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Design concept for wire-bonding reliability improvement by optimizing position in power devices

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Abstract

The most effective way to increase the reliability of wire bonds in IGBT modules is reduction of temperature difference between the aluminum wires and the device. However, this lowers the power handling capability of the modules. In this paper, we show that the configuration of aluminum wire bonds on power devices has a considerable effect on the temperature distribution of the device, and that the optimization of the layout by thermo-electric simulation can make the temperature distribution of the devices more uniform and consequently reduce the maximum junction temperature difference, ΔT_{jmax}. Tentative experiments showed that rearranging the bonding position resulted in reduction of ΔT_{jmax} by five to 8 °C, and that the chip temperature distribution estimated by the thermo-electric simulation was qualitatively similar to the actual measurement results. These results suggest that wire-bonding optimization by thermo-electric simulation can contribute not only to realizing more compact power modules but also to improving the module reliability.

Keywords: Wire bonding; Power module; Power semiconductor; Simulation; Reliability; Temperature distribution; Hybrid vehicle; Performance

1. Introduction

High power multi-chip modules are widely used for industry and traction applications. In general-purpose power modules with Insulated Gate Bipolar Transistors (IGBTs), air-cooling fins are used since the maximum junction temperature difference, ΔT_{jmax}, has usually been around 30 °C, suggesting that power output capability is largely limited by the relation between cooling capability of the power modules and the device's power losses. To reduce the power device losses, many studies of power devices have been made. For example, local control techniques of carrier lifetimes, and methods utilizing the FS structure or carrier accumulation concept have been proposed as approaches for improving characteristics of IGBTs [1–12].

Meanwhile, power modules operating at higher temperature is desired from automotive electronics because temperatures of the operating environment are rather high, as seen in Table 1 [22], and technologies, which enable higher temperature operation will enable design of more compact modules with and higher power density. At present, power modules in hybrid electric vehicles are connected to water-cooled heat sinks to increase the output power capacity while keeping the modules compact, and this configuration allows the operation with ΔT_{jmax} of about 50 °C [14,15,21]. However, vehicles having more powerful motors are expected to appear in the future. This means that the power module for motor driving will be subjected to more severe operation conditions, and increase range of temperature change, ΔT_{jmax}, is expected to be unavoidable.

Although recent improvements in power devices and module technologies allow the increase of ΔT_{jmax} to be slight, cooling of the modules are becoming more difficult task.Table 2 In addition, chip shrinkage of power devices to reduce the cost makes the number of wire bonds fewer, resulting in an increase of ΔT_{jmax} and hence threatening the device's safe operation. According to thermal situations of power modules, bonding of thick aluminum wires in power modules becomes a critical factor in determining the reliability of high-power modules [16–21], especially in high temperature operation. In order to increase the reliability of the wire bonds of the modules, limiting the increase of ΔT_{jmax} to be as small as possible is critically important, particularly for automotive applications.

In this study, the relationship between the shape of a power device and the configuration of wire bonds was investigated using thermo-electric simulation. The simulation results are also compared with the experimental results. The results

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Table 1
Examples of operating temperatures for automotive electronics

Location	Max. temperature (°C)
Passenger compartment	85…120
Engine compartment	150
Transmission	150
Exhaust system	590

showed that there was a significant difference in the surface temperature distribution of the power device after changes in the wire-bond positions.

2. Simulation setup and results

A three-dimensional finite element method (3D FEM) simulation, taking into consideration Joule heating, was conducted using the structure shown in Fig. 1. In the figure, the red marks indicate the positions of the wire bonds. A simple test structure for power device measurements on the heat sink was modeled and simulated using SOLIDIS 3D [13] simulator. Top and cross-section views of the model are shown in Fig. 2.

There is an aluminum layer of five microns a comprising top electrode on the silicon chip in Fig. 2 (b). A 0.4 mm thick aluminum layer was plated to the top and bottom sides of the AlN ceramic substrate of 700 μm. In an actual situation, the surface of the aluminum layer facing the substrate was also plated with Ni layer of a few microns. However, we neglect the layer in this simulation model. The thickness was thinner than that of Al plated layer, and we thought that the Ni layer would not affect the simulation results. The AlN ceramic substrate was soldered with an AlSiC composite three millimeter thick base plate, and the base plate was connected with an Al heat sink of six millimeter thickness via silicone grease of 65 μm as shown in Fig. 2 (b). The size of Si power devices in this study was assumed to be 6.5×6.5 mm and 200 μm thickness. The Si power device was set on the AlN substrate to the position in Fig. 2 (a), via the upper solder layer of 200 μm.

Table 1 and Fig. 2 show the parameters and the whole structure of the 3D model for the thermo-electric simulation. The heat sink is assumed to be cooled by forced water, and the corresponding heat transfer coefficient was set to about 210 W/m^{2}K at the bottom side of the Al heat sink of Fig. 2 (b). Thermal boundary condition at the top side of the simulation model was that the temperature was 300 K and constant. A fine mesh was applied to the Si power device to increase analysis accuracy. The heat transfer equation was modified by the dissipation power or Joule heating term in the device as follows [13]:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla(\kappa \nabla T) - H = 0, \tag{1}$$

$$\vec{\nabla}(\sigma(T)\vec{\nabla}\psi) = 0, \tag{2}$$

where ρ is density of silicon, Cp is the specific heat capacity, κ is the thermal conductivity, H is general heat generation term, $\vec{J} = -\sigma\vec{\nabla}\psi$ is current density, σ is conductivity and ψ is potential.

In this case, the general heat generation term H in (1) corresponds to the Joule heating term, $(|\vec{J}|^2/\sigma)$ because there is no heat generation source other than the Joule heating. Temperature dependence of σ was also incorporated in this simulation. Incorporated the Joule heating term into the heat transfer equation by applying a thermoelectric coupling option defined by the simulator, the temperature distribution of the model including the device with various bonding positions and/or conducting currents can be simulated.

Fig. 3 gives an example of the simulation results. All simulations were conducted under steady-state conditions. Patterns 1 and 2 have five wires, and pattern 3 has 10 wires, respectively. The positions and the number of wire bonds are only changed by varying currents at out/in terminals in the simulation, and the chip resistivity and its shape are the same. The contact area of each wire bonding on the device was assumed to be 0.5×1 mm, based on experimental footsteps of a 400 μm wire bonding.

As is clear from Fig. 3, both temperature distributions and locations of the maximum values have varied according to the wire bonding portions, even though the number of wires and the current are the same. This suggests that the reliability of the wire-bonding greatly depends on the position because the temperature swing varies depending on the position.

The Coffin–Manson empirical relationship suggests that the mean number of cycles to failure has an exponential relation with temperature swing or ΔT as follows:

$$N_f = a(\Delta T)^{-n}. \tag{3}$$

where N_f is the mean number of cycles-to-failure, α is a proportionality constant and n is a positive number. The value of n for automotive power modules is reported to be between 4 and 7 [21].

Fig. 4 is a graph showing the relationship between current and the chip surface maximum temperature difference, which was obtained by simulating two patterns of wire bonding

Table 2
Thermal and mechanical parameters used in the simulation

	Silicon	Aluminum	Ceramic	Solder
Thermal conductivity (W/m*K)	138.5	238.5	170	50
Thermal expansion (1/K)	2.60×10^{-6}	2.50×10^{-5}	4.50×10^{-6}	2.88×10^{-5}
Specific heat (J/kg K)	729	950	740	150
Density (kg/m^3)	2330	2700	3300	8400
Young's modulus (Pa)	1.60×10^{11}	7.00×10^{10}	3.45×10^{11}	1.60×10^{10}
Poisson ratio (Unity)	0.2	0.3	0.22	0.45