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Lasers

Optimizing ABF Drilling with Picosecond Lasers

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Picosecond lasers with "burst-on-the-fly" pulsing can improve processing speed, via quality, and total cost-per-via for Ajinomoto Build-up Film (ABF) drilling.

A CENTRAL CHALLENGE IN ADVANCED packaging today is routing large numbers of electrical connections through limited areas to connect ever denser integrated circuits with much larger printed circuit boards. The demand for this high interconnect density is driven by rapidly expanding, compute-intensive applications such as artificial intelligence (AI), high-performance computing (HPC) and 5G telecommunications.

Conventional PCBs lack the resolution required to support these densities. This has motivated the adoption of Sequential Build-Up (SBU) fabrication methods based on dielectric materials such as Ajinomoto Build-up Film (ABF).

SBU materials enable finer lines and spaces, together with smaller vias, yielding higher interconnect density. However, successful implementation of this approach is highly dependent on the ability to drill large quantities of microvias with high precision.

Laser drilling is already the industry standard for forming these microvias. Originally based on CO_2 lasers, it is transitioning to nanosecond pulsed ultraviolet (UV) lasers as via diameters continue to shrink. However, even nanosecond UV lasers present tradeoffs in system throughput, accuracy, and complexity.

UV picosecond lasers offer a path to overcoming many of the limitations of nanosecond UV lasers. However, the quality of their results is highly dependent on the exact operating parameters.

To explore this parameter space, MKS industrial laser application engineers conducted a series of ABF drilling tests with a UV picosecond laser. In particular, this work examined how various "burst-on-the-fly" pulsing configurations affected outcomes. The results presented here point towards a method for optimizing process speed and microvia geometry.

Process requirements

ABF is a composite material consisting

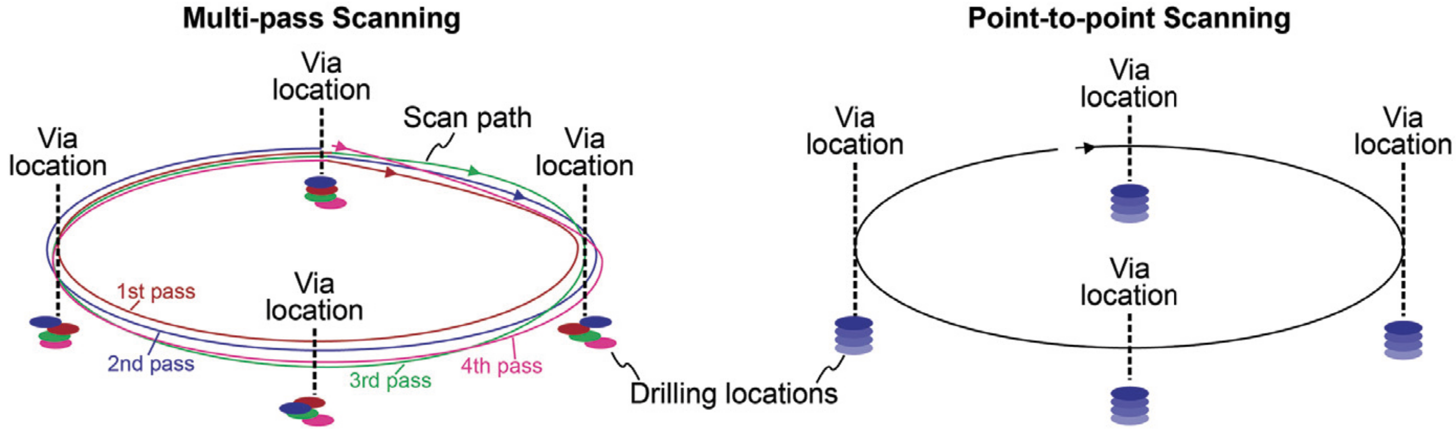

Figure 1. In multi-pass scanning, the beam retraces the same pattern multiple times, delivering a single pulse per pass to each location. This makes the process fast, but sensitive to positioning errors that can distort hole geometry. In point-to-point scanning, the beam traverses the pattern once. It comes to a stop at each location to deliver all the required pulses. This improves accuracy, but the repeated acceleration and deceleration limits throughput.

of hard inorganic (silica or other ceramic) filler particles suspended in epoxy resin. This construction makes uniform ablation difficult because the organic matrix and embedded particles absorb laser energy differently.

The most advanced high density interconnect (HDI) designs today utilize ABF layers that are 10 µm thick and microvia diameters in the 10 – 15 µm range. A primary requirement for drilling these vias is to cleanly ablate a hole and fully expose the underlying copper layer without damaging it. Furthermore, the vias must be highly circular and hole taper must be minimal. The heat-affected zone (HAZ) and debris produced by drilling are also important factors.

Process throughput remains another important consideration for manufacturers. Microvias are formed in large arrays, and practical manufacturing requires drilling rates on the order of thousands to tens of thousands of vias per second.

Taken together, these constraints leave a relatively narrow process window in which parameters are often coupled. For example, increased throughput may come at the expense of taper control, via roundness, or increased risk of copper damage.

UV laser drilling

UV nanosecond lasers have become the standard for drilling microvia diameters below about 50 µm. They enable smaller focused spot sizes and more localized energy deposition in ABF than CO_2 lasers. This helps address the non-uniform ablation that arises from the material's composite structure. The result is more precise material removal with reduced thermal impact.

It takes numerous individual pulses from a nanosecond UV laser to drill completely through a layer of ABF. This fact, together with the wide range of process conditions encountered in industry, has led to a number of different implementations of laser drilling. Most of these can be broadly classified into two categories: multi-pass scanning and point-to-point scanning.

In multi-pass scanning, the beam executes the same scan pattern repeatedly, delivering a single laser pulse at each location during each pass. The continuous motion of the scanner enables relatively high speed. However, positioning errors between subsequent passes can accumulate, leading to deviations in via shape.

In point-to-point scanning, the beam is sequentially moved to each location and stops at each. All the pulses necessary to completely drill the via are delivered before the beam moves on to the next location. This improves placement accuracy but at the expense of speed (**FIGURE 1**), since the scanning system must repeatedly accelerate and decelerate.

There are several variations in how these approaches are implemented. For example, the Gaussian beam profile of the laser can be reshaped to a uniform (flattop) distribution to improve control over via geometry, including reduced sidewall taper. Another variation used with point-to-point scanning systems is to rapidly dither the beam position between successive pulses using an acousto-optic (AO) modulator, which enables drilling of vias larger than the beam size through trepanning or crosshatching. This last technique offers very high throughputs for a range of via sizes but is also costly and complex.

These methods can improve performance under certain conditions, but they do not eliminate the underlying tradeoffs between speed, accuracy, and system complexity. And, as via diameters decrease toward the 10 – 15 µm range and below, these tradeoffs become more difficult to manage.

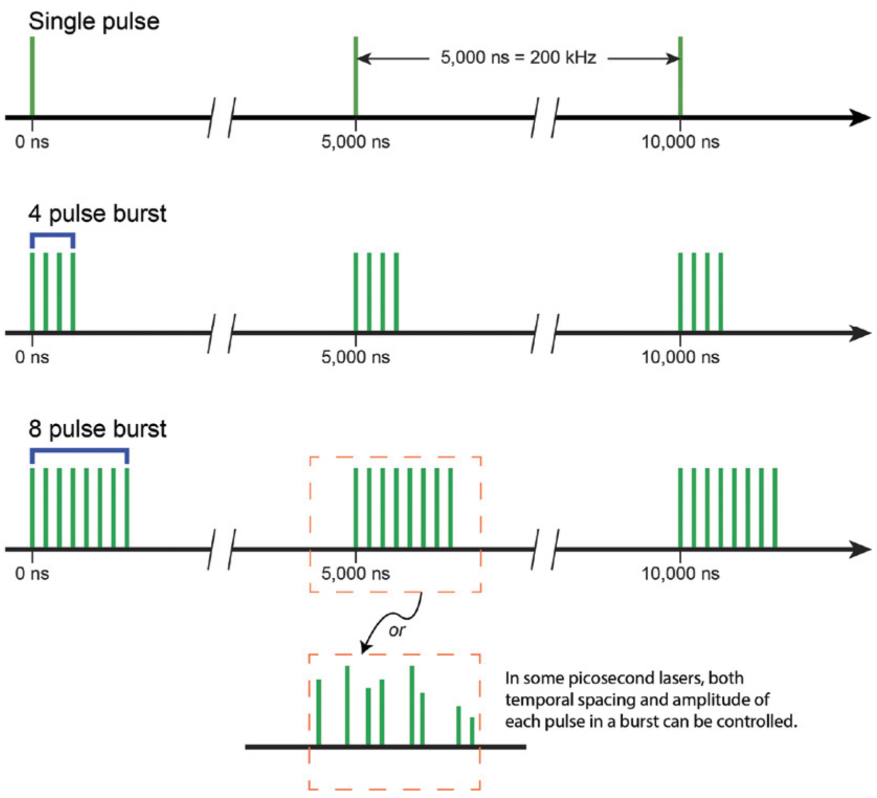

Figure 2. In burst mode, the picosecond laser emits a series of sub-pulses instead of just a single pulse. In some picosecond lasers, such as the Spectra-Physics® IceFyre®, both the temporal spacing and amplitude of each sub-pulse can be precisely controlled.

The picosecond laser alternative

Many of the limitations of nanosecond laser processing can be overcome by using an ultrashort pulse (USP) laser. One key reason for this is because picosecond lasers almost completely eliminate the thermal component of material removal and operate through "cold" ablation.

This occurs because the very short pulse duration (typically 10 – 15 ps) of picosecond lasers produces peak powers that are significantly higher than nanosecond lasers. This high power density drives non-linear absorption processes, which can directly dissociate chemical bonds, rather than ablating just through bulk heating. And, because the pulse duration is so brief, the ablated material is ejected before residual heat has sufficient time to spread into the surrounding dielectric.

Another major advantage of picosecond lasers, especially for high-volume ABF drilling, is the potential for burst mode operation. In burst mode, the laser emits a series of closely spaced sub-pulses rather than a single, high-energy pulse (**FIGURE 2**). It is well-established that pulse bursts can increase ablation rates in many materials while still providing the excellent feature quality – in terms of parameters such as surface roughness and HAZ – that USP processing is known for.

For ABF drilling, the high pulse energy and short temporal spacing between sub-pulses in a burst allows the picosecond laser to power a new type of process. This hybrid technique is called "burst-on-the-fly" drilling.

In burst-on-the-fly, the scanner only traces out the scan pattern once. The beam moves continuously, without stopping and starting.

At each desired point, the laser delivers a single pulse burst (consisting of numerous sub-pulses) which has sufficient combined energy to drill completely through the material. Even though the beam stays in motion, the hole produced is round (or nearly round). This is because the overall duration of the burst envelope is short compared to the speed of the beam's motion.

Burst-on-the-fly drilling combines the advantages of existing scanning methods while avoiding the disadvantages of each. Namely, it delivers the speed of multi-pass scanning with the accuracy of point-to-point scanning. Thus, it offers a path to high-yield, high-throughput production of ABF microvias.

Optimizing burst-on-the-fly

MKS conducted tests to explore the ablation characteristics of the picosecond laser on ABF, and to determine if burst-on-the fly drilling in fact provides advantages. The material used in all testing was 10 µm thick GL102 ABF on copper-clad prepreg and the target via diameter was 15 µm.

The laser employed was the MKS Spectra-Physics IceFyre UV50 which outputs 50 W (average power) at 355 nm. It delivers pulse widths of about 10 ps and can operate at repetition rates up to 10 MHz.

Optics were used to focus the beam to a spot size of about 14 µm at the work surface. The Gaussian intensity distribution of the laser was not altered.

The IceFyre implements an advanced form of burst mode output called TimeShift™. This feature allows programmable control of the number of sub-pulses in a pulse burst, as well as the temporal spacing and amplitudes of each sub-pulse. This capability was key to the testing.

The main goal was to establish how ABF ablation varies with total pulse energy, the number of sub-pulses in each burst, and the temporal separation of the sub-pulses. The two graphs in **FIGURE 3** and **4** summarize the data acquired.

Fig. 3 shows ablated volume of ABF as a function of total pulse energy. Six different pulse energies were used (from 0.4 µJ to 1.1 µJ), and in each case, the energy was divided evenly among 15, 20, 25, or 30 sub-pulses. The same set of tests was performed at two different sub-pulse frequencies (spacings): 500 kHz (2 µs) and 2 MHz (500 ns).

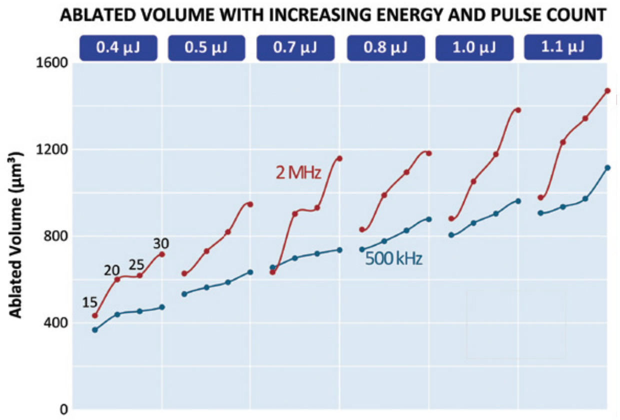

Figure 3. Material removal of ABF as a function of total pulse energy, total pulse count, and pulse frequency. At each pulse energy (shown in the column headers), data is plotted for bursts of 15, 20, 25 and 30 sub-pulses.

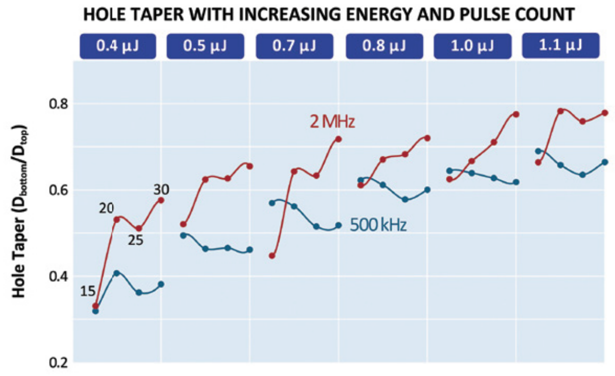

Figure 4. Hole taper as a function of total pulse energy (shown in the column headers), total pulse count, and pulse frequency. At each pulse energy, data is plotted for bursts of 15, 20, 25 and 30 sub-pulses.

As expected, more material was removed using higher pulse energy. But there was also a strong dependence on the number of sub-pulses used and their temporal separation. Clearly, more sub-pulses at closer temporal spacings delivered the highest ablation volumes.

Fig. 4 plots hole taper (defined in via drilling as the diameter at the bottom of the hole divided by the diameter at the top of the hole) from data acquired in this same test. Using this metric, a value of 1 means no taper whatsoever.

Once again, generally better results are obtained with the smaller sub-pulse spacing (2 MHz). And for this frequency, both higher pulse energy and higher pulse count usually improve taper. While taper also improves with higher pulse energy for the larger sub-pulse frequency (500 kHz), it generally degrades as pulse count increases at this frequency.

Copper Considerations

While it's desirable to remove ABF at the highest possible rate (largest volume per unit time) and also produce the least taper, there is another important factor in via drilling. This is avoiding damage to the underlying copper.

Extensive testing of picosecond-pulse copper ablation has been previously carried out by MKS researchers, and was referenced for guidance in these new investigations. The data from this prior testing is summarized in **FIGURE 5**.

The plot shows that breaking a pulse into a larger number of sub-pulses generally increases copper ablation rate. Most importantly, for all sub–pulse counts there is a local minimum in copper ablation rate at pulse separations of about 40 – 50 ns (25 – 20 MHz). Ablation increases dramatically at pulse separation times lower than this minimum (higher frequencies) and more gradually at those that are higher. Note that the separation time of 500 ns – the upper limit of the horizontal axis in the graph – corresponds to the 2 MHz pulse frequency used in the ABF volume ablation tests.

In the current testing of ablating ABF on copper a similar phenomenon was observed. This is summarized in the series of photos in **FIGURE 6** which show the tops and bottoms (exposed copper surfaces) of three different vias. All three vias were drilled with the same total pulse energy and sub-pulse count (30). The only difference between them is the temporal separation between sub-pulses.

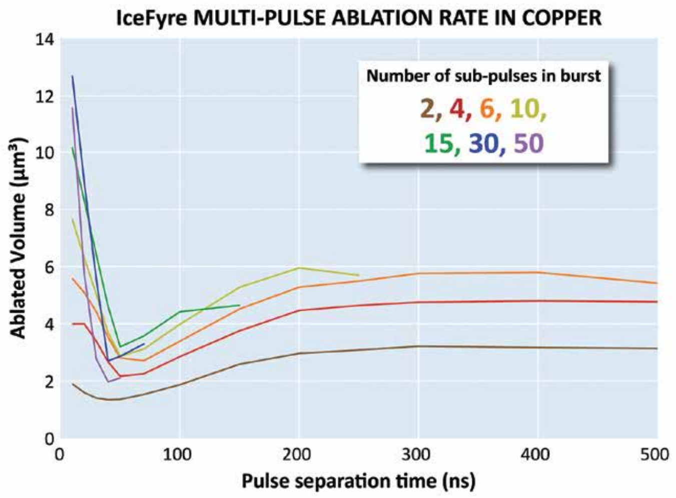

Figure 5. Copper ablation rates for a fixed pulse energy as a function of the number of sub-pulses in the burst and their temporal separation.

The leftmost photos show a hole with a substantial amount of taper, plus significant damage to the copper. In the middle set of photos, a much larger separation between sub-pulses (100 ns instead of 10 ns) has moved processing out of the regime where copper is being efficiently ablated and thus eliminated the copper damage. However, hole taper is not improved. Furthermore, because of the longer overall duration of the burst envelope, the scanned beam has moved enough during the burst to noticeably elongate the drilled hole, creating a roundness out-of-spec condition.

The rightmost images represent the optimal process window in this instance. An intermediate sub-pulse spacing of 40 ns prevents copper damage while simultaneously delivering a round via with the least taper. Together, these results illustrate the profound impact of burst pulse temporal spacing on ablation quality and underscore the necessity of having a laser that offers fully programmable burst characteristics for ABF drilling.

Discussion and outlook

Obviously, the high repetition rates possible with burst mode operation raise throughput by increasing the number of pulses delivered per unit time. But, just as importantly, the short times between sub-pulses also changes the thermal environment at the interaction site.

When sub-pulses are spaced closely enough, heat can accumulate locally, particularly near the copper interface. This "beneficial heating" can enhance material removal. In the case of ABF microvia drilling, it speeds the process and also reduces hole taper. But this effect must be carefully managed to avoid damaging the copper.

Using a laser like the IceFyre, which allows both the frequency and amplitude of each sub-pulse to be programmed, it's easy to imagine that pulse bursts could be tailored to specifically capitalize on this effect. Perhaps the amplitude of the sub-pulses could tail off near the end of the burst to further minimize copper damage. This might then be combined with a reduced sub-pulse spacing to further optimize ablation rate.

The TimeShift burst capability is truly a flexible, multi-faceted tool, shifting the burden of process excellence to the user's imagination. Precise

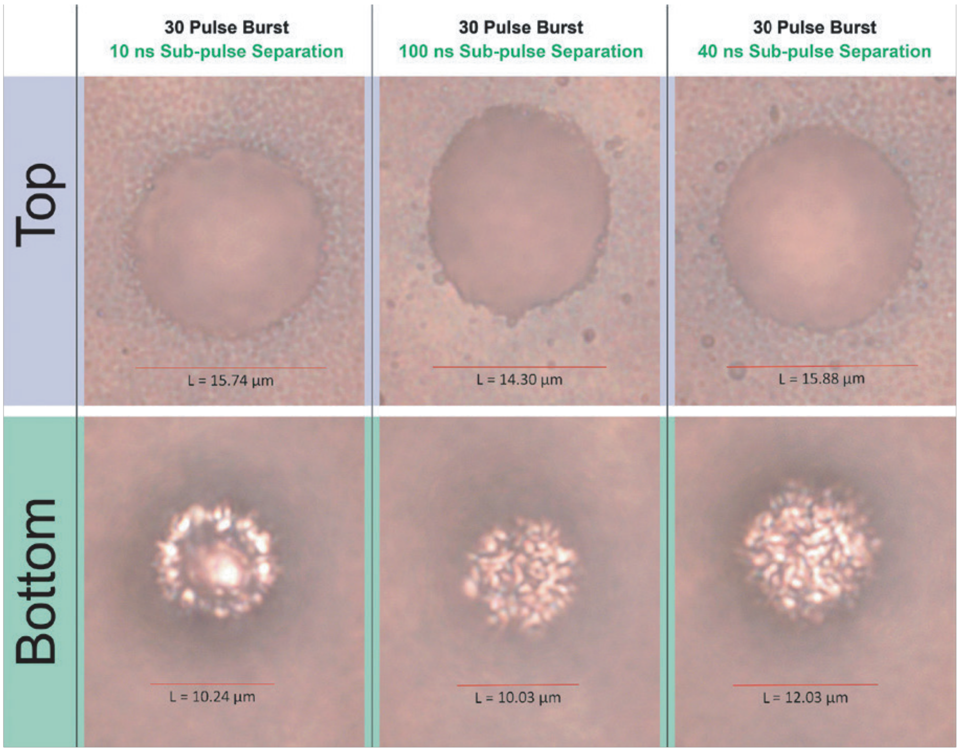

Figure 6. Comparison of three vias drilled with the same pulse energy and sub-pulse count, but with different temporal separations between the sub-pulses. This demonstrates how significantly sub-pulse spacing impacts results.

tailoring of the laser's output to meet the demands of specific processes in specific stacks of materials is now possible.

Though only limited testing has been completed to date, these results clearly demonstrate that picosecond lasers have the potential to enhance ABF via drilling. Compared to UV nanosecond lasers, they reduce the heat-affected zone and allow more controlled material removal. Plus, their high repetition rate pulsing enables burst-on-the-fly processing. This is a new technique which offers a better combination of speed and accuracy than the current methods in use based on UV nanosecond lasers.

About the Author

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