Smaller Microvias for Packaging Interconnects by Picosecond UV Laser With a Nanometer Metal Barrier Layer: A Feasibility Study

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***Abstract*—This study, to the best of authors' knowledge, is the first to investigate the feasibility of using picosecond UV laser ablation to fabricate ultrasmall microvias scaled down to 3 μm and less with a pitch of 8 μm in a 5-μm Ajinomoto buildup film (ABF). The state-of-the-art microvias are 20 μm in diameter by a nanosecond UV laser and 5 μm in diameter by a picosecond UV laser reported in our previous study, but microvias of less than 2 μm in diameter are needed to meet IO density requirements for today and future's high-bandwidth packaging and heterogeneous system integration. In this study, we have investigated the impact of laser power, beam sizes, and materials on the via size and explored the feasibility of picosecond UV laser ablation for ultrasmall microvias with an additional layer of 80-nm-thick copper on top of the dielectric as a barrier layer. The power used to fabricate the 5-μm microvias in a 5-μm-thick ABF could open 2-μm holes in the copper barrier layer due to the higher ablation threshold of copper. The drilled copper layer then serves as a mask to produce smaller microvias in the dielectric layer beneath the copper. In this article, fully opened microvias of 3 μm diameter in ABF will be demonstrated. Submicrometer openings in copper are also achieved, which suggests the feasibility to scale down via diameter to submicrometer level.**

***Index Terms*—Ablation thresholds, barrier layers, microvias picosecond UV lasers, redistribution layer (RDL).**

I. INTRODUCTION

MICROVIAS are one of the key elements of the redistribution layer (RDL) in high-density interconnect printed circuit boards (HDI-PCBs), wafer-level chip-scale packages (WLCSPs), flip-chip ball-grid-array packages (FC-BGA), HDI package substrates, 2.1-D and 2.5-D interposers (organic, glass, silicon, and so on), and fan-out packaging. Smaller microvias are crucial to achieve higher IO density by saving real estate in the die area for routing wires to escape through a fine IO pitch for multichip packaging (MCP). They also help protect signal integrity by lowering insertion loss and impedance discontinuity in high-speed PCBs [1]. The current IO density of traditional MCP is about a few tens of IOs/mm/layer and the minimum pitch is about 40–50 μm. Sabi [2] pointed out that the IO density requirements for MCP are in the order of approximately hundreds of IOs/mm/layer today and will be approximately thousands of IOs/mm/layer in the future. Meanwhile, the die-to-package interconnect pitch is currently around 50 μm and is expected to be around 10 μm in the future. Intel published a chart of IO density versus substrate features (CDs) in terms of the sizes of lines, spaces, and microvias [3]. The current 2-D packaging utilizes line/space/microvia (in μm) from 15/15/65 down to 5/5/40, where the microvias are fabricated by UV laser ablation. The next-generation 2-D packaging requires features down to 2/2/8, and organic photovias are the most viable approach to achieve smaller microvia fabrication. The next-generation 2.5-D enterprise computing will need features scaled down to 2/2/2 where the main difference from 2-D packaging is the microvia size (from 8 to 2), while the line/space remains at 2 μm. Thus, it can be inferred that microvias play the critical role in the next-generation 2.5-D packaging interconnects.

Laser drilling is a process of record (POR) in the packaging industry, and it is the most economical method for mass production. Ease of production, flexibility, performance, cost effectiveness, and availability of more material selections are the reasons for the widespread use of laser drilling. UV laser beams can be focused to a very small beam size which is of immense significance for small microvia formation [4]. Patel *et al.* [5] compared the micromachining quality and the cost of UV lasers with pulsewidths of nanosecond, picosecond, and femtosecond and then concluded that picosecond and femtosecond lasers are favored for high-throughput and high-quality micromachining at lower cost per watt of laser power. The state-of-the-art microvia reported was 20 μm in diameter by nanosecond UV laser [6]. Tan *et al.* [7] reported the first sub-10-μm microvia by using a high-repetition-rate femtosecond UV laser. In our previous study, we demonstrated 5-μm microvias in 5-μm-thick Ajinomoto buildup film (ABF) by using a UV laser with a pulsewidth of 5 ps [8], [9].

UV lasers can ablate not only polymer dielectrics but also metals, such as copper [10]. Resin coated on copper (RCC) foil approach is commonly used for via fabrication in the modified semiadditive process (m-SAP) for HDI-PCBs. In particular, two ablation methods are used in m-SAP. One is a hybrid laser ablation, which includes a combination of UV and

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CO_2 lasers [11], and the other is two-step UV laser ablation [12], [13]. Lei and Davignon [14] reported 18-μm blind via drilled in 25-μm polyimide on a copper foil and 100-μm blind via in liquid crystal polymer on a copper foil. In this study, 80-nm-thick copper was deposited by physical vapor deposition (PVD) on top of an ABF film. With the thin copper serving as a barrier, fully opened 3-μm microvias in 5-μm ABF were fabricated; 1-μm and submicrometer openings in copper were also achieved, which shows the potential of scaling down microvia diameter even further.

II. FUNDAMENTALS OF LASER ABLATION FOR MICROVIAS

A. Laser Systems for via Formation

Laser ablation was rapidly developed and has been dominating the microvia market since 2000. More than 93% products are drilled by laser [14]. There are four different laser systems for via formation: CO_2 lasers, UV lasers, hybrid (UV and CO_2) lasers, and excimer lasers. CO_2 lasers emit infrared beams over wavelengths in the range of 9.3–10.6 μm. The advantage of CO_2 lasers is the high drilling speed. However, they are not capable of making small microvias as these infrared beam sizes are large. UV lasers typically operate at a wavelength of 355 nm. It can produce precise and small vias in dielectric polymers. The hybrid laser drilling system, a combination of UV and CO_2 lasers, is used on RCC. An excimer laser having a wavelength of 308 nm utilizes an optical lens to project the laser beam onto the dielectric surface through a special mask to ablate the dielectric layer. Laser ablation is precise and flexible, and it has low induced stress in PCB and packaging processing. However, the ablation efficiency depends on the wavelength of the lasers employed and materials being processed. Resins typically have a very strong absorption in UV and IR wavelengths, whereas copper has strong absorption in the UV region [15].

B. Gaussian Beam and Ablation Threshold

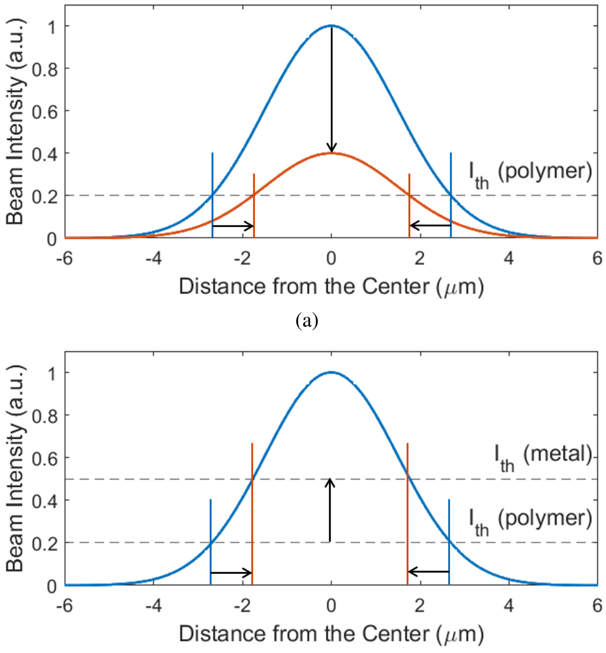
The laser beam intensity (I) as a function of the distance from the center (r) of the focal plane follows the Gaussian distribution and it could be described as

$$I(r) = \frac{P}{\pi r_0^2/2} e^{-2\frac{r^2}{r_0^2}} \tag{1}$$

where P is the average laser power and r_0 is the beam radium. The beam intensity reaches its maximum at the center ($r = 0$) and decreases as the distance from the center r increases. The beam intensity is directly proportional to the laser beam power but inversely proportional to the beam size. At a given laser power, the smaller the beam radius, the higher the beam intensity.

To simplify the discussion, let us consider $I_m = (P/\pi r_0^2/2)$ as the maximum beam intensity and $D_0 = 2r_0$ as the beam diameter. Thus, (1) could be rewritten as

$$I(D) = I_m e^{-2\frac{D^2}{D_0^2}}. \tag{2}$$



(a)

(b)

Fig. 1. Laser beam intensities and ablation thresholds of materials. Reducing the via size by (a) lowering laser power and (b) changing the material.

For a given material with an ablation threshold I_{th}, it could be derived from (2) that

$$D = \sqrt{\frac{1}{2} \ln \frac{I_m}{I_{\text{th}}}} D_0 \tag{3}$$

which describes the impact of the beam size D_0, the beam power in terms of the maximum beam intensity I_m, and the ablation threshold I_{th} on the diameter of the ablated via D. Three approaches could be pursued to achieve smaller microvias based on (3), which are reducing the beam size, lowering the beam power, and increasing the ablation threshold. For a laser drilling system, the beam size at the focal plane is already the smallest along the laser beam and could not be adjusted to even smaller. Once the laser beam is focused at the surface of the material to be drilled, only two other approaches could be considered to reduce the via size.

By reducing the laser power as shown in Fig. 1(a), via size could be reduced. Theoretically, as long as the maximum beam intensity is larger than the ablation threshold, the laser beam is capable of ablation on the material, so the via size could be infinitely small. However, when the maximum intensity is larger than but very close to the ablation threshold, the via quality would be degraded due to thermal effects and beam power fluctuation.

An alternative to fabricate smaller microvias is to increase the ablation threshold instead of lowering the laser power as shown in Fig. 1(b), which is to change the material to be drilled. By adding a material with a higher ablation threshold such as a thin metal film as a barrier layer, the same laser power would open a smaller hole in the barrier layer. The hole in the barrier layer confines the area of ablation in the dielectric material by the following laser pulses. The barrier layer then

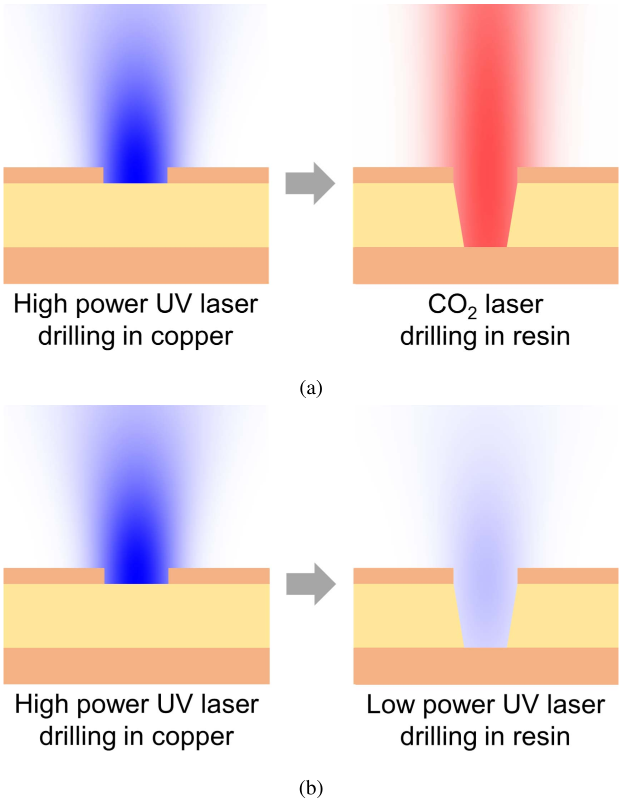


Fig. 2. Schematics of laser drilling on RCC with (a) hybrid laser system and (b) two-step UV laser drilling system.

serves as a mask for the polymer beneath and enables the fabrication of smaller microvias.

C. Laser Drilling on RCC

Adding a copper layer on resin for microvia ablation has been adopted before. To reduce the process complexity in the semiadditive process (SAP), an RCC approach was developed to replace electroless copper, which is called m-SAP [16]. In this approach, a few micrometer thick copper foil was employed as the seed conductive layer. A hybrid laser system, which consists of a UV laser and a CO_2 laser, to fabricate microvias on RCC for PCB manufacturing is employed in [17]. A controlled high-power UV laser was used first to make holes in copper, followed by a CO_2 laser ablation to remove the resin through the hole in copper to form microvias, as shown in Fig. 2(a). CO_2 laser would not damage the copper beneath the resin (via pad) since copper does not have any absorption at the IR wavelength of CO_2 lasers [15].

Another method for RCC is two-step UV laser drilling [12], [13]. Drilling copper was accomplished by using a controlled high-power UV laser. The power of the UV laser was well controlled in such a way that it does not lead to any damage to the resin used. Following the initial drilling, the same UV laser was adjusted to be working at lower power to accomplish drilling of the resin, as shown in Fig. 2(b). Using 355-nm UV laser, polyimide on copper was investigated theoretically and experimentally by Shin *et al.* [18]. Shin *et al.* [18] employed higher laser power for copper ablation and followed by lower power for polyimide ablation.

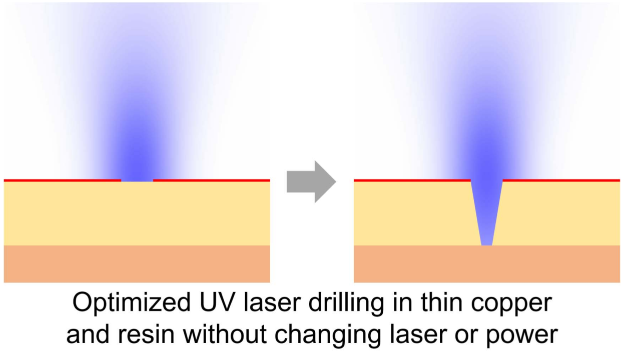


Fig. 3. Smaller microvias fabricated in thin copper and resin by optimized UV laser drilling without changing laser or power.

D. UV Laser Ablation on a Nanometer Copper Barrier Layer

The top copper foil in the RCC approach has a thickness of a few micrometers, which requires a high power to remove. By reducing the thickness of the top copper foil, it is possible for a laser beam with lower power to remove copper. With a well-controlled low-power laser drilling, the diameter of the opening in the copper layer could also be reduced.

After a hole is opened in copper, the subsequent laser pulses will ablate the exposed dielectric material and then remove the residue. Holes in the copper confine the area of ablation by laser pulses in the dielectric material. With the optimization of laser power and punch number, small microvias could be fabricated with minimum damage on the bottom copper layer. Fig. 3 shows the process of optimized UV laser drilling on thin copper and then dielectric layer without changing laser type or power.

III. EXPERIMENTAL SETUP AND PROCESS FLOW

A. Picosecond UV Laser System

The laser system used in this study is Corner Stone, a picosecond UV laser developed by Electro Science Industries. This laser system has a 16-W coherent solid-state laser that generates 355-nm laser pulses with a pulsewidth of 5 ps at a repetition rate of 80 MHz. Multiple drilling methods, such as spiral raster, tripling, as well as controlled number of punches, can be selected for via ablation. In this study, punch mode is used for small microvia fabrication. One punch consists of 400 laser pulses in this system.

B. Dielectric Material

ABF-GX92 is a low thermal expansion coefficient (CTE), nonphotoimageable dry film polymer dielectric, which is a very common material used in the packaging industry [19]. The basic material in ABF-GX92 is epoxy, and fillers are added to reduce CTE. Some properties of ABF-GX92 are listed in Table I. The dielectric material used in this study

TABLE I
PROPERTIES OF ABF-GX92

Property	Condition	Value
CTE / ppm/°C	TMA	39
T_g / °C	TMA	153
D_k	Cavity perturbation 5.8 GHz	3.2
D_f	Cavity perturbation 5.8 GHz	0.014
Young's modulus / GPa	23 °C	5.0

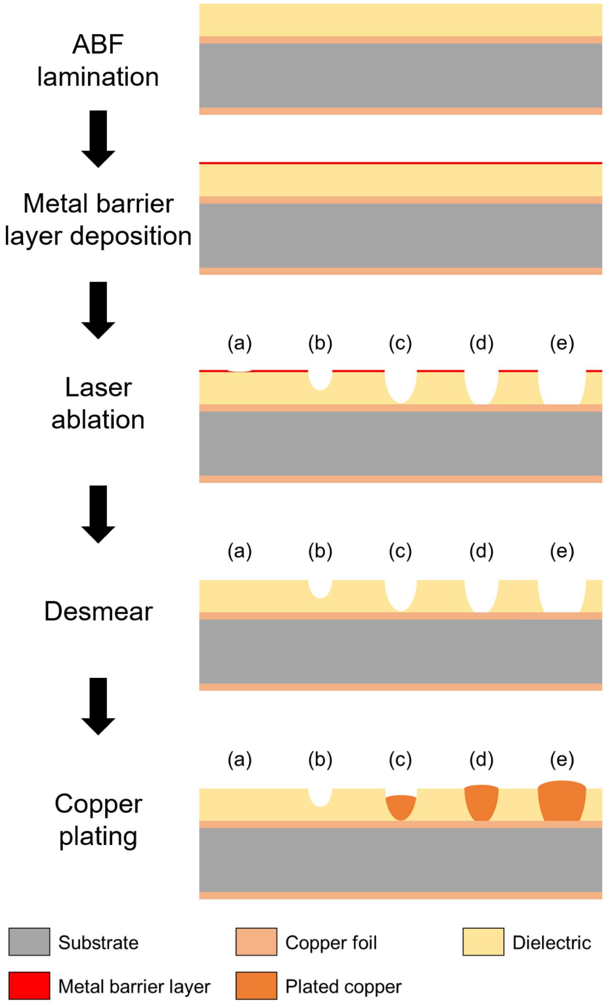


Fig. 4. Process development flow of ultrasmall microvia fabrication. (a) No via opened due to insufficient fluence on the metal barrier layer. (b) No via opened due to insufficient fluence on the metal barrier layer and the polymer layer. (c) Barely open via. (d) Small opening via. (e) Large opening via.

is ABF-GX92P, a modified ABF-GX92 with finer fillers to enable ultrafine RDL. The thickness of the dry film reported in this article is 5 μm.

C. Testing Structure and Process Flow

The substrates used in this study include organic laminates that consist of a 100-μm-thick core and 3-μm-thick copper foils on both sides. The process flow is shown in Fig. 4, and the details are listed as follows.

1) ABF-GX92P Lamination: ABF-GX92P (yellow in Fig. 4) was laminated on the substrate in Meiki MVLP 300, a vacuum laminator. The laminated substrate was then cured in an oven with the cover sheet on.

2) Metal Barrier Layer Deposition: After cure, the cover sheet was peeled off, and a copper layer of around 80 nm thick (red layer in Fig. 4) was deposited on top of the cured ABF-GX92P in Denton Discovery 635, a sputtering system, to form the barrier layer.

3) Laser Ablation: Sputtered samples then were placed in the laser drilling system for via fabrication. As we discussed in the previous study, laser power, the number of punches, and beam position are three key processing factors to optimize for small via formation. Various combinations of these parameters were utilized in the development of this process. One can visualize five scenarios highlighted in Fig. 4 that could happen after laser ablation depending on the settings of the parameters mentioned earlier. If the power and the number of the punch are not enough, scenario (a) could happen in which laser ablation does not remove enough copper to reach the polymer beneath. If the power and the punch number combination are sufficient in removing copper in the barrier layer but not enough to remove the polymer and then reach the copper foil as shown in scenario (b), a blind via or a dent is fabricated, but it could not be used for electrical interconnects from the top to the bottom copper foil. In scenario (c), a via is barely open. If the laser power and the punch number are optimized, a small and fully open via could be achieved, such as in scenario (d). When the laser power is larger than the optimized power in scenario (d), a larger via might be opened as in scenario (e), which reduces via density and consequently interconnect density.

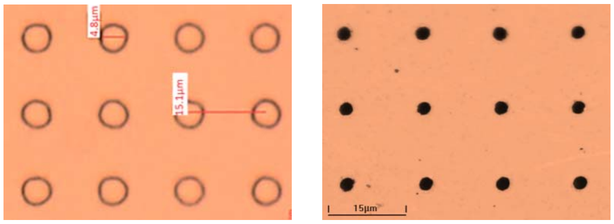
4) Desmear: The drilled samples were subjected to the plasma desmear process in a plasma chamber following the ablation process. The sample was cleaned by 2–4 min of plasma desmear (O_2 plasma with 250-W forward power). Plasma desmear would remove debris or residues in the drilled via holes without damaging the barrier copper layer. It could also help open the microvia and subsequently expose the copper foil in scenario (c).

5) Barrier Layer Removal and via Metallization: After the desmear process, the metal barrier layer was removed by chemical etching. With the copper foil at the bottom serving as a conductive layer, bottom–up electroplating was used to fill copper in microvias (orange in Fig. 4). With the copper filling up microvias from the bottom, it is easy to inspect samples under the microscope even though the via size is about a few micrometers.

D. Optimization of Laser Ablation

Laser power, punch number, and beam position are the three key operating parameters to optimize for small via formation. In our previous study, laser ablation was performed directly in the polymer layer. In this study, however, a metal barrier layer is added to further scale down the via size.

The first step in laser ablation optimization is to determine the optimal beam position so that the beam focal plane is at the surface of the substrate to be drilled. In the previous



(a) (b)

Fig. 5. 0.1-W laser fabricates (a) 5-μm openings in ABF and (b) 2-μm openings in copper.

study, the laser power for the smallest microvias was 0.1 W. Here, the laser power is set to be 0.1 W and the drilling is on the bare polymer film as a reference. The drilling system is set in which the beam focal plane moves along the Z-direction over a in a wider range (from -500 to 500 μm with an increment of 50 μm), and then, it is fine-tuned in a narrower range (from -400 to 0 μm with an increment of 20 μm) until the best beam position range is found where microvias are the smallest with the best quality.

The second step is to determine the power required for via formation in copper. Once the optimal beam position is found in the first step (Z is set to 0), a sample with metal barrier layer on top is placed on the vacuum stage in the laser drilling system. In the laser system, the power is set from 0.1 to 0.5 W where the power in increased slowly with an increment of 0.05 W. For each power, a matrix of 20 × 20 (400 in total) microvias is fabricated. Then, the optimal combination of laser power and beam position on copper will be found after the ablation is finished.

The final step is the optimization of the laser power, beam position, together with the number of punches to achieve fully open microvias with minimum via opening.

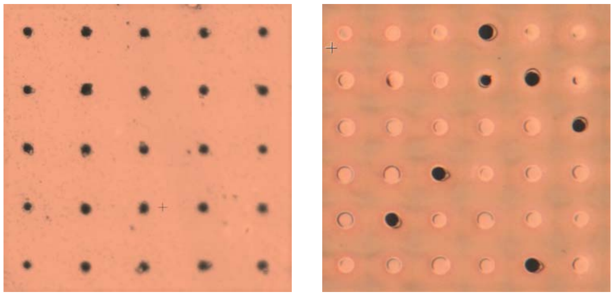
IV. Results and Discussion

A. Laser Ablation in ABF Versus Copper Barrier Layer

Laser ablation in the copper barrier layer on ABF and laser ablation on the bare ABF film were studied and compared. Under the condition of the optimal beam position, 0.1-W laser power, and 1 punch, the via diameter achieved in the bare ABF was around 5 μm as shown in Fig. 5(a), and the same condition resulted in around 2-μm holes in the 80-nm copper barrier layer, as shown in Fig. 5(b). The ablation threshold of copper is much higher than ABF, so the same laser power would open smaller microvias in copper than in ABF.

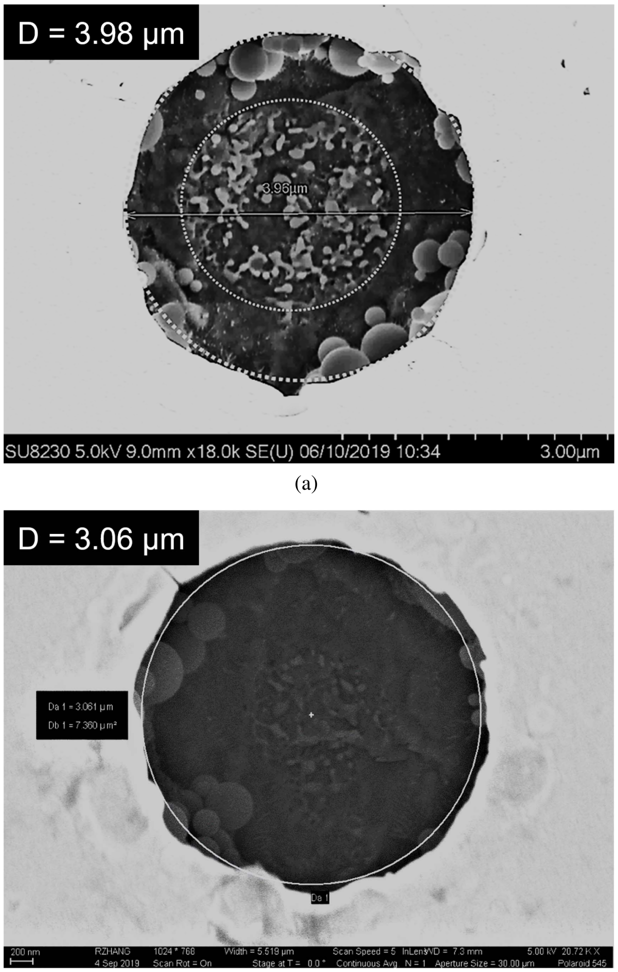
B. Impact of Beam Position on Laser Ablation

Beam position plays a critical role in small via formation. The highest beam intensity is at the center of the focal plane, and the laser beam becomes wider and has lower intensity along both sides away from the focal plane in the Z-direction. When the beam focal plane is at the surface of the substrate, the maximum amount of the photons in the beam would be used for ablation, the ablation would be the most efficient, and it could open a deeper hole in the substrate. When the laser power is 0.1 W and the beam is at the optimal position, the laser could open all 2-μm holes in copper, as shown in Fig. 6(a). If the laser beam is not at the optimal position, the barrier layer may not be completely removed and not all holes could be opened, as shown in Fig. 6(b).



(a) (b)

Fig. 6. (a) All 2-μm openings in copper are through when the laser beam is at the optimal position. (b) Some openings are through with a diameter of 3 μm when the beam is not at the optimal position.



(a)

(b)

Fig. 7. SEM images of laser ablated microvias in 5-μm-thick ABF with a diameter of (a) 3.98 and (b) 3.06 μ.

C. Fully Opened Small Microvias in ABF With 80-nm Metal Layer

After the optimal beam position was located and Z height was set to 0, different laser powers were used to fabricated

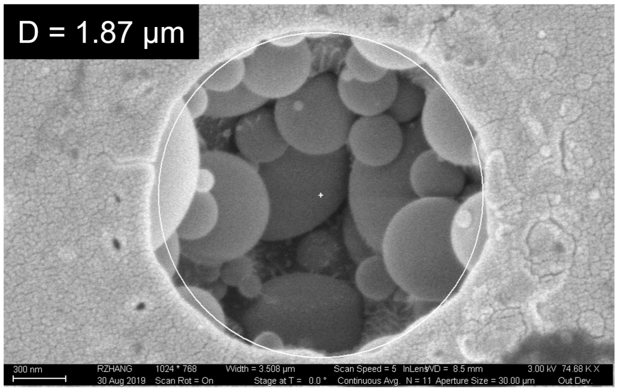


Fig. 8. 0.1-W laser ablates 2-μm opening with fillers inside.

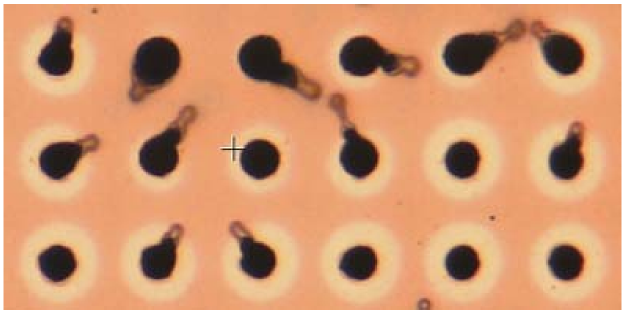


Fig. 9. Debris around the opening on the surface of copper barrier.

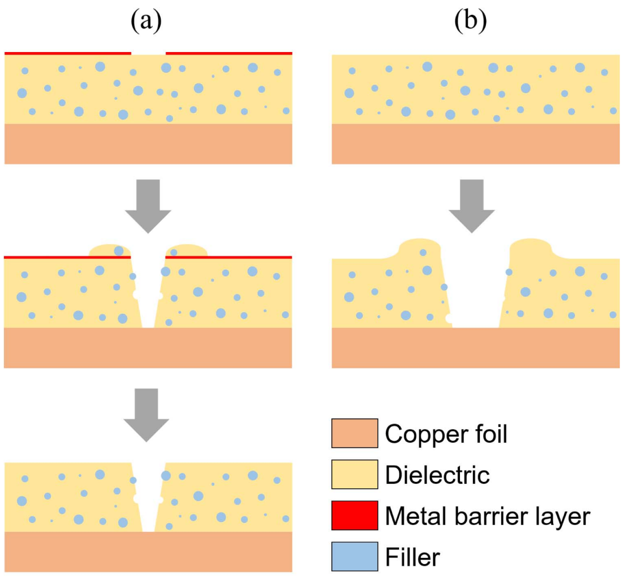


Fig. 10. Schematic of redeposition on (a) ABF with a metal barrier layer and (b) bare ABF.

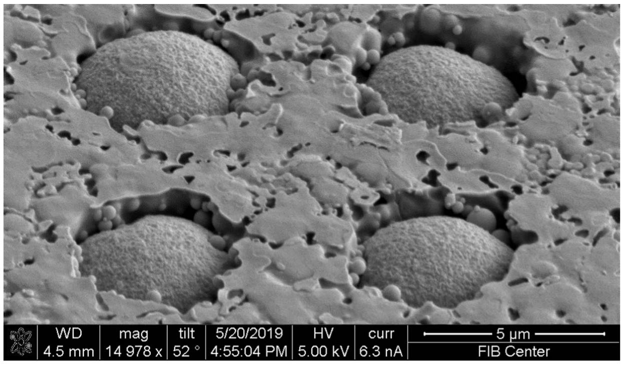


Fig. 11. SEM image of microvias with a clean surface after barrier removal and copper plating.

small microvias. SEM images of fully opened microvias with the diameters of 4 and 3 μm, ablated with the beam power of 0.2 and 0.15 W, respectively, are shown in Fig. 7. There are a few residues at the bottom and some fillers on the sidewall; however, these microvias have round openings, the surface is clean, and side walls are nearly vertical. It can be concluded that fully opened microvias with a diameter down to 3 μm in 5-μm-thick ABF were achieved by adding a thin copper barrier. The highest aspect ratio of fully opened microvias is 1.67.

Laser power of 0.1 W could open less than 3-μm holes in copper and then remove some material in ABF, but it was not able to form a fully opened microvia since fillers are too difficult to remove by laser, and they are large enough to block further laser ablation. Fig. 8 shows an SEM image of a 2-μm opening with fillers inside.

D. Surface Protection Due to Metal Barrier Layer

During laser ablation, the material in the ablated region will be vaporized and leave the region. After laser ablation, such vapor or plasma, might redeposit back to the substrate, as shown in Fig. 9. By adding a metal barrier layer, redeposition would be separated from the original substrate, as shown in Fig. 10(a). Without such a layer, redeposition together with thermal effects from laser ablation would lead to slugs around the opening, as shown in Fig. 10(b), which adversely affected the planarity of the surface. After laser ablation, chemical etching was used to remove the top copper barrier layer, followed by 4-min O_2 plasma descum to remove the debris at the bottom. By removing the copper barrier layer, redeposition on top of the copper would also be removed, which results in a more uniform and flat surface and higher quality opening on microvias, as shown in Fig. 11.

E. Desmear and Copper Plating

After copper removal and desmear, samples then underwent bottom–up electrolytic plating to fill microvias with copper. Fig. 12 shows a cross section of 4-μm microvias with 8-μm pitch prepared by focused ion beam. The bottom of the microvia has a diameter of 3.3 μm.

F. Feasibility of Submicrometer Microvias

As seen in (3), the via diameter can be infinitely small as long as the peak intensity is slightly larger than the material ablation threshold. By adjusting the power down, microvias with smaller opening can be achieved. Fig. 13(a) shows a matrix of 1-μm openings in the copper layer fabricated by the picosecond UV laser system with laser power lower than 0.1 W. Initial characterization shows that the microvias are

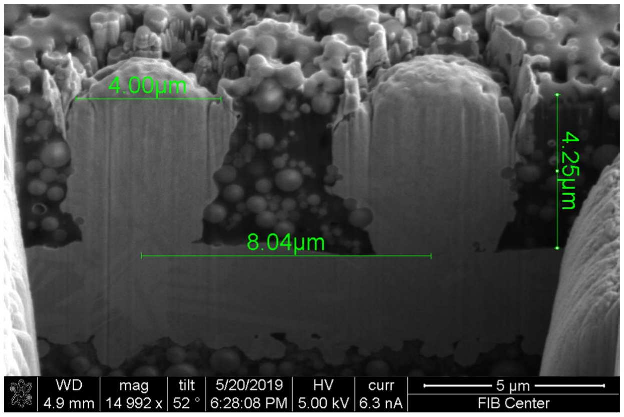
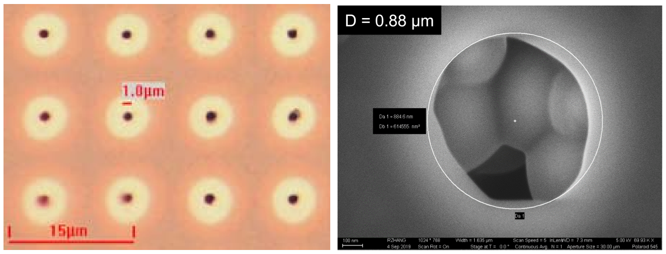


Fig. 12. SEM/FIB cross section image of microvias of 4-μm diameter and 8-μm pitch after barrier removal and copper plating.



(a) (b)

Fig. 13. (a) Optical image of a matrix of 1-μm openings in copper. (b) SEM image of a submicrometer opening and fillers trapped inside.

of good quality and uniform, which indicates the potential of volume manufacturing. An SEM image of a submicrometer opening is shown in Fig. 13(b). The opening is so small that the fillers inside are not capable of escaping through the opening. However, if the filler size is reduced or no fillers are added in the dielectric materials, microvias scaled down to submicrometer in diameter are feasible. This is under investigation and development now.

V. SUMMARY

As the semiconductor industry continues advancing from 7 to 5 nm and even further toward 3-nm node, the strategic needs for packaging interconnections are greater IO density ($\geq$500 IO/mm/layer) and finer ($\leq$ 10 μm) IO pitch. Reduction of critical dimensions of routing lines and spaces necessitates further reduction in the diameter of the microvias. The today's bottleneck of achieving denser IOs and smaller IO pitch is the microvia formation.

In this article, we discussed the fundamentals of picosecond UV laser ablation, analyzed the beam intensity of a Gaussian beam, and set up the relationship between the ablated via diameter and the beam diameter, laser power, and the material ablation threshold. Based on the relationship, an approach of adding nanometer copper barrier layer was proposed and tested. With the use of 80-nm copper, fully opened microvias as small as 3 μm in diameter with a pitch of 8 μm in 5-μm ABF were successfully demonstrated. This may correspond to an improvement of 6.7 times IO density of the state-of-the-art 20-μm microvias by a nanosecond UV laser and 1.7 times of our previously reported 5-μm microvias by a picosecond UV laser. Submicrometer openings in copper were also achieved, which indicates the feasibility of even smaller microvias if smaller fillers or no filler dielectric films are used.

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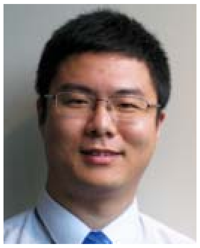

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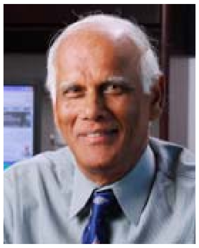

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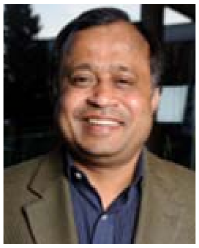

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