Transient thermal analysis of packaged SiC SBDs for high temperature operation

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\textbf{Abstract:} SiC power devices have high temperature operation capability compared to Si power devices. The thermal characteristics of packaged SiC devices are important for thermal management in high temperature range. This study investigates thermal characteristics of a packaged SiC device for high temperature operation. The transient and steady state thermal resistances of the packaged SiC SBDs are measured using JESD51-1 standard. In addition, the numerical thermal simulation of the packaged SiC SBDs using finite difference method (FDM) are carried out considering nonlinear thermal properties of package materials. In the current research, the thermal resistance of the packaged SiC SBD increases by about 10\% in the temperature rise from 27°C to 250°C.

\textbf{Keywords:} silicon carbide schottky barrier diode, transient thermal analysis, finite difference method, package

\textbf{Classification:} Electron devices, circuits, and systems

\begin{thebibliography}{9}
1 Introduction

Silicon carbide (SiC) devices can operate in high temperature range. The static and dynamic characteristics of the SiC devices over 400°C are reported in [1, 2], and the successful operations of the SiC devices in power electric applications over 300°C are introduced in [3, 4]. High temperature operation capability of SiC devices enables to increase power density and reduce a size of a power electronics system.

In high temperature operation of the packaged SiC devices, thermal management is important, because temperature margin to guarantee electrical and physical reliability of the packaged devices is reduced. The generated heat from the power loss increases the temperature of the device, and in the thermal management, the generated heat from the device should be dissipated through the package appropriately. The thermal characteristics of the packaged device such as thermal conductivity and specific heat are determined by thermal properties of the package materials, and high temperature operation of the packaged SiC devices induces the thermal properties change of the package materials [5]. The thermal characteristics variation of the package materials may result in the changed heat dissipation ability of the package. Therefore, the accurate thermal analysis of the packaged devices is necessary in order to operate the SiC devices at high temperature environment, stably. In this research, we have carried out the thermal analysis of the packaged SiC SBD for high temperature operation using experimentally measured transient thermal resistances and finite difference method (FDM) thermal simulation. The experimental and thermal simulation details are presented in section 2 and section 3, respectively. The comparison and analysis based on the measured and simulated results are described in section 4.

2 Experiments

A SiC SBD (600 V/10 A rating) with 1.8 × 1.8 mm² area and 0.2 mm thickness was assembled on a copper bonded silicon nitride substrate using AuGe (88/12) solder. Electrical connection between the cathode of the device and the copper pattern was made by an aluminum wire (diameter of 300 μm), and a high temperature resin was covered on the assembled substrate.

The transient thermal resistance ($Z_{th}$) between a device junction and a case defined in Eq. (1) is well used to characterize the thermal performance of the packaged device from transient to steady state.

$$Z_{th}(t) = \frac{T_j(t) - T_c(t)}{P_d}$$

(1)

Where, $T_j$ is the junction temperature and $T_c$ is the case temperature, and $P_d$ is the dissipated power. The transient thermal resistance ($Z_{th}$) of the packaged SiC SBD was measured through JESD51-1 standard [6]. Prior to the thermal impedance measurement, the temperature dependence of forward voltage drop ($V_T$) of SiC
SBD was measured in temperature range from 27°C to 290°C for junction temperature estimation. In the junction temperature estimation, the constant current of 1 mA was supplied to suppress the junction temperature change due to the self-heating in the $V_F$ measurement. A slope of the temperature dependence of $V_F$ is referred as $K$-factor [6], and the determined $K$-factor at 27°C, 100°C, 175°C and 250°C were $-1.84$ mV/°C, $-1.86$ mV/°C, $-1.88$ mV/°C, and $-1.90$ mV/°C. In the transient thermal resistance measurement, the device was heated using dissipated power ($P_d$) of 5 W, and the forward voltage drop was measured with supplying constant current of 1 mA in cooling phase. The case temperature was measured using a thermocouple attached on backside of the substrate with $V_F$ measurement simultaneously. The transient thermal resistance measurement was carried out in environment temperatures of 27°C, 100°C, 175°C and 250°C.

3 Numerical analysis

The heat transfer inside the packaged SiC SBD is governed by a following differential equation:

$$\rho c(T) \frac{\partial T(x, y, z, t)}{\partial t} = \nabla \cdot [\lambda(T) \nabla T(x, y, z, t)] + g(x, y, z, t) \quad (2)$$

Where, $\rho$ is the material density, $c$ and $\lambda$ are the specific heat and the thermal conductivity with temperature dependence, respectively. To solve the heat transfer governing equation, Eq. (2) is discretized by finite difference method (FDM) as follows [7]:

$$\begin{align*}
(rho)_{i,m,n} & \Delta x \Delta y \Delta z \frac{T_{i,m,n}^{p+1} - T_{i,m,n}^p}{\Delta t} \\
& = \lambda_{l-1/2} \frac{\Delta y \Delta z}{\Delta x} (T_{l-1,m,n}^p - T_{l,m,n}^p) + \lambda_{l+1/2} \frac{\Delta y \Delta z}{\Delta x} (T_{l+1,j,k}^p - T_{l,m,n}^p) \\
& + \lambda_{m-1/2} \frac{\Delta x \Delta z}{\Delta y} (T_{i,m-1,n}^p - T_{i,m,n}^p) + \lambda_{m+1/2} \frac{\Delta x \Delta z}{\Delta y} (T_{i,m+1,n}^p - T_{i,m,n}^p) \\
& + \lambda_{n-1/2} \frac{\Delta x \Delta y}{\Delta z} (T_{i,m,n-1}^p - T_{i,m,n}^p) + \lambda_{n+1/2} \frac{\Delta x \Delta y}{\Delta z} (T_{i,m,n+1}^p - T_{i,m,n}^p) \\
& + g(x_i, y_m, z_n, t)
\end{align*}$$

where, the subscript $l$, $m$, $n$ denotes the grid point, the subscript $p$ represents the current time step. $\Delta x$, $\Delta y$, $\Delta z$ express the distances between node point $(l \pm 1, m, n)$ and nodes $(l \pm 1, m, n)$, $(l, m \pm 1, n)$, $(l, m, n \pm 1)$, and $\Delta t$ identifies the time interval between the current time $p$ and the next time $p + 1$. Thermal conductivity $\lambda_{l,m,n} \pm 1/2$ are average value between the thermal conductivities of the node point $(l, m, n)$ and nodes $(l \pm 1, m, n)$, $(l, m \pm 1, n)$, $(l, m, n \pm 1)$. Temperature dependences of thermal conductivity and specific heat in node $(l, m, n)$ at time $p + 1$ are expressed by following expression:

$$\begin{align*}
\lambda_{l,m,n}^{p+1} &= \lambda_{l,m,n}^p + (\partial \lambda / \partial T)^p (T^p - T^{p-1}) \\
c_{l,m,n}^{p+1} &= c_{l,m,n}^p + (\partial c / \partial T)^p (T^p - T^{p-1})
\end{align*}$$

In solving the governing equation, the boundary conditions were set as follows: The dissipated power of 5 W in the SiC SBD was expressed by a uniform heat flux.
input at top side of the device. The lateral side was supposed to be thermally insulated, and bottom side was clamped with the initial device temperature. The packaged device is 0.9 \times 0.9 \times 0.2 \text{mm}^3 for the SiC SBD, 0.9 \times 0.9 \times 0.17 \text{mm}^3 for the AuGe (88/12), 3 \times 4.5 \times 5 \text{mm}^3 for the pattern and bottom copper layers and 3 \times 4.5 \times 0.35 \text{mm}^3 for Si$_3$N$_4$ layer. Due to the symmetrical structure of the device, a quarter of the packaged SiC SBD was modeled and simulated. For simulation, the time interval $\Delta t$ was set as 2.5 \mu s, and the grid sizes of $\Delta x$, $\Delta y$, $\Delta z$ were set as 150 \mu m, 150 \mu m and 10 \mu m, respectively. The thermal properties for solving FDM simulation are shown in Table I [8, 9, 10, 11]. The numerical simulation was carried out using Matlab in the ambient temperatures of 27°C, 100°C, 175°C and 250°C.

### Table I. Thermal properties for numerical FDM simulation

<table>
<thead>
<tr>
<th>Materials</th>
<th>Thermal conductivity (W/m·K)</th>
<th>Specific heat (J/kg·K)</th>
<th>Density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC</td>
<td>$(-0.0003 + 1.05 \times 10^{-3}T)^{-1}$</td>
<td>$925.65 + 0.3772T - 7.9254 \times 10^{-5}T^2$</td>
<td>3215</td>
</tr>
<tr>
<td>AuGe (88/12)</td>
<td>44.4</td>
<td>151.2</td>
<td>14670</td>
</tr>
<tr>
<td>Copper</td>
<td>$420.75 - 6.8493 \times 10^{-2}T$</td>
<td>$316.21 + 0.3177T - 3.4936 \times 10^{-2}T^2 + 1.661 \times 10^{-1}T^3$</td>
<td>8933</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>$74.359 - 0.0827T + 3 \times 10^{-5}T^2$</td>
<td>$61.576 + 2.4308T - 0.0018T^2 + 5 \times 10^{-7}T^3$</td>
<td>3500</td>
</tr>
</tbody>
</table>

### 4 Results and discussion

Fig. 1(a) and (b) shows the thermal steady state temperature distribution of the packaged SiC SBD and the profiles of the temperature difference between the junction and case in the different temperature ranges. In the simulation results, it is shown that the heat flows from the SiC SBD to the bottom copper pattern, and the maximum temperature on the SiC SBD is simulated as 37.6°C. The sharp temperature change is shown in the AuGe (88/12) layer, and the heat spreads...
widely through the pattern copper layer. The heat spreading is interrupted drastically in the \( \text{Si}_3\text{N}_4 \) layer. The variation in the temperature difference between the junction and case is 1.42°C as the ambient temperature changes from 27°C to 250°C, and the SiC SBD and the \( \text{Si}_3\text{N}_4 \) layer occupy the most of the overall variation (97%).

The transient thermal resistances of the packaged SiC SBD from the numerically simulated results were calculated using Eq. (1). The surface average temperature for the SiC SBD was used for the junction temperature. The calculated and the experimentally measured results are shown in Fig. 2 and Fig. 3. Fig. 2 shows the transient thermal resistance comparison results. The both results show same trends and good agreements, but, the simulation results have slightly faster responses than experimental results after about 10 ms. The transient thermal resistances decrease from 0 s and reach the thermal steady state around 90 ms. The period variation in transient thermal resistance is extended with temperature rise, and this represents increase of the thermal time constant of the packaged SiC SBD.

Fig. 3 shows the steady state thermal resistance for the measured and simulated results in different temperature conditions. The both results are in good agreement under maximum error 0.76% of and average error of 0.36%. The thermal resistance increase by about 0.26°C/W (about 10%) with ambient temperature increase from 27°C to 250°C.

The temperature changes the lattice vibration waves and the electrons movement of the package materials, and it leads to variation of the thermal conductivities and specific heats of the materials. In the experimentally measured temperature range, temperature rise increases the thermal conductivities and decreases specific

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**Fig. 2.** Transient thermal resistance of packaged SiC SBD between junction and case in different ambient temperature conditions.
heats of all of the package materials. The thermal simulation with the temperature dependent thermal properties was carried out, and the simulation results are well matched with the experimentally measured results. Thermal resistance rise represents the degradation of heat dissipation ability of the packaged device. It is recommended that heat dissipation system design with considering this point in the thermal management of the packaged SiC devices for high temperature operation.

5 Conclusion

In this paper, thermal analysis of the packaged SiC SBD was carried out using the experiments and the numerical simulation for high temperature operation. The steady state and transient thermal resistances of the packaged SiC SBDs were measured and simulated, and the comparison between both results shows good agreement. The temperature affects the thermal characteristic of the packaged SiC SBDs, and the steady state thermal resistance of the packaged SiC SBD increase with temperature rise. From the simulation results, it is found that the SiC SBD and the Si$_3$N$_4$ layer have contributed to overall thermal characteristics variation with temperature increase.

The consideration of the temperature effect on thermal characteristics of the packaged SiC devices is recommended for high temperature operation, and the FDM thermal model considering temperature dependent thermal properties introduced in this research can be applicable to design of the heat dissipation system of power electronics applications with SiC devices for high temperature environment.

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