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Study of the Evolution of Cu-Cu Bonding Interface Imperfection Under Direct Current Stressing for Three Dimensional Integrated Circuits

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ABSTRACT

While the ultimate goal of Cu interconnection in 3D-IC is to have Cu as both the glue layer and interconnection line, there has been numerous demonstration of Cu-Cu bonding that shows the bonding interface is not always perfect. This work investigates the evolution of Cu-Cu bond interface under prolonged current stress by combining electrical current stressing and bond interface cross-sectional analysis. Voids at the bond interface were observed to be driven by electromigration to the adjoining interconnect line, leading to early failures of the line. This may have significant impact on the future of 3D-IC technology that utilizes Cu-Cu bonding, and it may be mitigated by inserting a barrier layer in between the bond interface and the interconnect line.

INTRODUCTION

Cu-Cu bonding, particularly when used as a fine-pitch bonding that provides mechanical adhesion as well as inter-layer electrical interconnection, is the most sought after solution for three dimensional integrated circuits (3DIC) [1]. While there have been numerous demonstrations of Cu-Cu bonding [2], the bond interface is not always perfect. Micro-voids and oxide precipitates are readily present at the bond interface due to pre-bonding surface imperfections such as micro-roughness, CMP dishing or contamination on the Cu surface. As a result, true contact area of the bond interface is only a fraction of the nominal area of the bonding pad [3]. This poses serious mechanical and electrical reliability concerns, particularly in future fine-pitch Cu-Cu bonds that handle high current density.

In terms of electromigration, an imperfect bond interface that contains voids can act as a vacancy source. Electrical current flow can drive the migration of vacancies or the whole void [4] out from the bonding interface and subsequently accumulate somewhere else, e.g., in the adjoining interconnection line.

On the one hand, vacancy migration out of the bonding may mean an improvement in the bond interface properties by means of electromigration. Electromigration-induced bond interface improvement had been reported [5, 6] and modeled [7], whereby the phenomenon has been indicated by a contact resistance reduction under direct current stressing. However, vacancy accumulation following vacancy migration on the interconnection line may have an adverse effect on the interconnection reliability. Voids on the interconnection line can lead to current crowding, localized heating, subsequently melting and failures. If this is true, the coupling of a bonding interface with an interconnection line will have serious consequence, as it reduces the overall interconnection reliability.

With that in mind, the current paper attempts to study the Cu-Cu bond interface with adjoining interconnect lines under direct current stressing. In particular, we found that coupling of any bond interface with an interconnection line without a barrier layer would lead to serious reliability concern.

EXPERIMENT

Electrical stressing was carried out on four-point cross-bar contact test structures [5] and daisy chain structures as illustrated in Fig 1. Scanning electron microscope (SEM) equipped with Focus Ion Beam (FIB) was utilized for cross sectional analysis. The structures were fabricated by bonding two 200 mm patterned Cu wafers face-to-face followed by backside wafer thinning to access the probing pads for electrical characterization. The cross bar structures consist of only a single metallization layer and were fabricated by bonding three different line sizes, i.e., 6, 8 and 10 μm , to form two sizes of bonding interface, i.e., $8 \times 6 \mu\text{m}^2$ and $10 \times 8 \mu\text{m}^2$, respectively. The daisy chain structures consist of two Cu metallization, i.e., M1 (interconnection) and M2 (bonding pad). They are separated by Ta barrier layer. The bond interface was formed through the mating of the two M2 metallization.

The coupling effect between the bond interface and the interconnect lines were evaluated by comparing the results from two types of constant current stressing at room temperature, as summarized in Table I. In the first arrangement (type 1), the current source and ground terminal were placed in such a way that the stress current flowed through the bond interface as shown in Fig 1(a), where the source and ground are indicated by I^+ and I^- , respectively. At the same time, the voltage drop across the interface was monitored from V^+ and V^- terminals. In the second arrangement (type 2), the I^+ and I^- probes were placed in such a way that the current did not flow through the bond interface, as shown in Fig 1(b). Similar stressing was also conducted on daisy chain structures as shown in Fig. 1(c). SEM-FIB was used to characterize the bond interface, and GIMP and ImageJ software were utilized to quantify the interface voids.

RESULTS AND DISCUSSION

Table I summarizes the test structures' initial contact resistance as well as their stress condition. All structures were observed to have an ohmic behavior, with the $8 \times 6 \mu\text{m}^2$ and $10 \times 8 \mu\text{m}^2$ having an average initial contact resistance of $2.93 \pm 4.34 \times 10^{-3} \text{ m}\Omega$ and $2.77 \pm 2.98 \times 10^{-2} \text{ m}\Omega$, respectively.

It was observed from samples 4 to 9, that type 1 configuration (i.e. stress current passes through the bond interface) failed faster as compared to type 2 (i.e. stress current does not pass through the interface). Failed samples by open failure were observed from the abrupt increase in monitored resistance. The failure site was typically found in the adjacent Cu line away from the bond interface as shown in Fig 2.

Fig 3 (a) and (b) show the SEM cross sections of the cross structure from type 1, type 2 and an unstressed sample, respectively. It can be clearly observed that there is a distinct difference in the quantity of interface voids for different stress conditions. Voids quantification using ImageJ software as shown in Fig 4, reveals that the structures that had current stressing through the interface (Fig 4(a)), have less voids as compared to type 2 stressing (Fig 4(b)), as well as those samples that did not go through current stressing (Fig 4(c)).

SEM-FIB on the stressed daisy chain also shows similar trend in terms of the interface voids as shown Fig 5. Daisy chain that had gone through 1 hr stressing with 50 mA shows less voids at the bond interface as compared to non-stressed daisy chain structures. These observations have been confirmed by void quantity analysis, as shown in Fig 6.

Another interesting observation is that, after current stressing, more voids were observed to accumulate at the barrier-Cu M1 interface, as pointed out by solid arrows in Fig 5. The presence of Ta between M1 and M2, could effectively block any materials transfer between the two metallization,

which means that those voids can only originate from the interconnection lines instead of the bond interface.

Based on the current results, we can deduce that the voids from the bond interface could be driven somewhere else in the interconnect system by the electric current, which could improve the bonding properties. This observation is in agreement with earlier experimental results in [5, 6], and later modeled in [7], that is direct current stressing on the bond interface may improve the bond properties. However, the voids at the interface could accumulate in the interconnection lines under current stressing. This in turn weakens the interconnection line and accelerates the interconnection line failure.

Usage of barrier layer between interconnection line and the bond interface could thus help to prevent the interconnection-bond interface coupling effect. However, by doing that, it also undesirably increases the total interconnection resistance.

SUMMARY AND CONCLUSION

The behavior of a Cu-Cu bond interface under direct current stressing has been studied. Electrical stressing and SEM-FIB characterization show that current stress changes the interface properties in terms of reducing the quantity of interface voids. However, the study also reveals the adverse effect of coupling an interconnection line directly with a bond interface, i.e., faster failure time of the interconnect line. Electromigration driven vacancy/void movement from the interface to the interconnection line has been proposed as the mechanism of the coupling effect. The effect could be alleviated by incorporating a barrier layer between the bond interface and the adjoining interconnect line.

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Table 1. Samples' stress condition and failure time.

Sample No	Bond Size (μm)	Initial Contact Resistance ($\text{m}\Omega$)	Stress Current (A)	Type	Max Current Density		Stress Time/Failure Time (s)
					line (MA/cm^2)	interface (MA/cm^2)	
1	8×6	$2.86 \pm 4.03 \times 10^{-3}$	0.12	1	2	0.25	10000*
2	8×6	$3.03 \pm 4.00 \times 10^{-3}$	0.12	1	2	0.25	10000*
3	8×6	$2.96 \pm 4.41 \times 10^{-3}$	0.12	2	2	NA	10000*
4	8×6	$2.97 \pm 5.31 \times 10^{-3}$	0.18	1	3	0.375	160
5	8×6	$2.81 \pm 3.96 \times 10^{-3}$	0.18	2	3	NA	4600
6	10×8	$2.76 \pm 2.45 \times 10^{-2}$	0.3	2	3.75	NA	32400
7	10×8	$2.76 \pm 2.56 \times 10^{-2}$	0.3	2	3.75	NA	940
8	10×8	$2.80 \pm 2.65 \times 10^{-2}$	0.3	1	3.75	0.375	20
9	10×8	$2.76 \pm 4.28 \times 10^{-2}$	0.3	1	3.75	0.375	2

* No Failure

Fig 1. Test structure designs and stressing methodology. (a) Type 1 stressing, the stress current passes through the interconnect lines as well as the bond interface, (b) Type 2 stressing, stress current only passes through the interconnection line, (c) current stressing on daisy chain structure.

Fig 2. Failure site is typically observed on adjacent Cu line away from the bond interface, closer to the source terminal.

Fig 3. SEM-FIB cross section comparisons between structures that had gone through different stressing. (a) Type 1 stressing, (b) Type 2 stressing,, (c) no stressing was done on the sample.

Fig 4. Voids quantification of SEM-FIB cross section images by ImageJ, clearly shows the effect of direct current stressing. (a) Type 1 stressing, (b) Type 2 stressing, (c) no stressing.

Fig 5. SEM-FIB cross section comparison between daisy chain structures that were subjected to current stressing. Solid and dashed arrow points to voids found between barrier and M1- Cu interface and current direction, respectively. (a) No current stressing, (b) 50 mA for 1 hour.

Fig 6. Voids quantification and comparison of stressed and non-stressed daisy chain from SEM-FIB cross section images by ImageJ, stressed structure has lower average void quantity. (a) non-stressed daisy chains, (b) stressed daisy chain with 50 mA current for 1 hour.