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Numerical predictions of 3D power-supply on chip taking into considerations of proximity effect

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***Abstract*—3D Power-SoC (Supply on Chip), which can ultimately miniaturize the power supply, is attracted attentions. It integrates Si-LSIs, power devices and passive elements on a single chip. 3D Power-SoC requires frequencies above 30MHz. In addition, it realizes a very high power density, however handling power is small because of miniaturization. Therefore, parallel connection is required to increase the power handing capacity. Therefore, it is necessary to consider the proximity effect of the spiral inductor when the power supplies connected in parallel. In this paper, we report the proximity effect of the inductor through simulations.**

***Keyword*—powerSoC, DC-DC converter,**

high frequency, miniaturization, inductor

I. Introduction

Recently, there is an increasing demand for miniaturization and thinning of the power supply with the miniaturization and high performance of electronic devices. Passive elements, which occupy a large volume inside the power supply, are a major obstacle to the miniaturization of the power supply.

An effective way to reduce the size of passive devices is to increase the switching frequency. On the other hand, the higher the switching frequency, the severer the effect of the parasitic impedance caused by the wiring. It is effective to minimize the wiring length to reduce the parasitic impedance. However, there is a limitation to minimize the wiring and efficiency drops significantly when the switching frequency is over several tens of MHz [1,2]. To solve this problem, our research group previously proposed 3D power SoC (Supply on Chip) [2,3] (Fig. 1). 3D power SoC stacks Si LSIs, power devices, and passive devices in one chip. It is different from the conventional PCB(Printed Circuit Board) mounted POL(Point of Load). 3D power SoC can minimize the wiring length compared with the conventional PCB based POL. Thus, the influence of parasitic impedance can be reduced and it can realize high efficiency at high-frequency switching. In addition, 3D power SoC allows different types of devices to be manufactured separately and integrated into a single chip using wafer bonding technology, enabling heterogeneous integration such as integration of Si-LSI and GaN power devices.

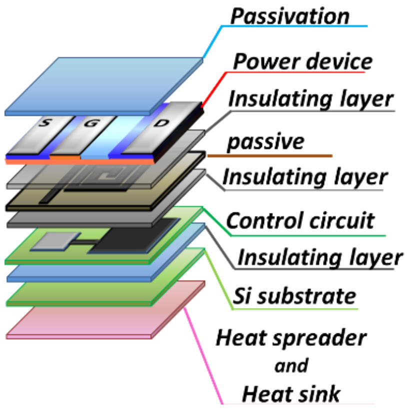


Fig..1 3D PowerSoC

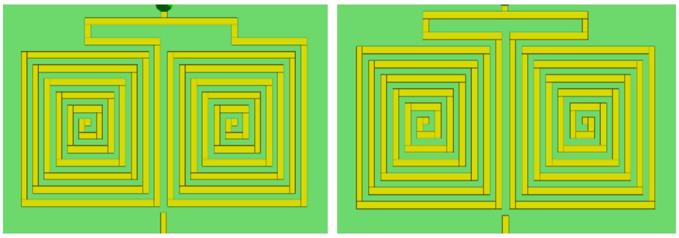
In power SoCs, solenoid inductors and spiral inductors are used properly according to the switching frequency [4]. Our research group revealed that spiral inductors are suitable for switching frequencies of around 30MHz [4]. On the other hand, the power density of the 3D power SoC is high, however the size is small (less than 3 mm sq), and the power handling capability is small. Therefore, 3D power SoCs are connected in parallel to increase handling power[5, 6]. It is necessary to considerations of proximity effect of the spiral inductor when 3D power SoCs are connected in parallel.

In this paper, we explore the proximity effect of inductors through simulations when 3D power SoCs are connected in parallel.

II. Simulations

A. *Spilal inductor*

The proximity effect of spiral inductors in parallel connection of 3D power SoCs is investigated using electromagnetic field simulation[6]. In simulations, we created a model of a 2 mm square spiral inductor and trench capacitor assuming a 3D power SoC. In order to achieve high efficiency in a 2 mm square, the spiral inductor has 6 turns and the trench capacitor has 1333 pieces[4]. In the electromagnetic field simulation, spiral inductors were connected in parallel, and the inductance value and internal resistance when the distance between each inductor was changed were calculated to evaluate the proximity effect. Figure 2 shows the structure of the spiral inductors used in simulations. In order to consider the influence of the direction of the magnetic field, two types inductors were simulated. Namely, one is same winding direction and the other is opposite winding direction.



(a) (b)

Fig.2 Inductor used in the simulations.

(a)same (b)opposite

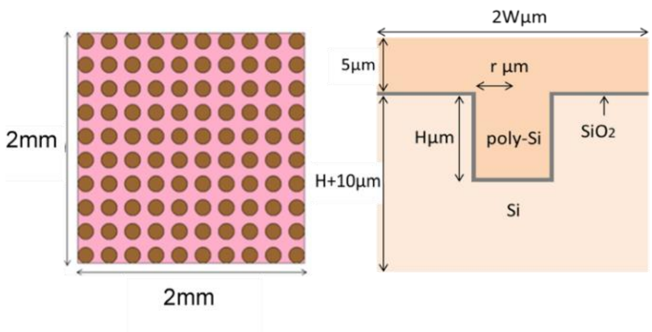


Fig. 3 Capacitor used in the simulation.

B. *Circuit simulation*

A circuit simulation[7] is performed using the inductance value and internal resistance value of the spiral inductor obtained by electromagnetic field simulation and, the capacitance value of the capacitor obtained by calculation, and the equivalent series resistance value.

A simulation was performed using a buck converter (Fig. 4) using the GaN power devices(EPC8004[8]). The conditions of the circuit simulation were a switching frequency of 30 MHz, an input voltage of 5.0 V, and an output voltage of 2.5 V.

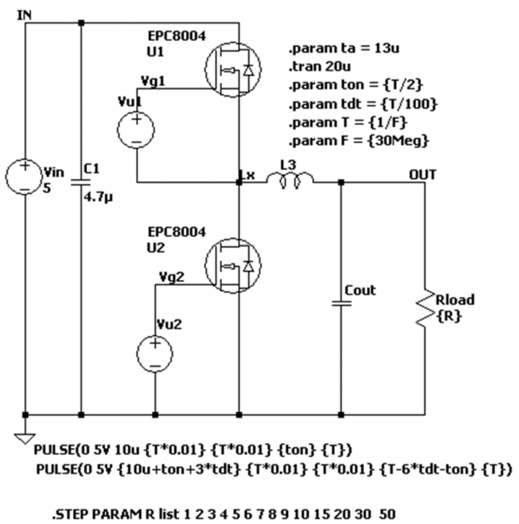


Fig.4 Buck converter circuit with LTspice.

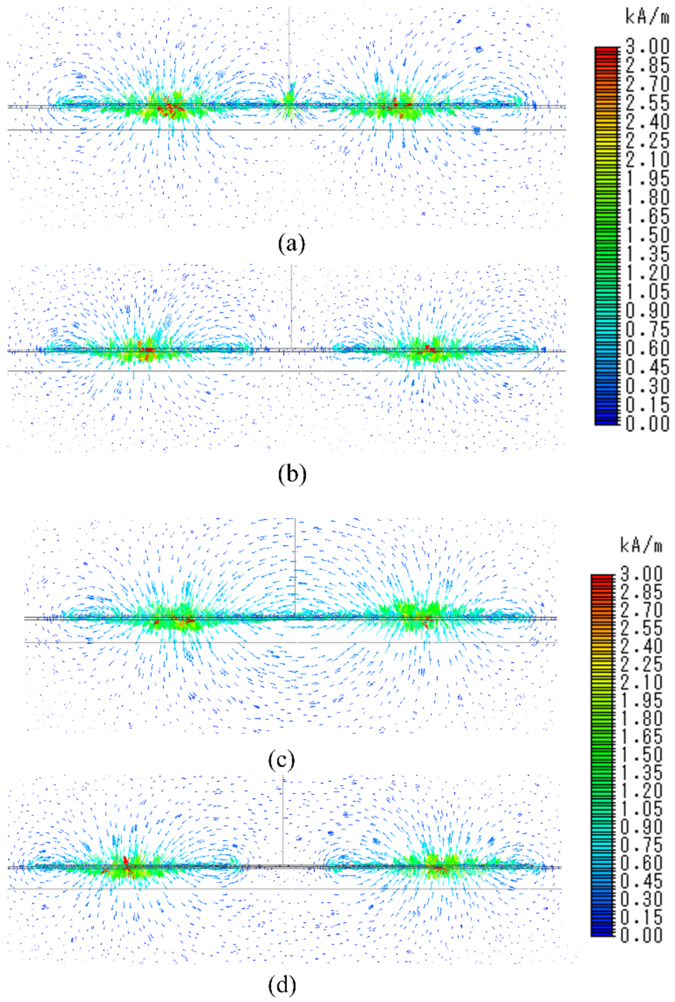
III. RESULTS AND DISCUSSION

A. *Electromagnetic field simulation*

Table 1 shows the simulation results of spiral inductors connected in parallel. Figures 5 shows the magnetic field distribution.

TABLE 1 Inductance value and internal resistance (30MHz).

	same		opposite	
distrance	L[nH]	R[Ω]	L[nH]	R[Ω]
one inductor	29.5	0.558	29.5	0.558
50u	29.14	0.608	34.1	0.628
100u	29.4	0.608	33.76	0.628
300u	30.24	0.608	32.86	0.626
500u	30.78	0.61	32.38	0.624
1000u	31.48	0.62	31.68	0.626



Figs. 5 Magnetic field distribution.

(a)same direction 50μm

(b) same direction 1000μm

(c) opposite direction 50μm

(d) opposite direction 1000μm

The inductance value and internal resistance of 2 mm square spiral inductors connected in parallel at 30 MHz increases, as the distance between the inductors increases in same winding direction as compared with a single inductor. However, the magnetic field are not affected by the proximity effect of above mentioned two inductors because increase in inductance is caused by change in wiring length according to the distance of two inductors.

The inductance value will be higher than that of a single inductor due to the influence of mutual magnetic fields when the winding direction is opposite. In addition, the amount of decrease in the inductance value for the opposite winding direction becomes larger than in the same winding direction as the distance increases because the effect of the magnetic field becomes smaller. In opposite winding direction, the results of electromagnetic field simulations show that the proximity effect exists.

B. Circuit simulation

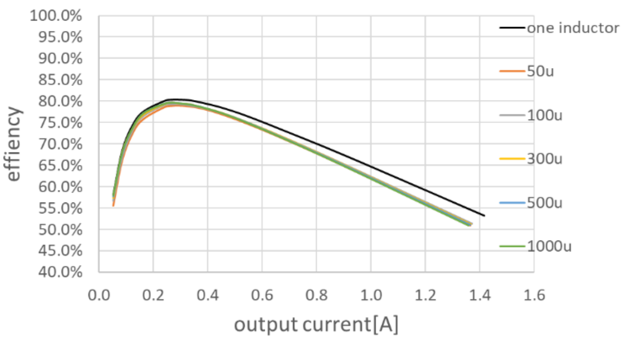
The efficiency of the buck converter was calculated based on the result of A and the calculation result of the capacitance of the trench capacitor in Fig. 3. The capacitance of the capacitor was calculated as follows.

$$C = \varepsilon_0 \varepsilon_{SiO_2} \frac{S}{d} \quad (1)$$

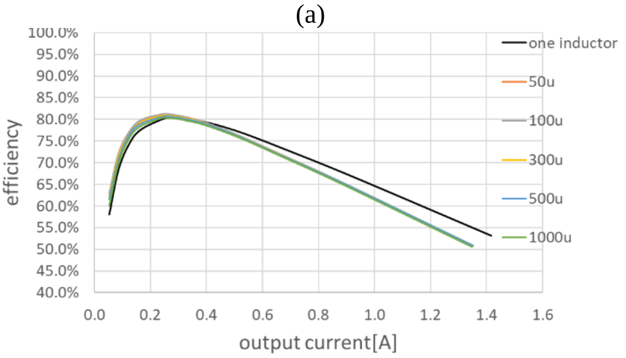
$$S = X^2 + 2rH \times N^2 \quad (2)$$

In (2), X is the size of the entire chip (2 mm), and N is the number specified this time, 1333 pieces. The permittivity of the vacuum is ε_0 = 8.854 × 10^{-12}, the relative permittivity of the silicon oxide film is ε_{SiO2} = 3.9, the trench depth is H = 10 µm, the trench spacing is W = r + 5 µm, and the trench width is r = 0.5 µm, and the capacitance value and resistance value were obtained from this.

Figures 6 shows the output current-efficiency characteristics of the buck converter at 30 MHz.



(a)



(b)

Figs. 6 Output current-efficiency characteristics
(a) same winding direction
(b)opposite winding direction

From Figs. 6 (a), in same winding direction, the efficiency of a single inductor is higher at any output current. In the winding direction opposite shown in Figs. 6 (b), the efficiency of the single inductor is lower when the output current is lower than 0.4 [A]. Above 0.4 [A], the efficiency of the single inductor is higher when the output current is more than 0.4 [A]. Table 2 shows the maximum efficiency. The maximum efficiency of the inductor in same winding direction is lower than that of a single inductor. On the other hand , that in opposite winding direction is higher than that of a single inductor.

These results indicate that the proximity effect affect the efficiency of buck converter when inductors are connected in parallel.

TABLE 2 Maximum efficiency at 30MHz.

	same	opposite
distance	effiency	
one inductor	80.37%	80.37%
50u	78.88%	81.18%
100u	79.25%	81.18%
300u	79.63%	80.89%
500u	79.68%	80.71%
1000u	79.56%	80.26%

C. Proximity effect and substrate

Impact of the substrate resistivity on the proximity effect is investigated. The insulator substrate was also investigated for comparison.

The simulated structure is shown in Fig. 7 and the results are shown in Fig.8.

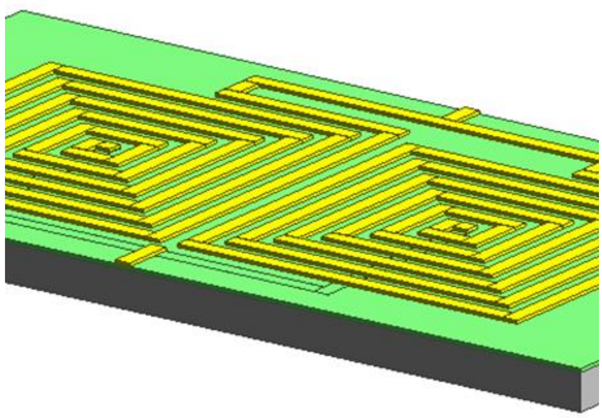


Fig. 7 Simulated structure.

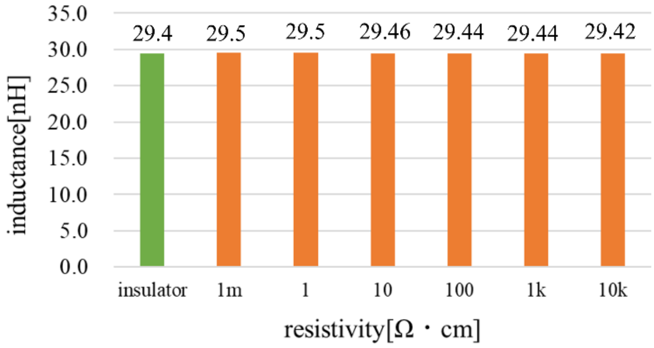
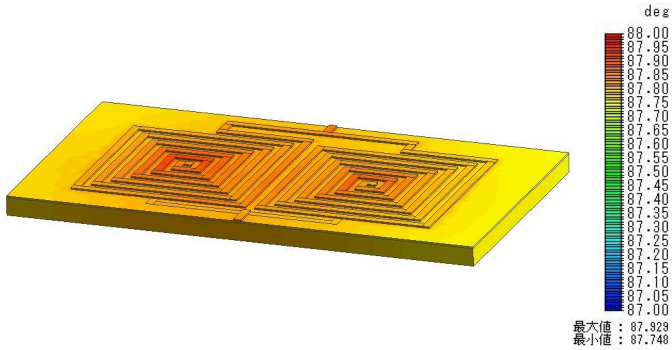


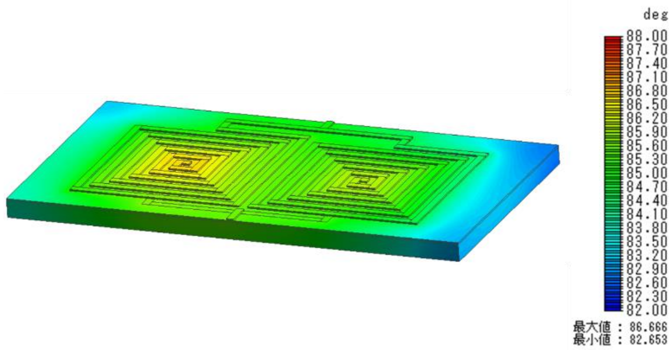
Fig.8 Inductance value vs. substrateresistivity.

For inductance vale, the proximately effect is not affected by substrate material and resistivity as shown in Fig. 8

We also simulate temperature increase when the inductor is working. The temperature distributions are shown in Figs. 9. Table 3 shows the maximum temperature, the minimum temperature, and the average temperature of each substrate.



(a)



(b)

Fig.9 Temperature distribution.

(a) Si substrate (1mΩ・cm)

(b) SiO_2 substrate

TABLE 3 Temperature of each substrate

material	Si	SiO2
	temperature(°C)	
maximum	87.93	86.66
minimum	87.75	82.653
average	87.8	84.851

It can be seen that the Si substrate(Figs.9 (a)) spreds heat more widely. The temperature increase is caused by loss from inductor and eddy current.

The maximum temperature of the insulator substrate is lower and the minimum temperature and average temperature of this substrate are lower. However, the difference in temperature for two substratw is small.

IV. Conclusion

In this paper, we evaluate the proximity effect of the spiral inductor used in the 3D power SoC and the effect on the back converter using electromagnetic field and circuit simulations. The following was clarified.

(1) The inductance value was affected by the proximity effect of the parallel connection of inductors.
(2) The inductance value changed by the proximity effect also affected the efficiency of the back converter.
(3) The proximity effect when the substrate is changed does not affect the inductance value of the inductor.
(4) From the viewpoint of heat spread, an insulator is suitable.

Acknowledgement

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