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# The Algorithm and Software Implementation of the Thermal Transient Testing Technology Applied in High-Power Electronics

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**Abstract:** Thermal transient testing technology is currently the most effective method for obtaining thermal characteristic parameters of high-power electronics and the structure functions can be used to evaluate the long life-time reliability. This paper briefly outlines the basic theory of the thermal transient testing technology, and then focuses on two key algorithms in the implementation of this technology: deconvolution and transformation of thermal network model algorithms. Meanwhile, a software system of the thermal transient testing applied to power semiconductor devices is established. Mathematicians used to solve the problem of data accuracy in network model transformation. By comparing the commonly used deconvolution algorithm, it is concluded that the thermal characteristic parameters of the device calculated by Bayesian deconvolution based on Richardson-Lucy algorithm have better accuracy. Finally, the measurement data of power semiconductor devices tested by mature commercial thermal transient testing equipment is set as an example to verify the accuracy and effectiveness of the proposed software system.

**Keywords:** High-power electronics, Structure function, Thermal transient testing technology, Deconvolution, Thermal network model transformation.

## 1. Introduction

High-Power semiconductor devices due to high voltage, high current, and excellent switching performance, have gradually been applied to high voltage and high power density applications, for example, IGBT (Insulated Gate Bipolar Transistor) devices are used in the electric traction and high voltage direct current transmission system. Thermal characteristic have always been a quite important concern in the application of power semiconductor devices. 55 % of the failure of electronic devices is caused by heat-related problems [1]. Therefore, it is quite important to accurately measure the thermal parameters of power electronics and analysis its thermal behavior.

For high-power IGBT devices, junction temperature and thermal resistance are two critical thermal characteristics. Many electrical parameters of the device are related to the junction temperature, which is also affected by its thermal resistance. Thus, accurately measuring the junction temperature and thermal resistance of high-power IGBT devices not only helps to optimize the heat dissipation structure of the device package, but also guides users to give full play to the device performance and prolong its service life. This has become a common concern for the manufacturers and users.

There are two most commonly used methods to obtain the thermal resistance or thermal behavior of power electronics: Traditional steady-state method and transient thermal method [2]. Traditional steady-state method takes a thermocouple to get the case temperature to calculate the thermal resistance. The thermal resistance measured by this method is the behavior of whole packaging, such as the junction to case or heatsink or ambient thermal resistance. It is not easy to obtain more details within packaging. The transient thermal method is to get the thermal behavior of the thermal dissipation path when the heat delivery from the chip to heatsink and the transient thermal impedance measure by this method denotes the thermal resistance and capacity change along with the heat path. Moreover, the transient thermal impedance can be transformed by mathematical transformations to structure functions to get the thermal resistance and capacity of each layer accurately [3]. Thus, the thermal transient testing technology can comprehensively analyze thermal properties of each layer structure within the device from chip to heat sink on the path of heat conduction, construct equivalent thermal model of devices, and provide reliable data base for the research on thermal characteristic of the device [4].

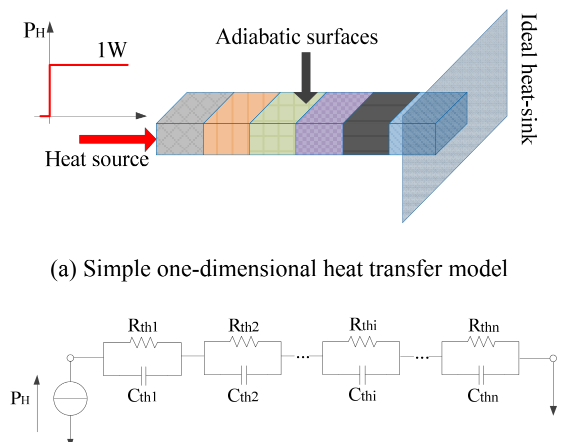
Hence, in order to give full information of the thermal characteristic parameters of high-power electronics, a complete set of software analysis and test system is proposed in this paper. The system can accurately measure the thermal characteristic parameters, and provide reliable data foundation for life expectancy, extreme operation and over-temperature protection [5]. The result has important reference value and practical significance.

## 2. Methodology

Fig. 1(a) shows a simple packaging model composed of different materials. The model is placed on an ideal heat sink and other surfaces are thermal adiabatic. Thus, the thermal conduction is considered as one-dimensional. When a constant power $P_H$ is applied to the model, the model can be equivalent to the $n$-order RC network shown in Fig. 1(b). Among them, the thermal transient response function $a(t)$ of the model under the power $P_H$ is

$$a(t) = P_H \cdot \sum_{i=1}^{n} R_{thi}(1-\exp(-\frac{t}{\tau_i})), \quad (1)$$

where $P_H$ is generally the unit power, $R_{thi}$ denotes the thermal resistance of the heat transfer model equivalent to an RC network, $t$ is the time, $\tau_i$ represents the time constant and can be calculated by thermal resistance $R_{thi}$ and thermal capacity $C_{thi}$. The thermal resistance and capacity of each layer is determined by its material properties and geometry [6]. Normally, the geometry of power electronics is not so explicit in application that we should get the transient thermal impedance through measurement [3].




(a) Simple one-dimensional heat transfer model

(b) The equivalent RC network

**Fig. 1.** Heat transfer model and its equivalent RC network.

When the applied power step denotes as a unit power, the time $t$ in Formula (1) is logarithmic and the Formula (1) can be derived to obtain the convolution formula shown in Formula (2).

$$\frac{d}{dz}a(z) = R(z) \otimes w(z) + n(z), \quad (2)$$

where $\otimes$ is the convolution operator, the $w(z)$ represents the constructor which can be calculated by the following formula

$$w(z) = \exp(z - \exp(z)) \quad (3)$$

The thermal transient response function $a(z)$ in Equation (1) can be obtained by measuring the change of temperature-sensitive parameters of the device in the cooling process and combining the relationship between the temperature-sensitive parameters and the junction temperature and thermal impedance. In addition, the time constant spectrum is clear in Formula (4) is the constructor is given.

$$R(z) = \frac{d}{dz}a(z) \otimes^{-1} w(z), \quad (4)$$

where $\otimes^{-1}$ is the deconvolution operator.

It should be noted that the actual measured thermal transient response signal is usually mixed with a certain noise signal $n(z)$. These noise signals can affect the results of thermal transient tests that must be taken into account when analyzing.

$$\frac{d}{dz}a(z) = R(z) \otimes w(z) + n(z) \quad (5)$$

The basic process of this technology is shown in Fig. 2 below. We can see that the precondition of the thermal transient testing technology is that the transient thermal impedance given as shown in Formula (1). Thermal transient response signal $a(z)$, time constant spectrum $R(z)$, constructor $w(z)$ and noise $n(z)$ in the Formula (1) are all expressed as function of logarithmic time $z$. In order to get the $R(z)$ from $a(z)$, the derivative and deconvolution should be conducted on $a(z)$. Then, split $R(z)$ into a number of segments having $\Delta z$ width and compute the thermal resistance and heat capacity parameters of the Foster model. Considering the heat capacity of Foster model with no clear physical meaning, hence thermal network model transformation algorithm is used to transform the Foster model to Cauer model, which can reflect the actual heat capacity transfer process. Finally, the structure function of the device can be obtained by accumulating the thermal resistance and heat capacity parameters of the Cauer model in stages, or taking the derivative after accumulating [7].

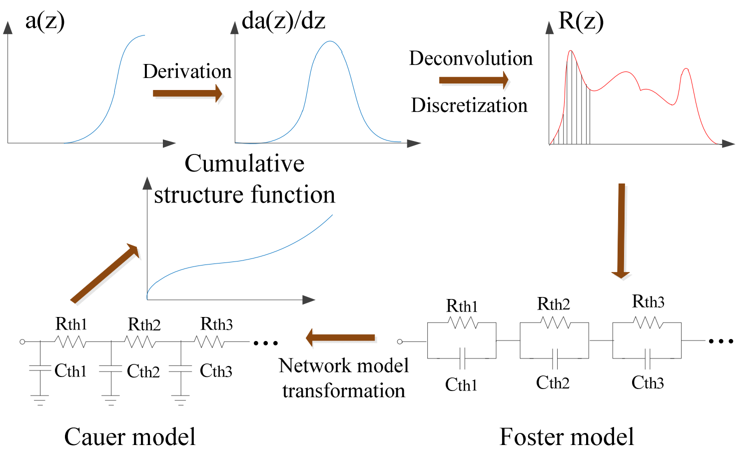



**Fig. 2.** The process of the thermal transient test technology.

## 2.1. Deconvolution Algorithm

Up to now, there are two deconvolution algorithms that have been successfully used in the thermal transient testing technology: Fourier deconvolution and Bayesian deconvolution.

### 2.1.1. Fourier Deconvolution

The Fourier deconvolution algorithm is based on the convolution theorem, which transforms the problem in the time domain to the frequency domain for operations. We have the equivalent formula

$$\begin{aligned} M^*(\Phi) &= V(\Phi)\cdot W(\Phi) + N(\Phi) \\ &= V^*(\Phi)\cdot W(\Phi) \end{aligned} \quad (6)$$

Thus theoretically we can obtain the required function by a simple division as shown in Formula (7).

$$R(z) = IFFT \left\| \frac{M^*(\Phi)}{W(\Phi)} \right\| \quad (7)$$

Because the noise corresponds to the high frequency component in the signal spectrum. Although the noise signal has smaller amplitude relative to the measured signal, the high-frequency components of the constructor are some very small items with a smaller magnitude. After the division operation, the noise signal will be amplified, resulting in many differences between the deconvolution reconstruction signal and the original signal, sometimes even resulting in unacceptable results. Therefore, it is necessary to properly handle the noise problem during the application process.

### 2.1.2. Bayesian Deconvolution

Different from the Fourier deconvolution, Bayesian deconvolution is based on Bayes' theorem and total conditional probability formula. It can avoid the noise problem in Fourier deconvolution algorithm. The procedure described by [8] is suitable for the time-constant spectrum identification has been proven. These applies the following iterative formulas

$$R^{i+1}(z) = R^i(z)\cdot\left(w(z) \oplus \frac{da(z)/dz}{w(z)\otimes R^i(z)}\right), \quad (8)$$

$$R^{i+1}(z) = R^i(z)\frac{w(z)\oplus(da(z)/dz)}{w(z)\oplus(w(z)\otimes R^i(z))} \quad (9)$$

The deconvolution algorithm using the iterative formula shown in Equation (8) is called Richardson-Lucy algorithms, and shown in Equation (9) is the Positive iterative deconvolution. Whether Formula (8) or Formula (9), the amplitude of the reconstructed signal will be amplified during each iteration. In order to make the reconstructed signal as close as possible to the original input signal, the correction *I* needs to be introduced to improve the formula.

$$R^{i+1}(z) = R^{i}(z)(w(z) \oplus \frac{da(z)/dz}{w(z) \otimes R^{i}(z)}) * I \, , \qquad (10)$$

$$R^{i+1}(z) = R^{i}(z) \frac{w(z) \oplus (da(z)/dz)}{w(z) \oplus (w(z) \otimes R^{i}(z))} * I \qquad (11)$$

### 2.2. Network Model Transformation Algorithm

Because the Foster network model describes the node-to-node thermal capacity without explicit physical meaning, the Foster network model needs to be converted into a Cauer network model that describes the thermal capacity between the nodes and reference nodes. The existing network model transformation algorithm has been relatively mature, and the detailed conversion process is given in [7]. However, due to the limitation of software accuracy, truncation error and operation error occur when the network model conversion operation is performed. The obtained structure function is inconsistent with reality. Therefore, appropriate calculation software should be selected during processing to avoid this situation.

The method that have been published and used to solve the data accuracy problem of the network model conversion process in the thermal transient testing technology is the GMP (GNU MP Bignum Library) open source math library mentioned in the JESD 51-14 standard. However, GMP library functions are written in C language. When calling in interpretive language programming software, you need to write a special interface function, or directly use it in the C language-based software. No matter which way the use should have the basic knowledge of programming. The simulation verified that using Mathematica, a multi-precision calculation software, not only can achieve the same accuracy as GMP, but also is simpler and easier to operate than GMP. This greatly reduces the difficulty of algorithm implementation.

Based on the above theory, this paper establishes a software system of thermal transient testing technology as shown in Fig. 3, which is used to measure the thermal characteristic parameters of power electronics.

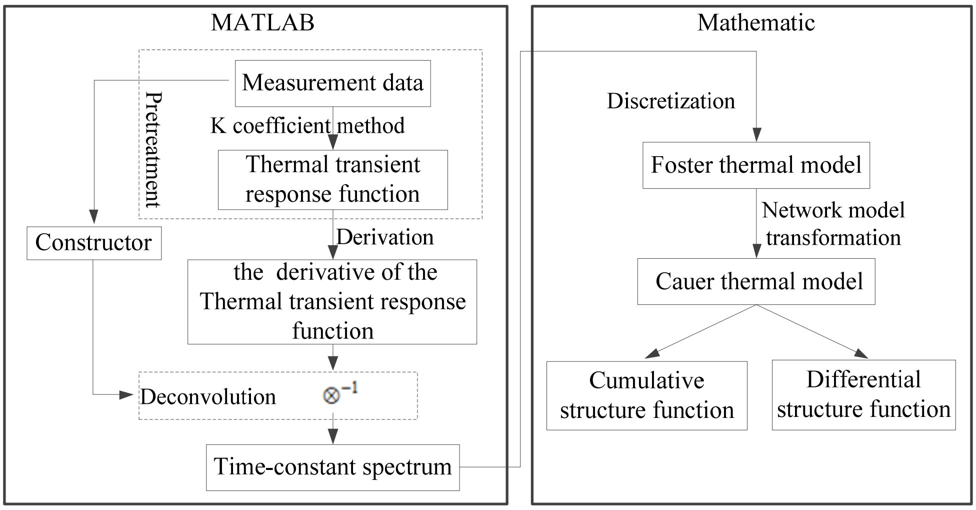



**Fig. 3.** The Thermal transient testing software system.

## 3. Case Study

Taking the thermal transient response signal of power electronics measured by commercial thermal transient tester as an example, and the time constant spectrum calculated by the equipment as a reference value. This article compares two kinds of common deconvolution algorithms. Meanwhile, the thermal transient testing software system established in this paper is used for simulation analysis to verify the validity and accuracy of the system. In order to make the results comparable, the simulation parameters are set with the testing equipment parameters.

### 3.1. Deconvolution Algorithms Comparison

In order to compare the accuracy of thermal transient test results when different deconvolution algorithms are applied, this paper uses different deconvolution algorithms to deal with the same measurement data. The time constant spectrum deviation Δ is defined as the criterion for measuring the accuracy of the algorithm. The simulation results are shown in Table 1 and Fig. 4.

$$\Delta = \frac{\sum [X(z) - \overline{R}(z)]^2}{n} \quad (12)$$

**Table 1.** The deviation of time constant spectral calculated by different deconvolution methods.

| Deviation | Fourier deconvolution | Bayesian deconvolution | |
|---|---|---|---|
| | | Richardson-Lucy algorithm | Positive iterative deconvolution |
| Δ | 0.00131 | 0.000199 | 0.000963 |

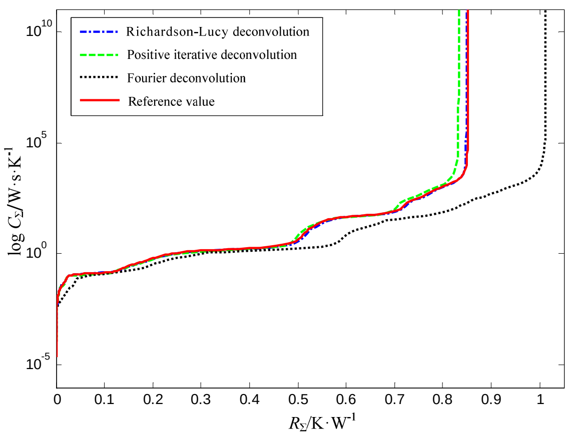



**Fig. 4.** The structure function of different deconvolution algorithms.

Table 1 shows that the result of Richardson-Lucy algorithm is closer to the reference value. The deviation of Richardson-Lucy algorithm is 0.000199, which is far less than the Fourier deconvolution, and less than the positive iterative deconvolution. The result also shows that compared with the Fourier deconvolution algorithm and the Bayesian deconvolution based on the Positive iterative deconvolution, the structure function using the Bayesian deconvolution based on the Richardson-Lucy algorithm is most consistent with the reference value.

## 3.2. The Simulation Verification of Software System

Taking the measurement data of a high-power semiconductor device as an example, the thermal transient testing software system established in this paper is used for simulation calculation. The device under test is a single IGBT chip submodule from press pack IGBT. The collector side of the submodule is cooled by heatsink and emitter side is thermal insulation during the transient thermal impedance measurement [9]. And then, the measured thermal impedance is used to obtain the structure function curves which is shown in Fig. 5 and Fig. 6.

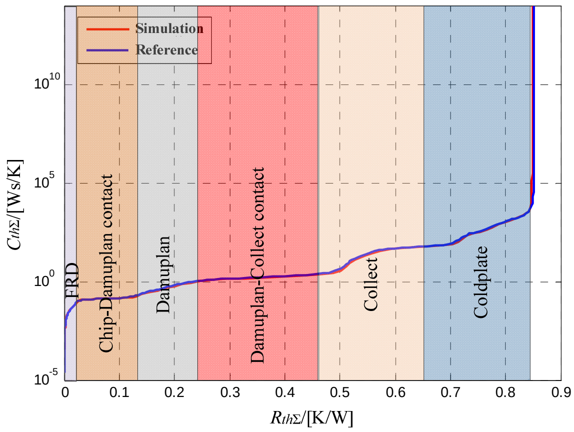



**Fig. 5.** Cumulative structure function.

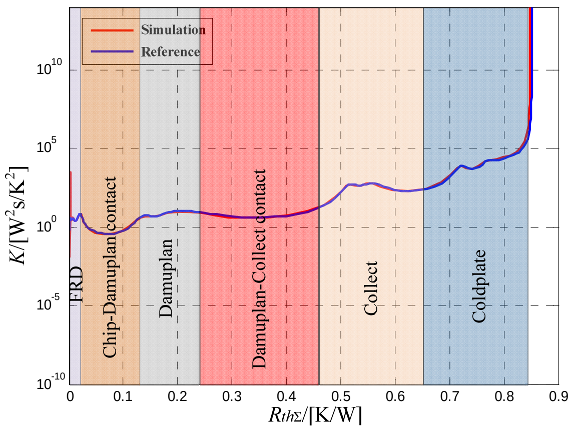



**Fig. 6.** Differential structure function.

Choosing the structure function curve obtained from the thermal transient testing equipment as a reference, it can be seen that the simulation results through the software system mentioned above are in good agreement with the reference values. The error between them is very small. Therefore, the software system established in this paper can obtain the thermal parameters of the device accurately and effectively. Furthermore, the internal structure of the device can be identified by combining two structure functions. Each layer structure is marked with different colors respectively.

The software established in this paper contains five main parts as shown in Fig. 7 below. Firstly, the transient thermal impedance should be loaded in the program and then make a derivation on it. After that the deconvolution is used to get time constant spectra and then transform to Foster thermal network model by discretization. Finally, we should transform the Foster thermal model to Cauer thermal model to get the cumulative and differential structure functions.

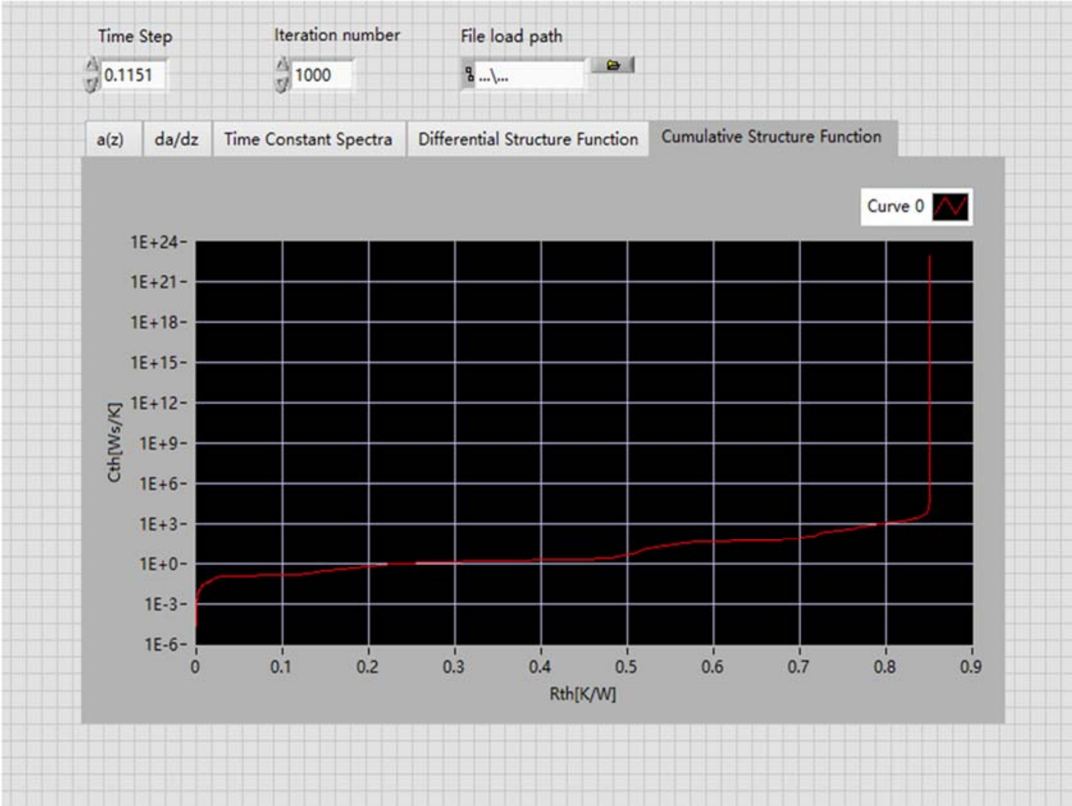



**Fig. 7.** The proposed software to realize the transient thermal technology.

## 4. Conclusions

A complete set of software system of the thermal transient testing applied to high-power semiconductor devices is established in this paper based on the research status of thermal transient testing technology at home and abroad. Aiming at the problem of deconvolution algorithm, this paper compares the commonly used deconvolution algorithm to get the conclusion that the Bayesian deconvolution algorithm based on Richardson-Lucy algorithm obtains the most accurate structure function. In response to another key issue: data accuracy in the process of network model conversion, it is proposed to reduce the difficulty of implementing the algorithm by using Mathematica to achieve the same effect as GMP. Finally, taking the actual measured data measured by a mature commercial thermal transient test equipment for power semiconductor devices as an example, the validity and accuracy of the system established in this paper are verified.

## Acknowledgements

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