# Chapter 8
# On the Accuracy and Repeatability of Thermal Transient Measurements

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Uncertainty, accuracy, repeatability, etc. are among the most important, generic problems of metrology. In modern metrology, estimation of measurement uncertainties is a basic requirement. Therefore, in this chapter, we aim to introduce the concept of measurement uncertainties first in a wider context from metrology aspect. After this, we aim to provide an inventory of possible sources of uncertainties in thermal transient testing.

## 8.1 Introduction to the Concept of Measurement Uncertainty

International metrology guides suggest that for the measurement of a certain quantity, a model of the measurement has to be set up, ideally based on analytic model equations. In Chap. 2, the theoretical background of measuring thermal resistance/impedance was given, and Chap. 3 provided a short summary of the standardized versions, the thermal resistance/impedance measurements that form the daily thermal testing practice in the electronics industry. For example, Eq. (2.19) in Chap. 2 for the *thermal impedance in general* or Eq. (3.4) or (3.8) of Chap. 3 for the *junction-to-ambient thermal resistance* or Eq. (3.9) for the *junction-to-ambient thermal impedance in particular* can be considered as such model equations. For the *real thermal resistance* and real *thermal impedance measurement of LEDs* e.g. Eqs. (6.33) and (6.34) are the measurement model equations.

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As it can be seen from these model equations, the thermal resistance is derived from the SI *base units* of *temperature* and *current* and from the SI *derived unit* of *voltage*, and thermal impedance measurements also rely on the measurement of *time*. In case of LEDs, the derived unit of the *emitted optical power (radiant flux)* is also involved.

The international definitions of these units are maintained by BIPM,[1] involving four international metrology areas, as follows:

- For measuring the electric *current*, *voltage,* and *power*: *international metrology in the field of electricity and magnetism*
- For measuring the *temperature*: *international metrology in the field of thermometry*
- For measuring the *time*: *international metrology in the field of time and frequency*
- For measuring the emitted *optical power*: *international metrology in the field of photometry and radiometry*

The *National Metrology Institutes*[2] (NMI-s) deal with the actual realizations of these units and maintain the corresponding etalons for the calibration of their own equipment and for the calibrations of the test equipment of *commercial calibration laboratories*.

These commercial laboratories provide calibration services for the industry, e.g., for *test equipment manufacturers*.

Ordinary *end-users of the test equipment* rely on the calibration certificates of their test equipment that are issued by the manufacturer. This way the values they measure can be traced back to the primary etalons of the NMIs.

In the above-unbroken chain of calibrations that is called *tractability or traceability chain*, there are multiple players involved. NMIs spend every effort in the implementation of their own measurement capabilities with the *highest possible accuracy* and *lowest possible uncertainty* available through the state of the art of the technology. From time to time, NMIs organize key comparisons of measurements of different units; therefore, one can speak about the NMI-level world average of *measurement uncertainty* (MU) of a given unit of measure.

The next level in the traceability chain is represented by the different commercial testing and calibration laboratories. Their etalons are based on regular calibrations performed by NMIs; thus, the uncertainty of their measurements adds to the uncertainty of the NMIs. Obviously, as further we are in the traceability chain from the primary standards of an NMI, the higher is the uncertainty of the measurement of a given unit.

In the assessment/calculation of the measurement uncertainty, one relies on the uncertainty of the measurements stated on the calibration reports of the metrological entity that precedes the given entity in the traceability chain.

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[1] International Bureau of Weights and Measures (Bureau international des poids et mesures, BIPM), https://www.bipm.org

[2] Such as NIST in the USA, PTB in Germany, AIST in Japan, KRISS in South, etc.

For example, in the temperature measurements for obtaining the thermal resistance/thermal impedance of semiconductor device packages, the weakest element in the traceability chain is the “TSP calibration” performed by the user of the thermal test equipment in a field laboratory.

Regarding this, the uncertainty factors related to this device calibration process detailed in different sections of Chaps. 5 and 6 are added to the uncertainty stated on the temperature calibration certificate of the thermostat being used. The advantage of the differential formulation of the *junction-to-environment X* thermal resistance (see Sect. 3.1.5) is that no further item needs to be considered for the uncertainty calculation of the junction temperature change used for the calculation of the thermal resistance/impedance – see also Sect. 6.10.5.

If the absolute junction temperature is to be identified, for example, during the combined thermal and radiometric/photometric measurements of power LEDs using Eq. (6.37) of Sect. 6.10.6, then it is important to use the same temperature-controlled cold plate for the TSP calibration and for the actual measurement; otherwise, if two different thermostats are used, their individual uncertainties need to be combined to obtain the final, combined uncertainty of the LEDs’ junction temperature setting/measurement.

For the sake of a common understanding on the concepts and methods behind the calculation of measurement uncertainties, the *Joint Committee for Guides in Metrology (JCGM)* and their partner organizations who are stakeholders in different fields of international standardization (such as ISO, IEC) have published the *Guide to the Expression of Uncertainty in Measurement* often referred to as GUM [49].

Some NMIs like NIST and bigger organizations such as NASA derived and published their own handbooks on the assessment of measurement uncertainty [50, 51]. Some standardization bodies in specific fields of metrology also issued their own guides on the assessment/calculation of measurement uncertainties, such as CIE’s guide on *determination of measurement uncertainties in photometry* [52]. Some specific measurement guidelines such as CIE’s recent document on the measurement of power LEDs [45] provides examples on the assessment of the measurement uncertainties related to the quantities they deal with.

Unfortunately, in the field of measuring thermal resistance/thermal impedance of semiconductor device packages, the relevant stakeholders (such as the JEDEC JC15 committee) did not provide their specific guidelines about the assessment and quantification of the possible factors of the uncertainty of the measurement of thermal resistance and thermal impedance. The topic exceeds the limits of this book chapter, and the authors of this book do not dare to undertake the years’ long task of a standardization committee in this regards. To highlight the complexity of the issue, in Fig. 8.1, we only quote a diagram from a temperature test chamber manufacturer that illustrates the factors of uncertainty of measuring the temperature of such chambers.

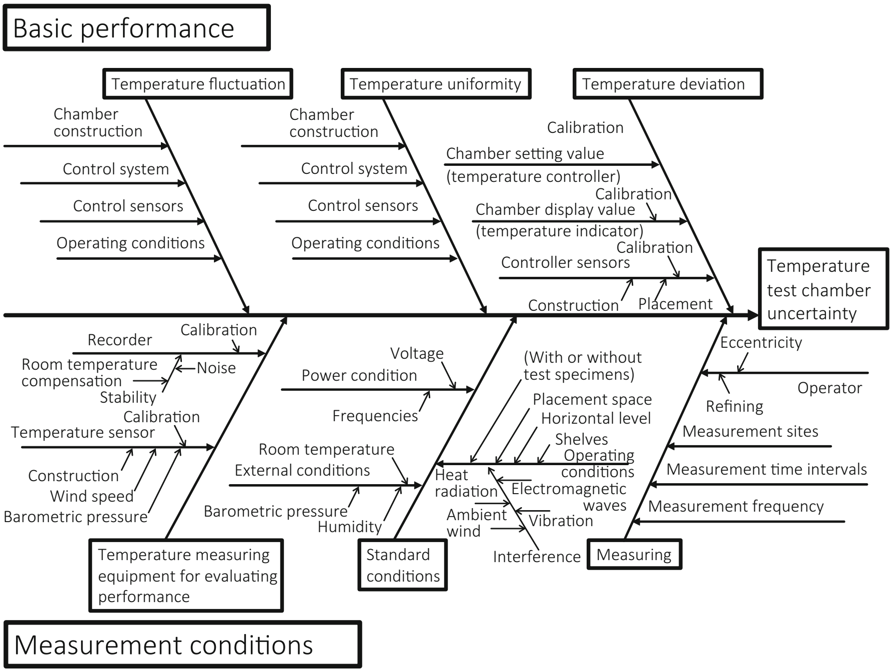

**Fig. 8.1** An overview chart about different factors influencing the temperature measurement in a temperature chamber. (Source: [169])

## 8.2 Common Factors of Measurement Uncertainty

Uncertainty estimation has always been a major issue in modern metrology, and since the first publication of the GUM, it is better and better understood, though it is not a topic that is easy to master as some knowledge in statistical analysis is also needed. As a general introduction to the topic, it is worth quoting a few sentences from Ref. [51]:

> Measurement uncertainty is an estimation of the potential error in a measurement result that is caused by variability in the equipment, the processes, the environment, and other sources.
>
> Every element within a measurement process contributes errors to the measurement result, including characteristics of the item being tested.
>
> Evaluation of the measurement uncertainty characterizes what is reasonable to believe about a measurement result based on knowledge of the measurement process. It is through this process that credible data can be provided to those responsible for making decisions based on the measurements.

Besides the detailed handbooks already quoted [51], there are a few, more easy to read works also available [170, 171]. Based on these handbooks, hereby we provide a short overview of the factors that need to be considered related to the measurement of thermal resistance/impedance of semiconductor device packages.

### 8.2.1 Measurement Process Selection

In terms of the measurement process, there is little choice left. All thermal resistance/impedance measurements of semiconductor device packages are based on JEDEC's JESD51-x series of standards [29], defining the so-called *electrical test method* [30], in case of certain device types like LEDs with a few further clarifications and additions [43, 44].

The choice left is between the JEDEC JESD51-1 *dynamic* or *static* test methods. In prior chapters of this book, several reasons have been given that suggest that the *static test method* with the extension of continuous transient measurement is the best choice; see Sect. 5.4 as well as Ref. [115]. Many aspects of these test methods have been discussed there except the question of measurement uncertainty. As in case of the JEDEC JESD51-1 dynamic test method, the complete heating curve of a device is composed from a series of measurements to single heating pulse; the uncertainty of a measurement based on this test method is obviously larger than the uncertainty of the measurement of the same device conducted according to the transient extension of static test method where the response to only a single switching in the heating power is involved.

The complete measurement process is best elaborated for LED devices. For this reason, we refer to the detailed example given in Sect. 6.10.3, which uses the transient extension of the static test method for power LEDs.

### 8.2.2 Measurement Error/Accuracy

All measurements are accompanied by error; one's lack of knowledge about the sign and magnitude of measurement error is the *measurement uncertainty*.

Prior to the publication of GUM [49], measurement errors were categorized as either random or systematic. The random components of the measurement error change when measurements are repeated; the systematic components remain constant in the repeated tests for the same quantity. According to the concepts of GUM, there are errors only, irrespective of their nature; therefore, each error is considered as a random variable contributing to the overall uncertainty of a measurement. Therefore, the different measurement process errors are the basic elements of uncertainty analysis.

- In the case of thermal transient testing, these different sources that disturb the measurement can originate from the transient behavior of the DUT, from the tester equipment and the related instrumentation, and/or from the ambient, not to mention the possible operator bias and the possible numerical and computational errors. As an example, the $Z_{\mathrm{th}}(t)$ curves are measured and post-processed on a logarithmic time scale. The discretized logarithm of the elapsed time definitely differs from the real logarithm of the time. This adds to the overall, inherent noise present in the measured transients.

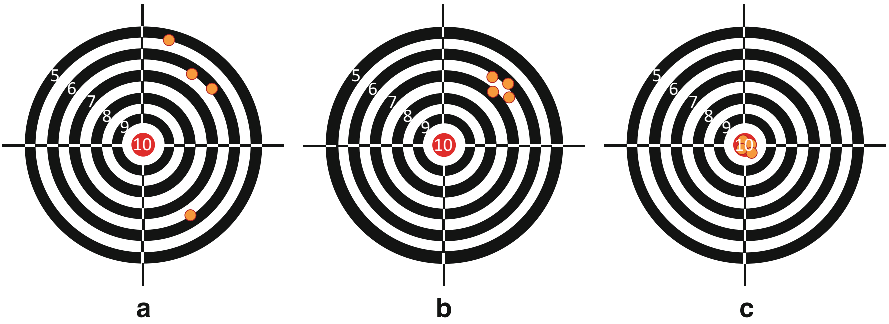

**Fig. 8.2** Illustration of the concepts of accuracy and repeatability of measurements repeated within a short time period. (**a**) neither repeatable, nor accurate, (**b**) repeatable but not accurate, (**c**) repeatable and accurate

- The NID method that is used to obtain structure functions has its own theoretical and practical limits [58] that lead, for example, to limiting the structural details that can be resolved by the structure functions. These are factors that also contribute to the uncertainty budget for certain structure function-based measurement methods.
- As the GUM [49] recommends, all the above factors need to be quantified either based on a statistical approach (these are called Type A uncertainties) or have to be elaborated by well-established engineering estimates (Type B uncertainties).

Before discussing these with more details, let us specify what we mean by accuracy and repeatability of measurements from an engineering standpoint with the help of Fig. 8.2, where we use the following notions:

- *Accuracy* is the degree of closeness of measurements of a quantity to that quantity's true value. Note that accuracy can be declared only within a certain bound. As seen in Fig. 8.2c, even in case of the highest repeatability and accuracy, the subsequent "shots" differ a little from one another, though they are all located within the smallest, innermost circle that represents the targeted smallest region. The most important aspect of measurement uncertainty is how small the area of acceptance is around the targeted "true value."
- *Precision* is the degree to which repeated measurements under unchanged conditions show the same results; precision can relate to:
  - *Repeatability* – the variation of measurements with the same instrument and operator and repeated in a short time period
  - *Reproducibility* – the variation among different instruments and operators (even among, e.g., different laboratories) and over longer time periods

- *Resolution* is the smallest change which can be detected in the quantity that it is measured.

*Reproducibility* could be illustrated in the same way, but over longer time periods of time and eventually at different laboratories and instrumentation.

*Resolution* can be defined in case of measurements where the results are transformed into digital values. In this case, it may correspond to the thickness of the black and white rings of the target circles in Fig. 8.2; i.e., if a shot is anywhere in a thick ring, the digital value associated with that shot is the number of the ring.

## 8.3 Factors in the Uncertainty of Thermal Transient Measurements

Several factors contribute to the uncertainty of thermal transient measurements. These may origin from the measuring equipment, from the methodology, from the test environment, or from the uncertainties in the operation of the devices themselves. In this section, we shortly summarize the most important and most frequent ones.

### *8.3.1 The Transient Behavior of the Tested Electronic Devices*

As it was discussed in Sect. 5.4.1 in details, in case of switching the point of operation of a semiconductor device, electrical and thermal transients occur simultaneously. The electrical transients are very fast but hide the first part of the measured thermal transient curve that has to be extrapolated. This extrapolation brings in certain amount of uncertainty, but this effects only the very first part of the measurements, and it may be corrected by the measuring instrument. The caused error depends on the construction of the device itself, but it is affecting less than the first microsecond of the measurement.

### *8.3.2 Effects of the Test Equipment*

Let us shortly consider the most common equipment-related sources of measurement errors. In case of the thermal resistance/impedance measurement of semiconductor device packages, the *offset* and *scale/calibration errors* can be handled by the proper choice of the test method/procedure. As discussed in prior chapters, if the JEDEC JESD51-1 electrical test method is applied in a differential approach, using solely the temporal difference of the junction temperature (see Sect. 3.1.5) and if the same current sources and voltage meters are used both for the TSP calibration and the actual measurements, the offset and scale errors cancel out, or, at least, their effect can be reduced to the possible minimum (as discussed in details for LEDs in Sect. 6.10.5).

*Linearity* and *quantization errors* cannot be mitigated on the level of test procedures. These parameters should be provided on the specifications sheet of the test equipment to allow application level-combined uncertainty calculations by the end-user.

### Properties of the Data Acquisition Channels

As discussed above, the data acquisition channels of the measurement instrument may have some *gain and offset errors*, and in case of transient measurements, the bandwidth of the channels limits the details of the thermal impedance that can be resolved with the measurement.

The finite resolution and the accuracy of the junction temperature measurement also depends on the device under test and on the properties of the thermostat used for the TSP calibration.

As a short example, if we assume that the junction temperature-induced change of a diode's forward voltage fits into a 50 mV differential voltage measurement range and the measured voltage change values are digitalized with 12 bits, the least significant bit corresponds to 12.2 μV. Assuming that the temperature sensitivity of the diode's forward voltage is cca. –2 mV/K, this would result in a temperature resolution below 0.01 °C.

The possible linearity error of the data acquisition channels can be checked with the help of an electronic only golden reference device discussed later.

### Noise

In thermal transient measurements, we measure in most of the cases electrical signals, current, and voltage values. These value can be measured today with an extremely high accuracy/low uncertainty. In case of measuring with electrical signals, the fundamental source of uncertainty is the always present *noise* on the electrical signals. When the electrical signals are converted into digital ones, the conversion adds the quantization noise to the budget, coming from the finite bit length of the digital representation. The effect of noise on the electrical signals usually can be mended with high sampling rate and with repeating and averaging the measurements. The devices under test are also sources of noise. The different mechanisms in device operation result in different noise characteristics for diodes and transistors. These affect the choice of the measurement current. For further details, refer to Sect. 5.7.

### Stability and Linearity of the Equipment and the Way of Testing It

Among the test equipment-related uncertainty issues, a very important factor is the stability of the test equipment. Stability of the test equipment means how the metrological properties of a test equipment remain constant in time, involving not only the actual readings of the values provided by the test equipment but including also the measurement process itself. Thus, equipment stability is also a factor to be considered in the overall uncertainty budget of a measurement.

The usual way of testing the stability of a testing apparatus is to maintain a physical object, an artifact, serving as an etalon that possesses a constant property that one aims to measure and use that physical object to check regularly how that object's property is measured by the test equipment. A widely known example for such an object was the international mass etalon, the 1 kg platinum-iridium cylinder known as the International Prototype Kilogram (IPK) maintained at BPIM in France that was used until recently as the base reference for measuring mass.[3] Similar to the IPK, one may think of establishing a physical prototype to realize a thermal resistance/thermal impedance etalon that could be used to check the stability of a thermal transient test equipment from time to time.

As described in Chaps. 3, 5, and 6, the thermal resistance/impedance measurement of semiconductor device packages is based on the electrical test method, meaning that the test equipment measures the changes of a temperature-sensitive parameter that indicates the change in the junction temperature. The measured change of the electrical signal is transferred to the temperature scale through the TSP calibration process that relies on the temperature control and the measurement capability of the calibration environment. Therefore, if this transfer to the temperature scale is separated from the measuring equipment, a real, physically realized thermal RC system as a thermal impedance etalon can be completely replaced by an electrical RC system that is built of components with precisely known resistance and capacitance values and with a long shelf lifetime.

This way, electronic golden reference devices can be built. Such a device is a linear, passive electrical RC circuit that comprises high-precision discrete resistors and capacitors. The schematic of such an electrical circuit was provided in Fig. 2.10 of Example 2.3 provided in Chap. 2.

A practical example of such a device attached to a test equipment is shown in Fig. 8.3. Besides getting rid of the need of the temperature calibration, the advantage of using such an electrical-only device for the stability checking of the thermal test equipment is that all uncertainties due to the thermal test environment are completely eliminated from these regular equipment stability control tests.

Another advantage of such electrical-only reference devices is that the sources of the $I_H$ heating current and the $I_M$ measurement current can be tested separately.

Besides checking the current sources and the voltage meters of the test equipment, its time base can also be tested by measuring the time-domain impedance function of the reference device and by identifying the time constant spectrum from this.

Figure 8.4a presents the unit step response of such an electrical-only golden reference device (translated to a quasi-thermal impedance by a dummy, constant temperature sensitivity). Applying the realization of the NID method with predefined numerical parameters yields the time constant spectrum of the circuit; see Fig. 8.4b.

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[3] Effective from 20 May 2019, new definitions of the SI base units are used, no longer requiring physical artifacts to be used as prototypes for an SI unit.

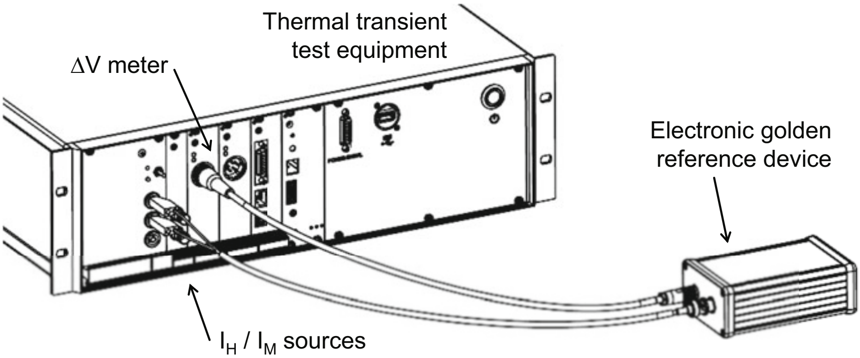

**Fig. 8.3** A passive electric RC circuit built of high precision discrete resistors and capacitors with precisely known unit-step response (e.g., a four-stage Foster network) used as a golden reference device to test the stability of the impedance measurement capability of a thermal transient tester equipment

The electronic-only golden reference device shown here has four well-defined time constants. If the locations and the heights of the maxima are within a tolerance band specified by the equipment manufacturer, the current, voltage, and time measurement capability of the equipment can be considered unchanged. This condition can be identified through a manual checklist or by a fully computerized process.

The same golden reference device can also be used for checking the linearity of the measurement channels: the same impedance measurement should be performed at different current levels. If the resulting impedance curves and time-constant spectra are the same, then the linearity of both the measurement channel and the golden reference device should be assumed. For further insight, refer to Example 2.13 in Sect. 2.12.3.

### 8.3.3 Reproducibility Issues of the Test Environment

The $R_{thJX}$ *junction to reference environment* thermal resistances are very sensitive to the applied test conditions. The two most common environments, still-air and infinite heat-sink (cold plate), represent practical limits of test environments (see Sect. 3.1). JEDEC's JESD51-x family of thermal testing standards provide specifications for the test environments with the aim of reducing the measurement uncertainties to the possible minimum and supporting the highest possible reproducibility of the measurements while allowing high level freedom for the physical realization of the environments.

For example, measuring IC packages in a natural convection test environment, i.e., in a JEDEC JESD51-2A [31], compliant still-air chamber also assumes using one of the JEDEC standard thermal test boards that would fit the package type.

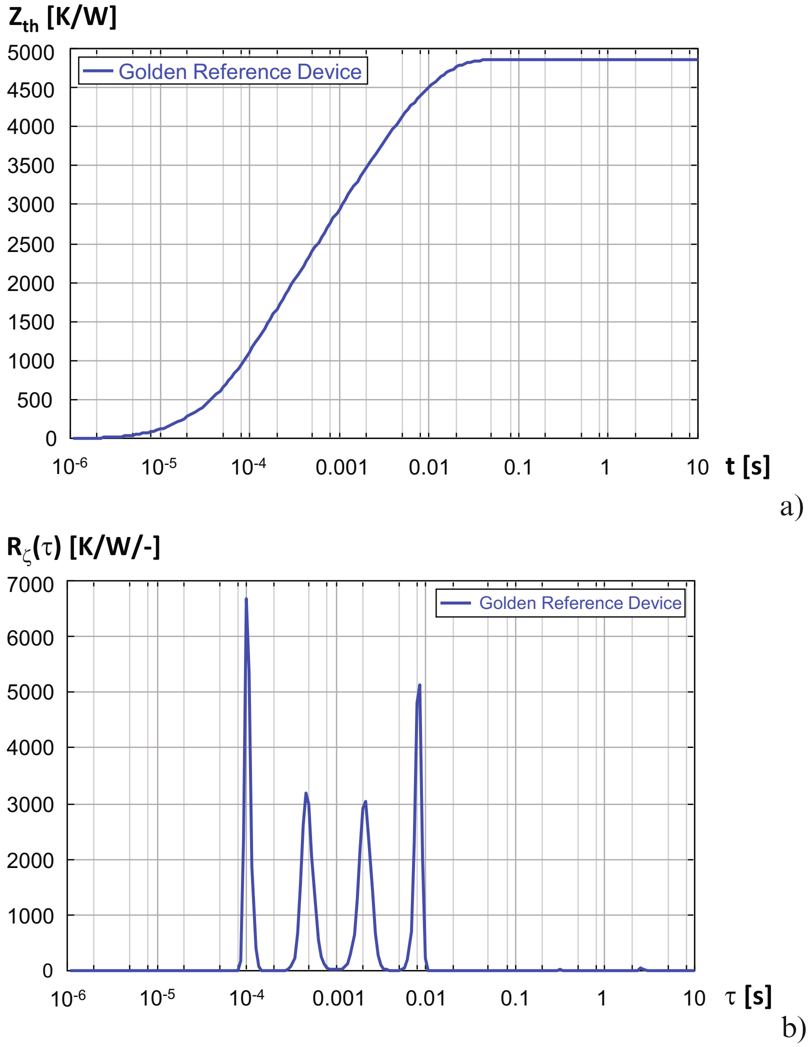

**Fig. 8.4** The equipment stability test results obtained with the help of the golden reference device: (**a**) the unit step response, (**b**) the time constant spectrum, both obtained with prescribed current source setting and prescribed parameters of the numerical deconvolution process

General guidelines for the design of such test boards for the main IC package types are also provided in the different documents of the JESD51-x family [33, 35–38].

While a JEDEC JESD51-2A [31] compliant still-air chamber assures that the wider environment, i.e., the thermal testing laboratory, does not affect the $R_{\mathrm{thJA}}$ measurement results, the small variability among the standard test boards from arbitrary manufacturers will have an influence, especially on the *reproducibility* of a certain measurement type. The main reason is that in case of the junction to ambient thermal resistance, $R_{\mathrm{thJA}}$, a large portion (e.g., 50..70%) of the total thermal resistance represents the test environment, mostly by the package attachment to the test board and the test board itself. This could be revealed by the structure functions, as illustrated by Example 3.1 in Sect. 3.1.2.

Using a cold plate as thermal test environment for power device packages considerably shortens the junction to ambient heat flow path, and most of the measured overall thermal resistance belongs to the package under test, though effect of the test environment also appears in the results.

The use of structure functions helps to separate the heat conduction path sections belonging to the package and belonging to the test environment (e.g., the thermal interface material between the package and the cold plate, the cold plate itself). The JEDEC JESD51-14 standard [40] defines the *transient dual thermal interface method* for this. Besides the definition of the test method, this document also provides hints on the proper construction of the cold plate to be used.

It has to be noted that despite such specifications, the realization of the cold plates, the different properties of the cold plates have a large scatter, since different laboratories apply different materials and geometries for the cold plate that is used in the measurement and use other formation of the liquid flow, and various surface roughness and planarities are used in the structures. Even if using the same equipment, the type and thickness of the applied thermal paste usually varies. Hints on the proper construction of cold plates are given in [40].

The above factors, however, usually do not affect the $R_{\mathrm{thJC}}$ junction to case thermal resistance values of the power semiconductor device packages identified this way. Most of the uncertainty factors of structure function-based methods are associated with the data processing procedures that are applied to the measured thermal $Z_{\mathrm{th}}(t)$ and thermal impedance curves; see Sect. 8.4.

If in the thermal resistance measurement process external temperature sensors are used besides the DUT's temperature-sensitive parameter as a thermometer, further issues arise. For example, the type and position of external temperature sensors may be different, with different properties. Sources of inaccuracy related to the probe position at two point measurements are discussed in details in [97], with the help of a simulation experiment.

In a real measurement, further error sources can be identified, such as:

- The thermal contact resistance between case surface and probe tip can be quite large, especially since the contact area in case of a spherical probe is just a point.
- The heat flow from the tip through the thermally conductive material of a thermocouple diminishes the probe tip temperature.
- There is a temperature drop inside the alloy joint of the thermocouple, since the thermocouple does not measure the temperature at its tip but at the point where the two wires of different alloys separate, etc.

### *8.3.4 Uncertainty from the TSP Calibration of the Samples*

Although the calibration of the temperature-sensitive parameter is not part of the measuring equipment, its accuracy is ultimately determining the accuracy of the measured thermal resistance/impedance results.

The uncertainty of the TSP calibration is primarily determined by the uncertainty stated on the calibration certificate of the temperature-controlled environment used for the TSP calibration. Other factors are the biasing of the device under test that is being calibrated for temperature sensitivity and the voltage meter(s) used.

The uncertainty is also determined by the authenticated accuracy of the thermal sensor that is used for the calibration of the device to be measured, but a number of inadvertent errors may further influence the accuracy of the calibration. The artifacts that may be created by the inappropriate calibration is presented in details in Sect. 2.12.2.

For details of the calibration process, refer to Sect. 5.6. Some specific recommendations for the TSP calibration of LEDs are provided in Sect. 6.10.5.

## 8.4 Uncertainty Issues Related to the Data Processing

In the prior chapters, many data processing aspects affecting the accuracy of the final results of thermal transient testing have been discussed already. In this section, we only recollect them.

### *8.4.1 Possible Uncertainty Related to the Initial Transient Correction*

Depending on the stray electrical capacitances of the test setup, the DUT and test equipment, and the actual speed of switching on/off the heating power applied to the DUT, the initial part of the captured voltage transient is rather related to electrical changes than to the change of the DUT's junction temperature. This transient has to be discarded and replaced by an assumed $\Delta T_J(t)$ junction temperature transient that is proportional to the square root of the elapsed time $t$. Since usually neither the geometry nor the thermal parameters of the dissipating chip area are known, the $\Delta T_J(t)$ function corresponding to *Eq.* (2.26) *should be fitted to the measured data points* following the time instance before which data points have been discarded.

The more data points are involved in the regression calculation in the fitting, the better accuracy of the fitted curve is foreseen up to a certain point. That is, if a too long real $\Delta T_J(t)$ transient beyond the $t_v$ time instance given by Eq. (2.28) is used for the fitting, where temperature data already correspond to a time when the dynamic heat propagation in the device already violates the assumptions made for Eq. (2.26), the quality of the fitted curve section would degrade. This happens, for example, when the heat generated at the junction would cross a boundary of two different, adjacent material layers.

It has to be mentioned that the quality of fitting, which depends on the operator's experience, affects the *reproducibility*. Table 2.2 provides practical hints about the $t_v$ time limits in typical material layers up to which the assumptions made for the $\Delta T_{\mathrm{J}}(t) \sim \sqrt{t}$ approximation are valid.

A possible way to avoid this problem is to create a detailed thermal simulation model of the chip/junction region of the DUT; fit this to a longer section of the measured transient and use the initial part of the $\Delta T_{\mathrm{J}\,-\,\mathrm{sim}}(t)$ transient provided by the simulation to replace the discarded portion of the measured one.

### 8.4.2 Properties of the Deconvolution Algorithms

One has to be aware of the properties of the deconvolution algorithm used for the implementation of the NID method when thinking about the final resolution of the time constant spectra and items at further stages of the data processing procedure yielding the structure functions.

To start with, let us refer to Example 2.4 of Sect. 2.4.1 where we had a known, lumped element model network (Fig. 2.16) with three distinct, discrete time constants. The unit-step response (see Fig. 2.17) of this model system was obtained by LTSpice simulation and was processed by the NID method, resulting in a time constant spectrum (Fig. 2.18).

All the three time constants are properly resolved, but instead of three Dirac–δlike single spectrum lines, we had a blurred, continuous distribution of the time constants with steep peaks having maxima corresponding to the discrete time constants calculated from the element values of the model network. Though in this example all time constants were nicely resolved, it is plausible to say that if two time constants are getting closer and closer, after a while they will not be distinguishable in the continuous spectrum calculated by the deconvolution process.

As a next example, let us consider another RC system with three discrete time constants at 0.5 ms, 1 ms, and 10 ms (see Fig. 8.5a), but in this case the distance between the first two time constants is small; it is only an octave of time, while the third time constant is in a decade distance from the middle one. Now, let us consider the first derivative of the unit-step response of this system, shown in Fig. 8.5b. This function has only two peaks. The second peak is exactly at the location of the 10 ms time constant while the first peak is located between 0.5 and 1 ms. That is, the effects of the first two time constants separated by an octave only are indistinguishable, but if the separation is already one decade, the effects of the two different time constants is clearly visible.

It is worth recalling Eq. (2.20) now. We can interpret it as if we had a linear system characterized by the $w_z(z)$ *weight function* (Fig. 8.6) to which an input with three Dirac-δ pulses with the $R$ magnitudes shown in Fig. 8.5a have been applied,

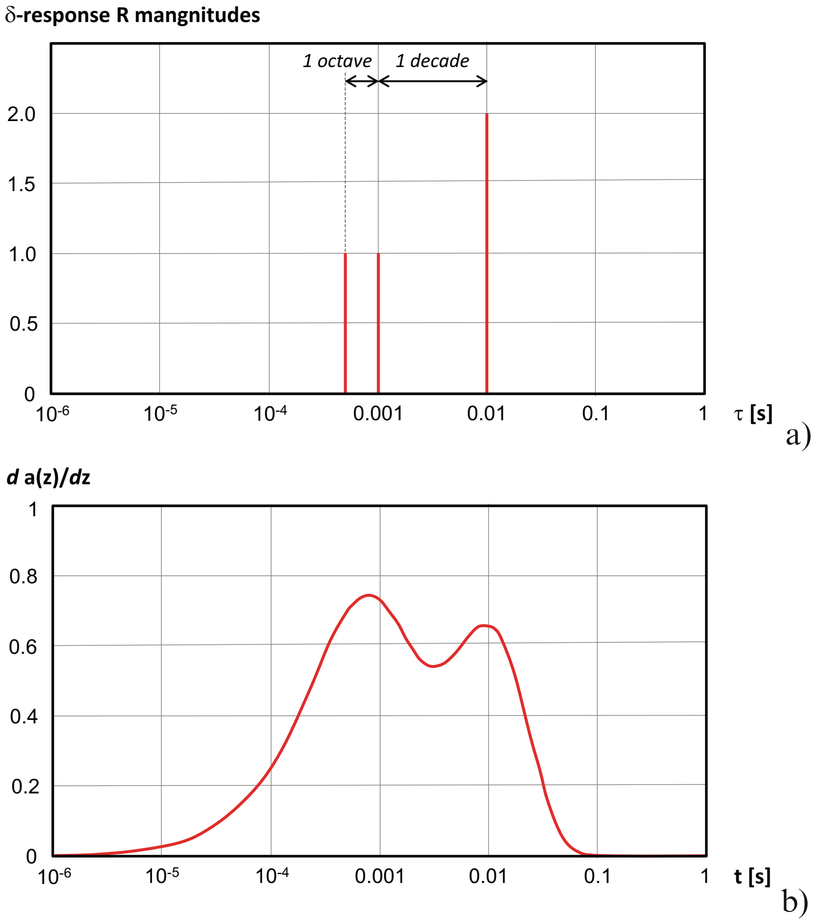

**Fig. 8.5** RC system with three discrete spectrum lines: (**a**) the time constant distribution of the system (**b**) and the first derivative of the system unit-step response in logarithmic time. (Based on Székely [58])

and as a response, the function shown in Fig. 8.5b was produced. The function shown in Fig. 8.6 is a typical weight function of low-pass filters; therefore, the sharp input – the three discrete spectrum lines of Fig. 8.5a – gets blurred as seen in Fig. 8.5b.

This blurring effect means a fundamental limit in the theoretically achievable resolution of the time constant spectra obtained by deconvolution. This "blurring effect" is determined by the half-value width of the weight function. For the above function introduced as $w_z(z) = \exp\,[z - \exp\,(z)]$ in Sect. 2.4.1, this value is about 2.45. For a rigorous description of the these fundamental issues, refer to [58] or [5].

*As a rule of thumb*, one can say that spectrum lines separated by a time distance of a decade can be well resolved in the time constant spectra.

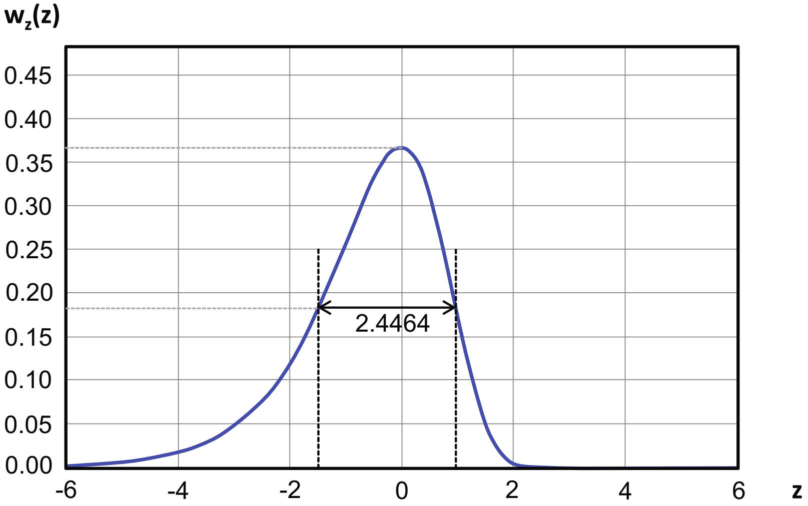

**Fig. 8.6** The $w_z(z)$ function used in Eqs. (2.20) and (2.21) in Sect. 2.4.1

Further limitations in the resolution of the time constant spectra may come from the actual implementation of the deconvolution operation presented in Eq. (2.21). Both the numerical derivation and the deconvolution itself on the right hand side enhance the noise that is already inherently present in the unit-step response function.

In the implementation that is using the so-called *inverse Fourier filtering*, an interesting mitigation is applied in the frequency domain: adding some white noise to the frequency domain spectrum of the derivative of the unit-step response function and applying frequency domain filtering before the actual deconvolution step. For a detailed explanation, see the fundamental paper of [58] or the papers describing an actual numerical implementation of the method [172, 173]. The resulting resolution of the obtained time constant spectra also determines how detailed the structure functions can be, i.e. what are the smallest structural details resolved. There are a few, further fundamental papers that describe some improvement options of the thermal transient results evaluation process described in this book, both in terms of possible error corrections and definition of acceptance criteria of the final results [174–177].

This step inherently adds to the uncertainty regarding the resolution of the time constant spectra. The advantage of the inverse Fourier filtering-based deconvolution process is, however, that it works properly for transfer impedances as well, which also have negative values in their time constant spectra.

In contrast to the above process, iterative numerical deconvolution methods based, e.g., on Bayesian iteration [6] are deterministic in the sense that if the process is repeated with exactly the same parameters, the resulting time constant spectra are exactly the same. The uncertainty factor in this case is the actual parameter set with which the process is executed, e.g., the chosen number of iteration.

Note that in time constant spectra obtained by Bayesian iteration, all values are positive, thus, this deconvolution algorithm cannot be applied to processing thermal transfer impedances.

*As a summary*, one can state that in order to assure reproducibility, the type of the deconvolution algorithm and its major parameters need to be reported together with the thermal transient test results (e.g., Bayesian iteration, with iteration number X).

## 8.5 Final Remarks

At the end of this book, we wish to summarize what we need to know about the accuracy and repeatability of thermal transient measurements.

Thermal transient measurements are considered in general to be very accurate in the realm of thermal measurements as they operate with easily, accurately, well-measureable electrical signals. According to the experience of the authors of this book, the repeatability of the measurements is the best of all thermal measurements.

In this chapter, we have summarized all the factors that influence the actual accuracy of the measurements.

For the last 30 years of thermal transient measurements, the authors of this book were requested many times to calculate a number that gives the accuracy of thermal transient measurements, but we never agreed to do it. The discussion in this chapter presents all the factors that influence the accuracy of thermal transient measurements and demonstrates that the actual uncertainty of the measurement is influenced by several components.

We have to emphasize here again that the accuracy of these measurements strongly depends also on the care with which these measurements are carried out. The better we follow the prescriptions and recommendations of the measurement standards and the recommendation of this chapter, the more we can guarantee that our measurement is repeatable and accurate.