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Identification of High Resolution Transient Thermal Network Model for Power Module Packages

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Abstract. A transient thermal network model is utilized to design and evaluate the transient thermal characteristics of power modules. Static test method identifies the transient thermal network model from the time response of the junction temperature, which is obtained by using the temperature dependency in I-V characteristics of power devices. This paper experimentally evaluates the transient thermal network model obtained by an AD converter with high-speed sampling and high resolution. The high sampling frequency and resolution for measuring time response of the junction temperature enable to clearly identify the boundary on the transient thermal network model of a power module with the direct bonding copper substrate.

Introduction

High-frequency switching operation using SiC power semiconductor devices enables miniaturizing power electronics systems [1][2]. Miniaturization makes thermal management difficult due to increased heat dissipation per unit area/volume. Therefore, thermal design is a key factor for the miniaturization of power electronics systems to maximize the capability of SiC power semiconductor devices.

Thermal design of power module packages aims at spreading and transferring heat dissipated in power semiconductor devices. Heat spreading and transferring capability depend on the structure and material property of power module constitutions. Transient thermal characterization plays an important role in the thermal design of power module packages. A transient thermal network model, which consists of the thermal resistance and capacitance, is utilized to design and evaluate the transient thermal characteristics of power module packages. Static test method [3] is the standard method for identifying the transient thermal network model of power module packages from the junction of the power device to the heatsink. The model is obtained by deconvolution calculation from the time response of the junction temperature with the temperature dependency in I-V characteristics of power semiconductor devices.

We developed a signal processing algorithm to improve the identified transient thermal network models [4]. The developed algorithm enabled clearly to distinguish the boundaries on the structure function related to power module packages. The numerical calculation also revealed that high-speed sampling and high resolution in measuring the time response of the junction temperature improve the accuracy in identifying the transient thermal network model. This paper establishes a measurement system adopting an analog-to-digital (AD) converter with high-speed sampling and resolution. Its performance in identifying the transient thermal network model is experimentally evaluated for a SiC power module with the direct bonding copper (DBC) substrate.

Experimental Setup

An experimental setup to obtain the time response of the junction temperature (Tj) for a device on a studied power module based on the static test method [3] is illustrated in Fig. 1. SiC SBD S6305 (50 A, 4.8 mm/4.8 mm/240 μm) is attached on a DBC substrate, as illustrated in Fig. 2. A high-speed and high-resolution AD board M2p.5933-x4 (Spectrum) is installed in the controller PC. This AD board can sample the voltage up to 40 MHz with 16-bit resolution. It measures the time response of the junction voltage in SBD for a fixed small measuring current in cooling transient after the thermal equilibrium condition by the self-heating for the large current. Thermal transient tester T3Ster (MentorGraphics) is used as a current source for heating and measurement current. T3Ster also measures the time response of the junction voltage with 1 MHz, 12-bit resolution, simultaneously as a reference. The floor noise of the installed AD board in the measurement system is evaluated in Fig. 3. "DUT w/o bias" denotes that the studied module is connected to the system, and all the equipment is in a power-on state. The peak-to-peak voltages of the noise are 1.68 mV, 1.10mV, and 83.2mV, respectively, for open, short, and the module is connected. The noise of the current source in T3Ster is significantly high, affecting the measured time response of the junction voltage. It is noted that the output data acquired in T3Ster is filtered for analysis, thus it is not shown here.

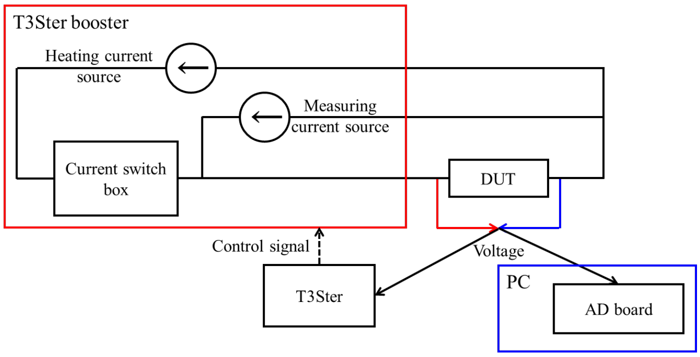

Figure 1 The experimental setup to obtain the time response of the junction voltage.

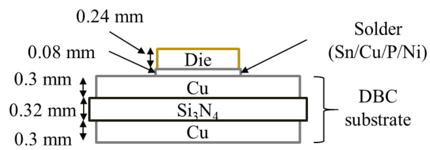

Figure 2 Cross-section image of studied power module substrate.

Table 1 Physical parameter of materials.

	Thermal conductivity [W/(mK)]	Specific heat [J/(kgK)]	Density [kg/m3]
SiC	495	680	3240
Sn/Cu/P/Ni	58	240	7300
Cu	401	384	8960
Si_3N_4	58	630	3500

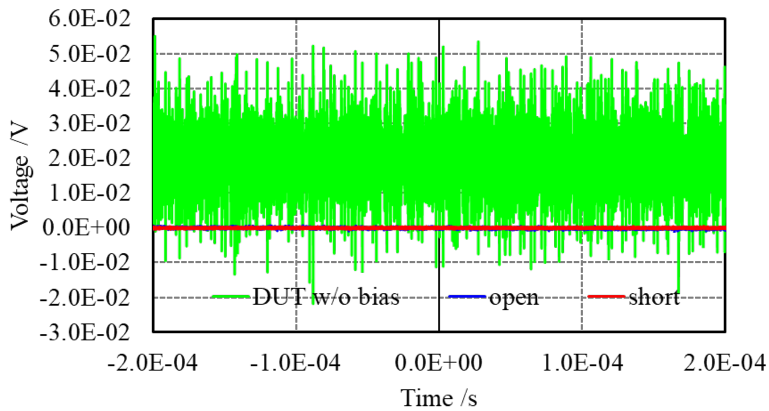

Figure 3 White noise into the AD converter.

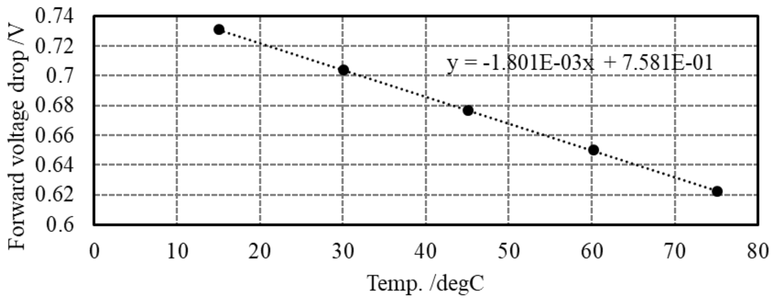

Figure 4 TSP of the DUT.

Heating and measuring current are 25 A and 10 mA, respectively. The heating and cooling time is the same 10 sec. The studied module is placed on the water-cooled heatsink, which is set as 20°C. The desired time response of the junction temperature is converted from that of the junction voltage using the temperature sensitive parameter (TSP). TSP is obtained in advance under the thermal equilibrium condition using thermostat SH-661 (ESPEC) from 15°C to 75°C at every 15°C for a constant small current 10 mA to SBD. The value of TSP for SBD is -1.801 mV/K, as shown in Fig. 4.

The procedure to obtain a transient thermal network model is summarized as follow, which is addressed in [4]. First, the time response of the junction temperature for unit input power $a(t)$ is transformed to $a(z)$ by introducing the logarithmic time domain $z=\ln t$, and numerically differentiated as $\mathrm{d}a(z)/\mathrm{d}z$. The $\mathrm{d}a(z)/\mathrm{d}z$ is filtered using the weighted Fourier transformation in the logarithmic frequency domain. The deconvolution calculation is performed for it. After this, the thermal time constant spectrum (TCS) $R(z)$ is obtained from the filtered $\mathrm{d}a(z)/\mathrm{d}z$ and a known weighted function. The Foster thermal network model obtained from TCS by deconvolution is transformed to Cauer thermal network model by Foster-Cauer transformation.

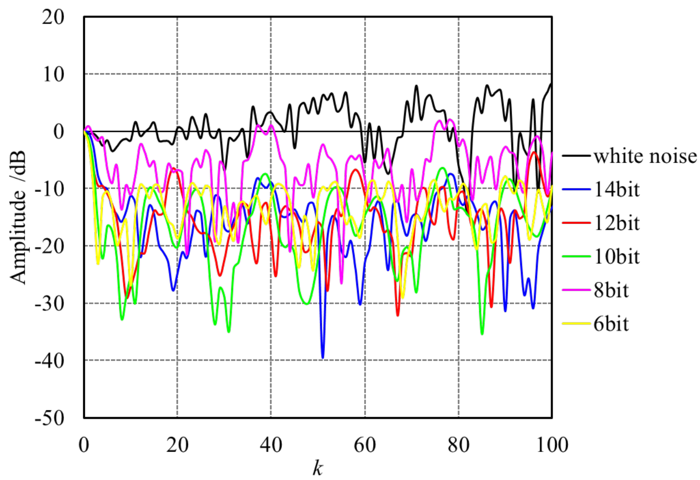

Figure 5 Power spectrum of $\mathrm{d}a(z)/\mathrm{d}z$. The effective bit length is the parameter.

Experimental Results and Discussion

The power spectra of experimentally obtained $\mathrm{d}a(z)/\mathrm{d}z$ are shown in Fig. 5. The horizontal axis k is the order to the fundamental frequency, and the amplitude is normalized for k=0. The sampling frequency is 40 MHz. Here, the effective bit length of the measured data for the installed AD board is given as the parameter. Though the longer effective bit length provides a higher resolution by suppressing the quantization error as discussed in [4], no significant difference exists in Fig. 5. The noise amplitude of the current source in the black line of Fig. 5 is not negligible to each power spectrum. A digital filter or an electrical design of a measurement system is required to suppress the measurement noise for utilizing the high resolution.

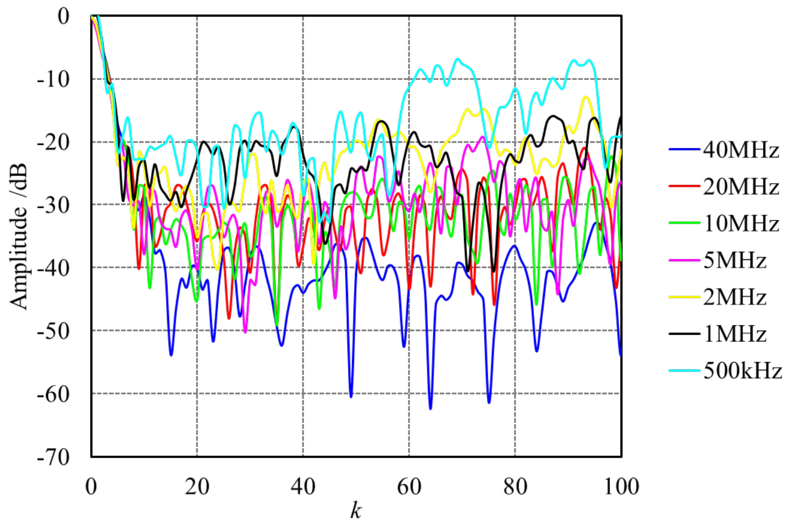

Figure 6 Power spectrum of da(z)/dz. The sampling frequency is the parameter.

The power spectra of da(z)/dz are shown in Fig. 6. Here, the sampling frequency of the measurement is given as the parameter, and the effective bit length is 14 bits. An oversampling and decimation to suppress the quantization error and eliminate the noise is adopted [5]. The higher sampling frequency of the measurement gives a higher resolution, which coincides with our previous discussion in [4]. For example, the oversampling ratio for 40 MHz sampling frequency to 1 MHz is 40. Then, the signal-to-noise ratio (SNR) improves by 16 dB [5]. This value coincides with the result in Fig. 6.

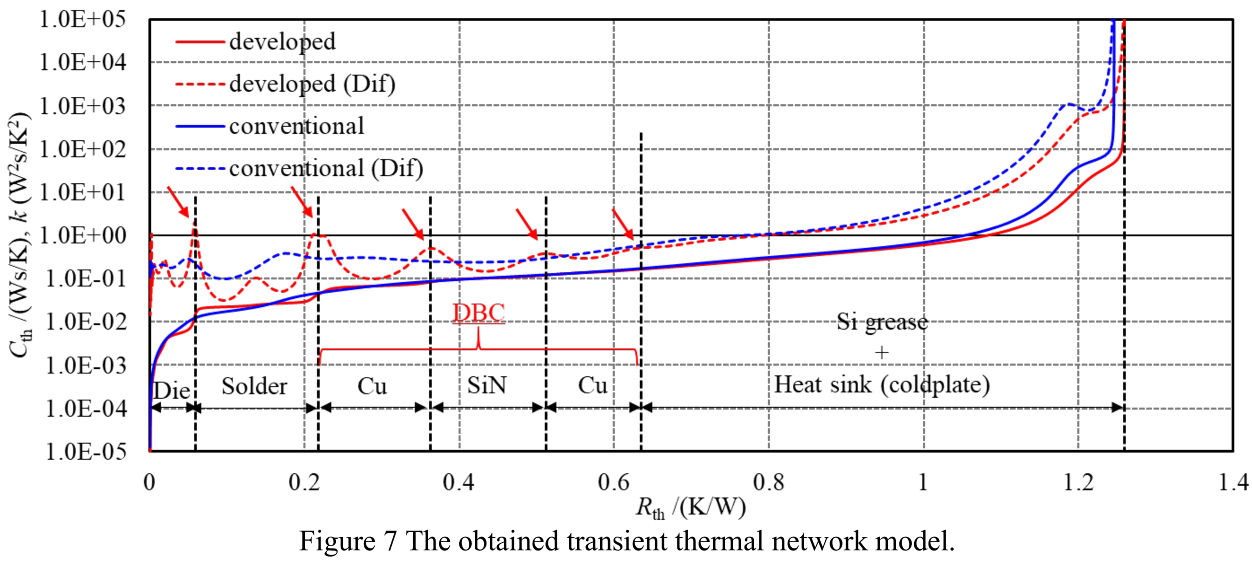

Figure 7 The obtained transient thermal network model.

The obtained transient thermal network model, or structure function, is shown in Fig. 7. The structure function represents the cumulative thermal capacitance C_{th} as a function of the cumulative thermal resistance R_{th} from the junction to the ambient based on the Cauer thermal network model. "Dif" denotes the differential structure function, which is obtained by numerically differentiating the structure function with R_{th}. The differential structure function is utilized to detect the inflection points corresponding to the interface of components in power module packages. The red line is calculated from the time response of the T_j by the installed AD board at 40 MHz sampling frequency and 14 bit effective bit length. The blue line is obtained from T3Ster as the reference. The differential structure function calculated from the time response of the T_j with the installed AD board has clear inflection points compared to that by the T3Ster. It is noted that the transient thermal network model gives the isothermal line in the power module package, thus the inflection point does not clearly give the boundary for the constitution of the actual power module package exactly. The high resolution and high-speed acquisition of the time response of T_j achieve the higher resolution of the obtained transient thermal network. This helps to evaluate and design the transient thermal characteristics of power module packages.

Conclusion

This paper experimentally evaluated the high-speed and high-resolution acquisition effect for identifying the transient thermal network model. A measurement system adopting an AD converter with a high sampling frequency and resolution was established in this paper. The higher resolution and the higher sampling frequency of the AD converter give the lower noise level. The established system was applied to identify the transient thermal network model of a SiC power module with a DBC structure. High sampling frequency and resolution achieved the higher resolution of the obtained transient thermal network model. This advantage helps to evaluate and design the transient thermal characteristics of power module packages.

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