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Finite Element Analysis of Power Module Packages with One-step Molding for Power Inductors

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Abstract—With the development of 5G communication technology and the rise of power semiconductors, the switching frequency of the circuit keeps increasing, which pushes for miniaturization of power modules and related components. Therefore, in this paper, a one-step molding technology was proposed for a DC/DC buck converter power module. We proposed a method of using Soft Magnetic Powder filled Epoxy (SMPE) adhesive as a molding material to encapsulate a power module, which is a DC/DC buck converter power module contains several passive components, 1 power inductor, and a high-efficiency switching regulator with two integrated N-channel MOSFETs. On the basis of Finite Element Method (FEM), models were firstly established with component level moldings and checked with actual module samples for calibration. Based on the calibrated model, inductors without component level molding were then simulated. SMPE with 4~7μm insulated carbonyl ferrous powder were prepared and measured the magnetic relative permeability. Such material was investigated to pot the whole power module as a one-step molding, instead of separate molding for the power inductor and the power module. After that, thermal analysis and inductance were calculated and compared.

Keywords—Finite element simulation, Power module packaging, Relative Permeability, Thermal management.

I. INTRODUCTION

With the development of 5G communication technology mobile communication technology, new-energy vehicles, aerospace applications, and the rise of power semiconductors, the miniaturization of power module is the most concerned at present. In the power module, the inductor occupies a considerable space of the whole power module, and the size of the inductor is determined by the switching frequency. A larger switching frequency will result in a smaller inductor, but will increase the switching losses in the circuit. [1]. For DC/DC power converters, main packaging solutions are based on PCB substrate with separated components assembled and followed by injection molding. DC/DC converters are usually divided into three types: Buck, step-down switching power supply; boost, step-up switching power supply; and Buck-Boost, step-up step-down series switching power supply.[2] All three kinds of switching power modules are mainly composed of the following components: 1) semiconductor devices, such as MOSFET, IGBT and diodes. 2) Filter capacitors. 3) Magnetic components. The main performance index of the inductor used in the power module is the inductance value. Only when the inductance reached a certain value that the DC/DC converter maintains its output voltage within the rated range under the specified current.

Components are usually soldered to substrates such as MOSFET devices with TO packages, power inductor with molded metal powder composites, resistors, etc. However, such package suffers from a low power density, low efficiency, and high thermal resistance [3]. Moreover, two levels of molding process are needed, namely component level and module level, which brings extra process steps and costs. Take power inductor as an example, it firstly required a transfer molding packaging of epoxy with high level of metal powders [4], followed by epoxy encapsulation of the power module, which brings challenges for miniaturized power inductors. The size shrinking brings high DC resistance, low inductance, and high thermal resistance from the heat sources to ambient.

Therefore, in this paper, a one-step molding technology was proposed for a DC/DC buck converter power module. The original power module contains 17 resistors, 19 capacitors, 1 power inductor, and a 6A Step-down Regulator with Integrated Switcher. In current packaging technology, the power inductor needs to be firstly molded and then soldered to PCB, followed by module potting. In this work, we proposed a method of using Soft Magnetic Powder filled Epoxy (SMPE) adhesive as a one-step molding material to encapsulate a power module with hollow coil, which not only protects components on the power module substrate, but also enables inductance for power converting.

II. MAGNETIC AND ELECTRIC ANALYSIS

In order to check whether the SMPE material is sufficient for bringing enough inductance to the hollow coil, its relative permeability was measured through the core method. The core method is to cure the SMPE into a toroidal shape and use the enameled wire to make a circle on it. Then, put the sample on the LCR Meter (an instrument used to measure the inductance, capacitance, and resistance of a component, sensor or another device) to measure its inductance. After that, inductance can be converted into the relative permeability by the inductance formula (1). The relative permeability is essential for the FEM analysis for magnetic simulations.

A. *The Relative Permeability Measurement of SMPE*

The relative permeability of SMPE with different proportions of soft magnetic powders were measured to support the FEM analysis. The sample preparation and testing process was shown in Figure 1. It includes the preparation of SMPE, the curing of magnetic core and the relative permeability measurement. Commercial powders consisting of insulated carbonyl ferrous powder (Jiangsu Tianyi superfine metal powder Co., Ltd, ⩾99.5wt% purity) particles with the range of size between 4~7μm were investigated as magnetic fillers to epoxy resins. Epoxy resin (E-51, provided by Baling Petrochemical Company), 30wt% curing agent (D-230) and 0.5wt% defoamer (A-10) were mixed as an insulating agent as well as the basic adhesive. Different amount of soft magnetic powder (8wt%-85wt%) was hereby added into the basic adhesive to get the SMPE. After sufficient stirring, the SMPE was firstly deformed in vacuum for 10 mins. Then, it was potted into a customized a Teflon mold, which was homogeneously daubed by WD-40 for a better molding releasing. After that, samples in the mold were cured through heating at 80 °C for 2h and 120 °C for 3h. Relative permeability of SMPE with different proportions of soft magnetic powder were finally measured by the LCR Meter, with the results shown in Figure 2. And it was clear that the relative permeability of SMPE increases exponentially with the proportion raise of iron powder.

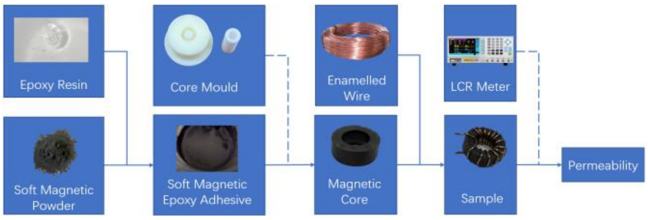


Figure 1. Schematic drawing of sample preparation and relative permeability measurement.

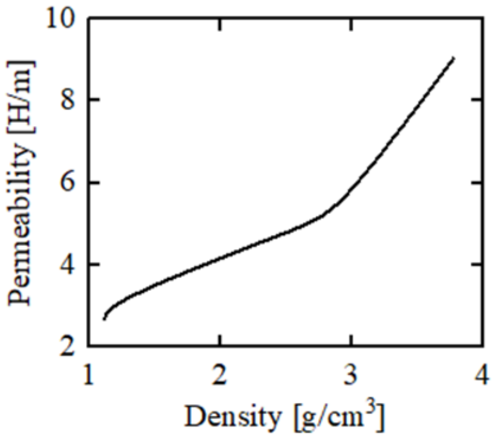


Figure 2. Results of relative permeability and the density of epoxy composite with different proportions of soft magnetic metal powders

B. *The MEF Simulation of the Power Module.*

In the magnetic and electric simulation, we focused on the calculation of DC resistance (DCR) between the original winding and the proposed winding. The original power module we studied is a 60mm×40mm buck converter with 12-V input and 1.2-V output, without encapsulation. In addition, the size of the original inductor is 6.6mm×7mm×3mm. According to the design specification of the power module, the required inductance value is 1μH.

At the packaging level, the SMPE enhances the magnetic flux density. The proposed one-step molding technology use SMPE to encapsulate the power module. The properties of main material used in the power module are presented in Table 1. As shown in Figure 3, in one-step molding, the dual-winded copper coil was placed on a 0.5mm PCB, surrounded by SMPE encapsulation of which the thickness was set as 3.5mm. We built the models of power module to mainly focus on SMPE encapsulation and magnetic core encapsulation respectively and concentrated on the inductance and DCR, so the IC chip and other passive components were simplified in the modeling. The inductance calculating equation is expressed as:

$$L = \frac{\mu_r \mu_0 N^2 A_e}{l_e} \tag{1}$$

where L is the inductance value, A_e is the effective area for flux, l_e is the length of magnetic path, N is the number of turns, and μ_r and μ_0 is the relative permeability of the magnetic material.

Under the assumption that the SMPE doesn't saturate at full load, the magnetic flux density is calculated by Formula (2). Since that the shape of the magnetic path is not regular, that we get more accurate flux density distribution by the following simulation.

$$B = \frac{LI}{NA_e} \tag{2}$$

where B is magnetic flux density, L is inductance value, I is the current value, N is the number of turns, and Ae is the effective area for flux.

Table 1.Material magnetic properties.

Material	Relative permeability	Electrical conductivity	Relative permittivity
Unit	1	S/m	1
Magnetic core	29	0	3.5
SMPE	10	0	3.5
copper	1	5.998E7	1

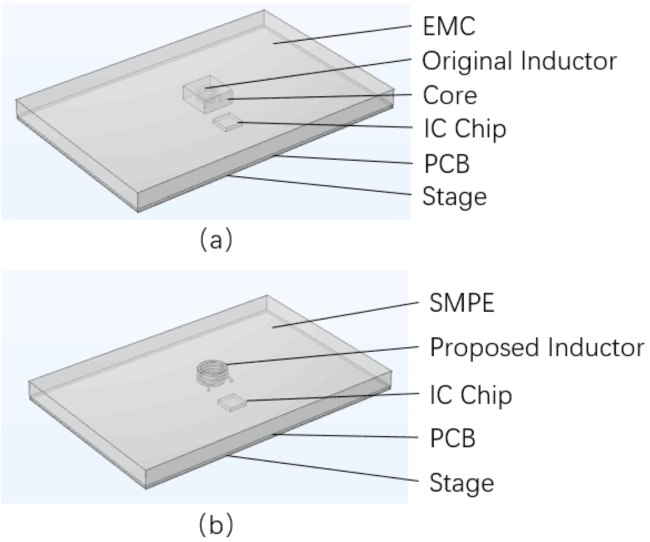


Figure 3. Model of power module configuration,
(a) Magnetic core encapsulation ; (b)SMPE encapsulation.

Power module geometric configuration was meshed by tetrahedral elements for computation and the mesh size was finer. The Ampere's Law and Current Conservation was used in the winding domain, while the Ampere's Law was applied in the encapsulation and the PCB domain since we assumed that the electrical conductivity of both domains is 0.

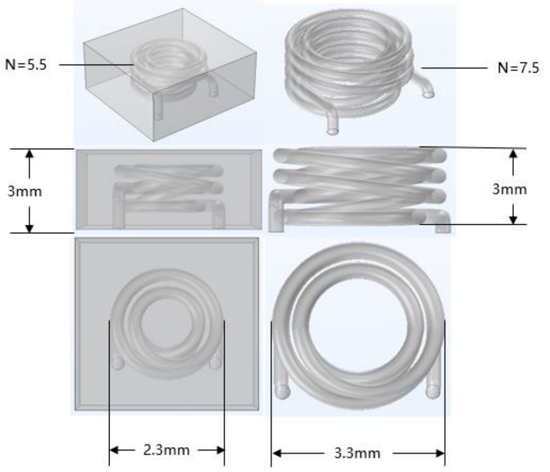


Figure 4. Model diagram of two inductors. (a) Original inductor. (b) Proposed inductor.

Figure 4 shows the original inductor (a) And the original inductor (b). The relative permeability of SMPE is lower than that of magnetic core material in the original inductor. According to formula (1), when μ_r decreases, the inductance will also decrease. Therefore, structure modification of the winding coil is necessary to meet the demand of inductance value. Benefiting from such one-step molding technology, extra space can be used for the winding coil design. The new designed winding has the same size as the packaged inductor itself. With the increase of major radius, the inductance was able to be kept at the same level with fewer turns and larger minor radius, when the thickness of two windings remained the same. The DCR for the original inductor was 5mΩ, while 8.66mΩ for the proposed inductor in order to meet the inductance of 1μH. Figure 5 shows the simulated flux distribution of proposed packaging. Through Figure 5, it is clear that the magnetic flux of the original inductor is more concentrated and has a higher maximum flux density, compared to the proposed inductor.

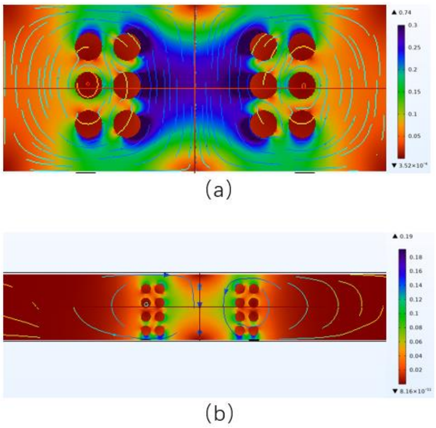


Figure 5. Simulated flux distributions. (a) Original power module (b) Proposed power module.

III. HEAT TRANSFER ANALYSIS

In this section, we first established and calibrated the model in COMSOL based on the prototype of the commercial power module and the thermal image from its datasheet. Then we re-designed the original winding with an increase of not only the major radius but also the minor radius under the constraint of the original inductor volume. EMC encapsulation to the PCB model was chosen as a control group in order to compare with one-step molding with SMPE package. Finally, we simulated and compared the temperature distribution of the power modules with EMC encapsulation and SMPE encapsulation, respectively.

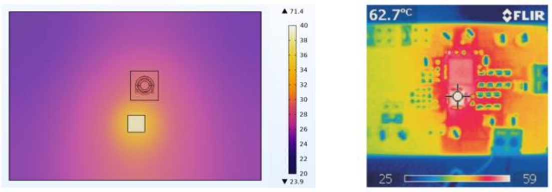
A. Establishment and Calibration of the Model

The main identified heat sources were power inductor and IC. To simplify the model, heat dissipated from resistors and conductors was neglected. In both module of COMSOL, conduction and convection heat transfer were taken into consideration, with boundary conditions of external natural convection for the top and the vertical sides of the power module and general inward heat flux for the bottom of the power module. The heat conduction and heat convection governing equation for power modules can be expressed as Formula (3) and Formula (4), respectively.

$$Q = KA(T_{Hot} - T_{Cold})t/d \tag{3}$$

$$Q = H_c A(T_{Hot} - T_{Cold}) \tag{4}$$

where Q represents the heat transferred through conduction or convection, and K is the thermal conductivity of the material. A is the area of the surface. T_{Hot} is the temperature of the hot surface, while T_{Cold} is the temperature of the cold surface, d is the thickness of the material, and H_c is the heat transfer coefficient. The t represents the time for the heat transfer process, the t is infinite for the heat transfer process in this paper since the simulations we did were all steady-state simulations. The Radiation was neglected in the following heat dissipation calculation, since the working temperature was below 100 °C. Figure 6 shows the result of calibration for the model.



(a) (b)

Figure 6. Calibration for the model. (a) Calibrated model. (b) Thermal image of the prototype[5].

At the packaging level, SMPE with potting technology is able to improve the heat dissipation of the two mainly heat sources of the power module. The proposed molding technology used SMPE to encapsulate the whole power module which reduces thermal resistance and increases thermal diffusion efficiency at the same time, since SMPE contains high doping levels of iron powders. Figure 7 shows the structure of two power modules. The original power module was encapsulated by EMC (Figure 7a), while the proposed power module was encapsulated by SMPE (Figure 7b). The EMC encapsulated IC chip and the inductor were placed on a 0.5mm PCB and the original inductor was molded individually. The size of the inductors of both power modules was presented in Table 2. 0.1mm Aluminum plates were applied for both power modules as heat sinks.

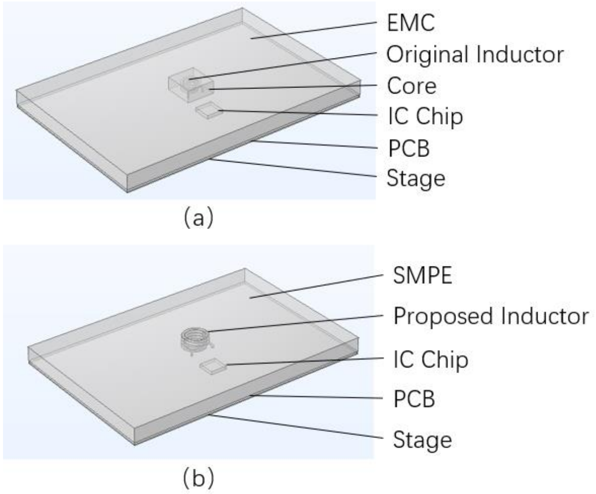


Figure 7. Structure of Two Power Module. (a) Power Module with EMC. (b) Power Module with SMPE.

B. The Heat Transfer Simulation of the Power Module.

In the heat transfer analysis, we mainly focused on the temperature distribution. The thermal conductivities of SMPE and the core were calculated by the weight proportion of each material contained in SMPE and is shown in Table 3 with other material properties. Heat conductivity of the PCB was 30 since the PCB substrate is cladded by copper wires which leads to a higher thermal conductivity. Heat transfer was calculated using a 3-D finite element simulation with COMSOL.

Table 3. Material thermal conductivities.

Material	*K*(W/m℃)
SMPE	32.2
EMC	1
Core	38.05
Copper	400
PCB	30
Stage (Aluminum)	200

Two main heat sources in the power module were identified, namely the IC chip and the coil. The heating power of IC chip is 1.43W, which was calculated by the highest temperature divided by junction-to-ambient thermal resistance, both referred from the datasheet of the commercial power module. The heat power is 0.180W for the original inductor and 0.306W for the proposed inductor. The power of heat of the inductor is calculated by Formula (5)

$$P_{total} = P_{core} + P_{dcr} + P_{acr} \qquad (5)$$

where the P_{total} is the total heat power of the whole inductor, the P_{core} is the heat power of the core, the P_{dcr} is the heat power caused by DCR, and the P_{acr} is the heat power caused by ACR (alternating current resistance). In this paper, we just focused on the P_{dcr} since P_{acr} and P_{core} are negligible compared to P_{dcr}. The natural heat convection to air was used to the top and vertical sides of the module. A -650W/m^2 general inward heat flux was used to the bottom of the module.

Figure 8 shows the temperature distribution of two power modules. With SMPE encapsulation, the junction temperature dropped from 54.0°C to 39.9°C, namely a 26.1% decrease. Meanwhile, the temperature distribution of the SMPE encapsulated power module was better than the one with two-step epoxy encapsulation. It is clear that with a better thermal conductivity of SMPE, the power module thermal management was improved, though the DCR loss of the proposed inductor increased 70% (original was 0.306W while SMPE was 0.18 W) due to the re-designed coils. Besides, the thermal resistance from heat source to the ambient of power module encapsulated by SMPE shrunk from 37.76°C/W to 27.90℃/W, namely a 26.11% decrease, compared with the power module encapsulated by EMC. It was also concluded that with higher doping levels of iron powder, the thermal conductivity of SMPE was able to increase further, which brings extra benefits for lowering the DCR loss of the re-designed winding structures. Therefore, for further developing the one-step molding technology for power modules, SMPE needs to be further investigated with higher thermal conductivity and permittivity. Furthermore, the winding design still have spaces for further improvement, together with new SMPE materials.

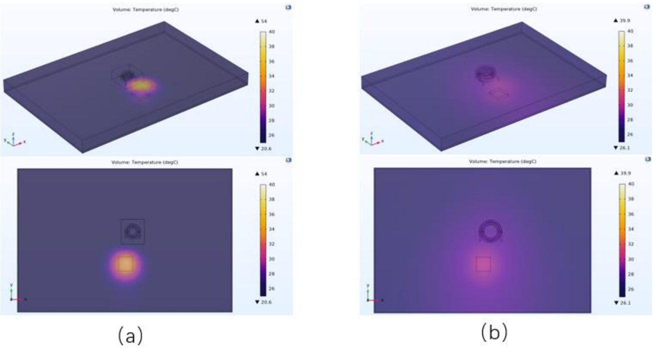


Figure 8. Temperature distribution of two power modules. (a) Power module with EMC. (b) Power module with SMPE.

IV. CONCLUSION

The one-step molding packaging method proposed in this paper provides a new way to encapsulate the power module while keeping the magnetic function. SMPE material were firstly prepared and measured, concentrated on the permeabilities of different iron powder proportions. The measurement of the relative permeability shows that with the increase of iron powder doping ratio, the relative permeability of SMPE increases, and the growth of relative permeability shows a trend from slow to fast. Then, the magnetic and electric simulation were conducted, calibrated, and further analyzed by heat transfer between the power modules encapsulated by EMC and by SMPE. Compared to the power module encapsulated by EMC, the one-step molded power module with SMPE encapsulation has a lower module junction temperature and lower thermal resistance, though embracing a higher DCR in order to keep the same inductance level. It is believed that with a better SMPE material and improved winding structures of the copper coil, it is possible to further shrink the DCR and improve the performance of power modules with one-step molding process.

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