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Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for thermal property measurements of metalized ceramic substrates —

Part 1: Evaluation of thermal resistance for use in power modules

Céramiques techniques — Méthode d'essai pour les mesures des propriétés thermiques des substrats céramiques métallisés —

Partie 1: Évaluation de la résistance thermique pour utilisation dans les modules d'alimentation

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Foreword

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

A list of all parts in the ISO 4825 series can be found on the ISO website.

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Introduction

Electrical energy is predicted to become an increasingly major modality of energy usage in the future, and power conversion technologies play a crucial role in its generation, transmission, storage and use. Against this backdrop, power modules that use semiconductor devices to provide high-efficiency conversion and control of electric power are becoming an extremely important technology. While silicon has long been used as the primary material for power semiconductor devices, wide bandgap semiconductors using SiC, GaN and other such materials as next-generation power semiconductors are drawing increasing expectations for their prospects of greater energy conservation, higher output and high-speed operation. Power modules using next-generation power semiconductors of this type are also anticipated to provide higher output and higher energy density, and likewise to capitalize on the characteristics of these materials for high-temperature operation (in the near future, junction temperatures are anticipated to reach 250 °C), thus heat-dissipating technologies are becoming more important than ever before.

In high-output power modules, an insulating substrate serving as an electrical insulator is one of the most important component materials. As power semiconductor devices increase in power output and energy density, the amount and density of heat dissipated by these devices are also increasing, creating a demand for higher thermal conductivity in substrate. For this reason, ceramics are generally used as insulating substrates because of their high thermal conductivity. In addition, to minimize interfacial thermal resistance between constituent materials, metallic conductor circuit layers are also joined to ceramic substrates at high temperature. Heat-dissipating structures of this nature are termed metallized ceramic substrates.

Techniques are available to measure the thermal conductivity of the individual materials comprising metallized ceramic substrates; however, there are no established methods to evaluate the thermal characteristics of metallized ceramic substrates per se, or the thermal characteristics of power semiconductor devices in mounted form, which are key issues in the design of power modules with a high heat-dissipating efficiency.

This document provides a technique for bonding a metallized ceramic substrate equipped with a heater chip to a cold plate and for using the amount of heat dissipated by the heater chip and the temperature differential between the heater chip and the cold plate to measure the thermal resistance of a system including a metallized ceramic substrate. Manufacturers of ceramic elements, modules and other such devices can use this standard to evaluate the heat-dissipating characteristics of metallized ceramic substrates under common conditions.

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Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for thermal property measurements of metalized ceramic substrates —

Part 1:
Evaluation of thermal resistance for use in power modules

1 Scope

This document specifies a method for measuring the thermal resistance between a heater chip and a cold plate with the heater chip mounted on a metalized ceramic substrate, imitating a silicon carbide (SiC) high-output power module. This measurement represents an index of the heat dissipation characteristics of a metallized ceramic substrate used in a high-output power module.

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 554, *Standard atmospheres for conditioning and/or testing — Specifications*

IEC 60584-1, *Thermocouples — Part 1: EMF specifications and tolerances*

3 Terms and definitions

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

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

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

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

3.1
metalized ceramic substrate
component in which metallic circuit layers are joined to a ceramic substrate

3.2
thermal resistance
thermal property representing resistance to heat flow from a higher temperature area to a lower temperature area in a structure

Note 1 to entry: In this document thermal resistance is expressed as the temperature difference in the structure across a thickness when a unit of heat energy flows through it in unit time. The SI unit of thermal resistance is K/W.

[SOURCE: IEC 60747-15:2010, 3.1, modified — Definition revised and note to entry added.]

3.3
thermal conductivity
quotient of the amount of heat flow per unit of time through a unit of surface area perpendicular to the heat flow in a solid material, divided by the temperature difference per unit length (temperature gradient)

Note 1 to entry: The SI unit of thermal conductivity is W/(m·K).

3.4
thermal interface material
TIM
material which fills small gaps or irregularities between components and has the function of efficiently transferring heat produced by a device to a heat-dissipating component

EXAMPLE Thermally conductive greases, silicone sheets, graphite sheets.

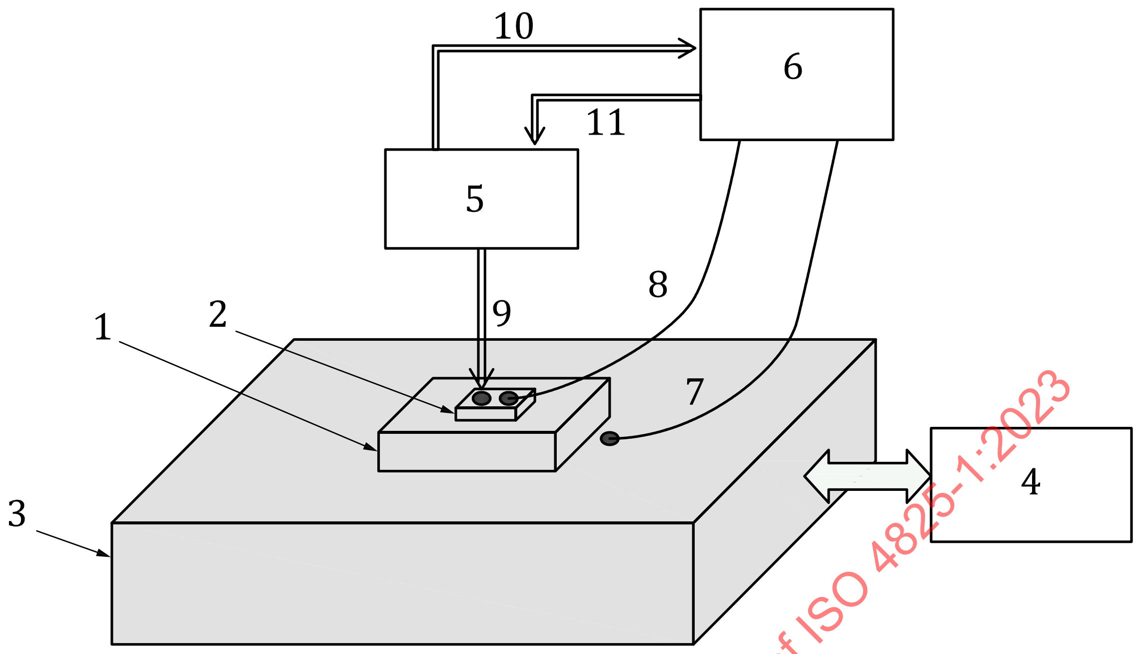
4 Principle

The thermal resistance between a heater chip and a cold plate in a direction perpendicular to the substrate is calculated by dividing the temperature difference between the heater chip and the cold plate by the amount of heat radiated from the heater chip in a structure where a metalized ceramic substrate bearing the heater chip is bonded to the cold plate. The cold plate is temperature-controlled by a chiller. This calculation method minimizes the error in thermal resistance value that develops as the aforementioned temperature difference increases. An interlaboratory comparison study (interlaboratory test) project on this method is described in Annex B.

5 Apparatus

Figure 1 presents a schematic of the test apparatus, which is composed of the following main elements.

Note See Annex A for an example of a detailed set-up for thermal resistance measurement.



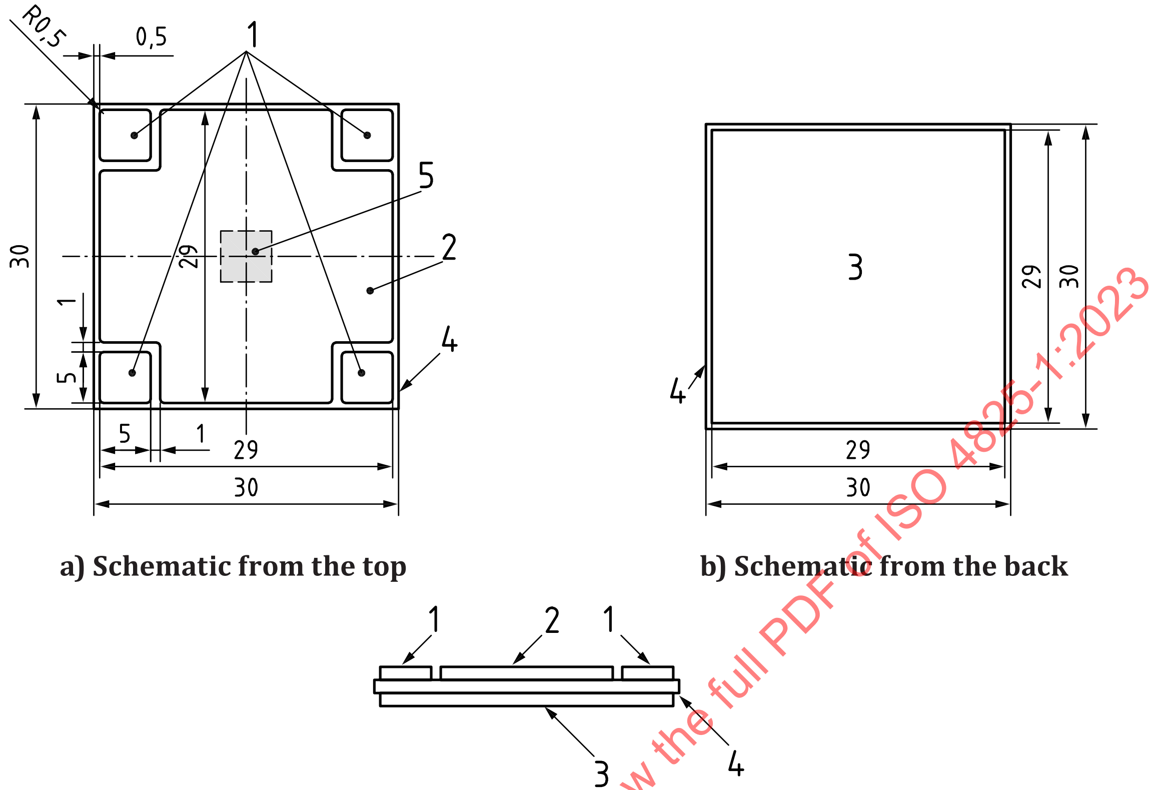
Key

1 metalized ceramic substrate
2 heater chip
3 cold plate
4 chiller
5 power supply
6 controller and recorder
7 thermocouple
8 temperature sensor
9 supply of electricity
10 recording voltage and electric current
11 turning on/off power

Figure 1 — Illustration of thermal resistance measurement apparatus

5.1 Metalized ceramic substrate. Unless otherwise specified, use a metalized ceramic substrate with a configuration as shown in Figure 2. The metallic pattern on the front of the metallized ceramic substrate shall include an installation area for bonding the heater chip and at least four electrode pads electrically insulated from this area. The entire back of the metallized ceramic substrate shall comprise a metal layer. The thickness of the metallized ceramic substrate and the metal layer are not stipulated specifically.

Dimensions in millimetres



a) Schematic from the top

b) Schematic from the back

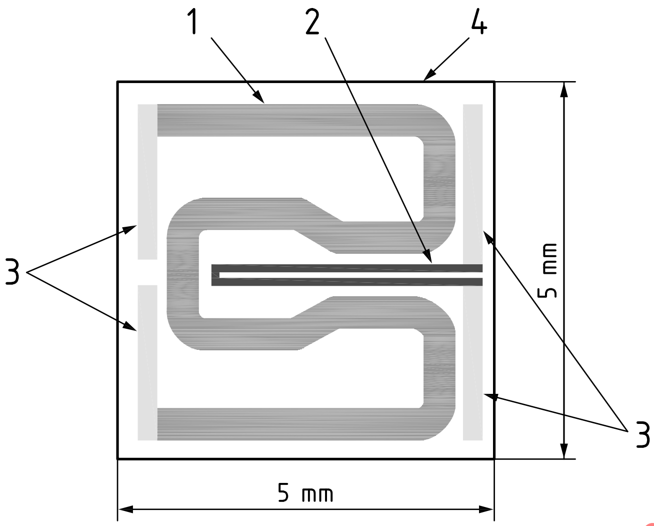
c) Schematic from the side

Key

1 electrode pad (metal)
2 metal layer (front)
3 metal layer (back)
4 ceramic substrate
5 adhesion location for heater chip

Figure 2 — Configuration of metalized ceramic substrate for thermal resistance measurement

5.2 Heater chip to imitate a semiconductor chip. It is composed of a substrate on which a heating element, a temperature sensor and electrode pads are formed. The heater chip shall be fabricated using a SiC single crystal or a substrate having an equivalent or greater thermal conductivity. Unless otherwise specified, heater chip dimensions shall be 5 mm × 5 mm (thickness 0,5 mm or less). The amount of heat generated by the heater chip shall be 200 W or greater. The heater chip shall include a sensor for temperature measurement. The heater chip shall have a heat resistance of 250 °C or more, given the temperature during heat generation and the temperature in the process of joining to a metallized ceramic substrate. An example of a heater chip is shown in Figure 3, where a platinum thin film is used to fabricate a heater element and a temperature probe for temperature measurement on a substrate made of SiC wafer used as a wide bandgap semiconductor. Electrode pads allowing additional wire bonding from the heater element and the temperature probe are formed on the surface of the chip substrate. By determining the temperature coefficient of the resistance value of the platinum thin film in advance, the temperature probe can be used to measure the temperature of the heater chip based on the change in resistance value.



Key

1 thin film heater

2 thin film temperature probe

3 electrode pad

4 substrate

Figure 3 — An example of a heater chip with a metal thin film temperature probe

5.3 Cold plate for cooling the back of a metallized ceramic substrate. Connected to a chiller in which the temperature of cooling media is kept at a predetermined temperature. As the cooling performance of a cold plate affects the measured thermal resistance, the same cold plate shall be used in a series of measurement. A cold plate having dimensions larger than 60 mm × 60 mm × 20 mm should be used.

5.4 Chiller for maintaining the cold plate at a constant, low temperature. To achieve measurement in a thermally steady state in the measurement operation, the chiller shall have a cooling capacity at least able to offset the amount of heat generated by the heater chip. As the cooling performance of the type of cooling medium and the flow rate used in the chiller affect the measured thermal resistance, it is required to keep these experimental conditions the same in a series of measurement.

5.5 Power supply to supply electrical power for heating the heater chip. A stabilized DC power source is used.

5.6 Controller and recorder to simultaneously record the electrical power which heats the heater chip, the heater chip temperature and the cold plate temperature, and which also turns on or off the electrical power for heating.

5.7 Thermocouple for measuring the cold plate temperature. It is stable up to the measurement temperature specified in IEC 60584-1 and is as thin as possible.

6 Procedure

6.1 Set-up

a) A heater chip shall be joined firmly to the front side centre of the metallized ceramic substrate by means of a joining material, as shown in Figure 4. In order to minimize perturbation of the measurement, the joining layer should have a thermal conductivity that is as high as possible and a thickness that is as thin as possible. The joining layer between the metallized ceramic substrate and heater chip shall have a heat resistance equal to or greater than the peak temperature of the chip reached during thermal resistance measurement. Unless otherwise specified, the aforementioned layer shall have a heat resistance of 250 °C or greater. Suitable joining materials include solder paste die-attach materials such as Au-based alloy, Cu-based alloy, Zn-based alloy and sintering die-attach materials such as Ag sintered paste and Cu sintered paste.

b) An electrical connection shall be made by means of wire bonding between the heater chip and the electrode pads formed on the four corners of the metallized ceramic substrate as shown in Figure 4. The wire bonding metal used for power supply should be selected such that its materials and configuration represent no more than 1/1 000 of the heat generated by the chip. Representative metals for bonding wire are Al and Cu.

c) The metallized ceramic substrate bearing a heater chip shall be bonded through a TIM to a cold plate as shown in Figure 5. In order to minimize perturbations, the TIM should have a thermal conductivity that is as high as possible and a thickness that is as thin as possible.

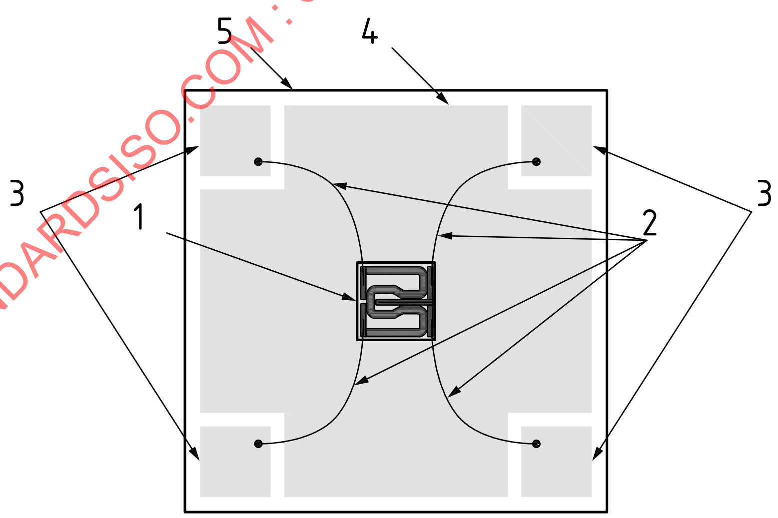
d) Electric connection for supply of electrical power and for temperature measurement shall be provided to the electrode pads on the metalized ceramic substrates. Use of contact pins is recommended for the foregoing electric connection.

e) A load shall be applied through four supporting rods to the metallized ceramic substrate under conditions recommended by the manufacturer providing the TIM. It is recommended that the supporting rods are 7,5 mm from the centre of the metalized ceramic substrate. Unless otherwise specified, a 10 kg load is recommended. The supporting rods should be made of a material with thermal conductivity lower than 30 W/(m·K) and their heads should be spherical. Representative metal used for the supporting rod is stainless steel.

f) A thermocouple shall be attached to the surface of the cold plate. The location of the thermocouple shall be within 5 mm of the end-face of the metallized ceramic substrate. The recommended thermocouple is a class 1 K-thermocouple.

g) A draft shield box to prevent drafts shall be provided to cover the entire mounting area of a test piece. In such instances, a thermometer should be provided within the draft shield to record the atmospheric temperature during experimentation.

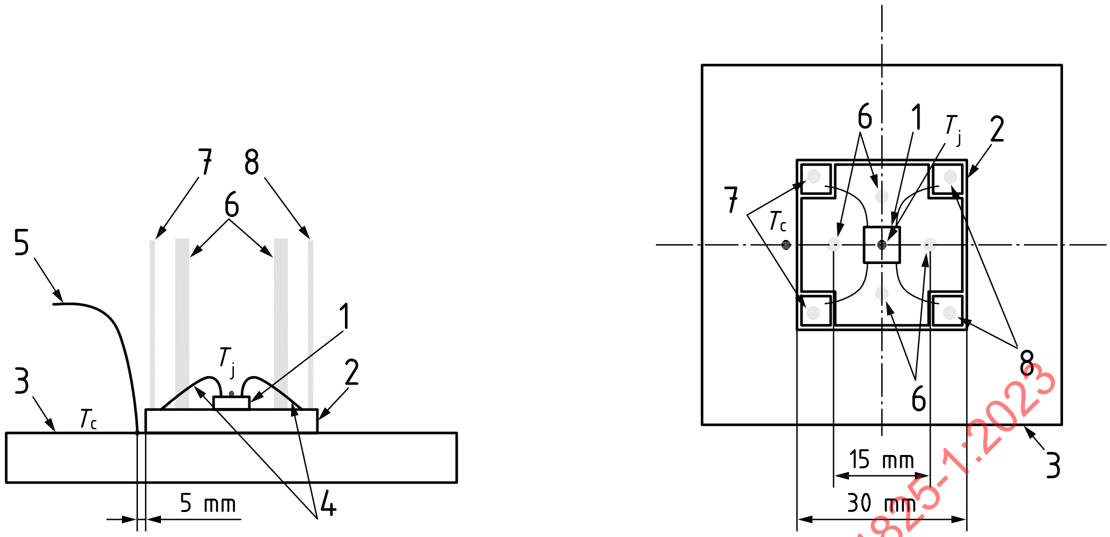
The thermal resistance measured by this specification includes, in addition to the thermal resistance of the metallized ceramic substrate, the thermal resistance of the TIM and that of the joining layer between the heater chip and the metallized ceramic substrate. Consequently, when comparing the heat-dissipating characteristics of metallized ceramic substrates, it is important that the set-up for measurements is conducted under the same conditions.



Key

1 heater chip
2 wire bonding
3 metal layer for electrode
4 metal layer for bearing heater chip
5 ceramic substrate

Figure 4 — Schematic of metalized ceramic substrate with heater chip and wire bonding



a) Schematic from the side   b) Schematic from the top

Key

1 heater chip
2 metalized ceramic substrate
3 cold plate
4 wire bonding
T_j heater chip temperature
T_c cold plate surface temperature
5 thermocouple
6 load applying supporting rod
7 contact pin for power supply
8 contact pin for temperature measurement

Figure 5 — An example of a set-up configuration for thermal resistance measurement of a metalized ceramic substrate with a heater chip adhered to a cold plate

6.2 Test environments

As specified by ISO 554, the atmospheric temperature during measurement shall be standard temperature class 5, i.e. (25 °C ± 5 °C), and standard humidity class 10, i.e. (50 % ± 10 %). However, measurement under other parameters is permissible by agreement of the parties involved.

6.3 Measurement

a) Check the temperature of the thermocouple adhering on the cold plate to ensure stability within ±0,5 °C versus the designated setting value. Unless otherwise specified, the designated setting temperature shall be 25 °C.

b) Apply a load representing a predetermined voltage (V) and current (I) to the heater chip and check that the temperature of the heater chip increases and levels off within ±0,5 °C.

c) Record the voltage and current applied to the heater chip, the temperature of the heater chip (T_j) and the surface temperature of the cold plate (T_c).

d) It is recommended that applied power is large enough to achieve a ΔT value (the temperature difference between T_j and T_c) of 100 °C or more. However, measurement with a value less than 100 °C is also permissible by agreement of the parties involved.

7 Calculation

Thermal resistance (R_{th}) is calculated according to Formula (1) using the temperature difference (ΔT) between the heater chip temperature (T_j) and the cold plate surface temperature (T_c) and the Joule heat generated by the heater chip (Q).

$$R_{th} = \Delta T / Q \tag{1}$$

where

R_{th} is thermal resistance (K/W);

ΔT is the difference between T_j and T_c ($\Delta T = T_j - T_c$) (K);

Q is the Joule heat generated by the heater chip ($Q = I \times V$) (W);

I is the current applied to the heater chip (A);

V is the voltage applied to the heater chip (V).

8 Test report

The test report shall contain items a) to h), and items i) and j) may be selected as agreed between the delivering and receiving parties:

a) a reference to this document, i.e. ISO 4825-1:2023;

b) type of metalized ceramic substrate (kinds of ceramic substrate and metal layer);

c) conditions during measurement, such as atmospheric temperature, setting temperature of chiller and applied load;

d) information on TIM used for thermal adhesion between the metallized ceramic substrate and the cold plate, such as kind of material and its claimed thermal conductivity;

e) test results (amount of heat generated by the heater chip (Q), heater chip temperature (T_j), cold plate temperature (T_c), temperature difference between the heater chip and the cold plate (ΔT) and calculated thermal resistance (R_{th}));

f) any deviations from the procedure;

g) any unusual features observed;

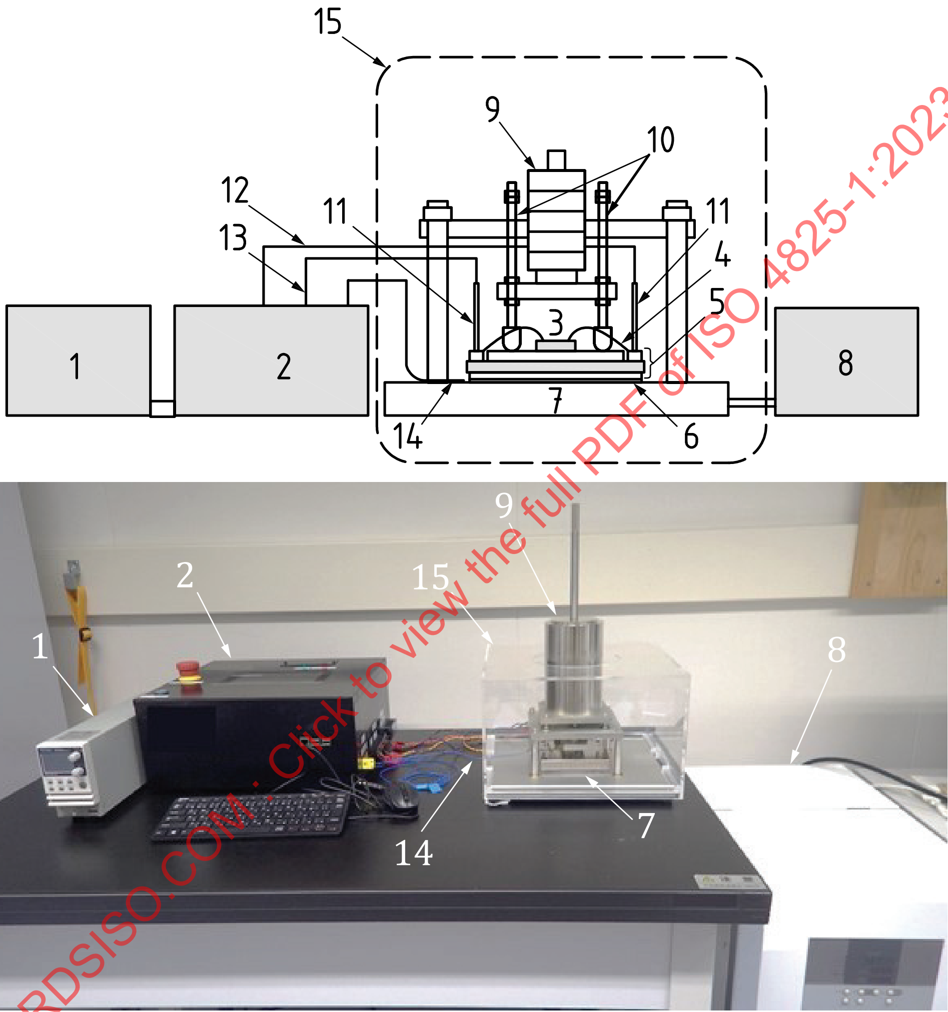
h) date of the measurement;

i) detailed information pertaining to the metallized ceramic substrate, such as thickness of ceramic substrate and metal layer, and a method for preparing the metalized ceramic substrate;

j) information relating to joining of the heater chip and the metallized ceramic substrate, such as kind of joining material and its claimed thermal conductivity.

Annex A
(informative)

Example of set-up apparatus



Key

1 power supply
2 control unit with recording function
3 heater chip
4 wire bonding
5 metalized ceramic substrate
6 thermal interface material (TIM)
7 cold plate
8 chiller
9 weight
10 load applying supporting rod
11 contact pin
12 temperature sensor line
13 power supplying line
14 thermocouple
15 draft shield box

Figure A.1 — An example of set-up apparatus for thermal resistance measurement

Annex B
(informative)

Interlaboratory evaluation of thermal resistance measurements

B.1 General

Interlaboratory tests were conducted by six laboratories (four companies, a university and an institute in Japan). In the interlaboratory tests the apparatus illustrated in Figure A.1 was used. This annex summarizes representative results of the interlaboratory tests.

B.2 Preparation of test specimen

A Cu metalized silicon nitride substrate was prepared using a square-shaped silicon nitride substrate with a dimension of 30 mm × 30 mm × 0,32 mm. Oxygen-free copper plates with a thickness of 0,3 mm were metalized on both sides of the ceramic substrate by means of an active metal brazing method, followed by a subtraction process for the formation of circuit patterns as shown in Figure 2. The thermal conductivities of Si_3N_4 and Cu claimed by the manufacturers are 90 W/(m·K) and 390 W/(m·K), respectively.

A micro heater chip as illustrated in Figure 3 was adhered to the centre of the metalized substrate by means of the Ag sinter die-attach process. Electric connection between four pads of the heater chip and four electrode pads of the metalized substrates was achieved with 150-µm diameter Al wires by means of a wire bonder.

B.3 Set-up for measurement

The Cu metalized silicon nitride substrate mounted with the SiC microheater chip was adhered to a water-cooling plate using 160 mg of heat radiation grease with thermal conductivity of 16 W/(m·K). In order to adhere the metalized substrate firmly to the water-cooling plate, a load of 10 kg was applied through four supporting rods to the metallized ceramic substrate. The water-cooling plate was temperature-controlled by a chiller at 25 °C and the ambient temperature was also kept at 25 °C. The chip temperature was measured by a sensor formed on the surface of the chip and the surface temperature of the water-cooling plate was measured by a K-type thermocouple 5 mm away from the edge of the metalized substrate.

B.4 Test conditions

Through interlaboratory tests the same metalized silicon nitride substrate with the heater chip and wire bonding lines as shown in Figure 4 was used in order to avoid the influence of variation in the characteristics of the specimen. A voltage of 110 V was applied to the heater chip. The chip temperature, the cooling plate temperature and the applied power were recorded after both temperatures became constant, then the power was turned off. After confirming that both chip and cooling plate temperatures had returned to a room temperature, 110 V was applied. This operation was repeated four times. After removing the thermal grease then applying a new grease on the back of the substrate, the measurements were carried out in the same manner three times. In this way twelve sets of data were obtained.

B.5 Results of thermal resistance measurements

Table B.1 summarizes the minimum, maximum and average values of the thermal resistances measured by the six laboratories. These data were taken from twelve sets of data. There was little difference

