Application of Broadband RF Metrology to Integrated Circuit Interconnect Reliability Analyses: Monitoring Copper Interconnect Corrosion in 3D-ICs

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Abstract— **In this paper we describe the application of high-frequency electromagnetic wave (in microwave frequency / radio frequency (RF in the range, i.e., 3 kHz – 300 GHz) based techniques to probe material and structural changes that occur in integrated circuits. These techniques fall under the general area of "Broadband Dielectric Spectroscopy". In this paper, we describe corrosion of the redistribution layer (RDL), required for the implementing 3-D integrated circuits (3D-ICs), during high-temperature storage. As an illustration of our techniques, we use the RF signal loss between ports 1 and 2 on a typical vector network analyzer (i.e., RF insertion loss, S21), to monitor the oxidation of the RDL copper interconnects. We compare the RF signal loss results to the direct current-resistance that was measured simultaneously with the S21. Using electrodynamic simulations, partition the RF signal loss in corroded copper interconnects, and discuss the significance of the roughness at the air-copper oxide interface.**

I. INTRODUCTION

Recent advances in technology and materials innovations have shifted the architecture of integrated circuits from two-dimensional planar to three dimensional (3D) systems, for example, as in stacked three-dimensional integrated circuits (3D-ICs). However, the performance demands of these 3D-ICs conflict with the reliability needs of these devices. That is, the 3D-IC devices are expected to operate at higher current densities but have lower voltage tolerances at higher electric fields. Thus, with 3D-ICs, the reliability of the electronic circuitry has shifted from being transistor-dominated to interconnect-dominated. These reliability issues are mostly materials related and include such effects as resistivity change, stress-induced unexplained early failures, corrosion, electromigration, etc. The traditional metrology techniques, such as DC resistance, have been unable to adequately address the measurement needed to characterize in-situ the underlying failure mechanism.

In this paper, we describe how appropriate test structures can be used in conjunction with broadband radio frequency dielectric spectroscopy (BDS)-based metrology to fill some of these metrology gaps. Specifically, we describe how we have used BDS to study the corrosion of the redistribution layer (RDL), required for the implementing 3-D integrated circuits (3D-ICs), during high-temperature storage. The redistribution layer (RDL) allows for circuitry fan-out and allows for lateral communication between the chips [1]. Figure 1 shows the basic elements of 3D-ICs, of which the interposer is arguably the most critical. Here, we use the RF signal loss between ports 1 and 2 on a typical vector network analyzer (i.e., RF insertion loss, S21), to monitor the oxidation of the RDL copper interconnects.

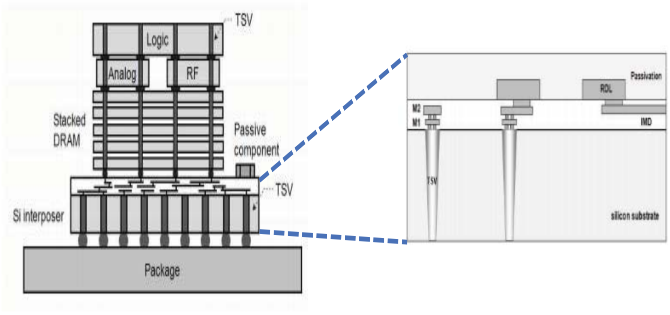

Fig. 1. Essential components of 3D stacked IC using TSV and a silicon interposer. The exploded area shows the elements within the interposer layer, pay attention to the passivation layer encapsulating the RDL (Adapted from [4])

II. RESULTS

In a common implementation of the RDL, polymers are used as passivation and Cu-plating is used to make the metal layer. Unfortunately, in this integration scheme, the polymer passivation limits the thermal budget of the back-end of line process flow. At temperatures above the glass-transition temperature (T_{gt}) of the passivating polymers, dimensional changes expose the copper material to ambient air, resulting in spontaneous oxidation of the metal. Figure 2 compares electron micrographs of the (A) 'as-received' and (B) oxidized RDL copper metal feature. The extent of copper oxidation increases with increasing temperature and time at temperature.

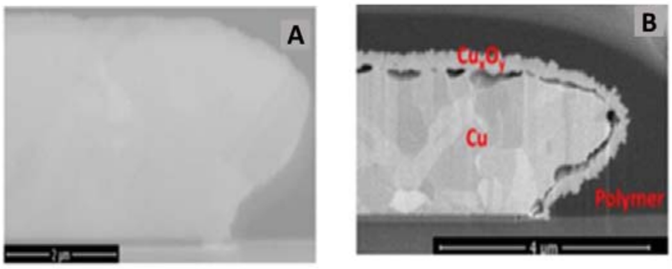

Fig. 2. Micrographs showing the development of copper oxide films around RDL feature: (A) “as-received” and (B) after 4 days at 200°C.

Figure 3 shows the microwave insertion loss (S21 at 100 MHz) as a function of the extent of corrosion of the copper RDL metallization (i.e., copper oxide film thickness measured by SEM, as in Figure 2) [2].

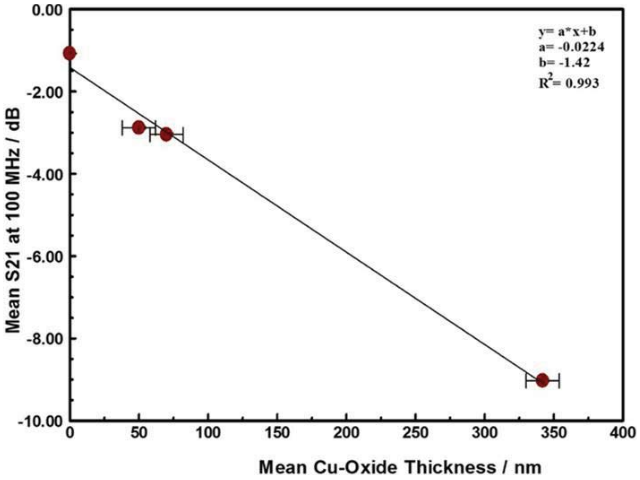

Fig. 3. Correlation between the Copper Oxide Film Thickness and the Insertion Loss (S21) at 100 MHz (Adapted from [2])

The changes in the electrical properties of the copper metal due to the oxidation are readily observed with BDS, as shown in Figure 4. In our experimental setup, we were able to monitor the direct current resistance (RDC) of the device under test (DUT). Figure 5 compares the RF signal loss results (at a single frequency (1 GHz) to the direct current-resistance that was measured simultaneously with the S21. The insertion losses increase dramatically with increasing DUT resistance (R_{DC}), suggesting that S21 may be a more sensitive measure of material changes (e.g., RDL corrosion).

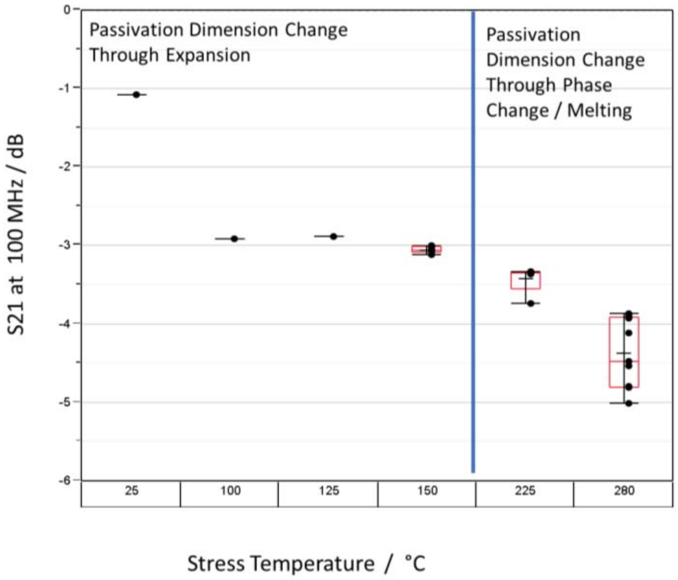

Fig 4: A comparison of the extent of oxidation (as indicated by S21) as a function of storage temperature. The data segments into two domains gated by the physico-chemical changes in the polymer passivation layer on the RDL

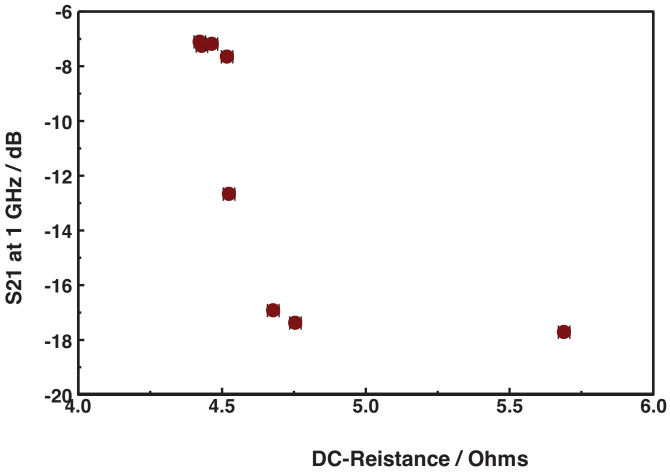

Fig 5: A comparison of the DC-resistance to the microwave insertion loss (S21) at 1GHz

Close analysis of the BDS data also provides information about the chemistry of the oxidation process, a product that techniques such as DC resistance (R_{DC}) cannot afford. For example, COMSOL Multiphysics (Burlington, MA, USA) electrodynamic modeling of the microwave signal loss (S21) through the corroded RDL required accounting for the roughness seen in Figure 2B. It turns out that the roughness of the copper oxide-air interface is attributable to the formation of electrically conductive polycrystalline copper oxide nanostructure mixtures (i.e., ranging from nanowires to nanotubes of Cu_2O and CuO) due to the thermal oxidation of crystalline copper nanowires at BEOL processing temperatures (200 to 300 °C) [3]. Figure 6, shows the simulated S21 spectrum as a function of the roughness of the oxidized RDL Cu.

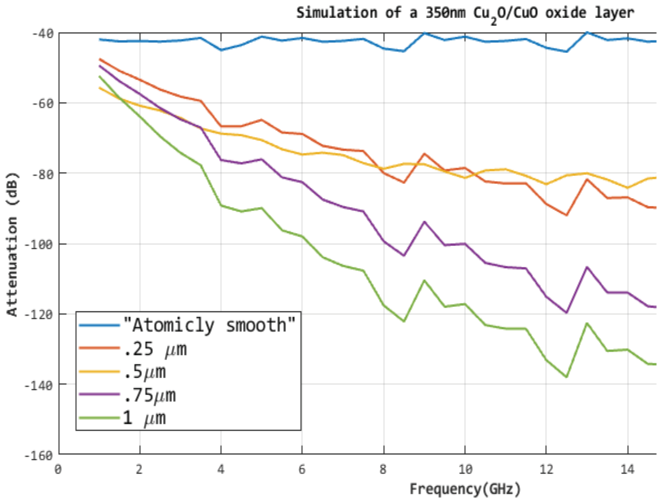

Fig. 6. Electrodynamic simulation, showing the impact of interfacial nanostructures, that manifest as roughness, on the microwave signal loss in the oxidized redistribution layer due to polymer passivation failure.

III. DISCUSSIONS/CONCLUSIONS

The traditional metrology techniques, such as DC resistance, have been unable to adequately address the measurement needed to characterize in-situ the underlying failure mechanism. In this paper we have shown that the broadband radio frequency dielectric spectroscopy (BDS)-based metrology allows us to monitor the material changes in real-time, as well as extract mechanistic information from appropriately designed test structures.

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