THE EFFECT OF MECHANICAL STRESS ON ELECTROMIGRATION BEHAVIOR

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ABSTRACT

Three-dimensional integrated circuit packages with through-silicon vias (TSVs) provide a good solution to the integration of different chips and help achieve high performance. The signals are transmitted to different layers directly through the vias, thereby enabling the high performance of the chips. Plasma-enhanced chemical vapor-deposited SiO_2, polyimide, and benzo-cyclo-butene are commonly used as the passivation layer for three-dimensional packages. In the 3D stacked chips, mismatch of the coefficient of thermal expansion between the passivation material and silicon will generate thermal/mechanical stress in the metal trace and the stress affects the behavior of electromigration. However, few studies have examined the relationship among the external mechanical stress and critical product of electromigration. In the present study, external stress is applied to the aluminum thin film by a four-point bending equipment. In order to apply higher external stress in the aluminum thin film, the fracture strength of the silicon substrate should be improved. Reduces the edge chipping of the test sample is a key factor for improving the fracture strength of the silicon substrate and a special cutting approach is employed to obtain higher silicon strength. A two-step cutting method is applied to reduce front side chipping and also a dicing before grinding approachis adopted to reduce backside chipping, the above-mentioned technology can enable more than 275MPa of external stress on the aluminum thin film and can make the critical length effect more visible. The residual stress of the aluminum thin film is at stress-free state after annealing at 300°C for 10h. The critical product is found to be reduced from 1,294A/cm to 1,281A/cm when 120MPa of mechanical tensile stress is applied. It increased to 1,315A/cm under 120MPa of mechanical compressive stress. Clearly, electromigration behavior is enhanced by tensile stress and decreased by compressive stress. In the current research, a modified equation for Blech condition is proposed with a stress-dependent effective charge number, the effective charge number increased when tensile stress was applied and decreased when compressive stress was applied.

Keywords: Finite element analysis, Electromigration, External mechanical stress, Four-point bending.

1. INTRODUCTION

As packaging trends lean toward small size, high performance, and multifunctionality, three-dimensional (3D) integrated circuit (IC) packages with through-silicon vias (TSVs) have been studied extensively. Numerous studies have attempted to stack layers of chips to form 3D IC packages. 3D IC packages with TSVs can integrate different chips and meet high-performance requirements because the signals are transmitted directly from the upper to the lower layers through vias, which have the shortest electrical path and

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minimum RC delay [1-3].

The redistribution traceline width in each layer of 3D IC/packaging is around 10μm to 20μm, in which the current density will rise to 10^6A/cm^{2}which could enhance the electromigration behavior in traceline [4-6]. Plasma-enhanced chemical vapor-deposited SiO_2, polyimide, benzo-cyclo-butene, and Ajinomoto Build-up Film are commonly used as the passivation layer for 3D packages, it is clear that the stress will be generated in the conducting metal due to the mismatch of the coefficient of thermal expansion (CTE) between the passivation material and silicon [7] and the stress from the CTE mismatch will affect the characteristics of electromigration [8,9]. Thus, the effect of the stress on electromigration urgently needs to be studied.

In the current study, the effect of external mechanical stress on electromigration was studied. External mechanical stress was applied to test samples using a four-point bending equipment, in order to see the stress effect on electromigration behavior, one should generate the stress on the traceline as larger as possible. Because silicon is a brittle material, if chipping or microcracking is occurred at the edge of the sample, local stress concentration effect will make the sample be easily breaked even for a low external loading. Therefore, methods for reducing front side and backside edge chipping were proposed to increase the external stress applied in an aluminum thin film during the electromigration test.

2. IMPROVE SI STRENGTH BY DICING PROCESS

2.1 Reduced Chipping by the Dicing Blade and DBG Methods

Silicon substrate was used in this study because it is more compatible with the semiconductor equipment and processes than other substrates such as glass, plastic, and ceramic. 10 samples are used for each silicon strength test by four-point bending equipment. Figure 1 shows the experimental result for the maximum stress applied in the aluminum with different thicknesses of silicon substrate. Although the maximum stress applied in the aluminum was not increased significantly with a thinner substrate, the displacement of the inner support of the four-point bending equipment increased, and this increased displacement means that a more precise stress can be controlled in the aluminum thin film. The thickness of 400μm was selected to fabricate the samples with the Blech structure.

An additional process of plasma treatment was used to reduce edge chipping and remove microcracks for the silicon substrate. The conditions of the plasma treatment are shown in Table 1. Figure 2(a) shows the result after dicing. The average distance from the edge to the crack was approximately 9.2μm. Figure 2(b) shows the plasma treatment process of the sample. About 2μm of silicon was removed via the plasma process, which was sufficient for a dicing blade with a grift size higher than #2000 [10]. Since the plasma treatment was an isotropic etching process, the angle of the chipping was rounded by the plasma process. The stress concentration at the sharp corner of the chipping was reduced dramatically, and the microcracks on the surface were removed by the plasma process.

After the plasma treatment for the samples diced by a resin bond blade, the maximum stress applied in the aluminum thin film increased dramatically. For the sample with a thickness of 400μm, the average stress in the aluminum increased from 87.3MPa to 109.6MPa (25.6% improvement), as shown in Fig. 3. Chipping at the edge of the sample led to stress concentration and dramatically reduced silicon strength. The strength of the silicon substrate can be improved and the stress applied in the aluminum thin film can be increased if the chipping is reduced.

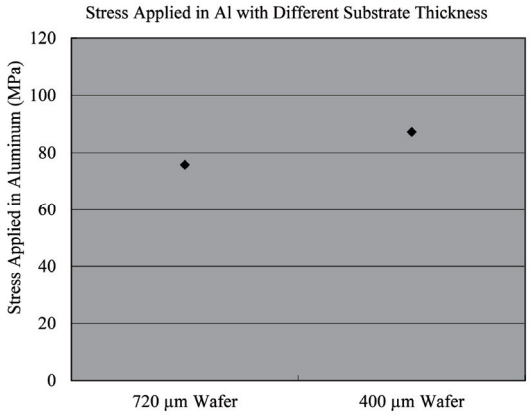
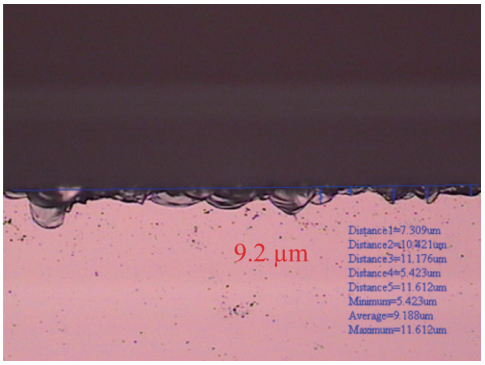
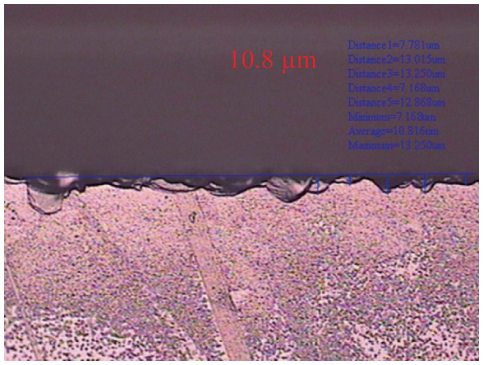


Fig. 1 Experimental result for the maximum applicable stress applied in the aluminum with different substrate thicknesses.



(a) After dicing using a resin bond blade



(b) After plasma treatment for 6min

Fig. 2 Top surface of the sample.

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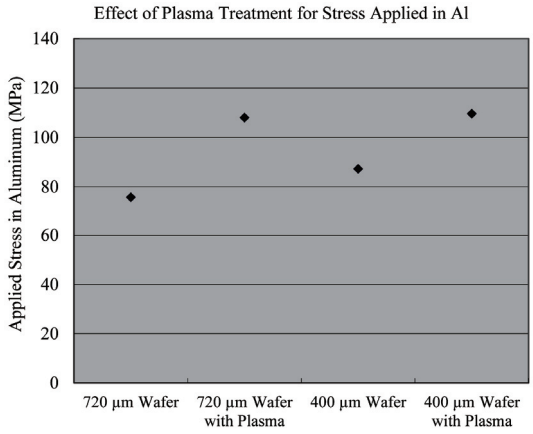


Fig. 3 Effect of plasma treatment on the maximum stress applied in the aluminum.

Table 1 Plasma process to reduce edge chipping and microcrack caused by the dicing process.

Process parameters	Process conditions
SF_6	300 sccm
O_2	30 sccm
Ar	500 sccm
Power	2 KW
Process Time	6 min.

The parameters for the resin bond and electroformed bond blades used in the silicon dicing process are listed in Table 2. The average chipping was measured at about 14.8μm for the samples diced using a resin bond blade and the average chipping was measured at 5.3μm for the samples diced by an electroformed bond blade. Using the electroformed bond blade instead of the resin bond blade dramatically reduced the chipping at the edge of the sample.

Figure 4 illustrates the effect of the dicing blade on the maximum stress that can be applied in the aluminum. The average stress applied in the aluminum increased from 117.0MPa to 177.3MPa which is about 51% improvement. A smaller deviation of the maximum stress applied in the aluminum was observed with the electroformed bond blade. This finding was due to the better edge chipping control using this blade.

Backside chipping is an important factor for improving silicon strength. Figure 5 illustrates how the dicing before grinding approach can reduce backside chipping. The traditional approach is shown in Fig. 5(a). The sample was initially ground and then the dicing process was conducted. During the dicing process, both front side and backside chipping were induced. Figure 5(b) illustrates the dicing before grinding approach. The dicing equipment cut the sample in half, and the wafer was ground from the backside to separate the samples. Backside chipping was reduced

Table2 Resin bond blade and electroformed bond blade used in the silicon dicing process.

Dicing Blade	Width of Blade	Material	Grit Size
Resin Bond Blade	100μm	Glass, Crystal, Quartz, packages	#400
Electroformed Bond Blade	35μm	Silicon, GaAS, GaP, $LiTaO_3$, *etc.*	#2000

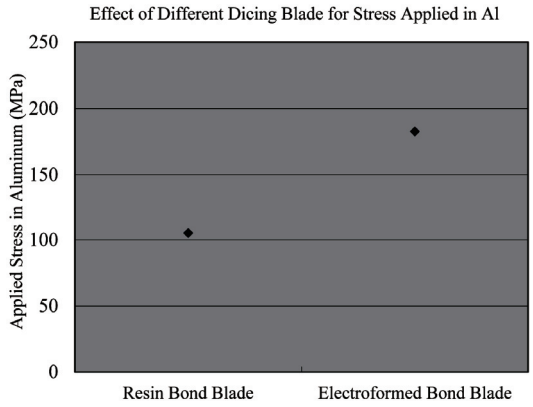


Fig. 4 Effect of different dicing blade on the maximum applicable stress in the aluminum.

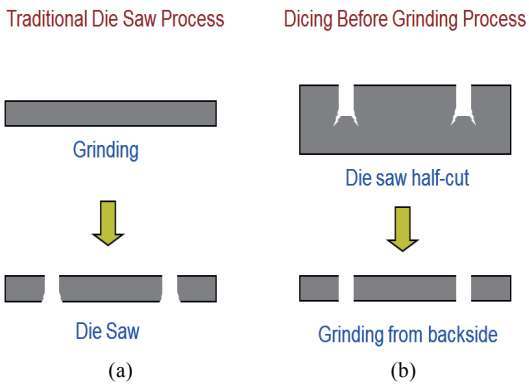
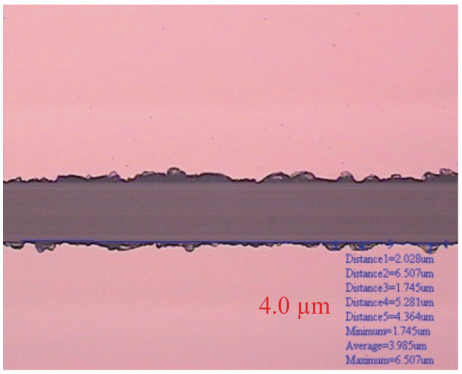


Fig. 5 Edge chipping at the backside of the sample is reduced by the dicing before grinding approach.

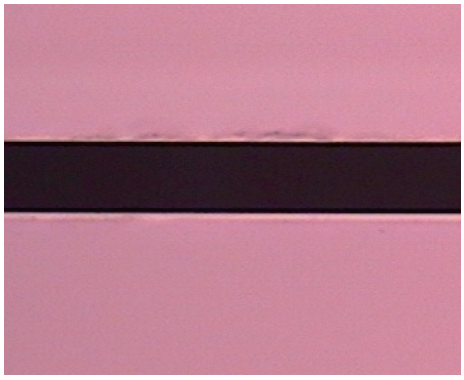
dramatically by this approach, as shown in Fig. 6. Figure 6(a) shows the optical microscopy (OM) image of the backside chipping using the traditional dicing method. Figure 6(b) shows the OM image of the backside chipping by the dicing before grinding approach. Almost no chipping was observed using this approach.

Figure 7 shows the effect of backside chipping on the maximum stress applied in the aluminum. This maximum stress increased from 177.3MPa to 187.3MPa. 5.6% improvement was obtained using the dicing before grinding approach and this finding was due to the strength of the silicon substrate being dominated by the front side chipping. The variation in the maximum

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(a) Traditional approach



(b) Dicing before grinding approach

Fig. 6 OM image of backside chipping.

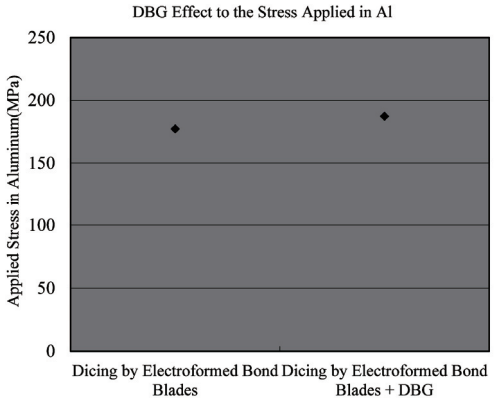


Fig. 7 Effect of backside chipping to the maximum stress that could be applied in the aluminum.

stress applied in the aluminum was reduced using the dicing before grinding approach, so the dicing before grinding approach was used to increase the maximum stress applied in the aluminum.

2.2 Reduced Front Side Chipping by DRIE and Two-Step Cutting

Front side chipping can be further improved by laser cutting [11,12] or DRIE [13]. The process flow for further reducing front side chipping using DRIE is shown in Fig. 8. Initially, photolithography was performed on the silicon substrate to define the cutting pattern. DRIE with Bosch process was then applied for depths beyond the final thickness of the silicon substrate after grinding. After removing the photoresist and grinding the wafer to the desired thickness, the samples were separated.

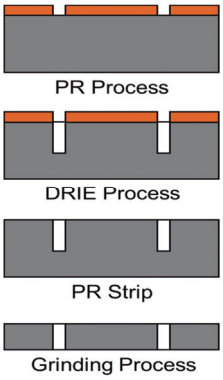


Fig. 8 Process flow for further reducing the front side chipping by DRIE.

Although DRIE has the potential to reduce the frontside chipping, the process flow is very complex. The cost for photolithography and DRIE with 450μm depth is also very high. An alternative approach to reduce front side chipping is two-step cutting. Figure 9 illustrates the process flow for a two-step cutting approach. The first step is the dicing process as previously described. An electroformed bond blade was used for the first cutting step. Given that the final thickness of the sample was 400μm, the first cut was in half to a depth of 450μm. Afterwards, an additional cutting with the same dicing equipment was conducted at exactly the same path of the first cutting. A V-shaped blade with a grift size of #4000 was selected to polish the chipped front side edge. Finally, the same backside grinding process was conducted for the sample separation. Figure 10 shows the top view of the two-step cutting process result. Figure 10(a) shows the OM image just after the first dicing process with an electroformed bond blade. The average chipping was measured as 4μm. Figure 10(b) shows the OM image after the second dicing using a V-shaped blade. The average chipping was reduced to 2μm. Figure 10(c) shows the OM image at a smaller magnification. The edge of the first and second dicing can be clearly identified. Figure 10(d) shows the backside surface after backside grinding. Almost no chipping was found at the backside of the sample after the backside grinding process.

Figure 11 shows the maximum stress applied in the aluminum thin film using different dicing methods on Si (100) substrate. For substrate dicing using a resin bond blade that underwent plasma treatment, the average stress applied in the aluminum is 117MPa. Changing the dicing blade from a resin bond blade to an electroformed bond blade with plasma treatment increased the average stress applied in the aluminum strip to 177.3MPa. Using the dicing before grinding technique can reduce the backside chipping dramatically, but the maximum stress applied in the aluminum was dominated by the front side chipping. The average stress applied in the aluminum is slightly increased to 187.3MPa via the dicing before grinding method. The average stress applied in the aluminum decreased to 155.7MPa for the etching before grinding method.

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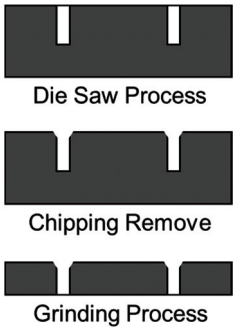
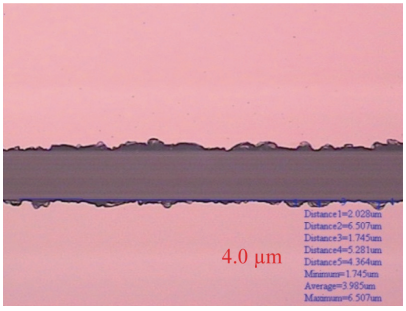
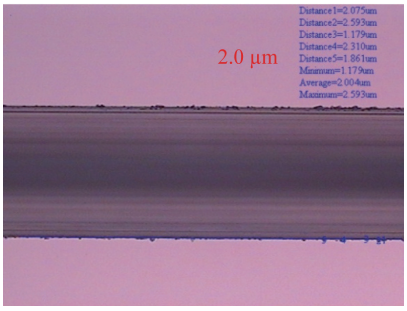


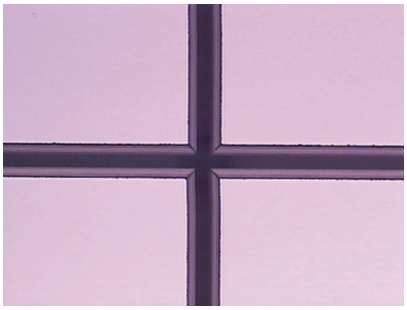
Fig. 9 Process flow of the two-step cutting to reduce front side chipping at the edge of a separated sample.



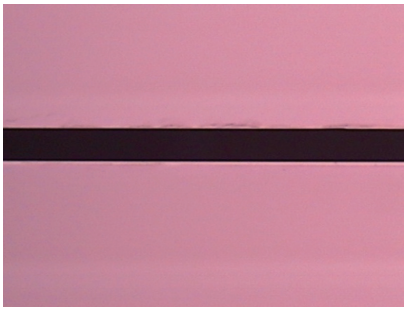
(a) First cutting



(b) Zoomed-in image of the second cutting



(c) Zoomed-out image of the second cutting



(d) Backside OM image after backside grinding

Fig. 10 Top view OM image of the result of the two-step cutting process.

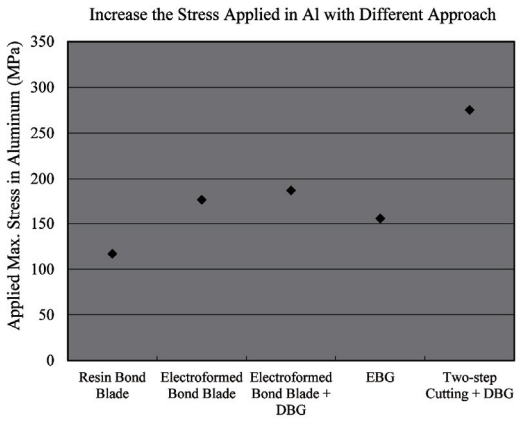


Fig. 11 Increased stress applied in the aluminum thin film on silicon substrate with different sample separation methods.

This finding may be caused by the poor quality of the plastic mask and the unoptimized photolithography process. The maximum value for etching before grinding was 272MPa, and it is much higher than that for the samples separated by the dicing method. Etching before grinding may increase the stress applied in the aluminum if the quality of the mask can be improved and the photolithography process can be optimized. The two-step cutting process can reduce front side chipping in a practical way compared with the etching before grinding method. The average stress applied in the aluminum increased to 275.3MPa, and the maximum stress applied in aluminum was 392.4MPa.

3. FABRICATION OF TESTING SAMPLES AND EXPERIMENTAL DESIGN

An aluminum Blech strip on silicon substrate was manufactured for the investigation of electromigration behavior. Wet etching process was used in the present study because it has no metal residual, and the photoresist is easy to remove. Figure 12 shows the SEM image for the unpassivated Blech strip after processing. The strip lengths were as follows: 25, 50, 100, 200, 300, 400, and 500μm which all have a width of 60μm. The cross-section SEM image of the unpassivated Blech strip after all the processes is shown in Fig. 13. Figure 14 shows the scanning electron microscopy (SEM) image after the electromigration test at 200°C for 20h. The electrons flowed from the right to the left hand side. Depletion was observed at the cathode of the strip, and extrusion was observed at the anode. Both hillock and aluminum whiskers appeared on the SEM image. Depletion can lead to open circuit failure, whereas extrusion can lead to short circuit failure. The critical length is observed by edge displacement method [8] with current density of $6 \times 10^5 A/cm^2$ for 20h because the depletion was saturated after 80 h for the strip lengths shorter than 100μm. External stress was applied in the aluminum strip using the four-point bending equipment. Residual stress was maintained at a stress-free state with an additional annealing process at 300°C for 10h. A higher stress can be applied by two- step cutting and dicing before grinding method. Five external stresses were tested: –120, –60, 0, 60, and 120 MPa.

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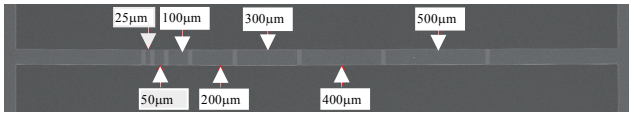


Fig. 12 SEM image for the unpassivated Blech strip after processing. The strip lengths were as follows: 25, 50, 100, 200, 300, 400, and 500μm.

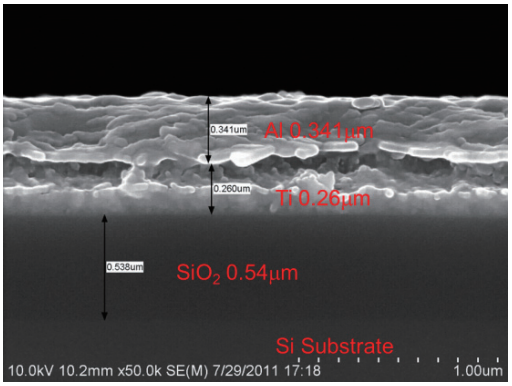


Fig. 13 Cross-section SEM image of the unpassivated Blech strip after all the processes.

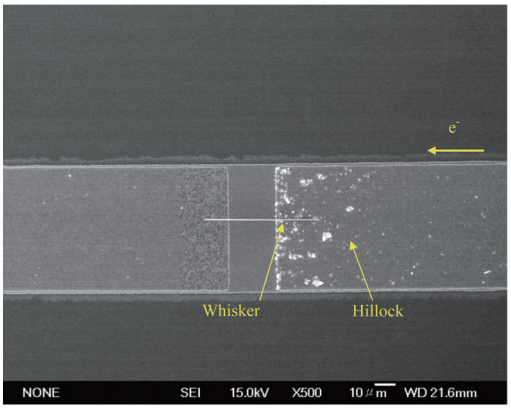


Fig. 14 SEM image of a short circuit failure due to aluminum whisker growth by electromigration.

4. RESULTS AND DISCUSSION

Figure 15 shows the relationship between the critical product ($j \times L$) and external stress applied in the aluminum strip. Four samples were tested for each stress level. The value of the critical product when no external stress was applied was 1,294A/cm, which is reasonable compared with previous studies [5,14]. A larger critical product was observed with the condition of compressive stress, indicating that electromigration is retarded when compressive stress is applied. On the other hand, a smaller critical product was observed when tensile stress was applied which indicating that electromigration is enhanced by tensile stress. The well-known Blech's equation could be expressed as:

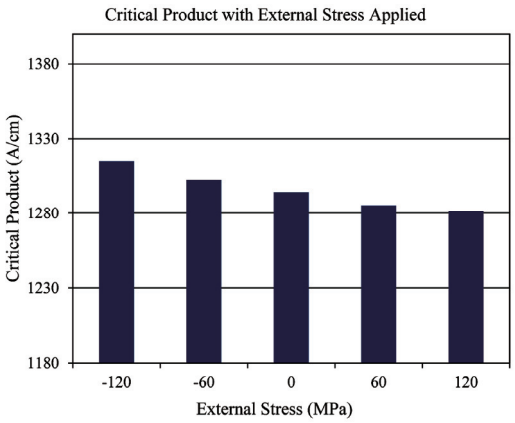


Fig. 15 The relationship between the critical product and external stress applied in the aluminum strip (current density = 6×10^5A/cm^2).

$$\Delta x_{crit} = \frac{\Omega \Delta \sigma}{Z^* e \rho j}$$

where Δx_{crit} is the critical length, Ω is atomic volume, $\Delta\sigma$ is the stress difference between anode and cathode in metal line, Z^* is effective charge number, e is the electron charge, ρ is the resistivity, and j is current density. The effective charge number Z^* was altered when an external stress was applied in the aluminum strip. Figure 16 shows the relationship between the effective charge number and the external stress applied. The effective charge number increased when tensile stress was applied, and it decreased when it is under compressive stress condition. In the present research, a modified effective charge number is proposed, and the equation is expressed as:

$$Z^*_{modify} = Z^* + A\sigma_{ext}$$

where Z^*_{modify} is the modified effective charge number, A is a constant, and σ_{ext} is the applied external stress. Then the modified Blech's equation could be expressed as:

$$\Delta x_{crit} = \frac{\Omega \Delta \sigma}{(Z^* + A\sigma_{ext})\, e \rho j}$$

From the fitted data, the constant A was 0.0002, and the effective charge number was 1.57 without external stress applied which is in good agreement with previously reported value of 1.6 [15].

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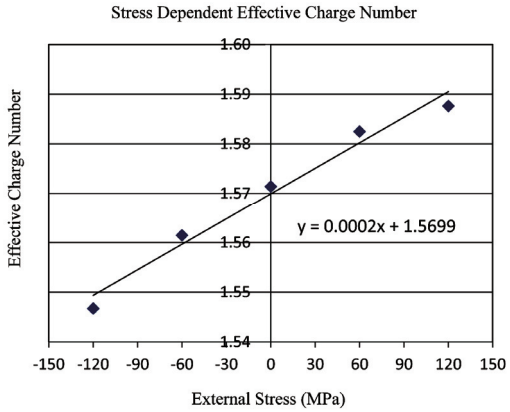


Fig. 16 The curve fitted data for the effective charge number under different external stress applied in the aluminum strip.

5. CONCLUSIONS

An aluminum unpassivated Blech strip was manufactured to evaluate the effect of external stress on electromigration behavior. An additional annealing process was conducted at 300°C for 10h to keep the aluminum strip in a stress-free state during the electromigration experiment at 200°C. External stress was applied to the aluminum strip using a four-point bending equipment to investigate the stress effect on the critical product. Surface chipping was the key factor for improving the stress applied in the aluminum strip. Frontside chipping was improved by replacing the resin bond blade with an electroformed bond blade as well as through DRIE and two-step cutting. Backside chipping was improved using the dicing before grinding method and almost no chipping was found at the backside after grinding process.

By changing the resin bond blade to an electroformed bond blade, the stress applied in the aluminum increased from 117MPa to 177.3MPa for the Si (100) substrates. For the sample cutting via DRIE, the applied stress was reduced to 155.7MPa, which resulted from the quality of the plastic mask and the photolithography process that were not optimized. Two-step cutting was used as an alternative approach to reduce frontside chipping. Two-step cutting was used for the sample preparation in the electromigration experiment, and the dicing before grinding approach to reduce backside chipping yielded an average stress of 275.3MPa that can be applied in the thin aluminum film.

Based on the SEM image, hillocks and aluminum whiskers were both observed at the anode of the strip. The critical product increased from 1,294A/cm to 1,315A/cm when 120MPa of compressive stress was applied in the aluminum, and decreased to 1,281A/cm when 120MPa tensile stress was applied. A modified equation for Blech condition is proposed with a stress-dependent effective charge number. It is observed that the effective charge number increased when tensile stress was applied and decreased when compressive stress was applied.

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