First Demonstration of Photoresist Cleaning for Fine-Line RDL Yield Enhancement by an Innovative Ozone Treatment Process for Panel Fan-out and Interposers

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Abstract — **This paper describes for the first time an innovative approach to improve re-distribution layer (RDL) yields in advanced semi-additive processes (SAP). An atmospheric pressure ozone based treatment is proposed as an alternative to oxygen plasma treatment. The ozone treatment process is scalable, being appropriate for process wafers up to large panels, and is suited for small feature sizes down to 1 micron that are required for interposers and future fan-out packages. The ozone process provides an environmentally friendly solution that can also replace wet cleaning processes, eliminating the need for hazardous chemicals that require abatement. The paper demonstrates the potential for two opportunities for integration of ozone treatment steps in the SAP flow for RDL fabrication. These particular steps are identified as 1) ozone treatment after dry film resist (DFR) patterning to improve the electrolytic copper plating yield and 2) removal of DFR residue prior to seed layer etch cleaning. Both these steps resulted in significantly improved RDL yields and demonstrate the feasibility of integrating ozone based cleans in high-yield, high volume cost effective manufacturing of RDL in Advanced Packaging. The paper also proposes ozone treatment as a higher throughput alternative to the plasma treatment process for electrolytic copper plating. Since the ozone gas is generated from oxygen, and reduced to oxygen upon process completion, no hazardous gas is required, or discharged into the atmosphere. To exhibit the scalability of the ozone treatment to both wafer-scale and panel-scale processing, two different types of copper seed layers, physical vapor deposition (PVD) Ti-Cu, and electroless plated copper, were evaluated. Samples were treated with either ozone or oxygen plasma, and the results were compared to a control sample with no treatment. After the photolithography step, in which 7 micron thick DFR laminated on the copper seed layers was resolved to 3 micron feature size, the substrates were subjected to ozone or plasma treatments. The subsequent water contact angle measurements show significant wettability improvement on the surfaces of substrates with copper seed layer, DFR, and DFR mesh patterned on a copper seed layer. Samples were then compared for the quality of the copper plating. Excellent copper metallization quality was achieved in the samples that had been treated with ozone and plasma due to the creation of a hydrophilic surface. An additional benefit emerged in that the ozone treatment was effective at 50 deg C, which minimized any impact on DFR stripping. The ozone treatment was also applied to clean the DFR residue after resist stripping and the results confirmed that the ozone process removed any remaining photoresist residue from the copper surface.**

Keywords- RDL, Semi-Additive Process, Fanout, Ozone, Resist Removal, Yield improvement

I. INTRODUCTION

Packaging technology continues to adapt to the ever-increasing needs for higher signal bandwidth connections between logic and memory chips, which in turn enable higher computing power in both high power applications and low power consumer devices. This signal bandwidth increase is achieved through the ability to increase wiring density and I/O pitch on a package with limited routing space. The limits of yield and minimum feature size of RDL are dictated by three crucial processes in the SAP flow: photolithography, electrolytic copper plating, and copper seed layer etch. The requirement that feature sizes scale down to 3 µm underlines the importance of high quality metallized copper structures. Traditional wet chemical cleans used for copper plating yield improvement feature hazardous chemicals such as trichloroethylene (TCE) that require high cost abatement systems for waste treatment. An alternative approach to mitigate the need for chemicals is an oxygen plasma treatment that can clean organic residue in DFR trenches and improve wettability of the seed layers prior to plating as well as DFR residue after copper plating and DFR stripping. However the implementation of plasma clean is an impediment to high volume manufacturing, as this approach requires a vacuum chamber that can reduce throughput. As transistor scaling in accordance with Moore's law faces technical and economic challenges, interconnect scaling in the chip back end of line (BEOL) and chip-to-chip interconnect scaling by advanced packaging technologies has emerged as a critical system level approach to increase data bandwidth at lower power and cost for a variety of electronics applications including consumer, high performance computing and automotive. The ever-increasing requirement for higher computing power and growing importance of memory is driving the need for higher signal bandwidth connections between logic and memory chips continuing the cost reductions without increasing the power consumption. 2.5D interposers and high density fanout have emerged as the primary options for high bandwidth logic-memory integration due to their many advantages over 3D IC stacking of single-chip SoCs [1, 2, 3]. In particular there is a drive towards increased wiring density and smaller I/O pitch using multiple re-distribution layers (RDL) to achieve high bandwidth interconnections on a package with limited routing space.

RDL yield management has always been a critical component of the IC process to scale wiring pitch and to reduce cost. Improving RDL yield has been identified as a critical need for high volume manufacturing integration in the advanced packaging domain [4]. Two key processes for enhancing yields in advanced semi-additive process for manufacturing RDLs are electrolytic copper plating improvement and dry film resist residue removal. This paper describes the first demonstration of an innovative approach using an atmospheric pressure ozone process to accomplish these process goals. Ozone treatment offers a practical and environmentally friendly alternative to both traditional chemical wet cleans, which incur water treatment costs to dispose of hazardous chemicals, and oxygen plasma processes, which require a vacuum chamber. The ozone process scales easily, allowing for application to both wafers and large panels and is suitable for cleaning feature sizes down to 1 µm. Ozone treatment improves copper plating yield by removing the organic contaminants that negatively affect the wettability of copper seed layers upon which the RDL structures are plated. The goal of this paper is to illustrate the effectiveness and benefits of the processes developed using an MKS ozone delivery system. It lays out the process basics and manufacturing tools, identifying the opportunities within the manufacturing flow to introduce yield improvement through ozone treatment. Also discussed are the figures of merit for these ozone processes, namely the improvement in residual DFR removal and the use of contact angle measurement to quantify the hydrophilicity of plating surfaces. Overall improvements in fine line RDL plating quality will be demonstrated.

II. EXPERIMENTAL METHODS

Fig 1. shows the manufacturing flow for a semi-additive process to fabricate the RDL [5] Two potential applications for integration of ozone treatments for yield improvements in fine-line RDL fabrication using SAP flow are illustrated as well.

A basic substrate of glass or silicon (500 µm thick) is first laminated with a 15 µm thick layer of ABF GY50 polymer. A 0.2 µm thick seed layer of electroless copper is then deposited upon the ABF polymer followed by the application of a dry film resist (DFR) with a thickness of 7 µm. The DFR is then patterned to define the RDL features using i-line exposure through a mask on a projection lithography tool. The features are then developed using a 1% Na_2CO_3 solution that prepares the panels for RDL plating step. It is important to note that any residue from the lithography step due to partial removal of the DFR impacts the yields from the plating process. Typically a plasma treatment process is used to clean up any resist residue from the plating surfaces as well as to improve the wettability of this surface for high plating yields. This is the first potential application for ozone treatment as an alternative to plasma treatments. After the treatment (plasma or ozone) the RDL structures are built up by electroplating copper on the seed layer exposed during the lithography step. The final two steps are: stripping the remaining layer of resist, followed by the removal of the copper seed layer in a chemical spray tank. This is the second potential application for ozone treatment as it is critical to remove any DFR residue from the seed layers prior to seed layer etch since partial removal of the seed layer results in electrical shorts between the RDL lines which reduces panel yields.

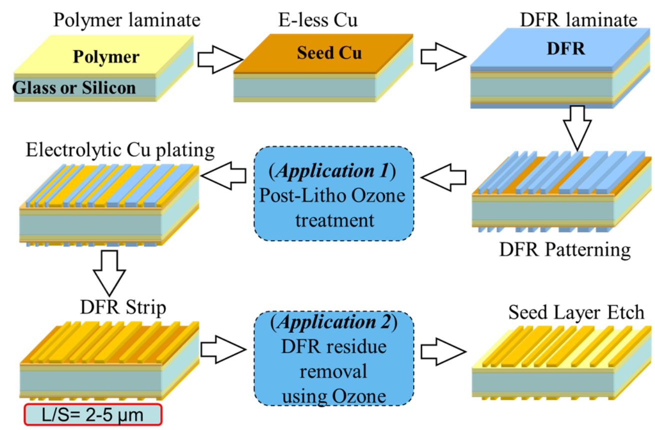

Fig. 1. Two potential applications of ozone treatments evaluated in a semi-additive process for RDL fabrication.

To facilitate the evaluation of the use of Ozone for these applications, MKS has provided a standalone two channel ozone delivery system (AX8550-247ECB6-42C) with two integrated ozone generators, an ozone concentration monitor and pressure control system that enables desired output of ozone from the generators from 6 SLM to 20 SLM O_2 flow with ozone concentration tunable up to 350 g/Nm^3[6]. For these experiments, the substrates were treated with ozone at a concentration of 300g/Nm^3. The ozone gas is delivered at atmospheric pressure to a box chamber with a heated platen wherein the panels were processed. The unused gas is then passed through a catalytic ozone destruction system that converts any unused O_3 back to O_2 before releasing to process exhaust. Since there is no electrical /RF bias required on the substrate platen as is the case for plasma treatment system, as well as no vacuum pump requirements the process chambers can be very cost effective and easily scalable for high volume manufacturing processes. Since the ozone treatment is isotropic, double side processing of the substrates can be accomplished readily. Furthermore there are no concerns for uniformity of the treatment (as is often the case in plasma treatment systems) as long as sufficient ozone is supplied to the process chamber. Lastly, a single ozone delivery system can be configured to support multiple process chambers via multichannel output configuration available on MKS's ozone delivery systems.

Fig. 2. Setup of the ozone treatment system at PRC. The ozone delivery system is on the right while the "box" chamber is shown on the left. The exhaust from the chamber is routed to an ozone destruct (not shown) to convert any unused ozone to oxygen.

The need to finely delineate the metallized copper structure feature sizes down to 3 µm and maintain high quality highlights the criticality of three particular steps within the work flow; the photolithography, electrolytic copper plating, and copper seed layer etch. Traditional techniques for improvement of copper plating yields involve wet chemical cleans to completely remove organic residue on the seed layer before electroplating can commence. However this approach incurs the costs of the wastewater management necessary to dispose of hazardous chemicals (e.g. trichloroethylene) utilized in these cleans. An alternative to the wet chemical process is an oxygen plasma treatment, which has been shown to be effective at both residual DFR removal and pre-plating seed layer clean. The plasma approach presents significant limitations to high volume manufacturing due to the vacuum processing requirements. This paper presents a viable third option: ozone treatment as a higher throughput alternative to the other techniques for surface preparation. Ozone treatment, like oxygen plasma, can be utilized in organic residue removal prior to electrolytic copper plating as well as for cleaning off the DFR residue that may remain on the substrate after resist strip with the added benefit of atmospheric pressure operation and compatibility with double side processing.

III. RESULTS AND DISCUSSION

To gauge the suitability of the ozone treatment for wafer-scale and panel-scale processing, RDLs fabricated using ozone and oxygen plasma treatment were contrasted against a control sample with no treatment. All samples received identical lamination, copper seed layer deposition, and lithography steps. Surface treatment by either oxygen plasma or ozone was then introduced for some samples prior to electroplating. Fig. 3 illustrates the differences in RDL line features post-plating.

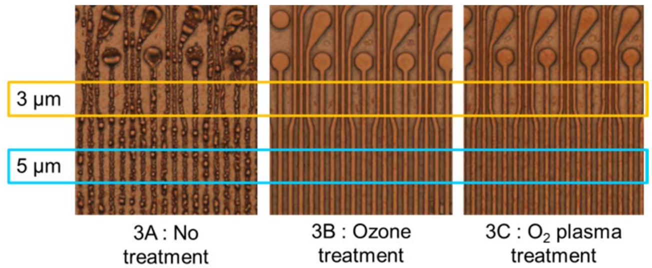

Fig. 3. Comparison of fine line RDL features after copper electroplating on substrates with No Treatment (3A), ozone treatment (3B), and O_2 plasma treatments (3C) illustrating the improvement in plated line quality resulting from wettability improvements of the surfaces with plasma or Ozone treatments.

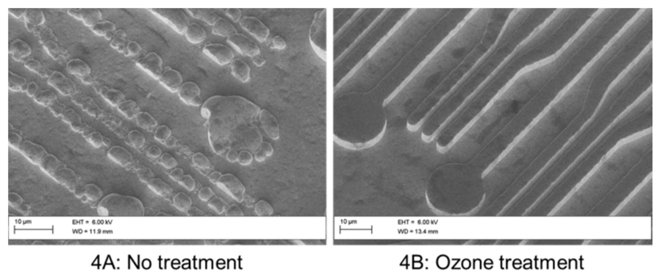

Fig. 4. SEM (10 µm scale) comparison of fine line RDL after copper electroplating on substrates with no treatment (4A) and ozone treatment (4B).

As is evident in Figs. 3 and 4, the RDL features on the untreated surface (3A) are poorly defined whereas the RDL features are well defined at both the 3 µm and 5 µm feature sizes after the copper seed layer surfaces were treated with either ozone (3B) or oxygen plasma (3C). Further evidence of the scalability of the ozone process is given in Fig. 4, as the definition of the features at the µm level is clearly defined. The issue with an untreated sample is that organic residue on the copper seed layer exposed after lithography negatively impacts the hydrophilicity of the substrate surface. This results in improper wetting of surfaces in the electroplating bath, which results in non-uniform and high resistance RDL structures. Thus a surface treatment step using an oxygen plasma or ozone treatment prior to the plating step significantly improves the plating process yields by effectively removing the organic residue from the seed layer surface and resulting in well-defined traces in the RDL as seen in Fig. 4B. One significant benefit of the ozone or oxygen plasma treatments prior to plating is the significant improvement in the wettability of all the surface regions on the panel to be plated as measured through water contact angle measurements (see Fig. 5). Both the ozone and oxygen plasma treated samples show significantly lower water contact angles on substrates prepared using two different seed layer deposition methods, (A) Substrates with PVD Cu and (B) Substrates with Electroless Cu deposition. It is notable that the wettability improvement was observed on all regions of the substrate. The copper seed layer, the DFR covered regions and the DFR mesh patterned surfaces indicate a uniform increase in the hydrophilicity of the surface that can help with uniform plating across the entire panel surface. This result implies that plating yields on large area substrates and panels would benefit from addition of an ozone treatment step prior to electroplating.

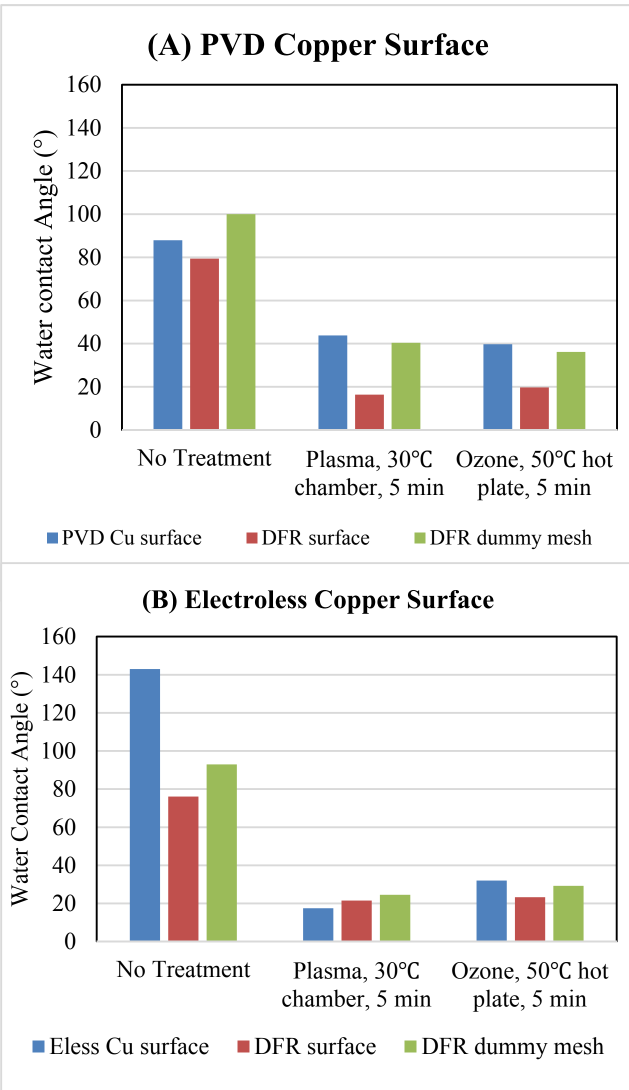

Fig. 5. Comparison of water contact angle (wettability) of the various regions on the panel surface on substrates with No treatment, O_2 plasma treatment or ozone treatments on two types of Cu Seed layers deposited using PVD (A) or electroless Cu (B). Both plasma and ozone treatments are effective in significantly reducing the water contact angle across different regions of the panel.

The improvements in RDL fabrication resulting from ozone or oxygen plasma treatments were further quantified through yield measurements of 2mm long copper lines with widths of 8 µm or 5 µm. 4-point resistance measurements of the lines were made as illustrated in Fig. 6. The lines were considered as yielded if the line resistance was measured to be lower than a specified threshold since lines with multiple defects had significantly higher line resistance. Multiple defects in the lines of the samples with no treatment (as evident in the SEM image Fig. 4A) resulted in high trace resistance and 0% yield. In contrast, samples prepared using the same process but having an additional ozone treatment had no defects (evident from Fig 4B) and 100% yields as quantified in Table 1. Similar improvements were also observed on samples with oxygen plasma treatment. These improvements, though illustrative of a lab process, underscore the need for surface preparation and cleanliness as a necessary step in the integration flow for high volume industrial implementation of the SAP.

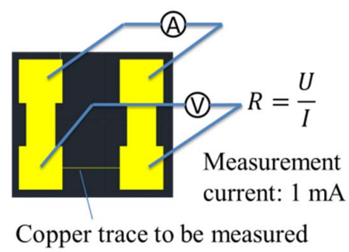

Fig. 6. Structures used for measuring line resistance and RDL yields, 2mm long traces were measured (with 5 µm and 8 µm widths) to quantify the yields. Note picture is not to scale.

TABLE 1: RDL trace line yields measured for samples processed with no treatment, with oxygen plasma treatment or ozone treatment prior to plating step.

Trace No.	Width	Length	No Treatment	Ozone Treatment
1	8 µm	2 mm	0 %	100%
2	5 µm	2 mm	0 %	100%

The second opportunity to introduce ozone treatment in the manufacturing flow is in the removal of any DFR residue after the resist strip process. Residual DFR negatively affects the subsequent removal of the copper seed layer, especially in processes where RDL fabrication requires thicker DFR films. Special samples were prepared in accordance with the steps in Fig. 1 in order to assess the ability of ozone treatment to remove residual DFR after the strip step. These samples featured thicker DFR (Hitachi 15 µm dry film). The plated Cu thickness was 10µm on these samples. As shown in Fig. 7, the panel processed with no ozone treatment after DFR strip showed several areas with defects while the panel that was processed similarly, but underwent an ozone treatment step after the DFR strip, showed no defects.

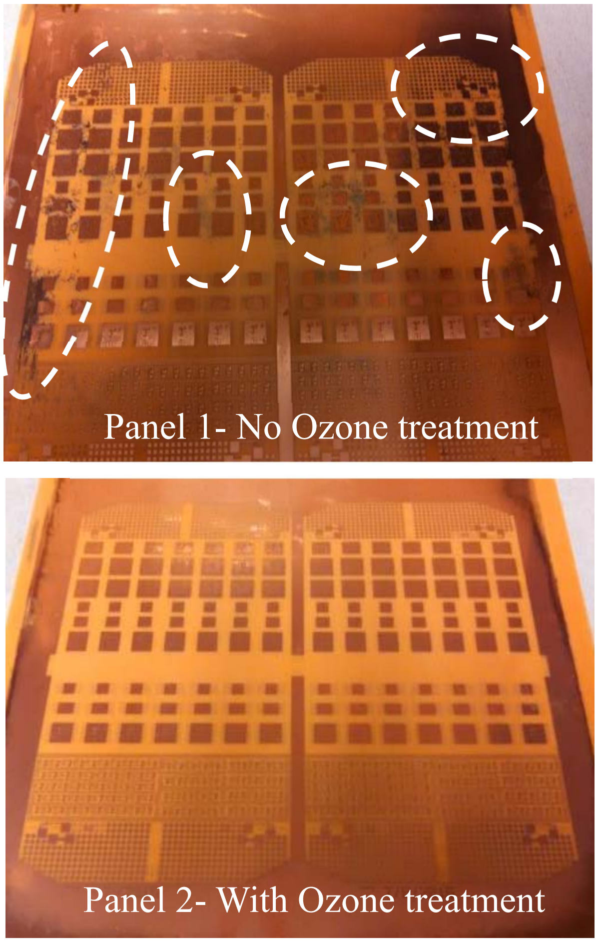

Fig. 7. Comparison of panels processed without (panel 1) and with additional ozone treatment step after DFR strip to highlight the effective removal of DFR residue from the panel using ozone treatment post DFR strip. Defective regions on panel1 are highlighted within the dashed ovals.

Analysis of the defective regions on panel 1 indicated the presence of DFR residue on the substrate after the resist strip step. This prevents the removal of the underlying copper seed layer during the seed layer etch and reduces the manufacturing yield. An ozone treatment step can be effectively integrated into the process flow to ensure complete removal of any DFR residue from the wafer or panel prior to seed layer etch and results in residue-free RDL layers as seen in panel 2.

A closer inspection of the DFR residue defect is highlighted in Fig. 8 where the same region of the sample was observed at different stages in the process flow. Both sample 1 and sample 2 show DFR residues after the DFR strip. Sample 1, directly taken to the seed layer etch steps, retained the DFR residue on the surface resulting in partial removal of the seed layer. Sample 2 that went through an ozone treatment (150 deg C, 5min) shows complete removal of DFR residue from the surface and resulted in complete removal of the seed layer thus yielding a defect free panel.

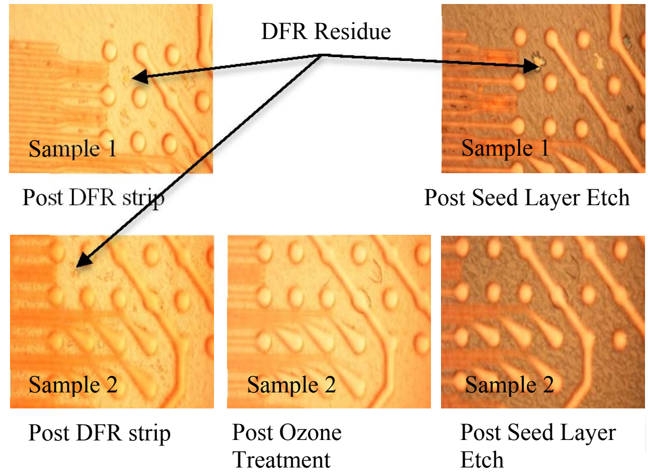

Fig. 8. Removal of DFR residue after strip using Ozone treatment of a panel with RDL illustrating the complete removal of DFR residue with the ozone treatment leading to yielded panel with no residual seed layer. Note the removal of DFR residue from the seed layer surface after the ozone treatment on sample 2.Untreated DFR residue (sample1) result in partial removal of seed layer causing losses in panel yields

IV. CONCLUSION

Incorporating ozone treatment as a part of RDL formation work flow provides excellent value in two crucial steps. Ozone improves the wettability of the copper seed layer in preparation for electrolytic plating of copper RDL features. DFR that remains on the surface post-strip, which impedes subsequent copper seed layer etch, is removed completely. These two process developments improve definition of the fine line features of the RDL, which increases yield at the panel level. Ozone delivery requires no vacuum equipment, making it a high throughput replacement for oxygen plasma treatment. Hazardous chemicals traditionally used to remove DFR residue are now eliminated from the work flow, and with them the need to abate the chemicals. The treatment scales effectively, allowing for single wafer processing up to large panel processing. It is appropriate for the fine-tuned requirements of 1 µm RDL features. Because the ozone process is run at atmospheric pressure it carries low infrastructure requirements, which can be easily incorporated into high volume manufacturing. The work flow steps enhanced by ozone treatment (photolithography, electrolytic copper plating) are crucial to developing RDL for interposers and fan-out packages; the addition of this treatment on an industrial scale offers a promising approach to addressing the semiconductor industry roadmap requirements.

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