PCB-level Electro thermal Coupling Simulation Analysis

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Abstract. Power transmission network needs to transmit more current with the increase of the power density. The problem of temperature rise and the reliability is becoming more and more serious. In order to accurately design the power supply system, we must consider the influence of the power supply system including Joule heat, air convection and other factors. Therefore, this paper analyzes the relationship between the electric circuit and the thermal circuit on the basis of the theory of electric circuit and thermal circuit.

Keywords. Electro thermal coupling; Joule heat; Voltage distribution; Thermal distribution.

1. Introduction
When PCB is working, Joule heat can change the Power supply design and the thermal design of system with high density device. And the high temperature can even cause smoke or fire. So it is necessary to combine electricity and heat to analyze electro thermal coupling.

2. Contents of the Study
Part 2.1 introduces the method of electro thermal coupling; Part 2.2 analyzes the interactions of thermal and circuit.

2.1. The Method of Electro thermal Coupling
This chapter briefly discusses the theory of electro thermal coupling.

Voltage distribution equation in steady state is represented by the formula (1):

\[ \nabla \left( \frac{1}{\rho(x,y,z,T)} \nabla \varphi(x,y,z) \right) = 0 \]

(1)

Among them, \( \rho(x,y,z,T) \) is Resistivity, \( \varphi(x,y,z) \) is Voltage distribution.

Solid and fluid thermal distribution equation in steady state is represented by the formula (2):

\[ \nabla \left[ K(x,y,z) \cdot \nabla T(x,y,z) \right] = -P(x,y,z) \]

(2)
\[ \sigma c_p \nabla(x, y, z) \cdot \nabla T(x, y, z) = \nabla (K_f \nabla T(x, y, z)) \]  

(3)

\[ P(x, y, z) \] Include device heat and Joule heat. The device heat is available from the device technical manual. Joule heat can be calculated by formula (4):

\[ P_{\text{joule}}(x, y, z) = \overline{J} \cdot \overline{E}(x, y, z) \]  

(4)

Among them, \( \overline{J} \) is current density, \( \overline{E}(x, y, z) \) is electric field distribution in PDN.

Effect of temperature on electrical properties formula (5) to calculate the new resistivity:

\[ \rho = \rho_0 [1 + \alpha (T - T_0)] \]  

(5)

Among them, \( \rho_0 \) is the resistivity at temperature \( T_0 \); \( \alpha \) is the factor that the resistivity is affected by temperature. As shown in Fig.1, the resistivity of the conductor increases as the temperature increases, and finally increases the DC voltage drop in PDN. Fig.2 shows the relationship between electricity and heat. This paper summarizes an analysis method of electro thermal coupling, as shown in Fig.3.

Fig.1 The resistivity of silver, copper and aluminum affected by temperature

Fig.2 Relationship between electricity and heat
2.2. Electro thermal Coupling Analysis

In this paper, Strati GX is used as the research object as Fig.4 shows. The system can be powered from a DC power supply from 14V to 20V. There are four experiments: Electrical analysis; Thermal analysis; Electro thermal coupling analysis without fan; Electro thermal coupling analysis with fan.

2.2.1. The effect of Thermal circuit on Electric circuit. (1) The effect of Temperature on Power supply

Table 1. Lists the Actual Voltage in the experiment.
Table 1. Actual Voltage of E, ET_without Fan and ET_with Fan (unit: V)

| Name                        | E     | ET_without Fan | ET_with Fan |
|-----------------------------|-------|----------------|-------------|
| SINK_U29_2P5V_GND           | 2.48073 | 2.47867       | 2.47923     |
| SINK_U19_2P5V_GND           | 2.48117 | 2.47918       | 2.47967     |
| SINK_U29_S5GX_VCC_GND       | 0.810279 | 0.805775      | 0.808855    |

Voltage has reached the power supply requirements if we only consider the Actual Voltage. But the difference is not fully demonstrated by the actual voltage. So we also need to discuss the difference by Voltage Margin.

(2) The effect of Temperature on Voltage Margin

Table 2. Lists the Voltage Margin in the experiment.

Table 2. Voltage Margin of E, ET_without Fan, ET_with Fan (unit: V)

| Name                        | E           | ET_withoutFan | ET_withFan |
|-----------------------------|-------------|---------------|------------|
| SINK_U29_2P5V_GND           | 0.105734    | 0.103667      | 0.104233   |
| SINK_U19_2P5V_GND           | 0.10617     | 0.104184      | 0.104674   |
| SINK_U29_S5GX_VCC_GND       | 0.0027792   | -0.0017251    | 0.00135501 |

The above table shows: the results that we only consider the circuit is better than the actual Voltage Margin. Although the effect of temperature on DC power supply is less than 5mV in the PCB-level Electro thermal Coupling Analysis, this value is sufficient to influence the judgment of whether the power supply system design meets the threshold requirements. The power supply performance of the system will be overestimated without the electro thermal coupling analysis.

(3) The effect of Temperature on Current Density

The current density on PCB mainly includes Current density of plane and Current density of via.

1) Current density of plane

According to the experimental analysis, we can find that the maximum current density is located on the S5GX_VCC (0.85mV) power supply of U2. Table 3. Shows the data results of plane current density. And Fig.5~Fig.8 shows the distribution of Current Density.

Table 3. Current density of plane (unit: A/mm2)

| Net Name | Start Layer | End Layer | E     | ET(without Fan) | ET(with Fan) |
|----------|-------------|-----------|-------|-----------------|--------------|
| S5GX_VCC | Plane$L18_PWR4 | Signal$ BOTTOM | 233.6299 | 248.2353 | 237.9395 |
Fig. 5 S5GX_VCC (0.85mV) of U2

Fig. 6 E

Fig. 7 ET (without Fan)
We can see from the above analysis: the result of electrical analysis without electro thermal coupling analysis is "The maximum current density is 233.6299A/mm²". Because it does not exceed the threshold experience value, it is likely to come to a wrong conclusion "current density design is qualified". The results of ET (without Fan) is "The maximum current density is 248.2353A/mm²", which is more than 240A/mm². So the design is not qualified. The result of ET (with Fan) is 237.9395A/mm², which is qualified.

2) Current density of via

In general, the current density of via is 20% greater than the current density of plane in the same case. The results of ET (without Fan) is 299.9253A/mm², which is more than 288A/mm². So the design is not qualified. The result of ET (with Fan) is 287.9061A/mm², which is qualified.

2.2.2. The effect of Electric circuit on Thermal circuit. (1) The effect of Route on Temperature Distribution

Material of PCB is composed of FR-4 and copper, the route will affect the temperature distribution of system.

![Fig.8 ET (with Fan)](image-url)
Fig. 9 Route distribution of PCB

Fig. 10 Temperature distribution

Fig. 9 shows that the route on the top of the chip is sparse. So the heat transfer is poor with less wiring and low copper coverage. Fig. 10 shows that the temperature on the top is higher.

(2) The effect of Joule heat on Temperature Distribution

The Joule heat generated by the current can affect the thermal conductivity of the material, which in turn affects the thermal distribution of the system and the design of the power supply.

Table 5 shows the data results and Fig. 11 shows the distribution of temperature. We can see that the effect of Joule heat is 1.41 °C.

| Table 5. Temperature change (unit: °C) |
|--------------------------------------|
| Thermal analysis | Electro thermal analysis | Effect of Joule heat |
| The maximum temperature | 95.42 | 96.81 | +1.41 |

Fig. 11 Devince temperature of Thermal coupling analysis

Fig. 12 Devince temperature of Electro thermal analysis

Summary

This paper analyzes the effect of temperature on supply voltage, voltage margin, and current density. By comparing the results of electrical analysis and electro thermal coupling analysis, we can see that the result with electro thermal coupling analysis is worse than the electrical analysis. The result of
effect of Electric circuit on Thermal circuit is similar. Therefore, if we do not consider the electro thermal coupling, we will make a wrong judgment on the system's power supply performance. And the result also fully illustrates the necessity of electro thermal coupling analysis.

References

[1] Bar-Cohen A, Srivastava A, Shi B. Thermo-electrical co-design of three-dimensional integrated circuits: Challenges and opportunities [J]. Computational Thermal Sciences, 2013, 5(6): 441-458.

[2] Shang Q, Li X, Mao J. Transient thermal analysis of global interconnects based on transmission lines [A]. In 2012 Asia-Pacific Symposium on Electromagnetic Compatibility (APEC) [C]. 2012: 245-248.

[3] Shao Y, Li X C, Mao J F. An electrothermal model of interconnects based on a transmissionline network [A]. In Microwave Conference Proceedings[C]. 2012: 1247-1276.

[4] Lu T, Jin J M. Electrical-Thermal Co-Simulation for DC IR-Drop Analysis of Large-Scale Power Delivery [J]. IEEE Transactions on Components Packaging & Manufacturing Technology, 2014, 4(2): 323-331.

[5] R ocas E, Collado C, Orloff N D, etc. Passive Intermodulation Due to Self-Heating in Printed Transmission Lines [J]. IEEE Transactions on Microwave Theory & Techniques, 2011, 59(2): 311-322.