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Understanding the Pre-Failure Thermo-Mechanical Issues In Electromigration of TSV Enabled 3D ICs*#

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Traditional metrology has been unable to adequately address the needs of emerging integrated circuits at the nano scale; thus, new metrology and techniques are needed. For example, the reliability challenges, and their root causes, in TSV enabled 3D-IC fabrication need to be well understood and controlled to enable mass production. This requires new approaches to the metrology. In this paper, we use microwave propagation characteristics (S-parameters) to study the thermo-mechanical reliability issues that precede electromigration failures in Cu-filled TSVs. The pre-failure insertion losses and group delay are reversibly dependent on both the device temperature and the amount of current forced through the devices under test. This is attributed to the plasticity of the copper fill in the TSVs.

Introduction

Metrology is needed to characterize, at the nano scale, the structure and composition in emerging integrated circuits. The reliability of the interconnects in such systems is a critical issue; for example, at 1 THz, the skin depth of Cu is only 65 nm, and even if the wire diameter remains several microns in size for 3-D interconnects, the current carrying capacity of such interconnects will be severely limited. In fact, the introduction of TSV enabled 3D-IC to the market has been hindered by many reliability challenges. Particularly, thermal stress related failures in this new technology are significantly worse than in the traditional planar integrated circuits. The stress buildup, due to mismatch in the thermal properties of the materials of construction, results in generation of defects such as cracks, voids, delamination, plastic deformation, substrate warping and buckling. This, in turn, introduces new reliability challenges such as the degradation of transistors in close proximity to the TSVs[1]. This situation is not all that unusual; about

65% of all microelectronic device failures are thermo-mechanical related, mostly due to thermally induced stresses and strains stemming from the mismatch in the neighboring dissimilar materials[2]. Thus, the various degradation processes and their impact on the different components have to be evaluated and well understood to enable mass production.

We have shown elsewhere that the microwave scattering characteristics in interconnects are sensitive to defect formation and material transformation[3, 4], and should be sensitive to the thermomechanical dynamics in electromigration (EM). EM is essentially the flux of material carried along with the dense electron current, that leads to stress build-up and void formation resulting in degraded device performance[5]. Given the large volume via fill in TSVs, the change in low frequency resistance (R_{dc}) from the void formation is difficult to measure, and may require the use of high temperatures and large forced currents to induce measurable damage. Indeed, during EM studies on TSV-enabled samples R_{dc} measurably increased only when voids larger than the TSV conductive diameter formed, forcing the electron flow to go through the resistive barrier shunts[6]. Thus, by the time a measurable resistance is detected the device under test (DUT) would have been long destroyed. On the other hand, the onset of void formation results in impedance changes which are easily measured with the insertion losses of broadband microwave spectrum. Furthermore, the phase changes in the propagating microwave can yield additional mechanistic information, such as changes in dielectric properties of the materials of construction.

In this paper, we discuss application of broadband microwave spectroscopy to investigate the pre-failure thermo-mechanical issues of TSV enabled 3D ICs during EM. Specifically, we present the results of a preliminary demonstration on the use microwave propagation characteristics (S-parameters) to study the impact of temperature and current on the pre-catastrophic-damage and thermo-mechanical reliability issues during EM of Cu TSV-based interconnects in 3D-ICs.

Experiments

Otherwise identical devices with different thermal histories were compared at various elevated temperatures, and direct currents, while monitoring the microwave insertion losses. Three types of DUT thermal histories were studied:

- Group 1: As received devices that had been stored in a dry N_2-box for about 18 months (green markers in Figures 1, 3 and 4, respectively);
- Group 2: The group 1 devices that had been subjected to up to 500 thermal cycles in the 30ºC to 125ºC temperature range (red markers in Figures 1, 3 and 4, respectively)
- Group 3: The group 1 devices that had been stored at 200C under N_2 for 72 hours, and then stored at room temperature for another 72 hours ((black markers in Figures 1, 3 and 4, respectively).

This initial demonstration involved about three of each device type. The EM-studies experimental plan is summarized in Table 1.

Dedicated group-signal-ground (GSG) test structures were used in these experiments. TSV-enabled two-level stacked dies, bonded together with polymer were used. The TSVs were located in the top chip. The samples were placed on a heated chuck in an open laboratory ambient, and dc current was forced through the signal line. The microwave signals were intermittently introduced and monitored with a 2-port network analyzer once the DUT reached the target temperature. Single devices from each group were subjected to step-wise increase in forced current at specific device temperatures. RF probes were landed on the GSG bond pads after the device reached the desired temperature to minimize drifts from expansion mismatch and potential damage to the probe tips.

Table 1: Compendium of materials and test conditions uses in the electromigration study.

Thermal History	EM Temperatures / ºC	Forced DC Current Range / mA
Group 1	25, 125	0-300
Group 2	25, 125	0-250
Group 3	300	0-250

For each sample, maximum current was maintained for up to 72 hours, with intermittent microwave measurements. At the end of the desired hold time, both the forced dc current and DUT heating sources were turned off. Insertion losses were measured again after a maximum of 72 hours at room temperature, to check DUT recovery.

Results and Discussion

Figure 1 shows the insertion-loss (S21) magnitude, at 35 MHz, as a function of the temperature and the forced dc current during the EM test. Relatively large changes in the insertion losses (S21 amplitude) were observed only at the highest temperature studied (300°C). As shown in Figure 2, the S21 losses were reversible. Specifically, the S21 losses were recovered once the samples were cooled back to room temperature, irrespective of thermal history and the maximum temperature or current endured.

As shown in Figure 2, the S21 amplitude depends on both the chuck temperature and forced dc current, and is reversible. The insertion losses increased with increasing DUT temperature and increasing dc current. Once the heating and forced currents were turned off the S21 returned to close to the original values measured at the start of the experiments.

The thermodynamics of the insertion losses were investigated; the Arrhenius-type dependence (as shown in Figure 3) suggests that the insertion losses are related to reversible temperature driven processes within the interconnect system. Interestingly, while the pre-activation factor did not change, the slopes (i.e., the activation energies) of the Group1 and Group 2 devices are different; the Group 3 devices were not tested. This suggests that the details of the RF signal loss may be dependent on the thermal history, i.e., stress state of the interconnects in the device under test[7, 8]. While material transport during EM in copper interconnect systems is known to occur predominantly along the Cu / capping layer interfaces, [9] grain boundary diffusion plays a significant role[10]. The reversibility of insertion losses suggest temperature-driven structural / phase transformations at the copper-dielectric interface and / or at copper grain boundaries[11, 12], that could lead to EM-induced plasticity in the copper interconnects[13]

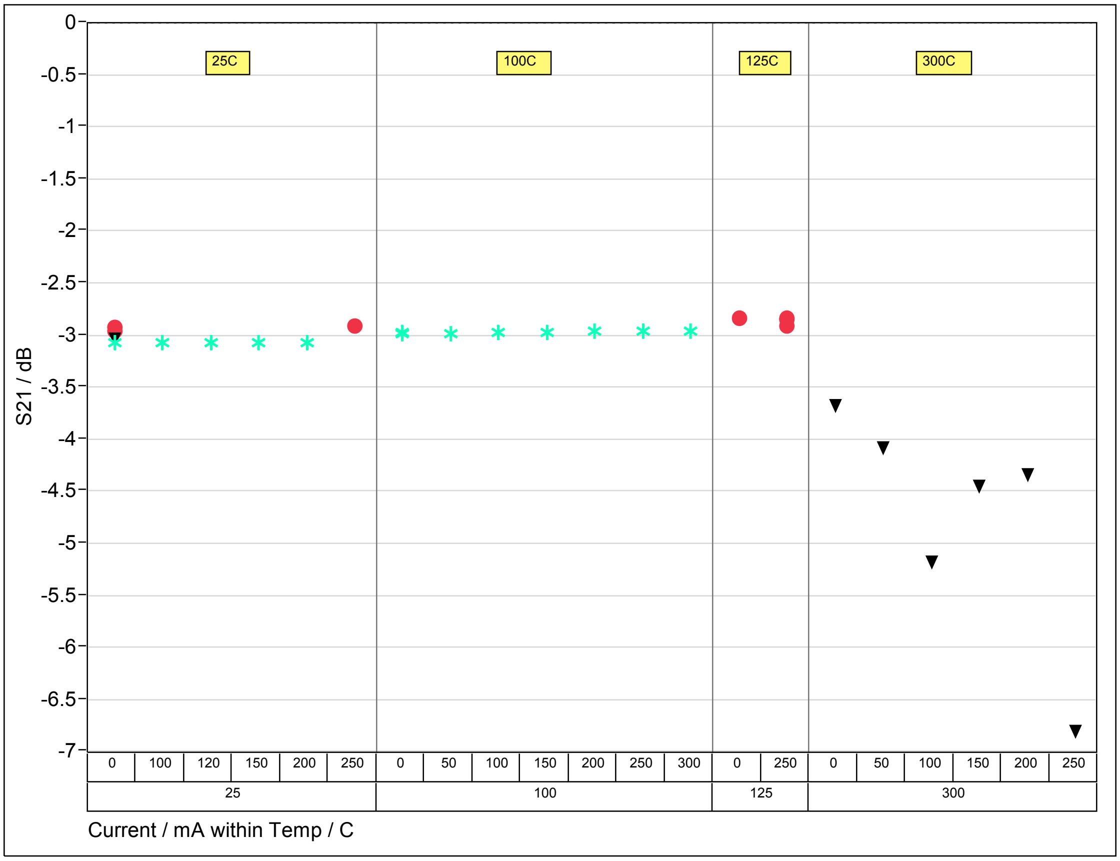

Figure 1: Impact of forced dc current (from 0 to 300 mA, as shown in the first row of the table) at various temperature 25°C, 100 °C, 125 °C and 300 °C, respectively, on microwave insertion loss (S21/dB) at 35 MHz

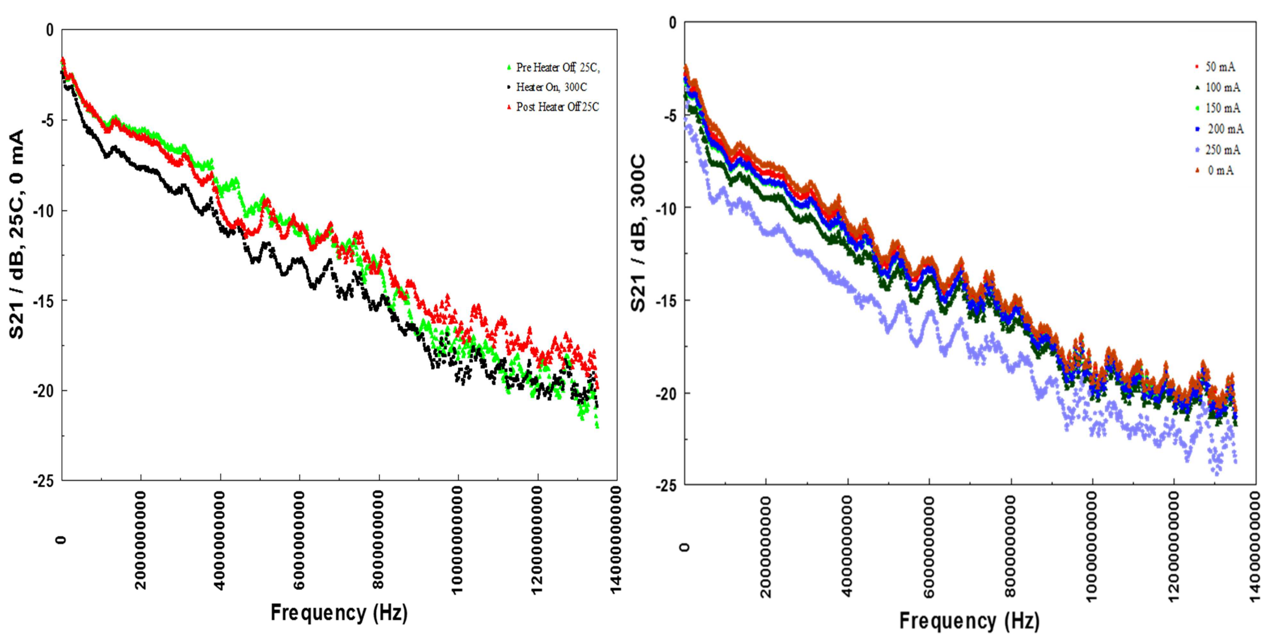

Figure 2A: Recoverable changes in S21 as a function DUT temperature Figure 2B S21 changes as a function of forced dc current at 300ºC for a typical group-3 device

The microwave propagation speed through the DUT is determined by the dielectric properties of the materials of construction[12]. Group delay is the slope of the phase angle dependence on the microwave frequency. Figure 4 shows the dependence of the microwave group delay as a function of forced dc current for all the devices studied, irrespective of thermal history or test temperature. The changing phase angle depends on the dielectric properties of the DUT; thus, the dielectric permittivity of the DUT depend on the magnitude of the forced dc current. The data suggest that the forced dc-current induces localized Joule heating in the interconnects, and increases the effective dielectric constant of the DUT.

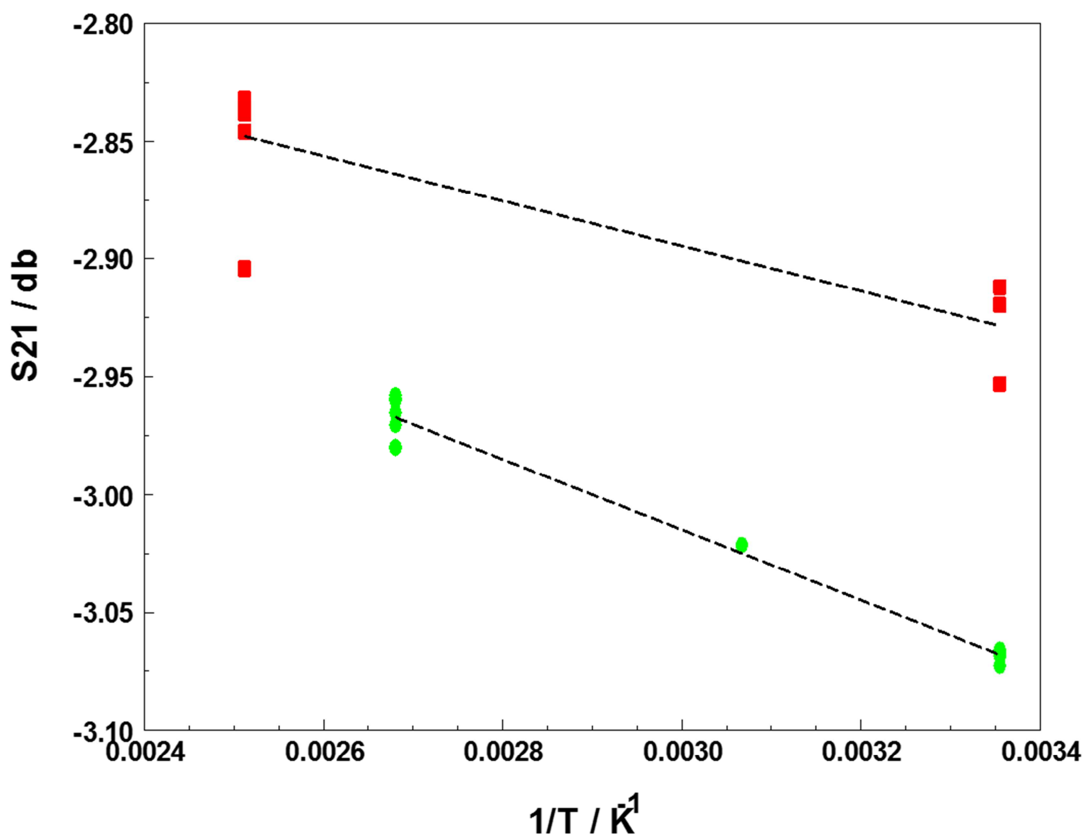

Figure 3: Impact of device temperature on microwave insertion loss (S21/dB) on device Group 1 (green dots) and Group 2 (red dots), respectively, monitored at 35 MHz.

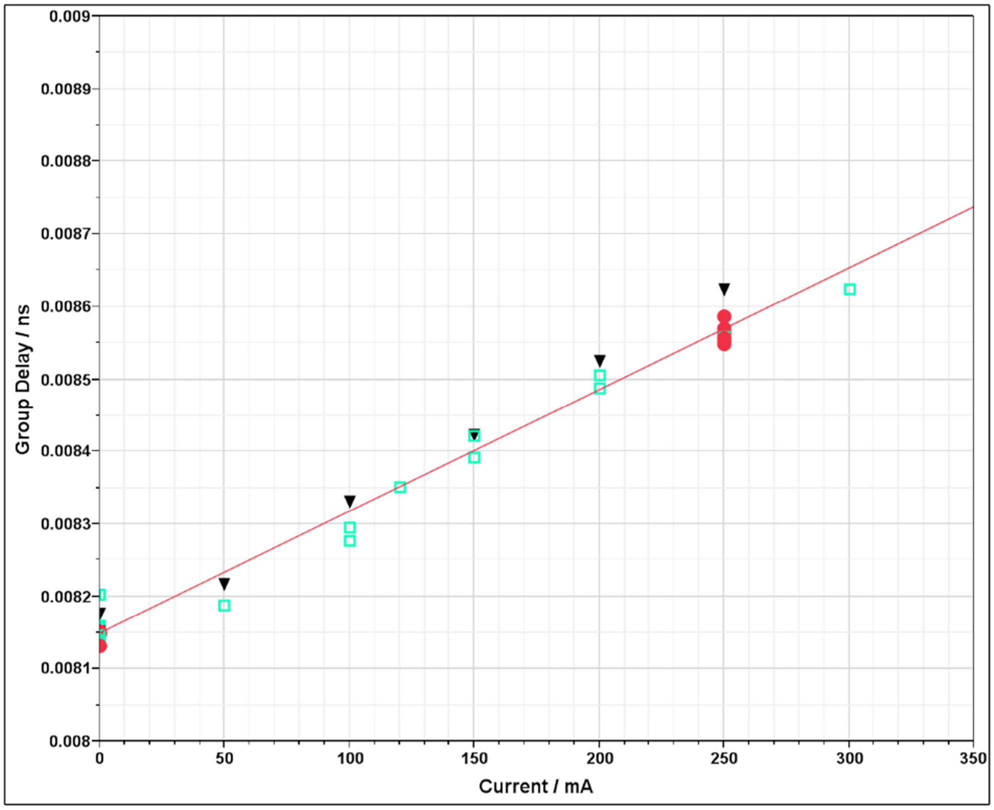

Figure 4: Impact of dc current at on group delay during microwave propagation at 35 MHz

Conclusions

Impedance changes occur long before electromigration induced damage in TSV enabled 3D-ICs interconnects. These changes are reversible in the low forced current domain, and on the short stress time-scales. Pre-existing mechanical damage in the interconnects, do not appear to affect the reversibility of the impedance changes.

References

1. A. Mercha, G. Van der Plas, V. Moroz, I. de Wolf, P. Asimakopoulos, N. Minas, S. Domae, D. Perry, M. Choi, A. Redolfi, C. Okoro, Y. Yang, J. Van Olmen, S. Thangaraju, D. Sabuncuoglu Tezcan, P. Soussan, J. H. Cho, A. Yakovlev, P. Marchal, Y. Travaly, E. Beyne, S. Biesemans and B. Swinnen, presented at the Electron Devices Meeting (IEDM), 2010 IEEE International, 2010 (unpublished).
2. B. Wunderle and B. Michel, Microelectronics Reliability **46** (9), 1685-1694 (2006).
3. C. Okoro, P. Kabos, J. Obrzut, K. Hummler and Y. S. Obeng, Electron Devices, IEEE Transactions on **60** (6), 2015-2021 (2013).
4. C. Okoro, J. W. Lau, F. Golshany, K. Hummler and Y. S. Obeng, Electron Devices, IEEE Transactions on **61** (1), 15-22 (2014).
5. J. Huang, A. Oates, Y. Obeng and W. L. Brown, Journal of The Electrochemical Society **147** (10), 3840-3844 (2000).
6. T. Frank, S. Moreau, C. Chappaz, P. Leduc, L. Arnaud, A. Thuaire, E. Chery, F. Lorut, L. Anghel and G. Poupon, Microelectronics Reliability **53** (1), 17-29 (2013).
7. C. Okoro, L. E. Levine, R. Xu, K. Hummler and Y. S. Obeng, IEEE Transactions on Electron Devices **61** (7), 2473-2479 (2014).
8. C. Okoro, L. E. Levine, R. Xu, K. Hummler and Y. Obeng, Journal of Applied Physics **115** (24), - (2014).
9. L. Zhang, P. S. Ho, O. Aubel, C. Hennesthal and E. Zschech, Journal of Materials Research **26** (21), 2757-2760 (2011).
10. L. Arnaud, T. Berger and G. Reimbold, Journal of Applied Physics **93** (1), 192-204 (2003).
11. Y. Mishin, M. Asta and J. Li, Acta Materialia **58** (4), 1117-1151 (2010).
12. T. Frolov, S. V. Divinski, M. Asta and Y. Mishin, Physical Review Letters **110** (25), 255502 (2013).
13. A. S. Budiman, C. S. Hau-Riege, W. C. Baek, C. Lor, A. Huang, H. S. Kim, G. Neubauer, J. Pak, P. R. Besser and W. D. Nix, Journal of Electronic Materials **39** (11), 2483-2488 (2010).