Relationship Between Wafer-Level Warpage and Cu Overburden Thickness Controlled by Isotropic Wet Etching for Through Si Vias

Jae Woong Choi, Lee Guan Ong, Hong Yu Li, Soon Wook Kim, Gil Ho Hwang, Steven Lee Hou Jang, Ramana Murthy, and Eugene Tan Swee Kiat

***Abstract*— In this paper, we developed an isotropic wet etching process in a capsule-type bevel etch chamber to reduce a Cu overburden of through Si via (TSV) for less wafer-level warpage with 300 mm wafers. We report the relationship between the wafer-level warpage and the Cu overburden thicknesses controlled by the isotropic wet etching with diluted solution of hydrogen peroxide and sulfuric acid, which is widely used for Cu wet etching. After Cu filling by electroplating, there are humps at the top of the TSVs; therefore, the isotropic wet etching can be considered as a solution to etch away the Cu overburden without any damages on the TSVs. We modified the capsule-type bevel etch chamber to avoid serious attack on TSVs at the center area of the wafer caused by the etchant delivery path. We also adjusted the process parameters to have a controllable Cu etch rate. The etch rate of ∼0.2 μm/s and the uniformity of ∼3% were achieved. The overburden was able to be etched up to 3 μm from the initial Cu overburden. While the Cu overburden decreased during the isotropic wet etching, the TSVs were protected from the etchant because of the humps at the top of the TSVs. After the Cu electroplating, there was a grain size difference between the Cu at TSV and the Cu at field area. Because the microstructural difference caused a galvanic corrosion during the wet etching, the etch rate of the adjacent Cu around TSV was faster than the Cu at any other area. That resulted in exposure of dielectric layer at the adjacent area around TSVs when the Cu overburden was etched heavily. It may be another protection mechanism of TSV during the isotropic wet etching. The wafer-level warpage of the wafer with the Cu overburden etched up to 3 μm after the annealing decreased by 50% from that of the wafer with the initial Cu overburden. The wafer-level warpage exhibited a linear relationship with the Cu overburden thickness controlled by the isotropic wet etching.**

***Index Terms*— Cu filling, Cu overburden, galvanic corrosion, isotropic wet etch, microstructure of Cu, through Si via (TSV), wafer warpage, wafer-level packaging.**

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I. Introduction

THROUGH Si via (TSV) has been widely used for 3-D integrated circuit packaging and 2.5-D interposer applications [1]–[3]. A typical TSV process consists of Si via etching, dielectric deposition for insulation, Cu seed layer deposition, Cu electroplating for via filling, annealing and chemical–mechanical polish (CMP) process, as shown in Fig. 1. There is a surplus Cu electroplated at the field area during TSV Cu filling process, called Cu overburden, as shown in Fig. 1, and Cu CMP for removing the Cu overburden is following the annealing.

The Cu overburden is, however, a major contributor to wafer stress causing warpage after annealing, as shown in Fig. 2, and it is also a burden to CMP [4]–[6]. With the published data, consumable cost for Cu overburden removal can be reduced by 70% if the overburden thickness decreases from 6.2 to 0.6 μm [7].

The thick Cu overburden will not only affect overall throughput but cause failures because of the serious warpage. A well-optimized TSV Cu filling process by electroplating such as a bottom–up filling can maintain the Cu overburden thickness of ∼4 μm for the TSV dimension of 10 × 100 μm excluding Cu seed layer. Even the optimized Cu overburden, however, causes a serious wafer warpage of ∼300 μm that will not be acceptable. In addition, because the Cu overburden thickness depends on the TSV dimensions, it can be much thicker for bigger dimensions of TSV applications such as a heat sink application, as shown in Fig. 3.

Mayer *et al.* [8] applied for a patent about an isotropic wet etching method to control the Cu overburden for damascene and TSV applications. This method is using an isotropic wet chemical solution provided by plural spray sources to remove the Cu overburden. This isotropic wet etching chemical solution contains main etchant and additives such as complexing agent, oxidizer, and pH adjustor.

The isotropic wet etching method to etch away Cu overburden was suggested to have CMP-less process for mechanically weak low-K dielectric materials. Even though the method with the specially designed etchant including complicated agents can achieve uniform Cu overburden removal without attacking on TSVs, it cannot eliminate a subsequent CMP process because of the Cu protrusion which is caused by a thermal

Fig. 1. Conventional TSV integration procedure. (a) Si etch. (b) Dielectric/Cu BS deposition. (c) TSV Cu filling. (d) Annealing/CMP.

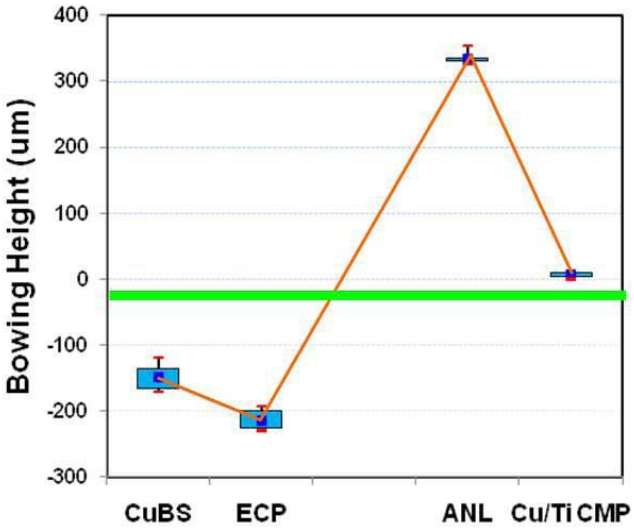

Fig. 2. Wafer warpage evolution of a wafer with TSVs of 10 × 100 μm in process procedure.

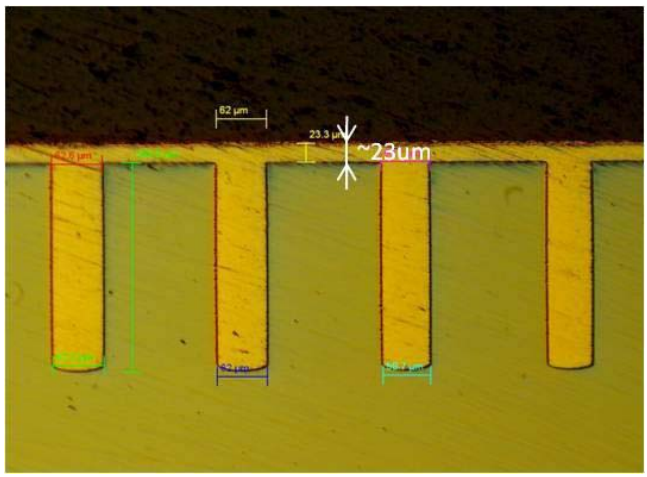

Fig. 3. Thick Cu overburden for heat sink application (60 × 250 μm).

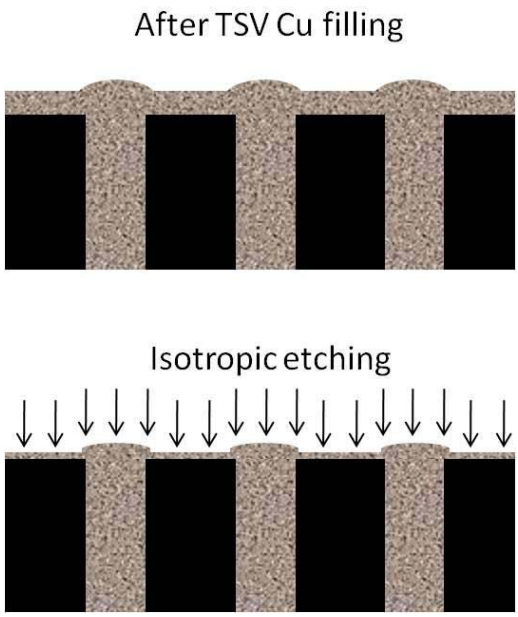

Fig. 4. Isotropic wet etching approach to reduce Cu overburden after TSV Cu filling.

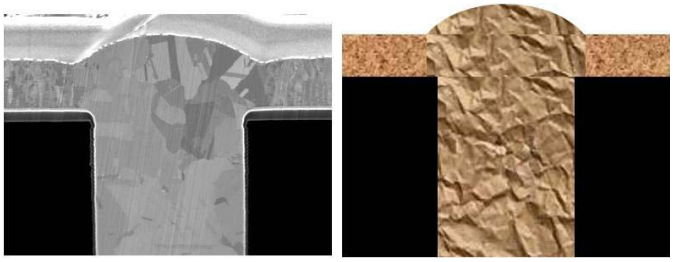

Fig. 5. Microstructural difference between the Cu (coarser grain) at TSV and the Cu (finer grain) at field area.

stress because of a high mismatch of thermal expansion coefficient (CTE) between Si and Cu during annealing [10]–[12]. It means that CMP must be needed to polish away those Cu protrusions.

In this paper, we suggest a simple isotropic wet etching method using a diluted solution of hydrogen peroxide (H_2O_2) and sulfuric acid (H_2SO_4) (dSPM), which is widely used for bevel etching after TSV and Damascene Cu electroplating. The reason that we suggest the simple isotropic wet etching method is that there is a height difference between the top of TSVs and the Cu overburden at the field area as shown in Fig. 4. Although the isotropic wet etching chemical can etch every Cu electroplated without selectivity, TSVs will not be damaged during the isotropic wet etching because of the humps. Another reason that we suggest this method is that there will be an etch rate difference between the Cu at TSVs and the Cu at field area because of the grain size difference as shown in Fig. 5. The finer grained area has higher density of grain boundaries than the coarser grained area and the microstructural difference will make the two regions form a galvanic cell locally under the electrolyte environment. While the finer grained area will act as anode, the coarse grained area will do as cathode. Therefore, the Cu at TSV will be protected during the isotropic wet etching.

In the industry, there are two types of bevel etch methods. One is a capsule chamber type and the other is a

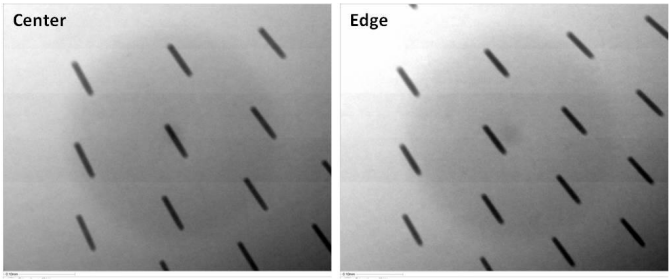

Fig. 6. X-ray inspection results after TSV Cu filling.

Fig. 7. FIB images of a TSV after TSV Cu filling.

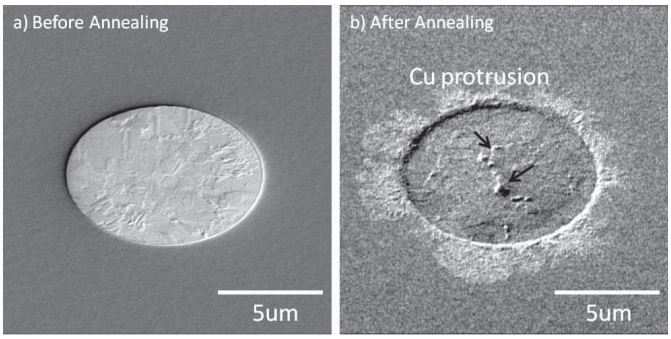

Fig. 8. SEM images of TSV prepared by CMP-first approach. TSV Cu (a) after CMP and (b) after annealing.

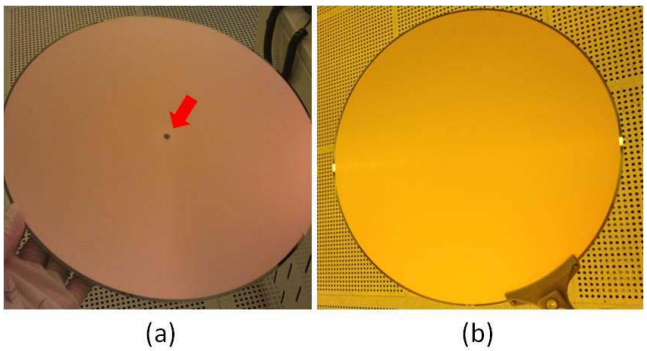

Fig. 9. Wafer center damage because of the dSPM delivery path (a) before modification and (b) after modification.

nozzle spray type. During the bevel etching, the wafer to be etched is placed frontside-up on a stage or in a chamber. The capsule chamber type delivers the wet etching solution (dSPM) to backside of the wafer and the nozzle spray type sprays dSPM to the bevel area directly. In this paper, we used a capsule-type bevel etch chamber for the Cu overburden thickness control after TSV Cu electroplating. We report the Cu overburden etch rate with the dSPM and the relationship between the wafer-level warpage and the Cu overburden thicknesses controlled by the isotropic wet etching.

II. Experimental Procedure

We implemented a process integration procedure of Si etch → dielectric deposition → barrier/seed layer deposition → Cu electroplating. We used 300 mm Si wafers with TSVs of 10:1 aspect ratio and the corresponding pattern density was <1%. TSV Cu electroplating was done on SEMITOOL Raider-S with a membrane separating catholyte and anolyte and the Cu electroplating chemical came from Japan Creation Udylite Corporation as Virgin Make-up Solution for the catholyte and the anolyte, respectively. The Cu electroplating chemical composition including three additives of suppressor, accelerator, and leveler, was maintained to electroplate Cu under the same condition by cyclic voltammetry stripping (ECI QL-10EX) method because different chemical composition may affect the film stress of the Cu overburden. The Cu electroplating was done with a direct current wave form but the current density was ramped up gradually from 1.0 to 3.5 mA/cm^2 to achieve bottom–up filling as quickly as possible. Si etch, liner deposition, and Cu seed layer deposition were done by AMAT Centura Silvia Etch, AMAT Producer Invia CVD, and AMAT Endura CuBS RFX PVD, respectively. The Cu overburden thicknesses and the uniformities were measured by sheet resistance measurement with KLA Tencor Omnimap Rs 300 before and after the isotropic wet etching, respectively, to optimize the isotropic wet etching process. We used a fixed volumetric ratio of dSPM (distilled water: H_2O_2: $H_2SO_4 = 6{:}3{:}1$) to etch away the Cu overburden, but the etch rate of the Cu overburden was not controllable because of the aggressive dSPM. Therefore, we diluted the dSPM *in situ* additionally with distilled water to have a controllable Cu etch rate by controlling the flow rates of the distilled water. After Cu overburden etching, all wafers were annealed at 400 °C for 30 min and the wafer-level warpage for all wafers was measured.

TABLE I
Cu Overburden Thicknesses Before and After Wet Etching and Their Uniformities

	Etch time	After Cu Plating		After Wet Etch		Delta
		Thickness	Unif.	Thickness	Unif.	Thickness
wafer 1	5sec	3.48um	3.50%	2.45um	3.01%	1.03um
wafer 2	10sec	5.81um	2.70%	3.31um	3.05%	2.10um
wafer 3	15sec	6.14um	4.20%	3.04um	3.57%	3.10um

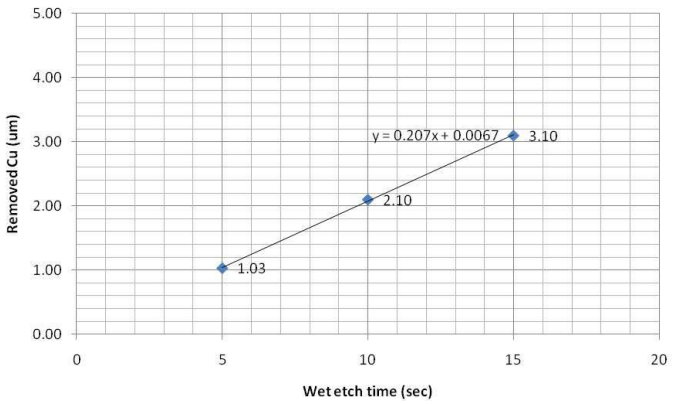

Fig. 10. Cu overburden etch rate with etching time.

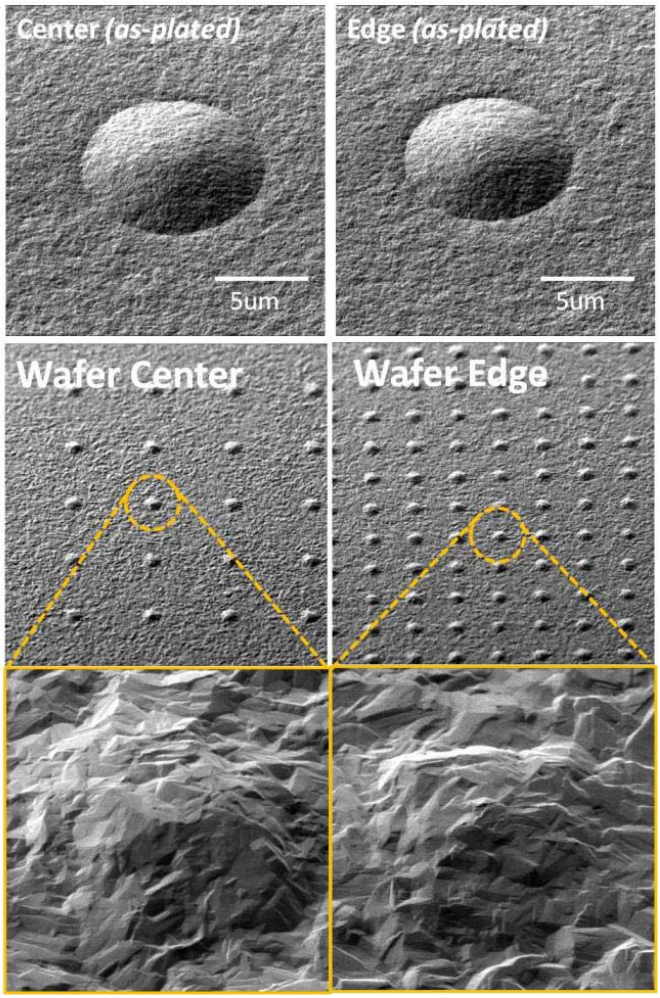

Fig. 11. SEM images of TSV area after isotropic etching to reduce Cu overburden.

III. Results and Discussion

Fig. 6 shows the X-ray inspection results of Cu-filled TSVs by electroplating showing TSVs were fully filled without any voids. Fig. 7 shows the focused ion beam (FIB) images of one of the TSVs after Cu filling and it also shows the TSV fully filled. As shown in Fig. 7, there is the Cu overburden at the field area causing a serious wafer-level warpage issue. It also has Cu hump at the top of the TSV which is thicker than the Cu overburden at the field area, as shown in Fig. 4. Although we adopt the isotropic wet etching to reduce the Cu overburden with dSPM, we can protect the TSVs from the etchant because of the thickness difference between the Cu overburden and the Cu at the TSVs, as explained in the previous session. As shown in Fig. 2, the wafer-level warpage becomes very high after the Cu annealing.

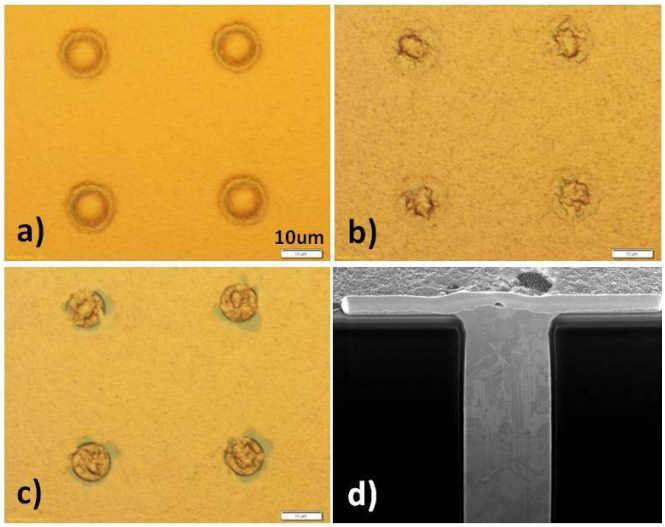

Fig. 12. Optical microscopic images of TSVs. (a) TSV of as-plated. (b) TSV after wet etch of $\Delta 3$ μm. (c) TSV after heavily etched. (d) FIB image of (c).

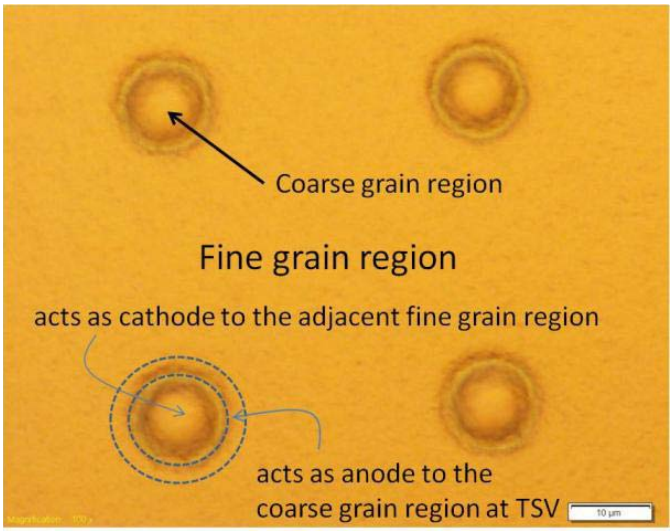

Fig. 13. Galvanic cell formed locally between the coarse grain area of Cu at TSVs and the fine grain area of Cu at field area.

Che *et al.* [9] reported two methods to reduce the wafer-level warpage with 200 mm wafers. The one is CMP-first process to remove all Cu overburden before the annealing. The other is a two step CMP process with a procedure of first CMP—annealing—second CMP. In this two-step CMP approach, the Cu overburden is reduced partially by the first CMP before the annealing then the remaining Cu overburden is fully removed after the annealing.

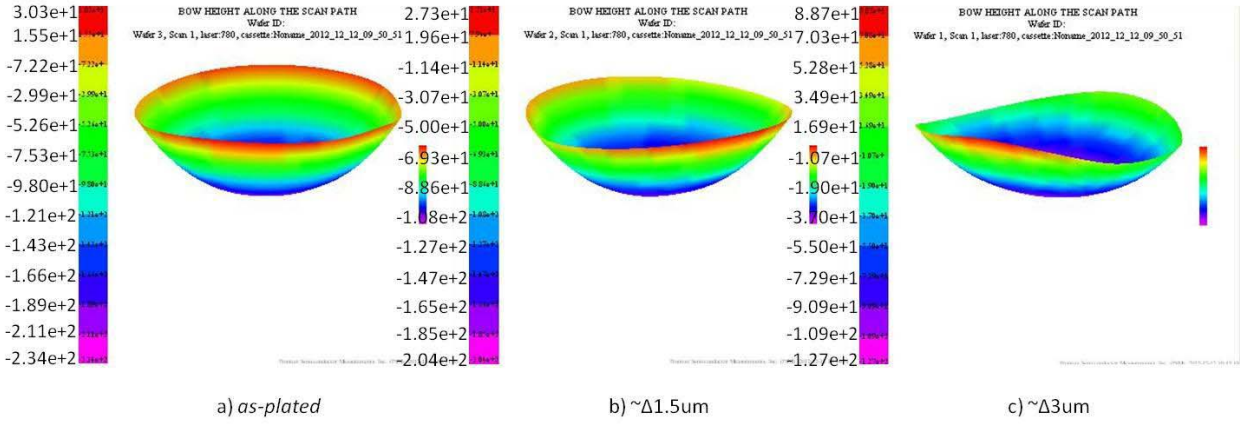

Fig. 14. Diagrams of the wafer-level warpage with the Cu overburden thicknesses controlled by the isotropic wet etching after annealing at 400 °C for 30 min. (a) As-plated. (b) Δ1.5 μm. (c) Δ3 μm.

Although we were able to mitigate the wafer-level warpage using the CMP-first approach before the annealing, we observed Cu protrusions caused by the serious difference in CTE between Si and Cu [10]–[12] as shown in Fig. 8. Therefore, this approach will need another CMP process after the annealing to remove Cu protrusions for the subsequent processes. Although CMP added approaches can reduce the wafer-level warpage, it would not help to reduce the process cost and the burden to CMP, as reported in [7].

When a capsule-type bevel etch chamber is used for a bevel etching, the wafer is placed in the chamber frontside-up and the etchant, dSPM, is delivered from the center of the bottom in the chamber. During the bevel etching, the wafer is rotated in the chamber and dSPM contacts only the bevel area to etch Cu seed layer without the frontside damage. To use the capsule-type bevel etch chamber for the Cu overburden isotropic wet etching, a wafer has to be placed frontside-down in the chamber so that the dSPM can etch Cu overburden.

If we, however, use the capsule-type bevel etch chamber as it is, TSVs at the center area of the wafer is more aggressively etched because of the etchant delivery path as shown in Fig. 9(a). Although the dSPM is diluted much with distilled water, the serious etching on TSVs at the center area of the wafer is not avoidable. Therefore, we modified the dSPM delivery path to protect the TSVs at the center area from the aggressive etchant attack then, the center-focused etching was resolved as shown in Fig. 9(b).

To optimize the Cu overburden etching we prepared the 300 mm blanket Cu wafers with different thicknesses of Cu electroplated. The Cu thicknesses and the uniformities were measured by sheet resistance measurement, as shown in Table I. The remaining Cu overburden thicknesses and their uniformities after the isotropic wet etching were also measured by the same method to calculate the etch rates. We achieved good etch uniformities with controllable etch rates as shown in Fig. 10, by changing the process parameters such as the wafer spinning speed and the period of *in situ* distilled water mixing to dilute the dSPM concentration. The etch rates measured from three different thicknesses of Cu electroplated were ~0.2 μm/s with the uniformity of ~3% at 1σ at 6 mm edge exclusion (EE).

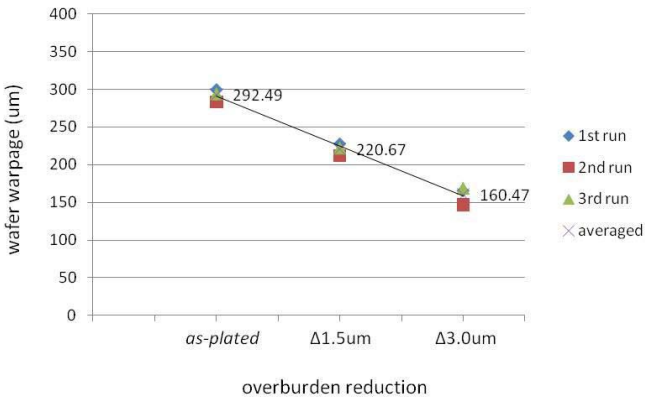

Fig. 15. Wafer-level warpage trend with Cu overburden thickness reduction by wet etching.

Fig. 11 shows the surface images after the isotropic wet etching of Δ3 μm. As shown in Fig. 11, the Cu humps remain higher than the Cu overburden on the field area, as shown in Fig. 4. This means the isotropic wet etching to reduce the Cu overburden does not attack the TSVs because of the Cu humps and hence the TSVs can be protected during the isotropic wet etching.

The Cu remained after the isotropic wet etching was not, however, mirror-like surface because the dSPM did not contain any additives to control the surface roughness during the wet etch process.

As shown in Fig. 12, the optical microscopic images show the surface morphology change with the isotropic etching time. When the Cu overburden was etched heavily, it started to reveal SiO_2 layer below the Cu overburden only at the area surrounding TSVs. As shown in Fig. 12(d), while the Cu overburden including Cu seed layer around TSV was almost etched, the Cu at the TSVs still remained because of the height difference from the initial state. As shown in Fig. 12, although SiO_2 layer is revealed at the area surrounding TSVs, the Cu at the field area far away from TSVs still remains. It means the etching rate of the Cu around TSVs was higher than that of Cu at the field area.

When two different microstructures exist in a layer, it will form a local cell in the wet etching chemical, so-called electrolyte, and the finer grain structure area (Cu at the area surrounding TSVs) acts as anode and the coarser grain structure area (Cu at the TSVs) does as cathode, as shown in Fig. 13, because the finer grain structure has more grain boundaries than coarser grain structure. It accelerated the etch rate of the Cu surrounding TSVs and which caused SiO_2 layer revealed.

Fig. 14 shows diagrams of the wafer-level warpage after annealing at 400 °C for 30 min with the Cu overburden thicknesses controlled by the isotropic wet etching. In Fig. 14(a), the as-plated Cu overburden thickness for TSVs of 10×100 μm was 4.5–4.8 μm. Then, the Cu overburden was etched by $\Delta 1.5$ and $\Delta 3$ μm, respectively. As shown in Fig. 14, the wafer-level warpage decreases with the Cu overburden thickness reduction.

Fig. 15 shows a repeatability result of the wafer-level warpage measured after the annealing at 400 °C for 30 min. To achieve the repeatability result, three runs (totally nine wafers) were performed and the wafer-level warpage was averaged. The graph shows that the wafer-level warpage decreases gradually as the Cu overburden thickness controlled by the wet etching decreases. The averaged wafer-level warpage measured from the wafers with the as-plated Cu overburden after the annealing was $\sim$292 μm and it decreased down to $\sim$160 μm as the Cu overburden was etched by $\Delta 3$ μm. This result shows the wafer-level warpage is associated with the Cu overburden thickness at the field area.

IV. Conclusion

We were able to reduce the Cu overburden using the isotropic wet etching in the capsule-type bevel etch chamber. Because the TSVs had humps at the top of the TSVs after the Cu filling, the TSVs were protected from the etchant during the isotropic wet etching without any damages. As the etch rates of the dSPM were not controllable, we diluted the dSPM with distilled water *in situ* right before the wafer etching to have a controllable Cu etch rate. We achieved the etch rate of 0.2 μm/s with the good uniformity of $\sim$3% at 6 mm EE Even though the Cu overburden was etched heavily, the Cu at TSVs was not damaged because of the height difference between the Cu at the TSVs and the Cu at the field area and the microstructural difference between the Cu at the TSVs and the Cu surrounding the TSVs. We were able to etch away the Cu overburden up to 3 μm from the as-plated Cu overburden and the wafer-level warpage was reduced by 50% from that of the as-plated Cu overburden. The wafer-level warpage exhibited a linear relationship with the Cu overburden thickness.

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