Embedded Trench Redistribution Layers at 2–5 \( \mu \)m Width and Space by Excimer Laser Ablation and Surface Planer Processes for 20–40 \( \mu \)m I/O Pitch Interposers

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Abstract—This paper reports on one of the first demonstrations of the formation and metallization of 2–5-\( \mu \)m lines and spaces by an embedded trench method in two dry-film polymer dielectrics, Ajinomoto build-up film and preimidized polyimide, without using chemical mechanical planarization. The trenches and vias in 8–15-\( \mu \)m-thick dry-film dielectrics were formed by 308-nm excimer laser ablation, followed by the metallization of the trenches and vias by copper electrodeposition. A low-cost planarization process was used to remove the copper overburden with a surface planer tool. Using an optimized set of materials and processes, multilayer redistribution layers with 2–5 \( \mu \)m trenches and vias were successfully demonstrated. Although thin film processes on silicon wafers have been able to achieve 40-\( \mu \)m I/O pitch for interposers, the materials and processes integrated in this paper are scalable to large panel fabrication at much higher throughput, for interposers and high-density fan-out packaging at lower cost and higher performance than silicon interposers.

Index Terms—Embedded trench, excimer laser, fan-out, interposer, microvia, panel scalable, polymer dielectric, redistribution layer (RDL), surface planar.

I. INTRODUCTION

Increasing component and I/O density in electronic systems have driven the need for higher functionality and integration density at the package level. As the demand for high-density packages has increased, redistribution layer (RDL) wiring technologies have evolved from subtractive etching processes to semiadditive processes (SAP). Organic substrates with SAP RDL have been demonstrated down to 5-\( \mu \)m line and space recently [1]–[3]. However, SAP methods face challenges in scaling below 5 \( \mu \)m, primarily limited by the side etching of the copper lines during seed layer removal, and poor adhesion of ultrafine lines on smooth dielectric surfaces. Demonstration of ultrasmall line formation down to 2 \( \mu \)m with SAP has been reported by several research groups [4], [5]. However, these processes utilized liquid dielectrics and chemical mechanical planarization (CMP) processes, which limits their application to panel-scale fabrication. As an alternative wiring process, embedded trench technology has been intensively researched and developed. One of the early examples is Via2 technology developed by Amkor, Atotech, and Unimicron [6], [7]. It emulates the dual-damascene process schemes used in wafer back end of line (BEOL) and replaces SiO\(_2\) dielectrics and reactive ion etching etching with polymer dielectrics and excimer laser ablation patterning. The advantages of such laser embedded trench approaches compared to SAP are: 1) higher aspect ratio line capability; 2) elimination of the seed layer removal process; 3) ability to pattern lines and microvias at the same time; 4) reduced number of process steps by eliminating photograph lithography processes; and 5) via pattern integrity. One of the main challenges of the embedded trench approach is the removal of the copper overburden after the copper filling of trenches and vias by electrolytic plating. In prior work on Via2 technology, CMP processes adopted from wafer BEOL were used to remove the copper overburden, which limits the process application for panels and increases the process cost. Furthermore, the resolution of the trench width by the excimer laser has been limited in the traditional dielectric polymers. A recent study by Unimicron reported the successful trench formation down to 3-\( \mu \)m lines and spaces in a build-up dielectric material with small-sized filler [8]. The presence of large filler particles in the dielectric polymer has limited the formation of small trenches or microvias by laser processes [9]–[11].

In this paper, 2–5-\( \mu \)m copper embedded trenches in polymer dielectric layers were demonstrated by combining new materials and optimized processes that are scalable to large panels and have the potential for higher throughput and reduced manufacturing costs. Epoxy-based dry-film Ajinomoto build-up film (ABF) by Ajinomoto and preimidized polyimide base dry film by Fujifilm were selected as the primary dielectrics in this paper because of their superior chemical and mechanical stability as well as processability. The effect of the filler size on the trench profile was investigated by analyzing the excimer laser trench formation process in ABF films with different filler sizes and a polyimide material without fillers. After down-selecting the suitable materials, 2-\( \mu \)m small trenches and 20-\( \mu \)m pitch microvias were successfully formed by excimer laser ablation. After the laser process, metallization was conducted with seed-layer deposition and copper electroplating.
processes to fill the trenches and vias simultaneously. The excess copper overburden was removed by a surface planarization tool (DISCO Japan) as a higher throughput alternative to CMP [12]. Fig. 1 summarizes the process schematic of the embedded trench approach in this paper:

1) lamination of polymer dry film on the core substrate;
2) formation of trenches and vias by excimer laser ablation;
3) seed deposition by Cu electroless (Eless) plating or Ti-Cu sputter processes;
4) electrolytic Cu plating to fill trenches and vias;
5) planarization to remove copper overburden on the surface.

This paper is organized as follows. Section II describes the dry-film polymer materials selections for this paper. Section III discusses the formation of trenches and vias structured with excimer laser processes and the effect of filler size in the dielectric polymer. Section IV explains the metallization processes of the trench and via structures, including plating and surface planarization processes. Section V describes the initial demonstration of the multi-RDL layer stack-up with reliability under thermal shock testing.

II. DRY-FILM POLYMER DIELECTRICS

Selection of proper materials is critical for achieving ultra-small embedded wiring structures. Three different dry-film materials, ABF GX92, ABF GY50, and preimidized polyimide were examined in this research.

ABF is a compound material of epoxy polymer matrixes and inorganic fillers, being widely used in the packaging industry [13]. The chemical and electrical properties of epoxy polymer can be easily tailored by changing the chemical components. For better mechanical and thermo-mechanical properties, inorganic fillers (such as silica) are mixed with an epoxy matrix to make compounds. In this research, a traditional epoxy polymer composite material ABF GX92 and a new type of material ABF GY50 with smaller sized silica filler particles were studied to see the impact of different filler size on small trench formation. Although the two materials have different sized filler particles, their mechanical and thermomechanical properties are comparable.

Polyimide has been also used for variety of packaging applications such as wafer-level packaging and flexible substrates [14], [15]. Polyimide has strong absorption of UV light especially from 200 to 450 nm, which makes it superior in UV laser processing [16]. Additionally, due to lower coefficient of thermal expansion of polyimide compared to other polymers, the material can be used without filler particles, which has a large advantage in making small feature by excimer laser processing [17]. Polyimide is well known for its outstanding chemical, mechanical, and thermomechanical properties because of the strong imide bonding and molecular packing. On the other hand, due to this strong molecular interaction, typical polyimide materials have very high melting point and are nonsoluble in most solvents, which makes it challenging to process the materials. Therefore, for the industrial use of polyimide materials, precursor polymers are molded or laminated first, then exposed to a thermal baking process to complete polyimide formation. For a dry film application, the thermal baking step has disadvantages such as requirement of high temperature (> 300 °C) and large shrinkage during the baking. To address this issue, a new preimidized polyimide material by Fujifilm was recently developed. This material can be manufactured as dry film type, processed by lamination step, and then cured at 200 °C–250 °C [18]. In this research, dry-film-type preimidized polyimide material was used for a dielectric layer.

ABF and polyimide dry film materials were laminated on FR-4 or glass core materials. ABF films (15-μm-thick GX92 and GY50) were laminated with vacuum laminator at 120 °C, then oven cured at 180 °C. Polyimide film (8 μm thick) was laminated and cured with hot press at 250 °C. These materials showed high material flow during the lamination process to achieve flat surface.

III. TRENCH AND VIA FORMATION BY EXCIMER LASER

For making trenches and vias in polymer dielectric layers, an excimer laser system was used. One of the advantages of excimer lasers is the efficient ablation of polymer materials. Photon energy of excimer lasers is typically more than 4 eV, which is at the same level as the molecular bonding energy in polymer materials (C-H, C-C, C-O etc.). Additionally, polymer dielectrics have strong absorption of ultraviolet light, operating wavelengths of the excimer lasers, which induces efficient photon penetration into the polymer materials. As a result, the absorbed photons of the excimer laser initiate photograph-induced decomposition of the polymers from solid phase to gas phase directly [19]. The energy discharged during the transition converts to the velocity of the decomposed fragments, which leads to the explosive ejection of the fragments, called ablation [20]. The efficient ablation leads to the clean etching of polymer without heat damage. Another advantage of the excimer laser is the capability of mask projection laser processing due to large beam size [21], [22], which enables the formation of ultrasmall features such as trenches and
vias, defined by mask opening size. Since the location of trenches and vias are defined by the mask, high-positional accuracy is guaranteed, enabling pad-less microvia formation and accurate layer-to-layer registration. Furthermore, capability of mask projection results in high throughput processing by step-and-repeat platform and scalability to large panel production [23]. Excimer lasers are available in different laser wavelengths based on the type of active gases in the tools; 157 nm (F_2), 193 nm (ArF), 248 nm (KrF), 308 nm (XeCl), and 351 nm (XeF). UV light below 250-nm wavelength has strong absorption by glass materials, therefore F_2, ArF, and KrF excimer lasers are useful for glass processing [24]. However, these lasers cause inherent damages to the optical system made of glass materials after long time usage. Additionally, strong attenuation of laser occurs in the air due to absorption by oxygen at the ultrashort wavelength, therefore optical paths should be purged with nitrogen or argon, or vacuumed, which makes the system more complicated and expensive. In this research, a 308-nm XeCl laser was selected because of the inertness in the air and much less damage to the optics while having high-processing capability of polymer materials. Fig. 2 shows the experimental scheme of excimer laser ablation of the samples with mask projection. The excimer laser system used in this paper was ELP300 Gen2, equipped with Coherent LPXPro 305 (XeCl) and projection lens of 0.1 NA.

Using the mask projection laser process, trenches were formed in the samples. The depth of the ablated trench can be controlled by changing the number of laser pulses. Depths of trenches were measured for the various numbers of laser pulses (5, 7, 8, 9 shots) at 800 mJ/cm^2 and plotted in Fig. 3. It was confirmed that the ablation depth and number of laser pulses had a linear relationship.

To investigate the effect of filler size in polymer dielectrics on trench size and profile, samples with different ABF films, GX92 and GY50, were prepared. GY50 has smaller filler particles compared to GX92. A sample with polyimide, which does not include filler particles, was also prepared. Trenches with 3–4 µm depth were formed in these dielectrics by excimer laser under the same process conditions (six pulses of laser ablation at 800 mJ/cm^2) using a mask with 2–4-µm line and space structures. After titanium or copper thin layer (<0.1 µm) deposition with sputtering to minimize the film transparency, the profiles of the trenches were measured with a laser confocal microscope. Top views and profiles of the trenches are shown in Fig. 4. Profiles of the trenches were measured at the red broken line in the top view pictures. Trench profile in GX92 was much rougher than that in GY50 or polyimide. Additionally, trench walls in GX92 were collapsed due to the side erosion. Line and space trench structures down to 3 µm in GY50 and down to 2 µm in polyimide were successfully formed.

For more detailed analysis, SEM micrographs (5000×) of the 4-µm trenches in the same samples were prepared as shown in Fig. 5. As seen in the SEM images, most filler particles with diameter of around 1–2 µm were found in GX92, whereas filler particles in GY50 were much smaller, less than 1/10 of the particle size of fillers in GX92. The trench side wall roughness was much higher in GX92, and this can be explained on the basis of the ejection of large filler particles from the side walls since the magnitude of the roughness in the trench side walls was approximately equal to the size of filler particles. The trench side wall roughness in GY50 was significantly lower, due to the smaller size filler particles, and the side wall roughness was roughly equivalent to the filler particle size. The trench side walls in the polyimide material had the lowest surface roughness, which is consistent with the fact that the polyimide dielectric did not include any filler particles.

Due to the rough surface in GX92 samples, large side erosion of the trench was observed and trench width was extended by more than 2 µm on each side. As a result, trenches below 5-µm line and space could not be yielded in GX92. In contrast, side erosion of trenches in GY50 was much smaller, below 0.5 µm on each side, which resulted in successful formation of trenches down to 3-µm line and space (6-µm pitch). In the case of polyimide, 2-µm line and space structures were successfully demonstrated due to minimized side erosion.

After the formation of trenches, microvias were drilled also by excimer laser. First, trenches with 20-µm width and 5-µm depth were created in 15-µm-thick GY50 with nine pulses of mask projection excimer laser ablation. Thereafter, using a different mask, 10-µm-deep microvia with 8 µm diameter were formed by 20 pulses of laser ablation. Top view and
profile of the structure are shown in Fig. 6. No damage in the bottom copper pad was observed. Side wall angle of a microvia were measured as 75°.

IV. METALLIZATION OF TRENCH AND VIA

Before the metallization step, cleaning processes were applied to the samples to remove residual debris sitting on the surface during the laser process. Chemical desmear processes included immersion of samples in three different chemicals sequentially: 1) swelling at 60 °C for 10 min; 2) permanganate etching at 77 °C for 10 min; and 3) neutralization at 50 °C for 5 min. Metallization fill processes of the trenches and vias were carried out with metal seed deposition, followed by electrolytic plating. For seed layer deposition, Eless Cu plating was used for ABF samples to form 0.2 µm thick Cu seed layer. For polyimide samples, Ti-Cu sputtering seed (0.03 µm Ti and 0.1 µm Cu) was deposited. After the seed deposition processes, trenches and vias were filled with copper by electrolytic plating. To achieve effective filling in the trenches and vias, right selection of plating chemistry and electrolyte flow is very critical, and two different configurations of plating processes were examined in this research. One configuration used Cupracid TP by Atotech and nozzles facing parallel to the samples (process tank A), while the other configuration used Inpro THF by Atotech and nozzles facing perpendicular to
The profile was measured at the red line in the top view.

Fig. 7. Trench filling by different electrolytic plating processes. (I) Before plating. (A) After 40 min plating at 10 A with tank A. (B) After 40 min plating at 10 A with tank B.

The samples (process tank B). Nozzles with parallel direction create a laminar flow on the surface, whereas one with perpendicular direction creates turbulence. The samples had trenches with 20-µm width, 60-µm length, and 5-µm depth. After 40 min of electrolytic copper plating at 10 A in each process, profiles of the plated trenches were observed with an optical profiler (Fig. 7), and thickness of copper on the sample surface was measured with an electrical thickness gauge. From tank A, plated copper thickness on the surface was 5 µm, and the depth of the dimple was 3.2 µm. From tank B, copper thickness on the surface was 6 µm, and the depth of the dimple was 0.2 µm. This result indicates the process with tank A was closer to conformal plating, whereas tank B process was more trench filling plating. Plating with tank B has an advantage in effective copper filling in trenches without depositing thick copper on top of the surface.

After filling of the trenches and vias, copper overburden on the surface needs to be removed for process completion. Copper etching is the simplest method, however, control of the etching thickness is extremely challenging. Given the as-plated complex surface profiles, wet etching process poses a high-risk of over-etching in the trench. In this research, DISCO’s surface planer process equipment was used for the planarization overburden removal step because of lower CoO and scalability to panel-base manufacturing due to its simplicities in the equipment kinematics. The surface planer process can effectively remove ductile materials such as metals and/or polymers from the surfaces of substrates. The process point consists of a single bit made of diamond, which is mounted on a spindle rotating at high speed at a fixed height. The substrate is fixed on a flat chuck table that is creep-fed under the rotating bit that is barely contacting the surface (Fig. 8). The surface of the chuck table is in precise parallelism with the plane defined by the rotation of the processing bit. As the tool shaves the substrate, the unevenness of the ductile material on the surface is carved off, leaving an extremely flat surface with excellent total thickness variation (TTV) control across the substrate. In case of this paper, the copper overburden was removed in this fashion.

Thickness variations under the top layers inside the samples can affect the precise cutting of the plated surfaces. To illustrate the impact of TTV on planarization, two samples with different core substrates were prepared. First, 15-µm-thick ABF GX92 films were laminated on both 6-in square FR-4 (700 µm thick) and glass (500 µm thick) panels. TTV of 6” square FR-4 panel was 4 µm, while that of glass panel was 1 µm. In the laminated ABF layers, trenches with 3-µm depth were formed by excimer laser ablation. Subsequently, trenches were filled with copper by Eless plating and electrolytic plating processes. The surface planer tool was used to remove overburden copper from the samples, and the inspection results were compared in Fig. 9. In the sample with FR-4 core, residual copper can still be observed in the center device area, while adjacent die areas were already showing
signs of over-cutting. This is because of the unevenness of the FR-4 core. In contrast, uniform cutting was observed in the sample with glass core, which has even TTV. Some residual copper was seen at the edge of the glass sample, which is due to the edge setups from the plating process. Magnified images of the four corner coupons in the glass core sample are displayed in Fig. 10. This result indicates low TTV core, or coplanar-base layer treatment, is critical for fine-line RDL formations.

To demonstrate small trench structures, samples with polymer dielectrics on glass panels were prepared, and embedded trench processes were applied. Fig. 11 shows the top view of the small trenches made by the processes. Trench structures with 5-µm width on GX92, 3 µm on GY50, and 2 µm on polyimide materials were successfully achieved.

V. MULTILAYER RDL DEMONSTRATION

A sample with a multilayer RDL structure was also fabricated by repeating the process steps. Initial demonstration was conducted using GX92 polymer dielectric, excimer laser, and surface planarization processes. After the first embedded copper layer formation on GX92, second metal layer was fabricated from lamination of 15-µm-thick GX92 film on top of the first layer. Thereafter, both trenches and vias were
formed in the top dielectric layer by two steps of laser ablation. Then, Eless copper plating and electrolytic copper plating were used for filling in the trenches and vias, followed by surface planarization to complete multilayer fabrication. Top view and cross-sectional view of the fabricated daisy-chain structure with 20-µm pitch microvias are shown in Fig. 12. Cross-sectional pictures from different locations in a sample with lower magnification are shown in Fig. 13. Highly planarized metal structures at large scale can be confirmed from the pictures. Via diameter was 8 µm, and pad width was 15 µm. Demonstration of multilayer RDL structure with smaller design rule using GY50 is currently under development.

Daisy-chain coupons at three different via pitches (20, 30, and 40 µm) were fabricated, and an initial reliability test was performed. Resistances of the daisy-chain coupons with 100 of microvias were measured before the test and after 100, 500, and 1000 cycles of liquid-to-liquid thermal shock test between −55 °C and 125 °C. The resistance of the coupon with 20-µm pitch was higher than those of 30- and 40-µm pitch because the wiring widths in 20-µm pitch design were narrower; 15 µm wide for 20-µm pitch design and 20 µm wide for 30- and 40-µm pitch design. No failure (failure criteria: 10% increase in resistance) was observed for all of the coupons (Fig. 14) up to 1000 cycles.

VI. CONCLUSION

High-density RDL with 2–5-µm trenches was demonstrated using advanced dry-film dielectrics with excimer laser-based embedded trench approach. The approach comprises excimer laser ablation, copper seed layer formation and electrodeposition, and surface planarization process steps. The effect of filler particles in the polymer dielectric materials on fine-pitch trench formation was investigated. It was concluded that dielectrics with smaller fillers have an advantage in fine-pitch trench formation. By down-selecting the suitable materials, small RDL copper transmission lines down to 2 µm were successfully demonstrated. The embedded trench approach also integrates small microvia formation for layer-to-layer interconnection, and multilayer RDL structures with 20 µm pitch was successfully fabricated. The materials and RDL formation processes discussed in this paper can be scaled to large panels, providing a path for high-volume manufacturing of high-density interposers and fan-out packages at lower cost than wafer-based silicon interposers.

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REFERENCES


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