Improved Productivity and Quality in Drilling Insulating Film Using GHz-burst DUV Picosecond Laser

Alexandre Rondepierre*[1], Naoyuki Nakamura[1], Nozomi Hirayama[1], Junichi Nishimae[1], and Keisuke Furuta[1]

[1]*Mitsubishi Electric Corporation, Advanced Technology R&D Center, Japan*
[*]*Corresponding author's e-mail:* Rondepierre.Alexandre@aj.MitsubishiElectric.co.jp

GHz-burst deep-ultraviolet (DUV, 266 nm) picosecond laser percussion drilling was evaluated for high-density microvia fabrication in a polymer resin with glass filler (Ajinomoto Build-Up Film™ (ABF™)) targeting next-generation printed circuit board (PCB) packaging. A custom burst module delivering intra-burst trains (with 2-16 pulses) at 1.9-3.8 GHz was applied with top-hat beams of 5, 10 and 15 µm (FWHM) on two ABF™ grades (A: fine filler ; B: conventional filler). Drilled vias were examined by digital and SEM microscopy to quantify ablation threshold, shots-to-completion, taper ratio, and bottom/copper morphology. Our experimental exploration demonstrates that GHz-burst operation lowered ablation thresholds by up to 50%, accelerated drilling by 40-50%, and improved taper ratios by 10-15% relative to single-pulse regime, while producing smoother ablation and reduced heat-affected features. These findings indicate that GHz-burst picosecond DUV drilling can substantially enhance both productivity and via quality for advanced, high-density PCB manufacturing.
DOI:10.2961/jlmn.2026.02.2011
Keywords: GHz burst, DUV, picosecond laser, microvia drilling, insulating film, processing speed and quality

1. Introduction

The rapid development of high-performance computing, artificial intelligence, and heterogeneous integration has accelerated the transition from monolithic system-on-chip architectures to advanced chiplet-based packaging. In these architectures, multiple functional dies are integrated within a unified package to improve yield, reduce cost, and increase design flexibility. As a result, the package substrate must support much higher interconnect density than conventional electronic packaging. Therefore, microvia diameters shrink and production throughput demands rise [1]. While increasing the processing speed is one key requirement, another one lies with the challenges of fabricating small and clean vias in insulating film especially in Ajinomoto Build-up Film™ (ABF™, a polymer resin with glass filler), which is widely used in package substrates for advanced semiconductor devices [2]. In particular, the via bottom, made of copper, must remain sufficiently clean and undamaged to ensure reliable subsequent metallization and plating.

Laser drilling is a promising approach for this application because it can provide high precision and flexibility. Among available laser sources, DUV picosecond lasers (in the presented work: 266 nm, 10 ps) provide multiple advantages compared to UV nanosecond lasers: from the wavelength point of view, there is a higher absorption inside the insulating film, and, for a given numerical aperture, small focusable spots can be obtained, therefore enabling vias as small as 5 µm. Thanks to the short pulse width [3], limited thermal damages occurred on the film while a clean hole can be drilled, but the average power limits (up to 100 W at about 100 kHz) constrain throughput compared with µs CO_2 systems. Since small vias imply higher density per unit area, this adds another issue of productivity, and new strategies must be explored with deep-ultraviolet (DUV) ps lasers to thwart throughput issues. What is more, a high taper ratio (defined as the ratio between the via bottom diameter and its entrance diameter; 100% stands for a perfectly straight via while 0% stands for a triangle shape) typically leads to better electrical connections (improved durability), thus new paths must also be explored to optimize taper formation in small vias.

Thus, the burst mode processing method that has attracted a lot of interest these days offers a great opportunity [4,5]. In the burst mode, multiple pulses are emitted within a very short time interval, on the order of hundreds of picoseconds in the GHz regime. Since the material has not fully relaxed between pulses, the later pulses in the burst interact with a modified, non-equilibrium state [6]. In particular, the GHz burst regime applied to dielectrics materials promotes enhanced absorption mainly via transient electronic excitation, bandgap modification and incubation, potentially improving ablation efficiency and via quality.

This work aims at exploring intra-burst pulse count up to 16 for three GHz frequencies (1.9, 2.5 and 3.8 GHz), three beam sizes (5, 10 and 15 µm top-hat beam FWHM) and two ABF™ grades (fine filler and regular filler). We have been quantifying ablation threshold, number of shots to drill through (oscillator shots) up to copper, taper ratio, and bottom morphology using SEM measurements.

2. Experimental setup

2.1 Laser source, burst mode and beam shaping

We used a modified commercial processing machine (Mitsubishi Electric GTW4-UVF20, Fig. 1) where the laser source (made by Spectronix) emits DUV pulses (266 nm) in the picosecond range (10 ps) at a repetition rate of 600 kHz with a total power of about 30W (up to 50 µJ per pulse). A custom burst system producing flat bursts (±20% (STD) of energy fluctuations inside the burst, as shown in Fig. 2 in the case of 16 IP) with tunable intra-pulse (IP) counts (1, 2, 4, 8, 16 IP) and intra-burst frequency (1.9, 2.5, and 3.8 GHz) is integrated inside the system.

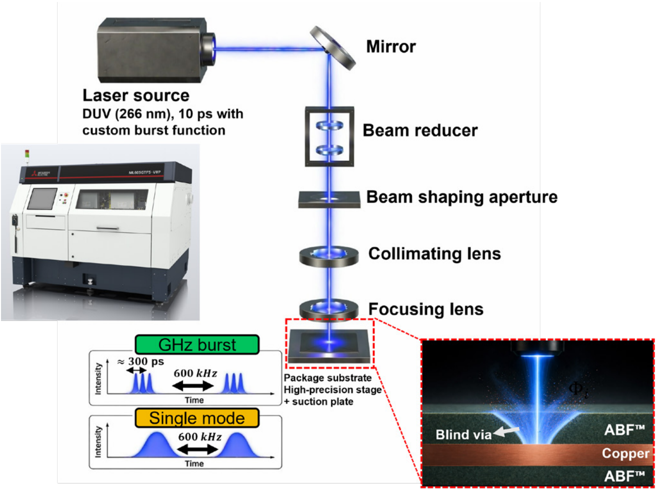

Fig. 1 Simplified experimental setup: customized Mitsubishi Electric laser processing machines (DUV, ps) including a burst function.

To process sharp vias, the laser beam is set as a top-hat profiles (5, 10, 15 µm FWHM on target) using a transmission mask and a relay system to set the appropriate magnification. The beam polarization is set circular to improve the symmetry of drilled vias.

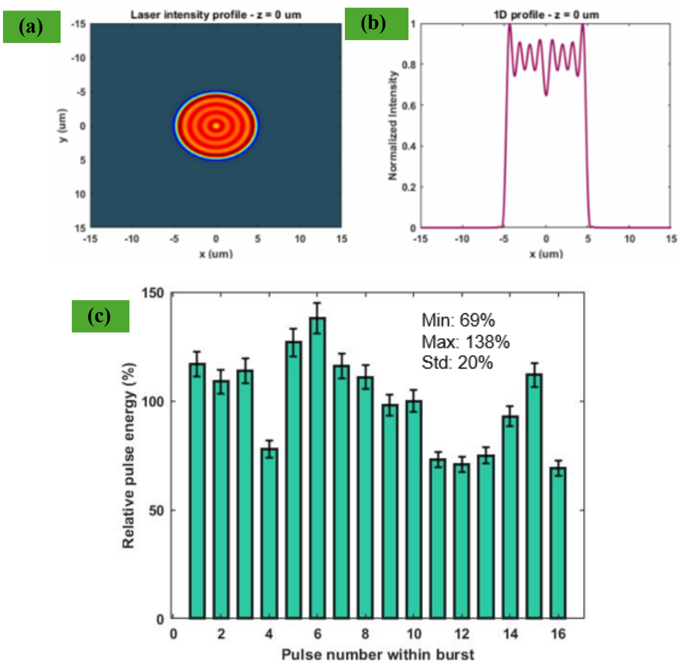

Fig. 2 Simulation of the 10 µm (FWHM) top-hat beam intensity distribution generated on target ((a) 2D profile, (b) 1D-cut along x direction), (c) typical energy distribution measured within one burst containing 16 IP.

The laser energy was measured at full power with a Ophir FL300A-SH and at low power (after mask) with a Thorlabs S130VC. Measurements showed on-target energy stability of about ±2.5% RMS.

2.2 Processing conditions and materials

The samples were processed with fluence ranging around 0.05-1.5 J/cm², even if values above 1.5 J/cm² induced thermal damage in some cases and were considered as inappropriate for good processing. Both single mode and burst mode used the same fluence, the last case being defined as the sum of all intra-pulses fluence. The number of shots delivered to the target was varied from 1 to 200. In single-pulse mode, one shot corresponds to one laser pulse, whereas in burst mode, one shot corresponds to one burst containing multiple (2 to 16) intra-pulses. Therefore, the shot count refers to the number of oscillator outputs, not the total number of individual pulses.

Two ABF™ grades were explored: (A) a fine filler one and (B) a more conventional filler one. Grade A had a resin thickness of 10 µm while grade B had a thickness of 20 µm. both deposited on a thick copper layer beneath (standard blind via stack).

2.3 Diagnostics

We used digital microscopy (Keyence VHX-X1) for rapid taper and quality checks, while full measurements at high-resolution were performed using a scanning electron microscope (SEM JSM-7800F made by JEOL) with both back-scattered electrons (BSE) and secondary electrons (SE) imaging mode; Prior to SEM measurements, samples were platinum-coated for conductivity purpose.

We characterized treated samples with ablation threshold (determined by visual onset of full-circle resin/filler removal (uncertainty of about ±15%)), taper ratio (measuring the entrance diameter of the via and the bottom diameter at the copper surface), and the processing speed (number of shots required to reach copper).

3. Results

3.1 Ablation Thresholds

One single shot was applied on ABF™ (one pulse for single mode, 2-16 IP for burst mode) with increasing fluence up to full removal of the surface resin/filler, as shown in Fig. 3.

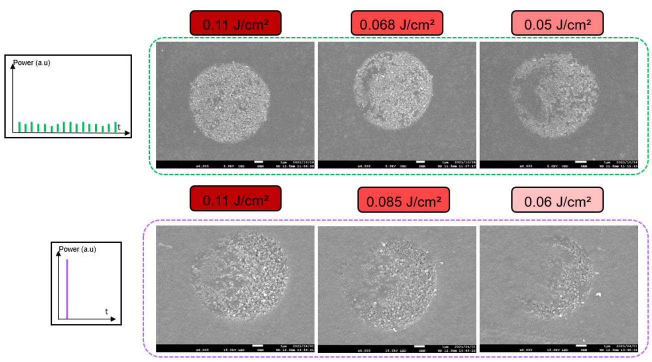

Fig. 3 SEM pictures obtained after single shot irradiation of ABF™ grade A for the burst mode (top with 16 IP) and the single mode (bottom)

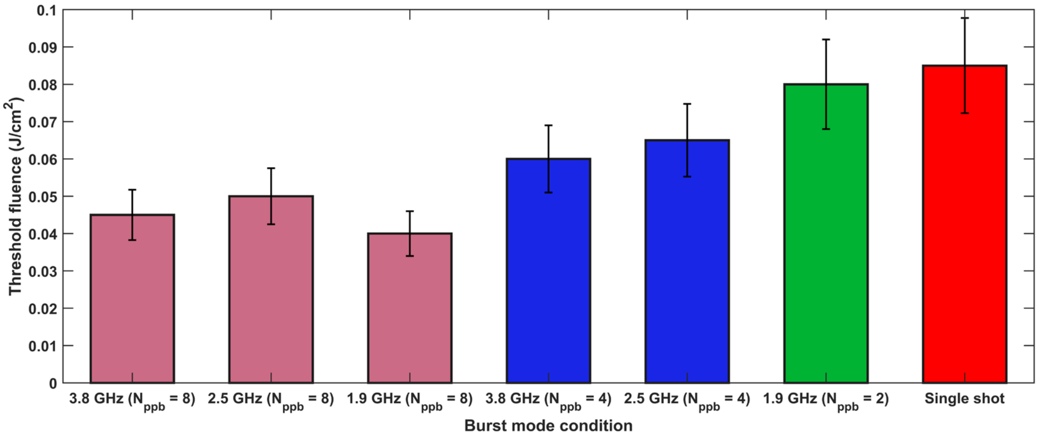

Fig. 4 Ablation threshold (J/cm²) for various configurations: 16 IP (cyan), 8 IP (purple, 1.9, 2.5 and 3.8 GHz), 4 IP (blue), 2 IP (green) and single mode (red). The burst mode can significantly reduce the ablation threshold by up to 2 times.

The Burst mode reduces effective threshold versus single pulse by about 50% in the best case (8-16 IP), with a threshold of about 45 mJ/cm² while 85 mJ/cm² were needed for single mode as shown in Fig. 4. Furthermore, we did not observe significant differences between the 3 burst frequencies (1.9, 2.5 and 3.8 GHz) but the effect seems to be mainly depending on the number of IP (2 and 4 IP gave reduced threshold of respectively 10 of 30% compared to single mode). This number of pulses per burst had a measurable influence on threshold reduction, but the improvement began to saturate at around 8 pulses per burst. Increasing the intra-pulse number to 16 did not significantly lower the threshold further. This saturation suggests that the relevant non-equilibrium process reaches a limit once sufficient energy is deposited within the burst duration.

Altogether, a significant reduction in ablation threshold was observed when applying GHz-burst processing. This result indicates that burst mode improves the energy coupling efficiency to ABF™. The reduction in threshold was consistent across the tested burst conditions, suggesting that burst interaction is generally effective for this material.

3.2 Taper ratio

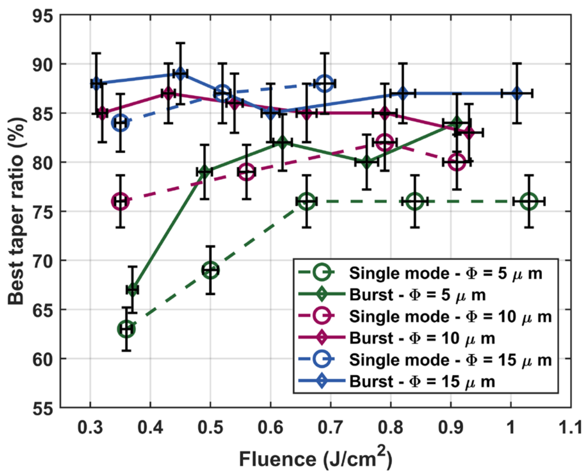

Fig. 5 Best obtained taper ratio for ABF™ grade A (fine filler) as function of the laser fluence. The burst mode with 8 IP and a burst frequency of 1.9 GHz is applied with 5, 10 and 15 µm (respectively green, blue and purple curves) spot size at FWHM. The single mode is shown with dashed lines.

As plotted in Fig. 5, the burst mode increases the best achievable taper ratio (whatever the number of laser shots) by about 5 to 15% (absolute) depending on spot size and fluence. For instance, with a 10 µm via at moderate fluence (0.5 J/cm²), the burst mode gives a taper ratio of about 86% while the single mode reaches only 78%.

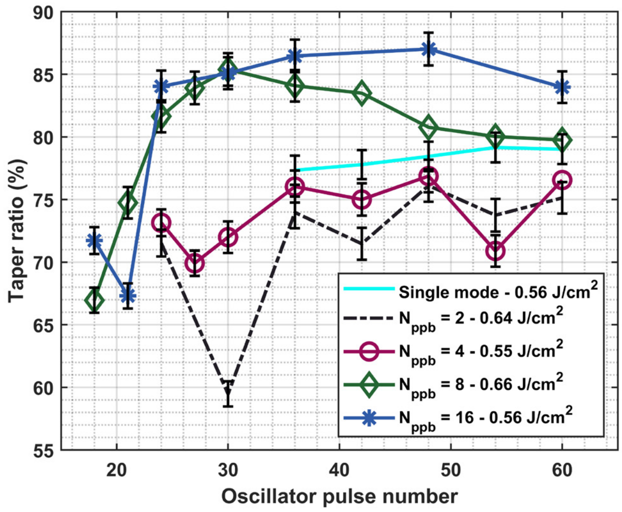

Fig. 6 Taper ratio for ABF™ grade A (fine filler) as function of the number of shots. The burst mode with 2 (black), 4 (purple), 8 (green) and 16 (blue) IP and a burst frequency of 1.9 GHz is applied with a 10 µm spot size and compared with the single mode (cyan) at around 0.5 J/cm².

Concerning the influence of the number of intra-pulses, we have compared the single mode with the burst mode applied at 2, 4, 8 and 16 IP (grade A with a 10 µm spot size at about 0.5 J/cm²) as shown in Fig. 6. It can be noted that 8 and 16 IP can clearly improve the taper ratio (+10-15% compared to single mode) and the processing speed (+50%) while 2 and 4 IP can only improve the processing speed by 30%. Indeed, for 2 and 4 IP, the taper ratio has decreased by about 5% compared to the single mode. It is possible that for these conditions, the burst mode can enhance the absorption (thus, improving processing speed) but each individual pulse still carries a lot of energy resulting in an abrupt ablation detrimental for the hole quality.

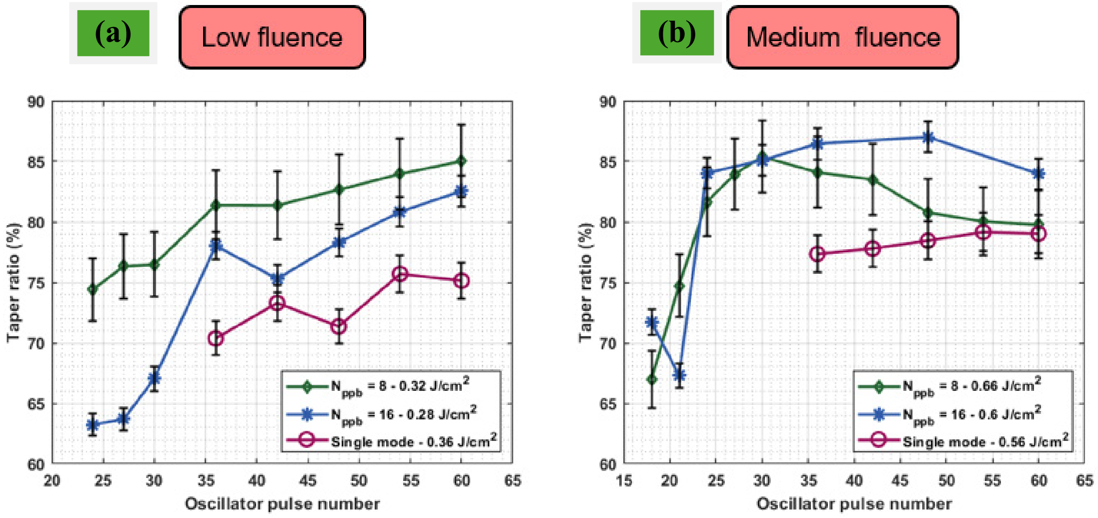

Fig. 7 Taper ratio for ABF™ grade A (fine filler) as function of the number of shots. The burst mode with 8 (green) and 16 (blue) IP and a burst frequency of 1.9 GHz is applied with a 10 µm spot size and compared with the single mode (purple), (a) about 0.3 J/cm², (b) about 0.6 J/cm².

Furthermore, we have compared 8 and 16 IP in Fig. 7 for two fluences. At low fluence (about 0.3 J/cm²) it can be seen that, even if still better than single mode, the 16 IP case is less efficient than 8 IP case (about 2-5 % lower taper ratio) while at higher fluence (0.6 J/cm² and higher) both 8 and 16 IP have the same level of improvement. At low fluence, each intra-pulse carries 40 mJ/cm² (8 IP) or 20 mJ/cm² (16 IP) so that it may be possible that even if heating and absorption process is still efficient with 16 IP, there is not enough energy to induce a sufficient and effective ablation and material removal compared to 8 IP. This suggests that the optimal burst duration depends on the deposited energy per pulse and the ability of the burst to sustain efficient material removal without excessive screening or saturation. No clear saturation due to plasma shielding or dust shielding was observed up to the conditions explored, although further investigation is required (e.g. up to 64 pulses per burst).

Concerning the burst intra-frequency effect (Fig. 8), it seems that 1.9 GHz appears to be the most suitable and balanced frequency for ABF™ drilling in our study (maximum taper of about 85% and best compromise between drilling speed and taper) while 2.5 GHz is the worst (maximum taper of about 80%), even if differences remain low as expected from ablation threshold improvements. For any burst frequency case, the processing quality was improved compared to the single mode (maximum taper of about 75%). However, the underlying physical origin of this frequency dependence is not yet fully understood and may be related to material-specific relaxation dynamics [6].

Regarding the material dependency, the taper ratio for the grade B ABF™ (regular filler) is shown in Fig. 9. Since grade B has larger filler but is also thicker (20 µm, resulting in an aspect ratio of 2 with a 10 µm spot size), one may expect to see differences compared to grade A.

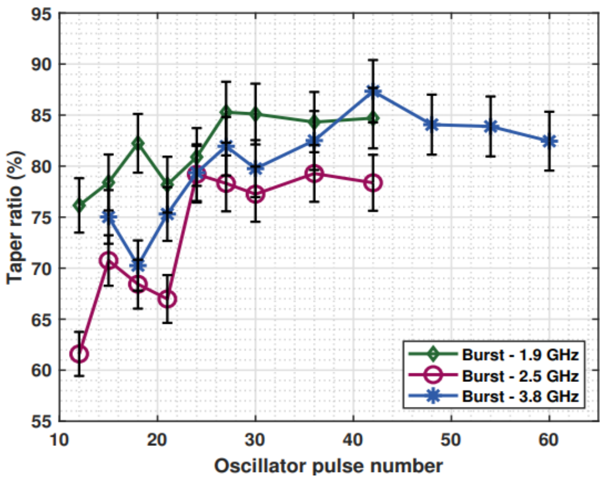

Fig. 8 Taper ratio for ABF™ grade A (fine filler) as function of the number of shots. The burst mode with 8 IP and burst frequencies of 1.9 (green), 2.5 (purple) and 3.8 GHz (blue) is applied with a 10 µm spot size.

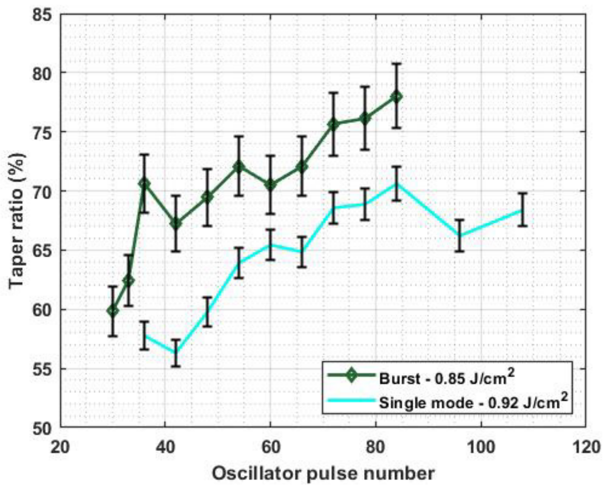

Fig. 9 Taper ratio for ABF™ grade B (regular filler) as function of the number of shots. The burst mode with 8 IP and at 1.9 GHz is applied with a 10 µm spot size at around 0.9 J/cm².

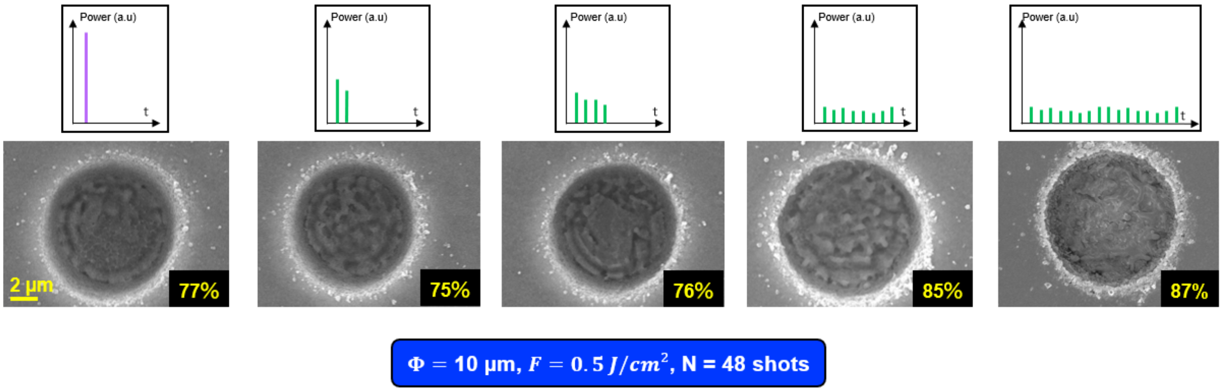

Fig. 10 SEM pictures taken for a 10 µm via drilled with 48 shots at 0.5 J/cm². From left to right, the burst length is increased with 1, 2, 4, 8 and 16 IP.

First of all, even with single mode the maximum taper ratio is about 70% for the grade B ABF™ (75% for grade A), probably because of the higher aspect ratio (2 instead of 1) and because grade B is slightly more difficult to drill (processing fluence has to be slightly increased). However, for this material as well, the burst mode can improve the drilling quality with a taper ratio of about 78%, which is about 5-10% higher than single mode. The processing speed was improved by about 15-35% (depending on the fluence), highlighting the positive effects of the GHz burst mode. Altogether, GHz burst improves quality and shape of drilled vias for two different materials. Across the tested conditions, the taper ratio increased by approximately 10-15%. In addition, the bottom of the via, corresponding to the copper layer, appeared less thermally damaged in burst mode than in single mode.

3.3 Hole morphology

We conducted SEM measurements to analyze the hole morphology (circularity (In this study, circularity is defined as the ratio of the minimum diameter to the maximum diameter measured along orthogonal directions (X and Y).), taper, thermal damages) as shown respectively in Fig. 10 for grade A ABF™ with various burst lengths (1, 2, 4, 8, 16 IP), and in Fig. 11 for grade A and in Fig. 12 for grade B where the effect of the number of shots (burst mode with 8 IP at 1.9 GHz versus single mode) is presented.

First of all, we can observe that the taper ratio clearly improves with 8 and 16 IP, while the hole morphology is also modified even for 2 IP: the copper surface seems a little bit smoother, with a more homogeneous melting of copper.

As shown in Fig. 11, where 10 µm vias drilled at 0.65 J/cm² are presented, the burst mode can significantly improve the processing speed since for 15 shots the copper surface is already reached and widely opened while for the single mode copper has not yet been reached at 21 shots and only partially opened at 24 shots. Thus, at constant shot number (30 shots), the burst mode can reach a very high taper via (84%) while the single mode only reaches 72%. It is also worth noting that the circularity is slightly improved with the burst mode (97%) compared to the single mode case. (95%)

Finally, for the regular filler material (grade B), glass protrusions are clearly visible and sometimes remain inside the via, preventing a straight shape especially with the single mode. Since the hole is thicker, a higher number of shots is required (up to 140 shots) and a reduced taper ratio is obtained (66% with single mode and 78% with burst mode) that lies also probably because of the large filler that might obstruct the laser beam. Concerning the bottom shape, burst mode provides a smoother and more uniform state, especially since there is no mountain-like structure in the center.

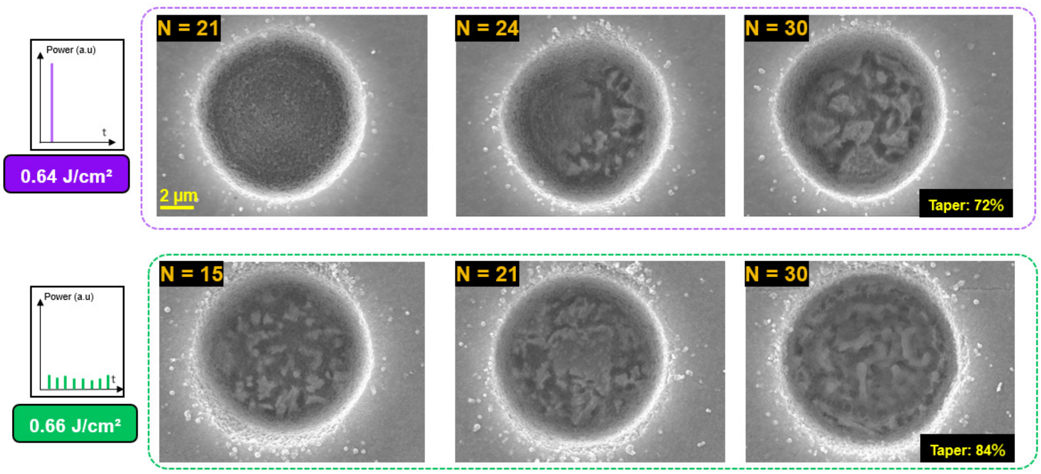

Fig. 11 SEM pictures taken for a 10 µm via drilled at around 0.65 J/cm² (grade A ABF™). Top: single mode; bottom: burst mode at 1.9 GHz with 8 IP. From left to right, the number of shots is increased.

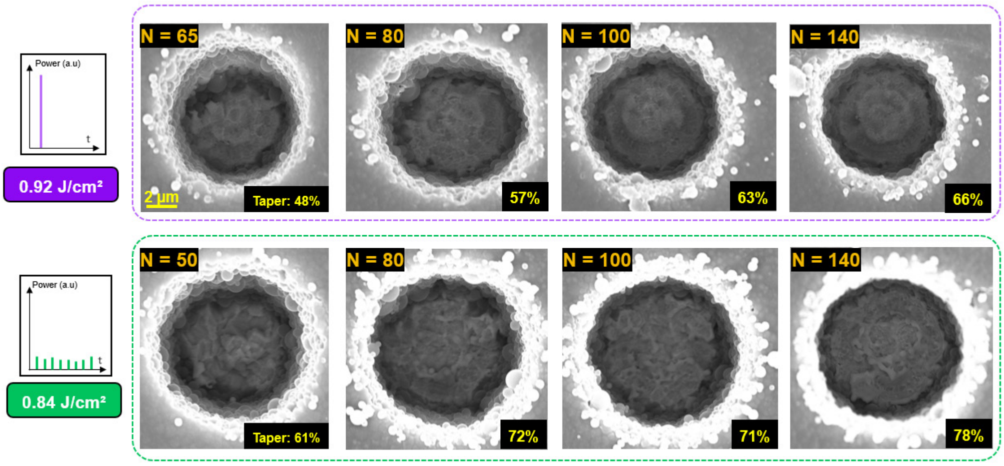

Fig. 12 SEM pictures taken for a 10 µm via drilled at around 0.9 J/cm² (grade B ABF™). Top: single mode; bottom: burst mode at 1.9 GHz with 8 IP. From left to right, the number of shots is increased.

Altogether, the burst mode results in a very different state for the copper (bottom of the via), and there are potential plating implications: this different copper state could improve plating adhesion and reliability, but dedicated post-plating reliability tests are required (outside current study).

3.4 Required shots to reach copper

As shown in Fig. 13, the required number of shots to ablate the whole ABF™ for grade A and reach copper is plotted as function of the fluence. The burst mode at 1.9 GHz and with 8 IP is compared to the single mode for 3 laser spot sizes. All conditions clearly show that the burst mode can improve the speed by 30-50% since copper is reached faster. It is worth noting that according to Fig. 5, the burst mode brings almost no improvement regarding the taper ratio for a 15 µm via (it is already a high taper via). However, it can clearly improve the processing speed by about 2 times thus offering great advantages (24 shots instead of 36).

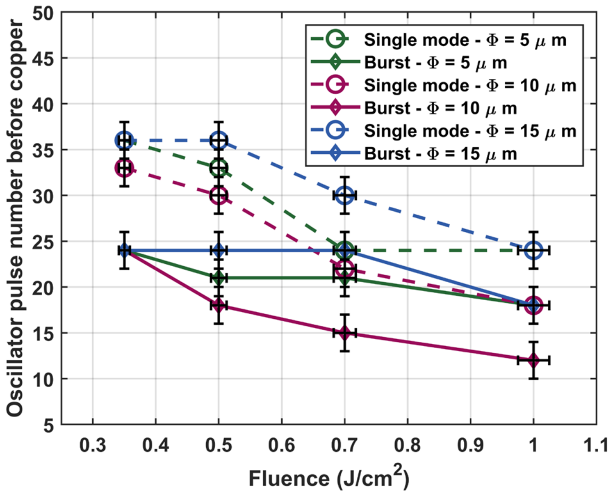

Fig. 13 Number of laser shots required to reach copper for ABF™ grade A. The burst mode with 8 IP and a burst frequency of 1.9 GHz is applied with 5, 10 and 15 µm (respectively green, blue and purple curves) spot size at FWHM. The single mode is shown with dashed lines.

For instance, at a fluence of about 0.5 J/cm² and with a 10 µm spot size, the number of laser shots required to reach the copper bottom was reduced by about 50% compared with single-pulse mode (18 shots versus 30 shots). Across fluence sweep, gains are most evident at low-to-mid fluence range (0.2-0.8 J/cm²). At very high fluence, single pulse performance approaches burst mode, probably because we start to over-open the via and plasma shielding prevents the whole burst energy to be transmitted to the sample.

In sum, this second result is significant because it demonstrates that quality improvements are achieved not at the expense of throughput, but alongside it. At higher fluence, however, the improvement in shot count became less pronounced, suggesting saturation and possible screening effects.

4. Discussion

Our experimental results clearly prove that GHz-burst DUV picosecond laser processing is an effective approach for via drilling in insulating film (ablation threshold halved, processing speed doubled, via taper and profile improved, copper damages reduced). These improvements suggest that the GHZ burst mode changes the interaction regime between the laser and ABF™. A likely explanation is that closely spaced pulses interact with a material that has not fully relaxed. In a dielectric material, this may enhance transient absorption or alter the local response in a way that favors more efficient ablation.

Globally, there are multiple likely mechanisms that could be contributing to the GHz burst benefits:

- Transient electronic excitation: early intra-pulses populate excited states, so following pulses see enhanced absorption (metal-like transient behavior).
- Bandgap reduction and localized heating: cumulative intra-burst pulses progressive heating reduces the glass or the resin bandgap, promoting absorption for later intra-pulses.
- Incubation and defect creation: repeated pulses can create chemical and structural changes and color

center formation, thus lowering subsequent pulse thresholds.

- Heat accumulation (similar as the well-known MHz burst effect [7]): although this may be a limited component compared to the transient electronic excitation, the GHz burst mode can also mimic some heat-accumulation benefits of MHz bursts, especially since thermal conductivity of ABF™ is low.

The dependence on burst frequency indicates that the optimum condition is not determined solely by the total pulse energy or number of pulses, but also by the intra-burst time scale. The best result at 1.9 GHz suggests that the characteristic relaxation time of ABF™ may be on the order of several hundred picoseconds, although a dedicated pump-probe study or numerical model would be needed to confirm this. Indeed, this path must be explored to confirm the absorption enhancement dependency with the burst frequency, since the frequency could also alter eventual plume/plasma dynamics.

Based on our experimental observations and considering possible mechanisms, the following explanation is proposed:

- The 50% reduction in the ablation threshold under GHz burst mode is attributed to the incubation effect and thermal/defect accumulation. High-repetition intra-pulses induce transient electronic states (lasting at least 300 ps) and localized heat, enhancing the material's effective absorption rate between consecutive pulses.
- The increase in drilling speed and improvement in via taper (straighter hole) may come from a combination of multiple mechanisms such as reduced ablation threshold (side wall are more easily ablated through direct beam irradiation or internal reflection of the beam), mitigated plasma shielding, and smooth progressive ablation (with 8 intra-pulses, the ablation can be described as a multiple layered process that can print a shape closer to the beam intensity profile). Indeed, instead of a single high-energy pulse being blocked by its own ablation plume, the GHz intra-pulses efficiently penetrate the via with weak or no plasma or plume.
- Although difficult to confirm and characterize, the smoother copper base without thermal damage is explained by the high ablation selectivity between the ABF (ablation threshold of about 0.1 J/cm²) and the copper layer (about 0.5-1 J/cm²). While the GHz mode enhances absorption in copper due to temperature-dependent reflectivity changes, this effect is much less efficient than the transient electron effect in ABF. Furthermore, the copper's high thermal diffusivity reduces heat accumulation. Additionally, it might be possible that fracturing the energy into multiple weak intra-pulses suppresses intense photomechanical shockwaves, preventing delamination and melt expulsion at the interface. It is also worth noting that a smaller number of shots are required in burst mode which could therefore reduce the total energy delivered to copper compared to the single mode, especially since sidewall absorption should be enhanced in the burst mode thus reducing the energy reflected toward the bottom part.

It is also noteworthy that improved quality does not come at the expense of speed. This is particularly important for industrial adoption, since manufacturing processes require both high throughput and reliable downstream plating performance. The observed reduction in copper damage is especially encouraging because the final electrical performance of the package depends on the quality of the via bottom and subsequent processing steps such as cleaning and plating.

5. Conclusion

We applied the GHz burst mode with a 266 nm and 10 ps laser to drill microvia in insulating film for next-generation packaging. We observed a reduced effective ablation threshold (up to 50% lower, from 85 mJ/cm² to 45 mJ/cm²), as well as a significantly faster processing speed (up to 30-50% depending on the burst parameters, 8 and 16 intra-pulses being the best). What is more, the GHz burst mode can provide a higher speed while also improving the quality (up to 10-15%). We were able to improve both grade A ABF™ (fine filler) and grade B (regular filler), with a practical operational window that is about 8 to 16 pulses per burst at 1.9 GHz with a total fluence of about 0.6 J/cm². Copper bottom morphologies have been modified by burst processing and require post-plating reliability evaluation. All obtained results are consistent with burst pulses interacting with a non-relaxed material, thus offering enhanced optical absorption and smoother ablation.

Overall, GHz burst mode is a pragmatic route to boost throughput and via quality for high-density PCB manufacturing; Future research could include time-resolved plume imaging and transient absorption spectroscopy to clarify intra-burst dynamics and frequency dependence, and extension of the burst length with 32 or 64 pulses per burst to evaluate possible shielding and saturation.

Acknowledgments

This work was funded by Mitsubishi Electric Corporation. The authors thank Spectronix Corporation and Ajinomoto Fine-Techno Co., Inc. for collaboration and sample supply. Colleagues who assisted with system modifications, fruitful discussions and SEM measurements are gratefully acknowledged (Shunsuke Fujii, Naohiro Makishima, Naoki Sato, Reona Hirayama, Hiroyuki Suzuki, Hiroshi Kurushima, Tatsuya Yamamoto, Masaki Seguchi, Kyohei Ishikawa, Masato Kawasaki, Kazuki Kuba, Tsukasa Shirafuji and Kazutaka Wajima).

References

[1] J. H. Lau, Semiconductor Advanced Packaging (Springer Nature Singapore, 2021), p.1.

[2] A. N. Jogalekar, M. McGarry, M. Lee, R. Murugan, M. Iyer, and R. Henderson: High frequency characterization of Ajinomoto Build-Up (ABF) laminates for millimeter wave applications, 103rd ARFTG Microwave Measurement Conference (ARFTG, 2024), p.1.

[3] K. Sugioka and Y. Cheng: Ultrafast lasers reliable tools for advanced materials processing, Light: Science & Applications, 2014, 3 e149.
[4] K. Sugioka: Will GHz burst mode create a new path to femtosecond laser processing?, International Journal of Extreme Manufacturing, 2021, 3 043001.
[5] M. Park, Y. Gu, X. Mao, C. P. Grigoropoulos and V. Zorba: Mechanisms of ultrafast GHz burst fs laser ablation, Science Advances, 2023, Vol. 9, Issue 12.
[6] S. Wu, D. Wu, J. Xu, H. Wang, T. Makimura, K. Sugioka, and K. Midorikawa: Absorption mechanism of the second pulse in double-pulse femtosecond laser glass microwelding, 2013, Optics express, Vol. 21, Issue 20, p.24049.
[7] D. Franz, T. Häfner, K. Bischoff, J. Helm, T. Kunz, S. Rung, C. Esen, and R. Hellmann: Picosecond laser microvia drilling of ABF material using MHz burst mode, Materials Research Express, 2023, Vol. 10, Issue 9.

(Received: June 2, 2026, Accepted: August 12, 2026)