Integrated CMOS Switch Buck DC-DC Converter Fabricated in Organic Interposer with Embedded Magnetic Core Inductor

T. Akiyama, S. Ishida, T. Shirasawa, T. Fukuoka, S. Harra, H. Yoshida, M. Sonehara, T. Sato, and K. Miyaji
Spin Device Technology Center, Shinshu Univ., 4-17-1 Wakasato, Nagano 380-8553, Japan

In this paper, the development of a CMOS switch buck DC-DC converter fabricated in an organic interposer with an embedded power inductor is described. The power inductor is fabricated by using a magnetic core made of an Fe-based amorphous alloy powder-filler/epoxy composite sheet to form a fully closed magnetic circuit and is embedded in the organic interposer in a lamination process. The fabricated power inductor is located under a CMOS control chip and has a footprint of 3.5 mm square. The CMOS switch buck DC-DC converter runs at 20 MHz, and the fabricated power inductor has an inductance of 150 nH and a Q-factor of 38 at around 20 MHz. Furthermore, the influence of magnetic flux leakage from the embedded power inductor to a copper wiring pattern on the surface was analyzed in a simulation that utilized three-dimensional electromagnetic field analysis software (ANSYS: HFSS). Based on the simulation result, the conduction losses of the inductor were calculated under the assumption of use in a synchronous buck converter operating with a 5-V input and 3.3-V 0.8-A output.

Keywords: power inductor, organic interposer, Fe-based amorphous alloy powder-filler/epoxy composite sheet, lamination process, DC-DC converter

1. Introduction

In recent years, power distribution losses between power supply and the loads have increased due to requirement of low-voltage and high-current loads such as LSIs. In order to reduce the power distribution loss, the distributed power architecture with Point of Load (POL) DC-DC converters has been widely used. However, development of the small power inductor is desired because the POL DC-DC converter occupies considerable footprint on the motherboard. The package integrated power inductor has been studied to make POL converter footprint smaller. INTEL has developed package-integrated POL converter using air-core solenoid inductor for their fourth-generation core processor Haswell. The air-core inductor can be easily fabricated by only the metal process, but has serious disadvantages such as low inductance value and undesired EMI noise due to widespread alternating magnetic flux. In order to reduce the footprint and reduce the EMI noise, it is expected to introduce a magnetic core in the inductor.

This paper describes the development of power inductor using soft magnetic powder-filler/epoxy composite sheets as a magnetic core. The embedded power inductor in the organic interposer is made by lamination process. Furthermore, CMOS control flip-chip IC and other Surface Mount Devices (SMD) are mounted on the organic interposer by reflow soldering at 180°C to fabricate 20 MHz switching buck DC-DC converter. The simulation results focusing on the influence of leakage magnetic from the power inductor to the surface wiring copper pattern at 20 MHz are also described. Surface wiring copper pattern locates just above the embedded power inductor and form a surface layer of the organic interposer which CMOS control chip and SMDs are mounted.

2. Outline of organic interposer

Figure 1 shows a cross-section view of the power inductor embedded in the organic interposer with a 1.6 mm thick glass-fiber/epoxy center core and 50 µm thick glass-filler/epoxy build-up layer. The glass-filler/epoxy build-up layer is formed by thermal laminator in the organic interposer fabrication process. In this work, the magnetic core power inductor embedded in the organic interposer is based on the conventional lamination process using soft magnetic powder-filler/epoxy build-up sheet. The soft magnetic powder-filler/epoxy composite sheet changed the glass-filler to soft magnetic powder-filler. In this method, it is unnecessary to change the conventional organic interposer fabrication process but only changing the laminating condition of the composite sheet.

3. Fe-based amorphous alloy powder-filler/epoxy composite sheet

The magnetic composite sheet consist of 2.56 µm-median diameter Fe-based amorphous alloy powder (Fe87.83Si6.59B2.54Cr2.53Co0.51 (wt. %)) and epoxy resin.

Fig. 1 Cross-section of organic interposer.
Figure 2 shows the static magnetization curve and complex permeability of amorphous alloy powder-filler/epoxy composite sheet measured using VSM (Vibrating-sample magnetometer, Riken Denshi: BHV-55), and RF Impedance/Material Analyzer (Hewlett-Packard; HP4291B) with coaxial waveguide. The saturation magnetization of Fe-based amorphous alloy powder-filler/epoxy composite sheet is about 0.8 T. A filling ratio of Fe-based amorphous alloy powder-filler in the composite sheet is estimated at 64 vol.%. The relative permeability $\mu'$ is about 9 at tens MHz. Also, the imaginary part of the complex permeability $\mu''$ related to magnetic loss is small up to around tens MHz. Furthermore, the coercivity of the amorphous powder-filler/epoxy composite sheet measured using coercivity meter (Denshi Industry: HC-1031) is 324 A/m (4 Oe).

4. Fabrication process of the power inductor

In the organic interposer, the Fe-based amorphous alloy powder-filler/epoxy composite sheet layer is formed by thermal lamination process. Since the composite sheet has a characteristic of thermoplastic and becomes soft at high temperature, the composite sheet is pressed and laminated to the FR-4 base substrate while it is heated at 150°C. By heating the composite sheet, it is possible to fill the composite material between the thick film coil conductors having large unevenness shown in Fig. 3 and can maintain the planarization of the composite sheet surface\(^{10}\). The base substrate and the composite sheet is heated at 150°C, then 190°C post curing is performed in a clean oven after the lamination.

The power inductor is embedded in the organic interposer according to the fabrication procedure shown in Fig. 4. A copper spiral coil having a thickness of 70 $\mu$m is fabricated by electroplating process using photo resist lift-off process. The power inductor embedded in the Fe-based amorphous alloy powder-filler/epoxy composite sheet and forms a fully closed magnetic circuit.
5. Power inductor using Fe-based amorphous alloy powder/epoxy composite sheet

5.1 Power inductor structure
Figure 5 shows the structure of the power inductor. A 70 μm thick electroplated copper 6-turn spiral coil winding with 130/50 μm line/space and 3.5 mm-square foot-print, has a DC coil resistance of 170 mΩ.

5.2 Electrical characteristics of power inductor
Figure 6 shows the measurement result of the electrical characteristics of the fabricated power inductor using RF Impedance/Material Analyzer (Hewlett-Packard: HP4291B) and simulation result of utilizing three-dimensional electromagnetic field analysis software (ANSYS: HFSS). As shown in Fig. 6, the inductance decrease slightly and equivalent series resistance increase with increasing frequency. Since the 6-turn spiral coil has 130 μm wide conductor lines, it is considered that skin effect and proximity effect in the conductor width direction cause the inductance to decrease and equivalent series resistance to increase. The fabricated power inductor has 150 nH at 20 MHz, which was almost the same value as the simulation result. Q-factor of fabricated power inductor was 38 at 20 MHz, which was 24% lower than the simulation result. Since the inductance is almost the same as the simulation result, the cause of the decrease in the Q-factor is an increase in the equivalent series resistance. The main reason for the increase in equivalent series resistance is presumed to be the contact resistance between the spiral coil and the via conductor and the parasitic resistance at the time of measurement. Furthermore, the peak of the Q-factor was about 40 MHz, it is necessary to change the structure of the power inductor and the filling ratio of Fe-based amorphous alloy powder of the composite sheet for that the peak value becomes 20 MHz.

5.3 Organic interposer integrated CMOS switch buck DC-DC converter
The surface wiring copper pattern formed just above the embedded power inductor made by electroplating process which is mount for CMOS control chip and SMD. The appearance of the fabricated the organic interposer integrated CMOS switch buck DC-DC converter is shown in Fig. 7. The footprint including the CMOS control chip and SMD is 7.2 mm x 6.0 mm. The X-ray photograph shows the power inductor is laid out under CMOS control chip and SMD.

5.4 Influence of surface wiring pattern formed above the power inductor
The eddy current is generated on the surface wiring copper pattern due to the leakage magnetic flux from the embedded power inductor. The magnetic flux generated by this eddy current has an opposite direction to the main magnetic flux from the power inductor and decrease of the Q-factor of the power inductor. In this section, the influence of leakage magnetic flux from the embedded power inductor to the surface wiring copper pattern has been analyzed by simulation utilizing three-dimensional electromagnetic field analysis software. A Simulation model is shown in Fig. 8. The analysis condition is a sine wave with an effective value of 1 A flow at 20 MHz. Figure 9 shows the magnetic flux density distribution of the cross-section A-A’ of the power inductor (Fig. 8(b)). From Fig. 9, it can be confirmed from the figure that the leakage magnetic flux is generated from the power inductor to the surface wiring copper pattern.
Figure 10 shows the current density distribution of the surface wiring copper pattern. The eddy current on the surface wiring copper pattern is generated by leakage magnetic flux from the power inductor embedded in the organic interposer. The eddy current flows on the surface wiring copper pattern increase the equivalent series resistance of the power inductor. Furthermore, the magnetic flux generated by the eddy current decrease main magnetic flux from the power inductor and its inductance value. It might be necessary to increase the relative permeability of the composite sheet and to increase the distance between the surface wiring copper pattern and the power inductor in order to the influence of the leakage magnetic flux.

5.5 Inductor conduction loss

Figure 12 shows an equivalent circuit of the synchronous buck DC-DC converter. Since capacitance C in Fig. 12 is considered to be insufficiently large, the inductor current waveform of the DC-DC converter using ideal inductor is a triangular wave as shown in Fig. 13. The inductor current increase/decrease linearly during on/off of the high side switch S1. When the inductor current is a triangular wave, the amplitude of the ripple current is expressed by Eq. (1).

\[ I_R = \frac{V_{in} \cdot D \cdot (1 - D)}{2 \cdot f \cdot L} \]  

(1)

The specification of the synchronous buck DC-DC converter are listed in Table 1 and as follows, input voltage: 5 V, load current: 0.8 A and constant on-duty ratio D of high-side switch: 0.66. The effective value of the inductor current is expressed by Eq. (2).
Fig. 11  Simulated (a) inductance $L'$, (b) equivalent series resistance $R'_s$, and (c) $Q'$-factor versus frequency $f$ with and without copper wiring pattern on surface.

Fig. 12  Equivalent circuit of synchronous buck converter.

Table 1  Specifications of buck DC-DC converter fabricated in organic interposer.

| Item          | Specification |
|---------------|---------------|
| Input voltage, $V_{in}$ | 5.0 V |
| Output voltage, $V_{out}$ | 3.3 V |
| Load current, $I_L$ | 0.80 A |

Table 2  AC conduction loss of power inductor.

| Item                              | AC conduction loss |
|-----------------------------------|--------------------|
| @ 20 MHz $P_{AC}$ (w/o surface pattern) | 3.90 mW |
| $P_{AC}$ (w/ surface pattern)     | 12.6 mW |

\[ I_{rms}^2 = (I_L^2 + I_R^2)/3 \]  \hspace{1cm} (2)

\[ P = R (I_L^2 + I_R^2)/3 \]
\[ = R_{dc} I_{out}^2 + R_s I_R^2/3 \]  \hspace{1cm} (3)

$I_L$ is a direct current superimposed current flowing in the inductor, which is the output current of the DC-DC converter. Therefore, the conduction loss $P$ of the inductor in the operating state of the DC-DC converter can be expressed by Eq. (3).

The conduction loss of the fabricated inductor is calculated by using Eq. (3), the DC conduction loss is 108.8 mW and the AC conduction loss is 5.8 mW. The AC conduction loss of power inductor with and without surface wiring copper pattern are shown in Table 2. Despite the increase in the AC conduction loss of the power inductor due to the influence of the surface wiring copper pattern, the DC conduction loss is much larger than the AC conduction loss. The large DC resistance of the power inductor results in the decrease of power conversion efficiency for CMOS switch buck DC-DC converter. It is necessary to study the structure of the power inductor and increase the relative permeability of the non-magnetic resin/soft magnetic filler composite sheet to achieve low DC resistance.
6. Conclusions

The CMOS switch buck DC-DC converter fabricated in the organic interposer with an embedded amorphous alloy powder-filler/epoxy composite sheet core inductor made by lamination process was developed and evaluated. The developed amorphous alloy powder-filler/epoxy composite sheet core inductor has a footprint of 3.5 mm square, inductance of 150 nH, Q factor of 38 at around 20 MHz. Although the Q-factor decrease due to the influence of the surface wiring copper pattern just above the embedded power inductor, it did not lead to large increase of the inductor power loss. The most important issue for power loss is the large DC resistance of the power inductor. The large DC resistance of the power inductor decrease power conversion efficiency of CMOS switch buck DC-DC converter.

In the future work, authors will investigate the novel structure and soft magnetic-filler/non-magnetic resin composite sheet design to achieve low DC resistance and high Q-factor power inductor.

Acknowledgments This research was partially supported by Semiconductor Technology Academic Research Center (STARC), and JST-Mirai Program “Realization of a low carbon society through game changing technologies”, Japan.

The authors thank Researcher Toshitaka Minamisawa, Shinshu University, for assisting the experiment of power supply circuit.

References

1) H. Kobayashi, F. Sato, K. Hagita, R. Takeda, M. Sonehara, T. Sato, N. Matsushita, K. Kobayashi, H. Shimizu, T. Fujii, K. Ishida, and T. Sakurai: J. Magn. Soc. Jpn. (in Japanese), 37, 4, pp.314-319 (2013).
2) X. Zhou, P. L. Wong, P. Xu, F. C. Lee, and A. Q. Huang: IEEE Trans. Pwr. Elec., 15, 6, pp.1172-1182 (2000).
3) S. Ji: Master of Sci Dissertation, Virginia Tech., (2013).
4) Y. Su: Ph.D. Dissertation, Virginia Tech., (2014).
5) K. Hagita, Y. Yazaki, Y. Kondo, M. Sonehara, T. Sato, T. Fujii, K. Kobayashi, S. Nakazawa, H. Shimizu, T. Watanabe, Y. Seino, N. Matsushita, Y. Yanagihara, T. Someya, H. Fuketa, M. Takamiya, and T. Sakurai: J. Magn. Soc. Jpn., 39, 2, pp.71-79 (2015).
6) J. Wibben, and R. Harjani: IEEE JSSC, 43, 4, pp.844-854 (2008).
7) N. Kured, M. Chowdhury, E. Burton, T. P. Thomas, C. Mozak, B. Boswell, P. Mosalikanti, M. Neidongard, A. Deval, A. Khanna, N. Chowdhury, R. Rajwar, T. M. Wilson, and R. Kumar: IEEE JSSC, 50, 1, pp.49-58 (2015).
8) W. J. Lambert, M. J. Hill, K. Radhakrishnan, L. Wojewoda, and A. E. Augustine: IEEE Trans. CPMT, 6, 1, pp.3-11 (2016).
9) H. Yamaguchi, R. Oka, T. Akiyama, T. Sato, M. Sonehara, and K. Miyaji: The Annual Meeting Record IEEJ 2017 (in Japanese), 2-118, (2017).
10) T. Akiyama, R. Oka, H. Yamaguchi, T. Sato and M. Sonehara: The Paper of Technical Meeting on Magnetics and Linear Drives, IEE Japan (in Japanese), MAG-17-070/LD-17-038, pp.47-52 (2017).

Received Jan. 20, 2019; Revised Mar. 06, 2019; Accepted Mar. 15, 2019