PLATFORM - A Journal of Engineering

Received: 17 March 2021, Accepted: 10 June 2021, Published: 30 June 2021, Publisher: UTP Press, Creative Commons: CC BY-NC-ND 4.0

COMPARATIVE ANALYSIS OF THERMAL STRESS OF Si AND SiC MOSFETs

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ABSTRACT

The performance of power MOSFET is affected by high thermal stress exposure. A high level of thermal stress is induced when the MOSFET experiences a temperature change. This finding is about the bonding wire lift-off on the solder pad. The MOSFET model is designed with the heatsink to ensure accurate results are obtained in this research work. The key intention of this research is to investigate the condition of silicon and silicon carbide power MOSFETs during thermal stress. The thermal properties of silicon and silicon carbide MOSFET were investigated by developing a 3D modal and thermal stress simulation in the COMSOL Multiphysics software. Thermal resistance was calculated by randomly selecting a power loss value of 100 Watts. Junction temperature for silicon and silicon carbide MOSFET was taken from several articles mentioned in the results and discussion.

***Keywords**: Thermal stress, bonding wire lift-off, temperature change, MOSFET.*

INTRODUCTION

Power MOSFET (metal-oxide-semiconductor field-effect transistor) is an electronic component designed to work with different power levels, especially for high power levels. The advantage of power MOSFET compared to other semiconductor devices such as an insulated-gate bipolar transistor (IGBT) or a thyristor are its high switching speed and good efficiency at low voltages. Traditional power MOSFETs have been made of silicon (Si). However, silicon carbide (SiC) is expected as an alternative material in recent [1]-[4].. The SiC is one of the most comprehensively investigated bandgap materials today due to its superior electrical, mechanical, and chemical properties.

In comparison with conventional silicon technology and considering that most of the power systems use several high-voltage switches operating from different potentials, using silicon carbide-based drivers to control silicon carbide power switches, the power electronic system's losses are highly uncertain reduced. Less switching energy is needed by adding a silicon carbide digital voltage control [5]-[6]. Power MOSFETs are now being designed for harsh environmental conditions such as high thermal stress exposure. Thermal simulation tools are needed to improve the component design and ensure a longer component lifespan due to the high degree of integration and applications that impose very constraining conditions on the power components. The primary purpose of this action is to develop power MOSFETs that are reliable at high temperatures. The usage of SiC as an alternative for Si in power MOSFET development would improve the thermal property of the power MOSFET. There is a high demand in the electronics industry for smaller products with increased functional density. As a result, higher power density electronics with higher operating temperatures are needed. The temperature limit of silicon electronics, which is around 150°C, is already reached in power electronics applications. For example, military and automotive control electronics. Alternative materials, such as SiC large bandgap semiconductors, are investigated to work at higher temperatures and higher power densities [7]-[8]. Consequently, it is necessary to develop cooling technologies capable of handling these high-power densities [9]. The heatsink plays a significant role in preventing self-heating in the transistor by keeping the transistor's temperature in the desired range and absorbs excess heat.

POWER MOSFET

The performance of Power MOSFETs is influenced by two main factors, which are threshold voltage and current drive. Power MOSFET is a current-controlled device, and it does not require a large amount of current. It is an active device, and it does not have a problem with the second breakdown. N-channel and P-channel are the two types of power MOSFET. The source and drain are placed on the opposite sides to support high current and voltage flow. Minimum gate bias must form a conducting channel between the drain and source for the MOSFET to operate. This minimum gate bias is called a threshold voltage. High electric fields are produced in power MOSFETs, and electron thermal energy (electron temperature) is much higher than lattice thermal energy (lattice temperature). In this case, two thermal energies, electron temperature and lattice temperature must be considered separately, and a two-energy model is required to analyse the temperature distribution of power MOSFETs [10].

THERMAL STRESS

The strain that arises due to changes in the ambient temperature is referred to as thermal stress. Semiconductor chips are the primary heat source in electronics and can be easily damaged by excessive heat. The thermal reliability of devices is developing more critically as the packaging density of power semiconductor devices increases. The system will be subjected to excessive thermal stress due to a mismatch in coefficients of thermal expansion between packaging materials. The material's thermal conductivity is linked to the chip's heat dissipation efficiency, which influences the thermal reliability of the device [11]. Therefore, thermal design is essential to prevent semiconductor chips from breakdown. The thermal analysis gives a clear understanding of temperature distribution in solid. In MOSFET, three forms of heat transfer occur, which are conduction, convection, and radiation. Heat transfer from the MOSFET chip to the heatsink is known as conduction, while the heat transfer from the heatsink to air is known as radiation. Convection occurs due to the buoyant force acting on the surrounding air. The provision of a heat flow model for the MOSFET, accurately predicting temperature effects for the switching elements on the PCB, will save time in development and allow for optimal space utilisation and power component distribution [12]-[15]. Thermal analysis is also essential as it requires knowledge of temperature decomposition throughout the device to protect other components such as the wiring network, capacitors, inductors, etc.

3D FINITE ELEMENT ANALYSIS

Thermal analysis is usually performed in a simulation tool called COMSOL Multiphysics. The COMSOL Multiphysics simulation tool is known for finite element analysis. It can also be used as a solver and simulation software package for various physical and technical applications like heat transfer modules. Surface design in electrical components, mechanical structure design and so on.

METHODOLOGY

The researcher took several research published articles related to the scopes to compare and understand the experiment. COMSOL Multiphysics software was used to carry out thermal analysis on silicon and silicon carbide power MOSFET. Before carrying out finite element analysis, the author had to build 3D geometry of silicon and silicon carbide power MOSFET on COMSOL through several methods, including trial and error until the desired structure of power MOSFET with the essential performable criteria was obtained. The author built silicon power MOSFET first because it is simpler in structure than silicon carbide power MOSFET. After constructing silicon and silicon carbide power MOSFET on the COMSOL simulation tool, the author layered the two modules with a heatsink to withstand higher thermal stress, create a better cooling condition, and avoid overheating the system. Thermal analysis for silicon power MOSFET was carried out first then followed by the thermal analysis of silicon carbide power MOSFET. Next, the author was required to identify the suitable temperature needed for thermal analysis. Finally, the author obtained thermal distribution in both modules. Based on observations made from the results, a conclusion was drawn.

MOSFET GEOMETRY

Several datasheets were referred to obtain MOSFET geometry [16]-[18]. Figure 1 shows the geometry structure of the MOSFET.

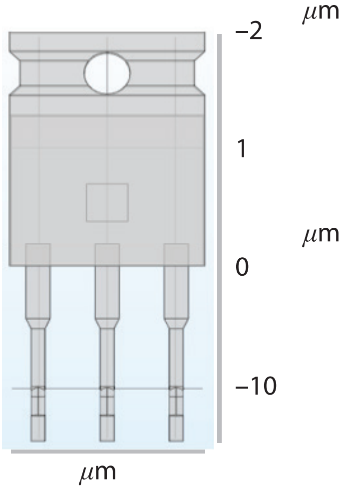

Figure 1 MOSFET geometry structure

RESULTS AND DISCUSSION

The 3-Dimensional structure of the MOSFET is built to perform thermal analysis. To build a heat sink attached to a MOSFET, the authors must build a 3-D MOSFET model. A three-dimensional view of a MOSFET with and without a heat sink is illustrated in Figure 2.

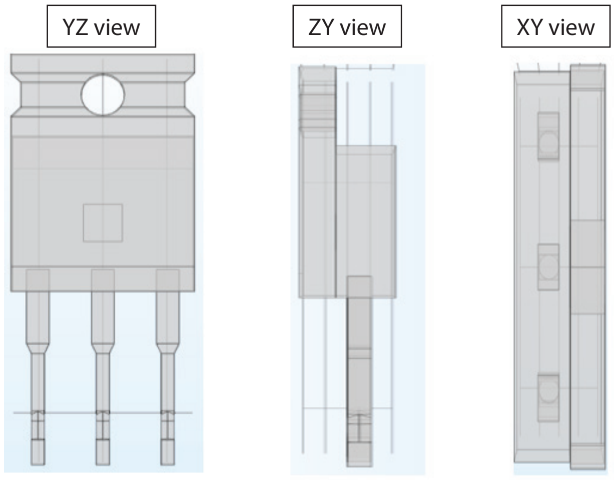

Figure 2 3D structure of MOSFET in YZ, ZY, and XY view

Before proceeding to thermal analysis, the heatsink is mounted on a silicon and silicon carbide MOSFET. Then material specifications are carried out on the simulation tool to ensure accurate results are obtained. The main purpose of the heatsink is to create better cooling conditions. The 3D MOSFET Model with a heatsink is shown in Figure 3.

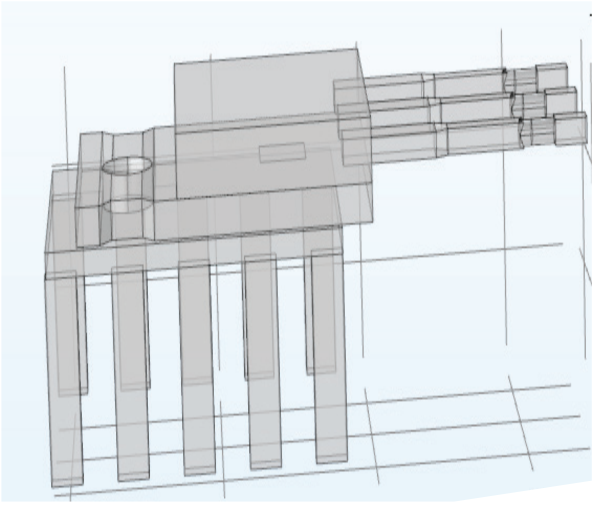

Figure 3 3D MOSFET model with heatsink

The MOSFET material specification is carried out to ensure that the results obtained to meet the research study's objectives and show that Figures 4 and 5 are outer and inner surface components, respectively.

The thermal resistance is estimated based on silicon and silicon carbide [13],[19]. The power loss in each MOSFET is a combination of conduction and switching losses [20].

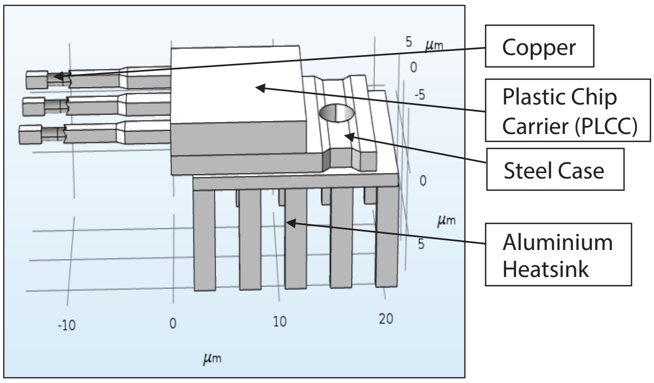

Figure 4 Outer surface components

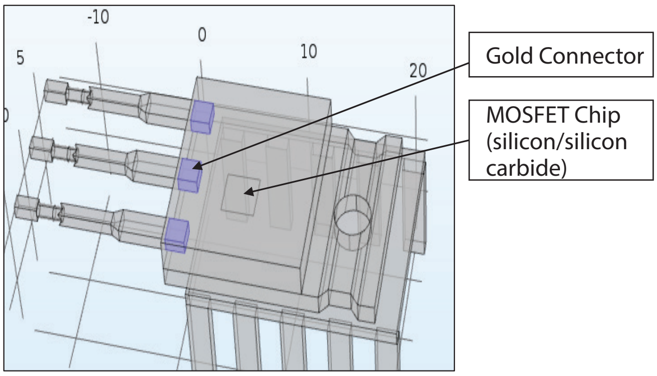

Figure 5 Inner surface components

Junction temperature for silicon carbide is estimated based on several research published papers [18], [21]-[23].

The thermal resistance value is determined by setting the power loss to 100 Watts:

$$R_{TR} = \frac{T_{JC} - T_A}{P_D} \qquad [1]$$

where,

T_{JC} – Junction Temperature (Max Temperature)
T_A – Ambient temperature
P_D – Power Dissipated (Power Loss)
R_{TR} – Thermal Resistance

Silicon MOSFET calculated parameters are as follows,

$T_{JC} = 157.85°C$
$T_A = 26.85°C$
$P_D = 100$ W
$R_{TR} = 1.31°C/W$

Silicon Carbide MOSFET calculated parameters are as follows,

$T_{JC} = 326.85°C$
$T_A = 26.85°C$
$P_D = 100$ W
$R_{TR} = 3°C/W$

The thermal analysis provides a clear understanding of the temperature distribution in solids. A good understanding and characterisation of thermal performance are essential for the success of high frequency. In MOSFET, two forms of heat transfer occur, which are conduction and radiation. Heat transfer from the MOSFET chip to the heatsink is known as conduction, while the heat transfer from the heatsink to air is known as radiation. Thermal analysis is also important because it is necessary to know temperature decomposition in the whole device to protect other construction elements, such as wiring networks, capacitors, induction elements, etc. Based on the simulation, heat distribution in Silicon MOSFET at temperature 300K to 431K (26.85°C to 157.85°C) is shown, while in Silicon Carbide, MOSFET heat distribution at 300K to 600K (26.85°C to 326.85°C) is shown in Figures 6 and 7.

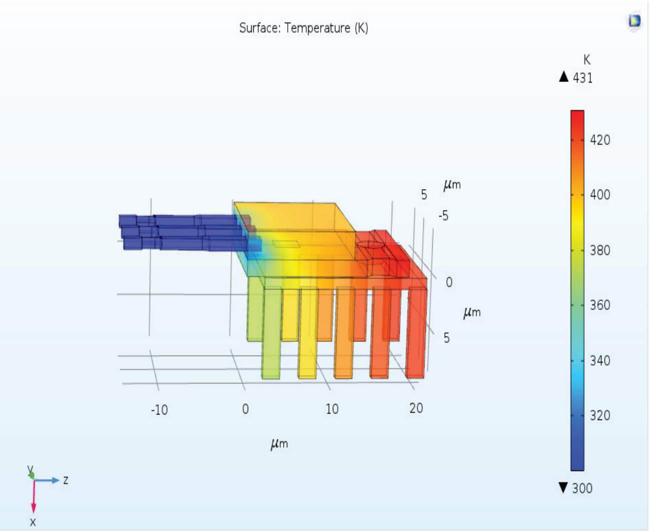

Figure 6 3D silicon MOSFET thermal stress analysis (300K to 431K) (26.85°C to 157.85°C)

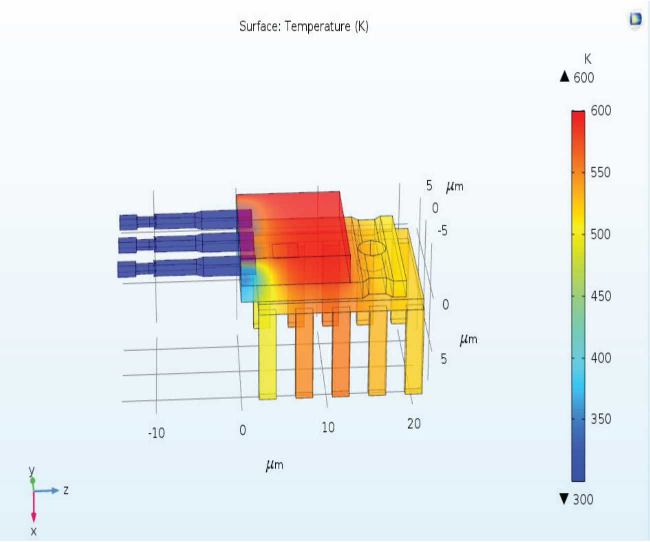

Figure 7 3D silicon carbide MOSFET thermal stress analysis (300K to 600K) (26.85°C to 326.85°C)

Silicon carbide as a semiconductor material is better suited for high-temperature operation than silicon because it can sustain higher temperatures before the intrinsic carrier concentration overcomes the intentional doping in the substrate [24].

CONCLUSION

This paper has investigated the heat distribution in silicon and silicon carbide power MOSFETs during thermal stress. Silicon acts as a substrate for the device. In addition, silicon has a smaller bandgap and low thermal conductivity. Therefore, the physical properties of silicon carbide are suitable for higher temperatures and high-power electronics.

Wide bandgap semiconductors with more extensive silicon carbide materials have helped the device perform better than silicon materials. As a result, silicon carbide devices offer functionality and performance that cannot be achieved with silicon devices and significant performance improvements. COMSOL Multiphysics software is used to design MOSFETs and perform thermal analysis.

RECOMMENDATION

Electronic systems in satellites or ordinary cars face exposure to high temperatures. The power MOSFET plays a vital role in the power converter to power the device. Therefore, it is essential to ensure that the power MOSFET is not affected by heat. Replacing aluminum heatsinks with copper heatsinks will improve the thermal conductivity because copper has a higher thermal conductivity. Measuring the electrical properties of silicon and silicon carbide MOSFETs in the presence of high thermal stress will allow us to see how heat affects device performance. Simulation reliability can be verified by carrying out grid independence test.

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