

# Direct Depth Measurement Tool of High Aspect Ratio Via-Hole for Three-Dimensional Stacked Devices

Makoto Nakamura,\* Hideki Kitada and Seiki Sakuyama  
Device & Materials Laboratories, Fujitsu Laboratories Ltd.,  
10-1 Morinosato-Wakamiya, Atsugi 243-0197, Japan  
\*marumakan@jp.fujitsu.com

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The three-dimensional stacking technology of heterogeneous devices is one of the most effective methods to realize high-performance devices without scaling down. The through-silicon via interconnect process is the most commonly for that purpose. The technology that measures the depth of the high aspect via hole with high accuracy is indispensable for metal contamination-free via-middle processes. Displacement measurements from the surface using interference spectra are more accurate compared with measurement from the back side. However, because such a system is not presently available, we decided to build one for trial purposes. As a result, we successfully build a system that was able to directly measure a high aspect via hole (diameter: 3.3  $\mu\text{m}$ ; aspect ratio: 15) by using a spectrum interferometer. We believe that this technology can use in the production of next-generation 3D devices for supercomputer.

## 1. Introduction

We are presently developing fundamental technologies to realize an exa ( $10^{18}$  flops) scale supercomputer system, the so-called “post K computer”. The operational speed of the new system will be 100 times or faster than the K computer. For that purpose, three-dimensional (3D) stacked devices are essential.

A 3D device has the following advantages [1] ; (1) small foot-print; (2) multi-functionality (multiple device integration); (3) high data transfer rate; (4) low power consumption because of short wiring; (5) high performance without scaling down (capital investment decreases following micro fabrication). 3D devices are used in high-end servers as well as consumer products, such as cellular phones.

The through-silicon via (TSV) fabrication process is used to make 3D stacked devices. The TSV is an electrode that penetrates through the surface and the back of the device chip. In general, there are four types of TSV fabrication processes (Fig. 1). The differences among the four types have to do with the timing of the TSV fabrication. We plan to adopt the via-middle process. Furthermore, accurate measurement methods of high aspect ratio vias are indispensable in the manufacturing of new

devices. For, such methods prevent copper contamination from the TSV electrode and protect the transistors from failing owing to contamination.

## 2. Nondestructive depth measurements

Nondestructive technologies that measure the depth of deep via are indispensable to evaluate the reactive ion etching process. Because the probability of the copper contamination grows according to the dispersion of hole depth.

Systems that measure via depths are already in the market. Such systems indirectly estimate via depths by measuring the silicon thickness from the infrared (IR) interference pattern coming from the back. [2] It is impossible to measure the via depth with high accuracy because the refractive index of silicon wafers is not constant. The refractive index of silicon changes owing to amount, type and distribution of impurities, in the silicon wafer. In this method, the difference in the refractive index becomes the measurement error. In addition, when films exist on the back, even the position of the hole might not be recognized using IR cameras. Moreover, confocal scanning laser microscopy is unsuitable, because the probe light does not reach the bottom with

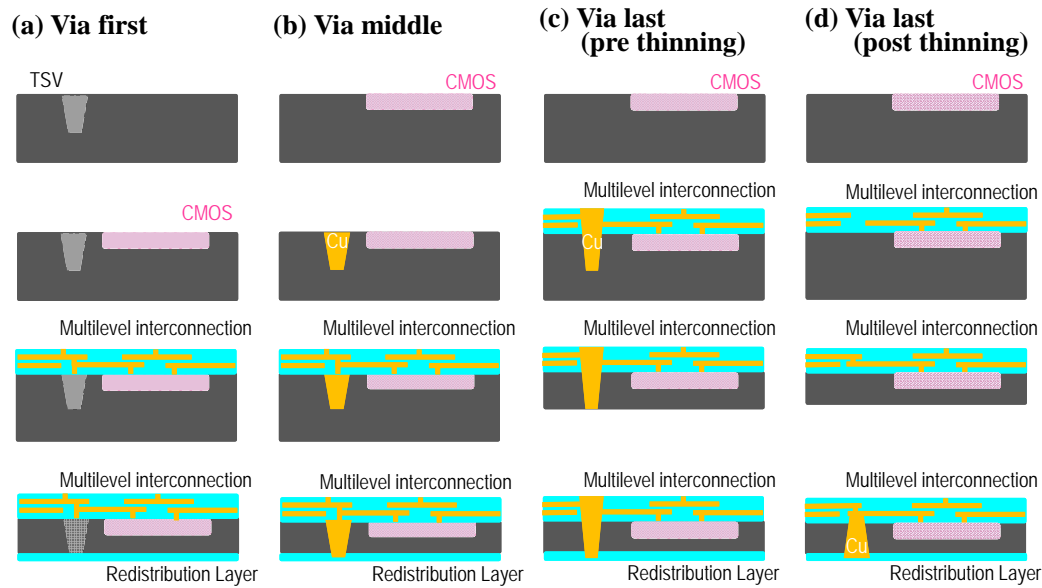


Fig. 1 Comparison of four types of TSV manufacturing processes. Only (a) via first process cannot use copper for the electrode material because the high temperature process for activation is necessary.

Table 1 Comparison of depth measurement methods for high aspect ratio hole.

	<b>Interference from surface</b>	<b>Interference from back</b>	<b>Confocal laser microscope</b>
<b>Accuracy</b>	Excellent	Decent	Decent
<b>Speed</b>	High	High	Low
<b>Structure dependence</b>	No influence	Influence	No influence
<b>High aspect hole</b>	Possible	Possible	Impossible
<b>Fine alignment</b>	Necessity	Unnecessary	Unnecessary
<b>3D map</b>	Impossible	Impossible	Possible
<b>Warping</b>	Possible	Impossible	Possible
<b>Completion rate</b>	Proto type	Available	Available
<b>Judgment</b>	<b>Suitable</b>	<b>Insufficiency</b>	<b>Unsuitable</b>

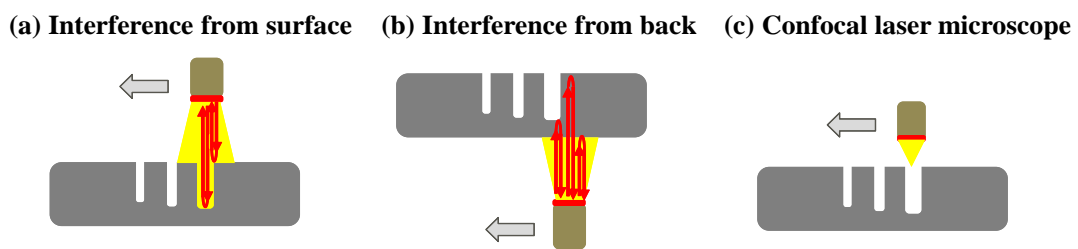


Fig. 2 Comparison of depth measurement methods for high aspect ratio hole.

enough intensity because the convergent angle is large and the reflected light from the bottom is extremely weak.

We tried to directly measure the via depth using an optical interferometry displacement sensor using near infrared light. Only the refractive index of the air, which is always constant, affects the measurements. Even though, the sample structure does not affect the measurements,

the optical axis and the axis of via hole had to be adjusted.

Table 1 and Fig. 2 show the features of several nondestructive technologies that measure the depth of holes.

### 3. Experiments

Our goal is to establish nondestructive method for measuring the depth of high-aspect ratio holes whose

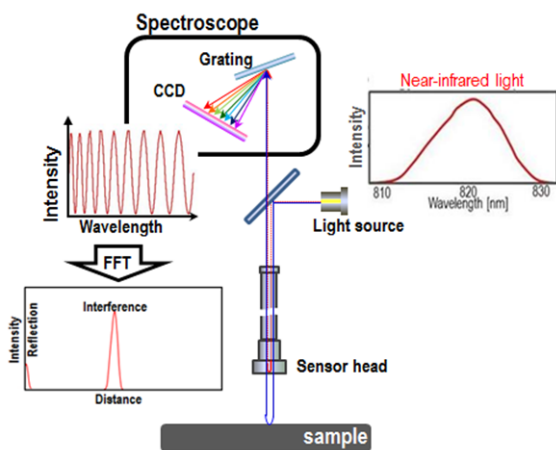


Fig. 3 Measurement principle of displacement sensor used to experiment.

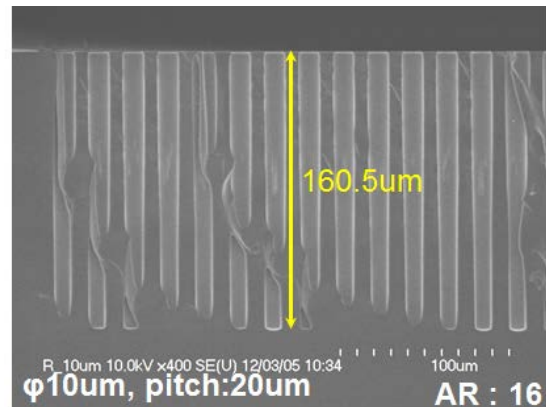
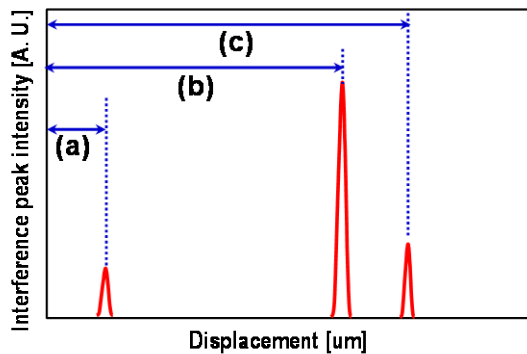


Fig. 4 SEM image of the sample cross section.

(1) Measured spectrum



(2) Origin of spectrum

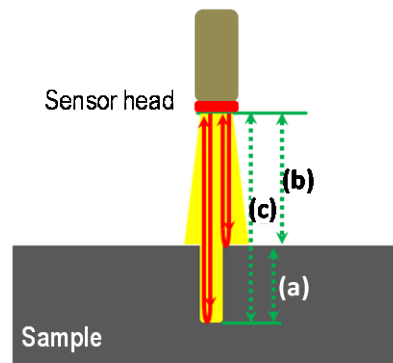


Fig. 5 Example of spectrum actually measured and origin of each peak. (a) Interference peak of light from via bottom and surface, (b) Interference peak of light from sensor head and surface, (c) Interference peak of light from sensor head and via bottom.

diameters and aspect ratios are 5  $\mu\text{m}$  or less and 10 or more, respectively, and then return the sample to the production line. As for the accuracy of the measurement, the plus or minus 0.5  $\mu\text{m}$  or less are needed. We have tried a system with sensor head attached to an optical microscope (OM) with a linear stage that automatically moves to a previously specified location with the OM and measure the via depth. The offset of the sensor and the microscope is known beforehand.

We used a market-available displacement sensor to measure the distance between the sample and the sensor. The distance is measured by the Fourier transform of the interference spectrum of the reflected light from the sample to the sensor head. The measurement principle of displacement sensor used in this experiments is shown in Fig. 3. The depth measurement resolution of this sensor is 0.01  $\mu\text{m}$ , and the measurement value is corrected by

using block gauge.

This was the first time that this sensor was used to measure the depth of hole. Fig. 4 shows scanning electron microscope (SEM) image of the cross section of the sample used in the experiments. It is thought that the cross-section SEM measurement is only reference value because the measurement accuracy is insufficient ; (1) the vertically incident of the probe is unwarrantable, (2) the working distance is not made constant easily, (3) the sample making in a specific cross-section is difficult.

In the measurements, the signal from the bottom of hole and the surface are measured simultaneously because probe diameter is enough large compared with the hole diameter (40  $\mu\text{m}$ ). Therefore, three peaks appear as shown in Fig. 5 (1) when the area of the via is measured. The origin of these peaks is attributed to (a) the interference peak reflected light from the surface and the bottom

of the via, (b) the interference of the reflected light from the sensor and the surface, (c) the interference of the reflected light from the sensor and the bottom of the via. (Fig. 5 (2)) The left peak is relatively weak even though it directly measures the via depth compared with the other peaks. We decided to measure the depth of the hole from the difference between the peak at the center and the right peak.

#### 4. Results

We tried to measure the depth of vias of different diameters and depths. We faced the problem that the reflected light from the bottom of the hole was not detectable in diameters smaller than 7  $\mu\text{m}$ . The intensity of the reflected light generally decreases because the flat area in the bottom of the hole decreases when the diameter decreases. When vias of small diameter and high aspect ratio are to be measured, the center axis of the hole and the optical axis of the probe have to be accurately aligned. Because the reflected light from the bottom of the hole does not reach the sensor and the probe light does not reach the bottom of the hole if both axes are out of alignment.

We improved the alignment mechanism to measure the depth of the vias with small diameters and high aspect ratios. Fig. 6 shows the results of this effort. Fig. 6(a) shows the via depth with respect to diameter and Fig.

6(b) shows the aspect ratio with respect to diameter.

We were able to measure vias of small diameter and high aspect ratio with the trial system. For a 3.3  $\mu\text{m}$  diameter, the measured aspect ratio was 15. For a 3.2  $\mu\text{m}$  diameter, the measured aspect ratio was at least 11.

#### 5. Discussion

Clearly high-accuracy alignment is critical when measuring the depth of minute vias with high aspect ratio. This can be inferred from the SEM image of the sample cross section.

The depth measurements of small diameter vias become possible using more parallel probe light. Because, sufficient light will reach the hole bottom and then reflect back to the sensor.

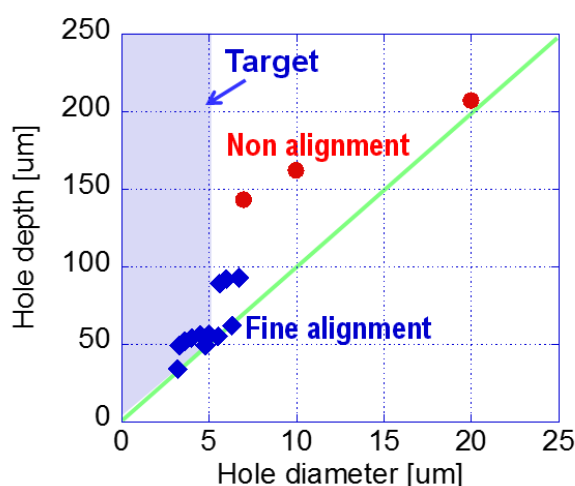
We successfully measured the depth of deep vias using this system. The only variables are the light wavelength and the refraction index of air. The measurements don't depend on the sample structure.

We did not clarify whether the measurements limits are the via diameter, the aspect ratio, or the area of the flat region in the via bottom. This is something that we plan to do in the future.

#### 6. Summary

A highly accurate hole depth measuring system for next generation 3D devices was developed. Vias with

(a) Hole depth vs hole diameter.



(b) Aspect ratio vs hole diameter.

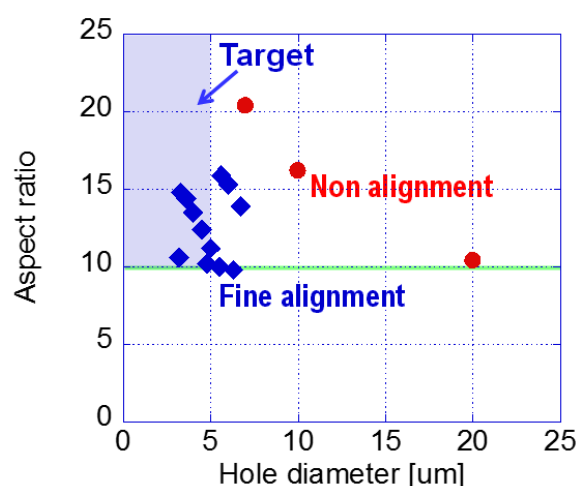


Fig. 6 Result of actually measuring hole with different diameter. Our targets of this study is to establish nondestructive method for measuring the depth of high-aspect ratio holes whose diameters and aspect ratios are 5  $\mu\text{m}$  or less and 10 or more, respectively. "Non alignment" shows the result of the measurement after the sensor is installed. "Fine alignment" shows the measurement result after it adjusts it by using the mechanism that adjusts the axis of tilt of the sensor. Here, the straight line is a borderline where aspect ratio 10 is shown.

small diameters and high aspect ratios could be measured using this system.

The system has the following features: (1) highly accuracy and repeatability; (2) it is fast and simple, no model is required; and (3) it is not sample dependent. Thus, we have successfully accelerated the development speed of the 3D stacked device process. Likely, the development of next-generation supercomputers will also improve.

The developed measurement system is applicable to all the TSV processes.

## **7. Acknowledgment**

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## **8. References**

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