Published in final edited form as:

J Appl Phys. 2017 November 7; 122(17): . doi:10.1063/1.4992135.

Microwave evaluation of electromigration susceptibility in advanced interconnects

Christopher E. Sunday, Dmitry Veksler, Kin C. Cheung, and Yaw S. Obeng

Engineering Physics Division, Physical Measurement Laboratory, National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, Maryland 20899, USA

Abstract

Traditional metrology has been unable to adequately address the needs of the emerging integrated circuits (ICs) at the nano scale; thus, new metrology and techniques are needed. For example, the reliability challenges in fabrication need to be well understood and controlled to facilitate mass production of through-substrate-via (TSV) enabled three-dimensional integrated circuits (3D-ICs). This requires new approaches to the metrology. In this paper, we use the microwave propagation characteristics to study the reliability issues that precede the physical damage caused by electromigration in the Cu-filled TSVs. The pre-failure microwave insertion losses and group delay are dependent on both the device temperature and the amount of current forced through the devices-under-test. The microwave insertion losses increase with the increase in the test temperature, while the group delay increases with the increase in the forced direct current magnitude. The microwave insertion losses are attributed to the defect mobility at the Cu-TiN interface, and the group delay changes are due to resistive heating in the interconnects, which perturbs the dielectric properties of the cladding dielectrics of the copper fill in the TSVs. <https://doi.org/10.1063/1.4992135>

INTRODUCTION

There is a need to identify and understand all the prevailing performance limiting reliability failure mechanisms in the emerging advanced integrated circuit (IC) nodes.¹ The various degradation processes and their impacts on the different components must be evaluated and well understood, but the traditional metrology has not been able to address such needs at the nanoscale. For example, the reliability of the interconnects is a critical issue as the thermal stress-related failures in through-substrate-via (TSV) enabled three-dimensional integrated circuits (3D-ICs) are significantly worse than in the traditional planar integrated circuits.² The stress buildup, due to a mismatch in the thermal properties of the materials of construction, results in the generation of defects including cracks, voids, delamination, plastic deformation, substrate warping, and buckling. This stress build-up introduces new reliability challenges, such as the degradation of transistors near the TSVs.³ Unfortunately, traditional reliability methods (e.g., the monitoring degradation of DC resistance caused by electromigration) are slow,⁴ they do not provide many mechanistic insights, and in some cases, they provide rather misleading information.⁵ A new metrology is therefore needed to characterize, at the nanoscale, the structure and the composition of the TSV-enabled interconnects and to relate them to the reliability of the emerging integrated circuits.^{6,7} It would be desirable to fully understand what happens to the interconnect system prior to the

catastrophic failure^{8,9} and use that understanding to rapidly assess the interconnects' susceptibility to the electromigration failure. Along these lines, Beyne *et al.* recently explored the use of 1/f noise measurements in the advanced microelectronic interconnects as a technique to detect the onset of electromigration (EM). With this technique, they confirmed the electromigration properties of tungsten, as well as demonstrated a dependence of the EM failure mechanism on copper grain size and distribution, where the grain boundary diffusion was found to be a dominant failure mechanism.⁶ It is difficult to discuss the reliability of the dielectric-cladded copper interconnect systems without considering the contribution of the metal-dielectric interface,^{10,11} and an additional work is needed in this direction.

We have shown elsewhere that microwave scattering characteristics in the interconnects are sensitive to the defect formation and material transformation.^{12,13} Thus, we expect the broadband dielectric spectroscopy (i.e., microwave scattering characteristics) to be sensitive to the thermo-mechanical dynamics in the EM as well. After all, the EM is essentially the displacement of material, carried along with the dense electron current, that leads to the build-up of the mechanical stress and the formation of voids resulting in the degraded device performance.¹⁴ During EM studies on the TSV-enabled samples, the R_{DC} measurably increased only when the voids larger than the TSV's conductive diameter were formed, forcing the electron flow to go through the resistive barrier shunts.¹⁵ Thus, by the time a measurable resistance change is detected the device under test (DUT) would have been destroyed long ago. Given the large volume of the via fill in the TSVs, the change in the direct current resistance (R_{DC}) caused by the void formation is rather difficult to measure, and may require the use of higher temperatures and larger forced currents to induce a measurable damage. On the other hand, the onset of void formation results in the impedance changes, which can be easily measured with the insertion losses extracted from the transmission scattering parameters (S_{12} or S_{21}) of the broadband microwave spectrum. Furthermore, the phase changes in the propagating microwave signal can yield additional mechanistic information such as the chemical changes in the dielectric properties of the materials of construction.¹⁶ It would be interesting to relate the chemical changes to the mechanical artifacts, such as void formation, decohesion, delamination, and dielectric degradation, of a material system (conductor, cladding, dielectric, processing condition, etc.) and to the environmental factors. Such a link would provide a quick feedback for the process and the material integration optimization during device fabrication.¹⁷

Diligenti *et al.* have suggested the existence of a threshold current density beyond which strong and irreversible modifications in the interconnects occur.⁷ So, if we do not stress the test samples beyond the threshold current densities we should be able to investigate the pre-failure thermo-mechanical issues in the interconnects. Gousseau *et al.*,¹⁸ in agreement with Doyen *et al.*,¹⁹ observed a three-phase evolution of the electrical resistance in the TSV-enabled samples during EM, in which a long quiescent period is followed by a jump of about 10%, and then a rapid resistance rise. The jump in resistance has been shown to coincide with the catastrophic-damage, when the EM-induced void cross section becomes larger than the TSV's cross-section, thus forcing the current to travel through the more resistive glue layer.¹⁵ However, the nature of the quiescent/incubation period in the EM is not fully understood.^{20,21} In this paper, we present the results of a preliminary demonstration

of the use of microwave propagation to probe the impact of temperature and current on the device properties during the latent period before the first rise in resistance in the Cu TSV-based interconnects in 3D-ICs as described by Gousseau *et al.*²²

EXPERIMENTS

The dedicated ground-signal-ground (GSG) test structures, shown in Fig. 1(a), were used in these experiments. The TSV-enabled devices-under-test (DUTs) comprised the two-level stacked dies, bonded together with polymer, and with the TSVs in the top chip. The top die contained a daisy chain of 60 TSVs, with a pitch of 16 μm . Each TSV has a diameter and depth of about 5 μm and 50 μm , respectively. This test structure has a GSG configuration, with three parallel rows of TSVs 15 μm apart. Each row is terminated by probe pads at both ends. The low-frequency characteristic impedance of the TSV test structure is approximately 45 Ω . In the TSV construction, the thicknesses of the isolation silicon-oxide liner, the barrier layer (TaN), and the damascene oxide thickness are 0.5, 0.02, and 2 μm , respectively. The conductivity of the Si substrate is estimated to be 18 $\Omega\text{ cm}$. The top metallization was not passivated. The samples were placed on a heated chuck in an open-air environment. The direct current (DC) was forced through the signal line, as shown in Fig. 1(b). The chuck temperature was managed to within $\pm 1^\circ\text{C}$ of the desired set-point.

The DUT was inserted between the two air-coplanar GSG probes in Fig. 1(b), and was subjected to step-wise increases in the forced current, while maintaining the DUT temperature at the desired set point. The microwave probes were placed on the bond pads after the device reached the desired temperature to minimize the drifts from an expansion mismatch and a potential damage to the probe tips. Special care was taken to prevent the stray current from entering the vector network analyzer (VNA) circuit. The microwave signals were intermittently monitored (i.e., every hour during the work day, but less frequently during the after-hours) with a 2-port network analyzer (PNA-L N5230C, 10 MHz–40 GHz, Agilent, Inc.). The reference plane of the measurements was moved to the probe tips by following the standard electronic calibration techniques using a Cascade calibration substrate.²³ We did not directly measure the expected Joule heating from the forced DC current through the DUT.^{15,24}

Otherwise, the identical devices with different thermal histories were compared at various elevated temperatures and direct currents as described in Table I. This initial demonstration involved three representatives of each device type. For each sample, the maximum current was maintained up to 72 h, and the microwave measurements were taken intermittently. At the end of the desired hold time, both the forced DC and the chuck heating sources were turned off, and the insertion losses and the DC resistance (R_{DC}) were measured at room temperature to evaluate the device recovery. All measurements were made in the open laboratory air. We were unable to directly measure the DC resistance (R_{DC}) of the DUT during the electromigration experiment because of equipment limitations. However, a measurement circuit was created in series with the DUT using a high-quality ceramic (1 Ω) resistor to extract the DUT resistance during the measurements.

RESULTS AND DISCUSSION

In this work, we arbitrarily identified two regions in the insertion losses (S21) spectra: a low frequency region (<1000 MHz) and a high frequency region (>1000 MHz). When the discrete insertion loss data was required for comparison purposes, we arbitrarily focused on the losses and the signal propagation characteristics at 350 MHz because we observed the largest changes in the signal characteristics at that frequency. The S21 losses in the low-frequency domain, are attributed primarily to signal scattering due to molecular polarization events occurring within the dielectric and ceramic cladding (i.e., dangling bond rotations within SiO₂ and TiN layers surrounding the copper),¹⁶ and the eddy currents within about 1000 nm of the skin of the copper TSV fill. Since the copper and the claddings are adhered to each other albeit weakly,^{25–27} we discuss the observations at an integrated system level.

Impact of current and temperature on microwave insertion losses

The devices were conditioned, as discussed in Table I earlier, before the electromigration studies. Figure 2 shows a side-by-side comparison of the insertion losses (S21) for the three device types at 350 MHz as a function of the forced DC current (mA) at different chuck temperatures (°C). The inspection of the figure shows that the insertion losses were the largest and distinctly different only at 300 °C, the highest chuck temperature possible in our experimental set-up. We have shown elsewhere that the additional post-processing thermal treatments (e.g., extensive thermal cycling) induced the material deformation and increased the room temperature microwave insertion losses in the test structure investigated in this work.²⁸ Thus, we had expected to see significant differences between the room temperature S21 values of the three device types. However, the differences were only seen at 300 °C. The magnitude of the forced current also appears to contribute to the signal losses at 300 °C. These observations suggest that both the global device temperature and the localized resistive heating within the interconnects contribute to the microwave signal loss, irrespective of the device's thermal history.

These effects were further investigated by exploring the microwave propagation characteristics of the various devices under a variety of experimental conditions. Figure 3 compares the full spectra of the S21 insertion losses in the 0 to 14 GHz microwave frequency range for the type-2 devices under stress at 25 and 125 °C over time. The S21 amplitude depends on both the chuck temperature and the forced DC current. Increasing only the current does not change the S21 significantly. Increasing the chuck temperature alone with no forced current only slightly reduces the insertion loss (i.e., less negative S21). Significant changes in S21 were observed only when both heat and DC current were increased. Interestingly, for devices stressed for less than 72 h, the S21 is almost always reversible; i.e., when the current and heat are removed the S21 values returned to the pre-EM room temperature S21, as shown in Fig. 4. On the other hand, the room temperature S21 did not recover if the samples were stressed for longer than 72 h (as shown by the room temperature S21 trace for the samples stressed for 148 h in Fig. 3).

Figure 5 shows the full S21 spectra for the type-3 devices at 300 °C, as a function of forced current. The insertion losses at 300 °C were substantially higher than those observed in type-1 and type-2 devices at lower temperatures. This suggests that the interconnects in the

type-3 devices at 300 °C were more resistive than those in the type-1 and type-2 devices. This can be attributed to agglomeration of the pre-existing defects in the interconnects created during the thermal seasoning before the EM tests.

Microwave propagation characteristics

The microwave propagation characteristics through a DUT are determined, in part, by the dielectric properties of the materials of construction.¹² In this work, group delay (τ) was used as an index of the distortions experienced by the microwave signal as it travels through the device. The group delay was extracted from the rate of change of the phase angle as a function of the microwave frequency, according to Eq. (1), where ϕ is the phase in radians and ω is the angular frequency (in radians/s)

$$\tau = - \frac{d\phi(\omega)}{d\omega}. \quad (1)$$

Figure 6 shows the group delay for type-3 devices at 300 °C. As with the S21, the group delay increased substantially with the increase in the forced current. Figure 6 shows that the group delay for 0 mA traces was identical at both 25 and 300 °C, respectively. Similar curves were obtained for the type-1 and type-2 devices, but the dispersion in the group delay is greatest in the type-3 devices.

Figure 7 shows the dependence of group delay at 350 MHz, as a function of the forced DC current for all the devices studied, irrespective of the thermal history or the EM test temperature. The forced current is expected to result in an increase in the localized temperatures due to resistive heating, and the temperature increase will change the dielectric properties of the materials surrounding the metal lines. The strong dependence of the group delay on the forced current magnitude suggests that the group delay depends primarily on the local temperature in the interconnects. Thus, the group delay effectively probes the details of the materials of construction surrounding the copper fill. The temperature-dependent dispersion of group delay, as seen in Fig. 6, could be a useful probe into the physical/chemical nature of the dielectrics' cladding of the interconnects. This supposition will be explored in the future work.

To resolve the main effects in the disparate observations, the experimental data was statistically analyzed (using JMP software, SAS, Cary, NC). Figure 8 shows the result of a multivariate least square analysis of the insertion losses and the group delay data presented in Figs. 2–6. An analysis of the data shows that for all the device types, the insertion losses (S21) increased with the increase in chuck temperature, but were weakly dependent on the forced current magnitude. In contrast, the group delay was dependent on the forced current magnitude and independent from the chuck temperature for all device types.

The differences in microwave interactions with the three device types point to the importance of the interfaces in determining the mechanical behavior of the layered interconnect structures. We have previously correlated the post-manufacture thermal treatments with changes in the chemistry of the silicon oxide insulating dielectric layer

underneath the TiN copper-adhesion layer in these devices.¹⁶ It is also known that the Cu-TiN interface is thermally stable to at least 475 °C;²⁹ hence, the post-manufacture thermal treatments, at modest temperature stress, should not change the nature of the interface.³⁰ However, we have shown elsewhere that the post manufacture thermal treatments do result in changes in the hydrostatic stress of the copper fill.^{32,33} Thus, while the resistive heating from the forced current may not alter the bulk material properties of the cladding dielectrics,³¹ it could change the nature of the Cu-TiN interface from the changing hydrostatic stress of the copper fill because the Cu/TiN interface is extraordinarily “weak” in shear, and significantly weaker than either the bulk form TiN or Cu.²⁵

Thermodynamics

We assumed that the insertion loss mechanisms described in this paper are the result of the thermally driven events (e.g., motion of ions and other point defects/vacancies) that affect the energy storage and dissipation in the 3-D interconnect system. We further assume that these events can be described by the Arrhenius equation, with well-defined activation energies and a pre-exponential factor as in

$$S_{21} \propto A \exp\left(-\frac{E_a}{kT}\right), \quad (2)$$

where A is a pre-exponential factor, E_a is the activation energy (eV), k is the Boltzmann’s constant ($1.38 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$), and T the chuck temperature (Kelvin). The limited variable temperature studies on the devices, type-1 and type-2, allow the determination of the activation energy (E_a) for the microwave insertion loss using the linear Arrhenius relationship. This resulted in an activation energy (E_a) of about 150 meV for the type-1 (“as-received”) devices, and about 100 meV for the type-2 devices (thermal cycled for 500 times in the 30 °C to 125 °C temperature range), respectively, and a pre-exponential factor (A) of 2.6 for both device types. The type-3 devices were not tested at multiple temperatures to allow such analysis. The activation energy of approximately 0.15 eV is much lower than the typical E_a of 0.9 eV for Cu diffusion at Cu-dielectric interfaces,¹⁵ 2.3 eV for bulk copper diffusion, or the 1.2 eV for grain boundary diffusion.¹⁰ However, the low E_a is reminiscent of ion transport at interfaces between amorphous and crystalline phases in nanocrystalline glassy matrices and in polymer electrolytes.^{34,35} This suggests that the elementary processes responsible for the microwave insertion loss, in these pre-EM experiments, may involve the motion of ionic species or point defects along an interface within the TSV-interconnect system. Such motion of the charged species should result in the increased interfacial conductivity, and will result in the increased insertion loss, which is indistinguishable from loss due to dielectric damping.³⁷ In the microwave environment, the rapidly changing electric fields could cause repolarization at the Cu-TiN, TiN-SiO₂, or SiO₂-Si dielectric interfaces.³⁶ The difference between the activation energies for type-1 and type-2 devices suggests that the post-manufacture thermal treatment of the samples before the EM test activated different defect modes in type-2 and type-3 devices, respectively. In contrast, the pre-exponential factor (A) does not depend on the device’s thermal history, but depends only

on the geometry of the test structure studied, which is the same for all device types in this study.

These observations suggest that the thermodynamics of the pre-EM failure processes are dependent on the post-manufacture thermal history of the interconnects.^{33,38} As we have shown elsewhere, the temperature-driven transformations within the isolation dielectrics are irreversible,¹⁶ and are less likely to be responsible for the signal loss' recovery once the stress is removed. Hence, the reversible insertion losses observed here are probably more related to the diffusion processes at the Cu-TiN interface in the TSV. This idea is buttressed by the observation that the S21 never totally recovers when both the temperature and the current are turned off, especially in the high-frequency region. This phenomenon indicates that defects, such as micro-voids, have aggregated at an interface. We have observed such aggregation of micro-voids at Cu-TiN interfaces after extensive thermal cycling in the test structure used in this work.²⁸ This is a reasonable inference as the quality of the adhesion of copper to the cladding barrier layer has been shown to determine the lifetime in conventional electromigration tests.³⁹

The electromigration failure rate, based on some resistance change criterion, is essentially a measure of the accumulation of all the competing elementary processes in the stressed sample including, but not limited to, the thermal and other induced mechanical stress, metal atom migration, void growth, dielectric phase change, etc.⁴⁰ Thus, depending on rate determining process in the EM, we might be able to use the pre-failure microwave signal propagation characteristics to predict the eventual EM failure rates of the interconnects. We note that not all the elementary processes that lead to the electromigration failure may be amenable to interrogation by the microwaves, as described in this paper. Because of this, further work will be needed to firmly establish such a relationship between the characteristics of the quiescent period and the electromigration failure rates.

CONCLUSIONS

The changes in the microwave propagation characteristics occur when direct currents are forced through the advanced interconnects in three-dimensional integrated circuits. These changes are reversible once the heating and forced currents are turned off. The microwave insertion losses (S21) returned to close to the original values measured at the start of the experiments. From the multivariate analysis of the microwave insertion loss data, the losses are strongly dependent on the device test temperature, and weakly dependent on the magnitude of the forced current. In contrast, the dependence of the group delay dispersion on the magnitude of forced current suggests that the current induces localized Joule heating in the interconnects. The pre-existing mechanical damage in the dielectric cladding the interconnects influence the activation energy for the processes responsible for the microwave insertion loss in the interconnects. Unfortunately, it is difficult to unambiguously parse out the individual changes in this work, as they could be confounded with the temperature-dependent behavior of the Si substrate. In any event, depending on the rate the determining process, we might be able to use the pre-failure microwave signal propagation characteristics to predict the eventual EM failure rates of the interconnects, but further work is needed to firmly establish such a relationship.

With this fast technique, it should be possible to conduct the extensive experiments to help develop potential guidelines in the 3D-IC interconnection design and material selection, such as to map out the desired properties of the dielectrics and metals for the electromigration-robust interconnects.

Acknowledgments

Certain commercial equipment, instruments, or materials are identified in this report in order to specify the experimental procedure adequately. Such identification is not intended to imply the recommendation or the endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

Official contribution of the National Institute of Standards and Technology; not subject to copyright in the United States.

References

1. Oates AS. ECS J Solid State Sci Technol. 2015; 4(1):N3168–N3176.
2. Abbaspour R, Brown DK, Bakir MS. J Micromech Microeng. 2017; 27(2):025011.
3. Mercha A, Van der Plas G, Moroz V, de Wolf I, Asimakopoulos P, Minas N, Domae S, Perry D, Choi M, Redolfi A, Okoro C, Yang Y, Van Olmen J, Thangaraju S, Sabuncuoglu Tezcan D, Soussan P, Cho JH, Yakovlev A, Marchal P, Travalay Y, Beyne E, Biesemans S, Swinnen B. paper presented at the 2010 IEEE International Electron Devices Meeting (IEDM). 2010
4. Neri B, Diligenti A, Bagnoli PE. IEEE Trans Electron Devices. 1987; 34(11):2317–2322.
5. Lloyd JR. Microelectron Rel. 2007; 47(9–11):1468–1472.
6. Beyne S, Croes K, Wolf ID, T kei Z. J Appl Phys. 2016; 119(18):184302.
7. Diligenti A, Neri B, Bagnoli PE, Barsanti A, Rizzo M. IEEE Electron Device Lett. 1985; 6(11):606–608.
8. Yokogawa S, Okada N, Kakuwara Y, Takizawa H. Microelectron Rel. 2001; 41(9):1409–1416.
9. Petrescu V, Mouthaan AJ, Schoenmaker W. Microelectron Rel. 1997; 37(10):1491–1494.
10. Li B, Sullivan TD, Lee TC, Badami D. Microelectron Rel. 2004; 44(3):365–380.
11. Andideh E, Scherban T, Sun B, Blaine J, Block C, Jin B. Proceedings of the IEEE 2001 International Interconnect Technology Conference. 2001Cat. No. 01EX461
12. Okoro C, Kabos P, Obrzut J, Hummler K, Obeng YS. IEEE Trans Electron Devices. 2013; 60(6):2015–2021.
13. Okoro C, Lau JW, Golshany F, Hummler K, Obeng YS. IEEE Trans Electron Devices. 2014; 61(1):15–22.
14. Huang J, Oates A, Obeng Y, Brown WL. J Electrochem Soc. 2000; 147(10):3840–3844.
15. Frank T, Moreau S, Chappaz C, Leduc P, Arnaud L, Thuair A, Chery E, Lorut F, Anghel L, Poupon G. Microelectron Rel. 2013; 53(1):17–29.
16. Obeng YS, Okoro CA, Amoah PK, Franklin RR, Kabos P. ECS J Solid State Sci Technol. 2016; 5(4):P3025–P3030.
17. Janezic MD, Williams DF, Blaschke V, Karamcheti A, Chi Shih C. IEEE Trans Microwave Theory Tech. 2003; 51(1):132–136.
18. Gousseau, S., Moreau, S., Bouchu, D., Farcy, A., Montmitonnet, P., Inal, K., Bay, F. paper presented at The 39th International Symposium for Testing and Failure Analysis—ISTFA 2013; San Jose, California, USA. 2013;
19. Doyen L, Petitprez E, Waltz P, Federspiel X, Arnaud L, Wouters Y. J Appl Phys. 2008; 104(12):123521.
20. Valek BC, Bravman JC, Tamura N, MacDowell AA, Celestre RS, Padmore HA, Spolenak R, Brown WL, Batterman BW, Patel JR. Appl Phys Lett. 2002; 81(22):4168–4170.
21. Valek BC, Tamura N, Spolenak R, Caldwell WA, MacDowell AA, Celestre RS, Padmore HA, Bravman JC, Batterman BW, Nix WD, Patel JR. J Appl Phys. 2003; 94(6):3757–3761.

22. Gousseau S, Moreau S, Bouchu D, Farcy A, Montmitonnet P, Inal K, Bay F, Zelsmann M, Picard E, Salaun M. *Microelectron Rel.* 2015; 55(8):1205–1213.
23. Koche RS. Portland State University. 2012
24. Moreau S, Bouchu D. paper presented at The IEEE International Reliability Physics Symposium (IRPS). 2013
25. Yadav SK, Ramprasad R, Wang J, Misra A, Liu XY. *Modell Simul Mater Sci Eng.* 2014; 22(3): 035020.
26. Yasushi I, Tomomi Y, Tetsuo Y, Satoshi N, Toshio I. *Jpn J Appl Phys, Part 1.* 1994; 33(1S):462.
27. Lee WJ, Lee YS, Rha SK, Lee YJ, Lim KY, Chung YD, Whang CN. *Appl Surf Sci.* 2003; 205(1–4):128–136.
28. Okoro C, Kabos P, Obrzut J, Hummler K, Obeng YS. paper presented at the 63rd IEEE Electronic Components and Technology Conference (ECTC). 2013
29. Chang TS, Wang WC, Wang LP, Hwang JC, Huang FS. *J Appl Phys.* 1994; 75(12):7847–7851.
30. Taurino A, Signore MA, Catalano M, Farella I, Quaranta F, Giulio MD, Vasanelli L, Siciliano P. *IEEE Trans Device Mater Rel.* 2014; 14(3):890–897.
31. Stuerge, D. *Microwaves in Organic Synthesis*. 2nd. Loupy, A., editor. WILEY-VCH Verlag GmbH & Co, KGa; Weinheim: 2006. p. 1–61.
32. Okoro C, Levine LE, Xu R, Tischler JZ, Liu W, Kirillov O, Hummler K, Obeng YS. paper presented at 63rd IEEE Electronic Components and Technology Conference (ECTC). 2013
33. Okoro C, Levine LE, Xu R, Hummler K, Obeng YS. *IEEE Trans Electron Devices.* 2014; 61(7): 2473–2479.
34. Schirmeisen A, Roling B. *Monatsh Chem.* 2009; 140(9):1103–1112.
35. Bachman JC, Muy S, Grimaud A, Chang HH, Pour N, Lux SF, Paschos O, Maglia F, Lupart S, Lamp P, Giordano L, Shao-Horn Y. *Chem Rev.* 2016; 116(1):140–162. [PubMed: 26713396]
36. He, M., Lu, TM. *Metal-Dielectric Interfaces in Gigascale Electronics: Thermal and Electrical Stability*. Springer Science & Business Media; 2012.
37. Pozar, DM. *Microwave Engineering*. 4th. J. Wiley; Hoboken, NJ: 2012.
38. Okoro C, Levine LE, Xu R, Hummler K, Obeng Y. *J Appl Phys.* 2014; 115(24):243509.
39. Lane MW, Liniger EG, Lloyd JR. *J Appl Phys.* 2003; 93(3):1417–1421.
40. Scorzonni A, De Munari I, Impronta M, Kelaidis N. *Microelectron Rel.* 1999; 39(11):1647–1656.

FIG. 1. (a) The dedicated ground-signal-ground (GSG) test structures comprised more than 50 TSVs connected in series to each other, to maximize influence of EM, along with a SEM cross-section of the TSV daisy chain showing the two-level stacked dies bonded together with polymer, (b) A schematic showing the measurement setup used for the electromigration experiments in the current studies.

FIG. 2. Side-by-side comparison of the insertion losses (S21) at 350 MHz for device type-1 (green open diamonds), type-2 (solid red circles), and type-3 (solid black triangles), as a function of the forced DC current at different chuck temperatures. The horizontal dashed line at 3 dB is a visual aid only and depicts the mean insertion loss (S21) of the “as received” (Type-1) devices at room temperature.

FIG. 3.
Impact of forced direct current on S21 magnitude at 125 °C for a typical type-2 device:
Insertion loss increases with the increase in forced direct current.

FIG. 4. S21 recovery for type-1 and type-2 after short-time (less than 48 h) electromigration stress. The S21 returned to near pre-stress levels when both the heater and the forced current are turned off. Only the data in the 0 to 5 GHz frequency range plotted in to ease readability.

FIG. 5.

Impact of forced direct current on S21 magnitude at 300 °C DUT temperature for a typical type-3 device: increasing the forced current resulted in the increased insertion losses.

FIG. 6.

Impact of forced direct current on group delay at 300 °C for a typical type-3 device. Group delay increases (i.e., microwave signal is increasingly distorted) as the magnitude of the forced current increases.

FIG. 7. Impact of DC current on group delay during microwave propagation at 350 MHz for device type-1 (green open diamonds), type-2 (solid red circles), and type-3 (solid black triangles).

FIG. 8.

The result of a multivariate least square analysis showing the contributions of device type, chuck temperature, and forced DC current to microwave insertion losses (S_{21}) and group delay during the EM experiment. The dashed blue lines define the 95% confidence intervals of the model. The dashed red lines are settings that can be used to interrogate the model. The model indicates that the largest contributors to the insertion loss are the device type and the chuck temperature during the EM experiment. In contrast, only the forced current magnitude impacts the group delay.

TABLE I

Compendium of materials and test conditions used in the electromigration study.

Device type	Thermal history	Test temperatures (°C)	Forced DC current range (mA)
Type-1	“As received” devices were stored in a dry N ₂ -box at room temperature for about 18 months before use.	25, 100, 125, and 280	0 to 300
Type-2	Type-1 devices were subjected to additional 500 cycles of thermal profile (between 30°C to 125 °C temperature limits under N ₂) and stored for additional 72 h in N ₂ at room temperature before use.	25, 100, and 125	0 to 250
Type-3	Type-1 devices were subject to additional high temperature storage at 200 °C under N ₂ for 72 h, and then stored for another 72 h in N ₂ at room temperature before use.	25 and 300	0 to 250