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3D Current Path in Stacked Devices: Metrics and Challenges

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Abstract- Although magnetic current imaging (MCI) is useful in fault isolation of devices with 2D current distributions, MCI alone cannot give the exact information of current paths in complex 3D stacked devices. Previous work has demonstrated the ability of a simulation approach to find a short circuit in 3D geometry. This approach has been challenged in the case of dense and complex 3D current paths. In this paper, the aim is to demonstrate how we can overcome this issue by using a new simulation approach instead of the previous segment by segment approach. The new approach has been validated on a complex chip with daisy chains vertically connected by vias. From the study of the simulation of three hypothesized current paths of various current lines of interest, excluding and including the interactions with neighbouring current lines (both locally and globally), it was found that interactions of a current line with its global neighbours have very important effects, compared to no interactions or only interactions with local neighbours. By simulating all the currents, it was possible to minimize the error given by the presence of several current lines in a small volume.

I. INTRODUCTION

In order to meet today's demands for devices with high speed and performance, and multiple functions at reduced cost and power consumption, three-dimensional (3D) multi-die/package stacked technology, a method of stacking dice or packages in a vertical manner (in the z direction), is being developed. In 3D multi-die/package stacked technology, stacked dice or packages can be interconnected by wirebonds, flip chip or through silicon vias (TSVs) [1].

Although 3D technology is promising, the ability to accurately detect or localize failures is a challenge, especially with the miniaturization, complexity and density of such devices. With line dimensions approaching $10\ \mu\text{m}$ and the presence of defects that could be in the nm range or non-visible, traditional failure analysis (FA) techniques such as 2D x-ray imaging, scanning acoustic microscopy (SAM), infrared (IR) thermography, or liquid crystal are reaching their limitations in detecting and localizing shorts and leakages buried beneath the multiple layers of metal, flip chip or System in Package (SiP) devices. Additionally, for FA applications, it is sometimes important to determine the root cause of failures without destroying or altering the failure itself. However, some physical FA techniques such as chemical or laser decapsulation and physical deprocessing are destructive [2, 3].

Several non-destructive techniques are able to overcome

some of the issues described above and are of increasing interest in the research. They are magnetic microscopy, 3D X-ray computed tomography (CT), time domain reflectometry (TDR), thermal imaging etc. [4].

II. MAGNETIC MICROSCOPY

Magnetic microscopy is a non-destructive technique for failure analysis and fault isolation. A magnetic microscope is shown in Fig. 1. When a current flows through a wire, magnetic fields are generated and the relationship between the magnetic field and the current is given by the Biot-Savart Law, as shown in Eq. 1 [3]:

$$d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{d\vec{l} \times \vec{r}}{r^3} \quad (1)$$

where B is the magnetic induction, $I dl$ is an element of the current, μ_0 is the permeability of free space, and r is the distance between the current and the sensor.

Fig. 1: Magma C20 magnetic microscope

A. Magnetic Current Imaging

From the magnetic field image, a direct and an inverse Fourier transform have to be applied in order to obtain a current density image. This is known as magnetic current imaging (MCI).

For the case of studying 3D stacked devices, the sensor chosen was the superconducting quantum interference device (SQUID), as the SQUID is very sensitive and can measure magnetic fields as low as $10^{-15}\ \text{T}$ [3], which is critical in order to obtain a good z resolution, especially for deep buried weak currents that are far away from the sensor [5].

B. The simulation approach

A simulation approach [5-8] has been used in complementary with MCI for failure localization in integrated circuits (ICs) and 3D devices. This approach uses an iterative algorithm; the current path is built segment by segment. Each segment's position is determined according to the best correlation between the z component of the magnetic field generated by the simulation and that of the field measured in a x - y plane. Fig. 2 summarizes the simulation approach.

Fig.2: Correlation calculation for (a) one line with reconstruction line by line and (b) layer by layer, starting from the bottom to the top layer [6]

In Fig. 2(a), the correlation is evaluated between the measurement of the magnetic field in a x - y plane parallel to the sample and the simulation of the field generated by a series of hypotheses of the current location on the same plane. The correlation has a maximum when the simulated line coincides precisely with the real current. Fig. 2(b) shows how the correlation value evolves when adding layer by layer all the single currents to the simulation model. On every layer of a 3D sample, the presence of different current lines was simulated until the best correlation value was found.

This approach has been proven to be very useful for a number of cases. It is however being challenged in the case of dense and complex 3D stacked devices with high density current distributions, whereby evaluation of a current line independently from the rest of the current lines is insufficient.

In this paper, the objective is to demonstrate how a new simulation approach can overcome the limitations of the previous approach and added to MCI to help determine the 3D current path flow in a dense and complex stacked device with

vertical connections by vias.

III. THEORETICAL STUDY

In the simulation approach, for each segment, the position given by a good correlation can be biased by the presence of multiple sources of magnetic field.

For instance, an infinite line with a current I , parallel to the x axis and at the position $z=h$ and $y=d$ can be considered (as shown in Fig. 3).

Fig. 3: Current position diagram

The z component of the magnetic field generated by this line in a constant z plane is calculated from the Biot-Savart law:

$$B_z(x, y, z) = \frac{\mu_0 I}{2\pi} \frac{(y-d)}{(y-d)^2 + (z+h)^2} \quad (2)$$

where z is the distance between the magnetic sensor and the x - y plane where the line lies. Without any other contributors, the exact position of the line can be found by the simulation approach.

Using a normalized form B_{Nz} :

$$B_{Nz}(x, y, z) = \frac{B_z(x, y, z)}{\frac{\mu_0 I}{2\pi}} = \frac{(y-d)}{(y-d)^2 + (z+h)^2} \quad (3)$$

and normalizing the variables by z as follows:

$$X = \frac{x}{z}, Y = \frac{y}{z}, H = \frac{h}{z}, D = \frac{d}{z}, Z = \frac{z}{z} = 1 \quad (4)$$

Eq. 5 is obtained, which is a normalized form of the expression of the magnetic field of Eq. 3 divided by z , where everything is now expressed in terms of the working distance z :

$$B_N(X, Y, 1) = \frac{(Y-D)}{(Y-D)^2 + (1+H)^2} \quad (5)$$

When there are two contributors, B_{N1} and B_{N2} , the highest correlation will take both into account. The solution with the highest correlation, B_{N0} , can be computed with the Generalized Reduced Gradient method [9]. In the case of currents flowing in the same direction, the solution is given by the minimization of the following function:

$$\int_{-\infty}^{+\infty} |(B_{N1} + B_{N2})^2 - B_{N0}^2| dY \quad (6)$$

For example, for two contributors at $D_1=0$, $H_1=1$ and $D_2=1$, $H_2=0$, respectively, the highest correlation is at $H=-0.21$ and $D=0.81$. From this result, it is clear that close lines have strong interactions.

To illustrate this, two other different configurations have been studied, as shown in Fig. 4(a) and 4(b).

Fig. 4: (a) B_N for a current line at $D=-1, H=1$ and (b) B_N for two current lines at $D_1=1, H_1=1$ and $D_2=-1, H_2=1$

With the two lines at $D_1=1, H_1=1$ and $D_2=-1, H_2=1$ respectively, Eq. 6 will have a minimum on the position of both lines (expected result). However, with two lines at $D_1=2, H_1=1$ and $D_2=-2, H_2=1$, respectively, Eq. 6 will have a minimum on a third “ghost line” at $D=0, H=0$. On a real case study, this line could correspond to a real copper trace, and the current localization could be wrong.

This theoretical approach clearly demonstrates the importance of taking into consideration the interactions of a current line of interest with the neighbouring current lines.

IV. EXPERIMENTAL DETAILS AND MCI RESULTS

To illustrate how to overcome the limitations given by the simulation approach, a complex case study is shown here. The Device Under Test (DUT) is a chip with two bonded wafers connected vertically to form daisy chains on two planes (i.e. top and bottom planes). MCI was carried out on the daisy chain area terminating at pins 5 and 6, circled in red in Fig. 5. A schematic of the test structure is shown in Fig 6.

Fig. 5: Device Under Test

Fig. 6: Schematic of test structure with high density current distributions

Fig. 7(a) shows the resulting MCI image overlaid onto the optical image. From Fig. 7(a), the current distribution can be observed. However, it is not possible to tell where exactly the currents are flowing; more precisely, from this image, it is impossible to determine on which of the two layers each current segment is flowing.

In order to understand the flow of the current path, simulation was performed on the optical image superimposed with a 2D x-ray image of the same area. Simulation of three hypothesized current paths (Fig. 7(b)-(d)) of various current lines of interest excluding and including the interactions with neighbouring current lines (both locally and globally), was carried out with the assumption of the top plane at $z=0 \mu\text{m}$, and the bottom plane at $z=-150 \mu\text{m}$.

From the test structure, the MCI image and the superimposed optical and x-ray image, it was deduced that the correct current path should be the one as hypothesized in current path 1.

(a)

(b)

(c)

(d)

Fig. 7: (a) Resulting MCI image superimposed onto the optical image; hypothesized current paths (b) 1, (c) 2 and (d) 3

V. RESULTS FROM THE NEW SIMULATION APPROACH

A. Simulation excluding interactions with neighbouring current lines

Table 1 shows the simulation results of current lines excluding interactions with neighbouring current lines.

Table 1: Simulation results of current lines excluding interactions with neighbouring current lines. The highlighted boxes show the highest average correlation values.

Current line of interest	Hypothesized Current Path 1	Hypothesized Current Path 2	Hypothesized Current Path 3
	Average Correlation Value	Average Correlation Value	Average Correlation Value
1	0.258	0.284	0.269
2	0.0592	0.0492	0.149
3	0.0915	0.0805	0.101
4	0.0149	0.00314	0.0601
5	0.0673	0.0544	0.0531
6	0.00913	0.00263	0.00637
7	0.00735	0.0123	0.0628

From the results in Table 1, it was not possible to conclude which is the correct current path flow in the device. In most cases, in fact, the highest correlation is obtained for the wrong current path hypothesis.

B. Simulation including local interactions with neighbouring current lines

Since it was not possible to determine the correct current path with the approach excluding interactions with neighbouring current lines, simulation of each current line of interest including interactions with local neighbouring current lines was carried out, as shown in Fig. 8. The results of the simulation are shown in Table 2.

Fig. 8: Local interactions of a current line of interest and its neighbours with hypothesized current paths (a) 1, (b) 2 and (c) 3

Table 2: Simulation results of current lines including local interactions with neighbouring current lines. The highlighted boxes show the highest average correlation values.

Current line of interest	Hypothesized Current Path 1	Hypothesized Current Path 2	Hypothesized Current Path 3
	Average Correlation Value	Average Correlation Value	Average Correlation Value
2	0.223	0.0316	0.222
3	0.0425	0.0751	0.0150
4	0.119	0.0417	0.118
5	0.0766	0.0651	0.0560
6	0.0673	0.0194	0.0738

The simulation approach including local interactions with neighbouring current lines still did not provide a conclusive result. Hence, simulation including global interactions with neighbouring current lines was carried out.

C. Simulation including global interactions with neighbouring current lines

Fig. 9 shows the interactions of a current line of interest with its global neighbours and Table 3 summarizes the results of the simulation.

(c)

Fig. 9: Global interactions of a current line of interest and its neighbours with hypothesized current paths (a) 1, (b) 2 and (c) 3

Table 3: Simulation results of current lines including global interactions with neighbouring current lines. The highlighted boxes show the highest average correlation values.

Current line of interest	Hypothesized Current Path 1	Hypothesized Current Path 2	Hypothesized Current Path 3
	Average Correlation Value	Average Correlation Value	Average Correlation Value
2	0.243	0.0606	0.228
3	0.234	0.173	0.214
4	0.248	0.101	0.228
5	0.236	0.154	0.203
6	0.244	0.103	0.243

From the simulation including global interactions with neighbouring current lines, it was verified that the hypothesized current path with the highest correlation value (i.e. current path 1) corresponds to the real current path in the chip. The interactions of a current line with its global neighbours have very important effects, compared to no interactions or only interactions with local neighbours.

VI. CONCLUSION

In this paper, a new simulation approach of three hypothesized current paths of various current lines of interest, excluding and including the interactions with neighbouring current lines (both locally and globally), have been studied on a complex chip with daisy chains vertically connected by vias.

With the new simulation approach, it is possible to tell where the current is flowing from the top plane to the bottom plane in such dense and complex 3D devices. The use of the new simulation approach has also enabled the determination of the exact current path flow in dense and complex 3D stacked devices with vertical connections, where the information from MCI alone is insufficient, and the previous simulation approach was biased by the presence of a high number of current

distributions.

VII. PERSPECTIVES

Future work can include the automation of the new simulation approach, reduction in the time taken to generate the simulation results and improvement on the accuracy.

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