 9	**141**	0,677 2	0,322 6	**242**	0,388 9	0,395 2
41	0,346 7	0,356 6	**142**	0,679 5	0,320 2	**243**	0,386 4	0,392 9
42	0,347 1	0,357 2	**143**	0,681 8	0,318 0	**244**	0,384 1	0,390 7
43	0,347 5	0,357 9	**144**	0,683 9	0,315 9	**245**	0,381 9	0,388 5
44	0,347 9	0,358 7	**145**	0,685 9	0,313 8	**246**	0,379 9	0,386 5
45	0,348 4	0,359 5	**146**	0,688 0	0,311 9	**247**	0,377 9	0,384 6
46	0,348 9	0,360 3	**147**	0,689 9	0,310 0	**248**	0,376 2	0,382 8
47	0,349 4	0,361 2	**148**	0,691 7	0,308 1	**249**	0,374 5	0,381 1
48	0,349 9	0,362 1	**149**	0,693 4	0,306 4	**250**	0,372 9	0,379 4

Region 6H-SiC								
No.	**CIE X**	**CIE Y**	**No.**	**CIE X**	**CIE Y**	**No.**	**CIE X**	**CIE Y**
49	0,350 5	0,363 1	**150**	0,695 1	0,304 7	**251**	0,371 4	0,377 9
50	0,351 1	0,364 1	**151**	0,696 7	0,303 1	**252**	0,370 0	0,376 4
51	0,351 7	0,365 2	**152**	0,698 3	0,301 6	**253**	0,368 7	0,375 0
52	0,352 4	0,366 3	**153**	0,699 8	0,300 1	**254**	0,367 4	0,373 7
53	0,353 1	0,367 5	**154**	0,701 2	0,298 7	**255**	0,366 2	0,372 4
54	0,353 9	0,368 8	**155**	0,702 6	0,297 3	**256**	0,365 1	0,371 2
55	0,354 7	0,370 2	**156**	0,703 9	0,296 0	**257**	0,364 0	0,370 0
56	0,355 6	0,371 6	**157**	0,705 2	0,294 7	**258**	0,363 0	0,368 9
57	0,356 5	0,373 1	**158**	0,706 4	0,293 5	**259**	0,362 0	0,367 8
58	0,357 4	0,374 8	**159**	0,707 6	0,292 3	**260**	0,361 1	0,366 8
59	0,358 5	0,376 5	**160**	0,708 7	0,291 2	**261**	0,360 2	0,365 9
60	0,359 6	0,378 4	**161**	0,709 8	0,290 1	**262**	0,359 4	0,365 0
61	0,360 8	0,380 3	**162**	0,710 8	0,289 1	**263**	0,358 6	0,364 1
62	0,362 1	0,382 5	**163**	0,711 8	0,288 1	**264**	0,357 8	0,363 2
63	0,363 4	0,384 7	**164**	0,712 8	0,287 1	**265**	0,357 1	0,362 4
64	0,364 9	0,387 1	**165**	0,713 7	0,286 2	**266**	0,356 4	0,361 7
65	0,366 5	0,389 7	**166**	0,714 6	0,285 3	**267**	0,355 8	0,360 9
66	0,368 1	0,392 5	**167**	0,715 4	0,284 5	**268**	0,355 2	0,360 2
67	0,370 0	0,395 5	**168**	0,716 2	0,283 7	**269**	0,354 6	0,359 6
68	0,371 9	0,398 7	**169**	0,717 0	0,282 9	**270**	0,354 0	0,358 9
69	0,374 0	0,402 1	**170**	0,717 7	0,282 2	**271**	0,353 4	0,358 3
70	0,376 3	0,405 8	**171**	0,718 4	0,281 5	**272**	0,352 9	0,357 7
71	0,378 8	0,409 8	**172**	0,719 1	0,280 8	**273**	0,352 4	0,357 1
72	0,381 4	0,414 1	**173**	0,719 7	0,280 2	**274**	0,351 9	0,356 6
73	0,384 3	0,418 7	**174**	0,720 3	0,279 6	**275**	0,351 5	0,356 0
74	0,387 4	0,423 6	**175**	0,720 9	0,278 9	**276**	0,351 0	0,355 5
75	0,390 8	0,428 9	**176**	0,721 4	0,278 5	**277**	0,350 6	0,355 0
76	0,394 4	0,434 5	**177**	0,721 9	0,278 0	**278**	0,350 2	0,354 6
77	0,398 3	0,440 5	**178**	0,722 4	0,277 5	**279**	0,349 8	0,354 1
78	0,402 5	0,446 9	**179**	0,722 9	0,277 1	**280**	0,349 4	0,353 7
79	0,407 0	0,453 6	**180**	0,723 3	0,276 6	**281**	0,349 0	0,353 2
80	0,411 8	0,460 7	**181**	0,723 7	0,276 2	**282**	0,348 7	0,352 8
81	0,416 9	0,467 9	**182**	0,724 1	0,275 9	**283**	0,348 3	0,352 4
82	0,422 2	0,475 5	**183**	0,724 4	0,275 5	**284**	0,348 0	0,352 1
83	0,427 7	0,483 0	**184**	0,724 8	0,275 2	**285**	0,347 7	0,351 7
84	0,433 4	0,490 4	**185**	0,725 1	0,274 9	**286**	0,347 4	0,351 3
85	0,439 1	0,497 4	**186**	0,725 4	0,274 5	**287**	0,347 1	0,351 0
86	0,444 7	0,504 0	**187**	0,725 7	0,274 3	**288**	0,346 8	0,350 7
87	0,450 1	0,509 7	**188**	0,726 0	0,273 9	**289**	0,346 6	0,350 3
88	0,455 2	0,514 4	**189**	0,726 2	0,273 7	**290**	0,346 3	0,350 0
89	0,459 9	0,518 0	**190**	0,726 5	0,273 5	**291**	0,346 0	0,349 7
90	0,464 1	0,520 4	**191**	0,726 7	0,273 2	**292**	0,345 8	0,349 4
91	0,467 8	0,521 7	**192**	0,726 9	0,273 0	**293**	0,345 5	0,349 2
92	0,471 0	0,522 0	**193**	0,727 2	0,272 8	**294**	0,345 3	0,348 9