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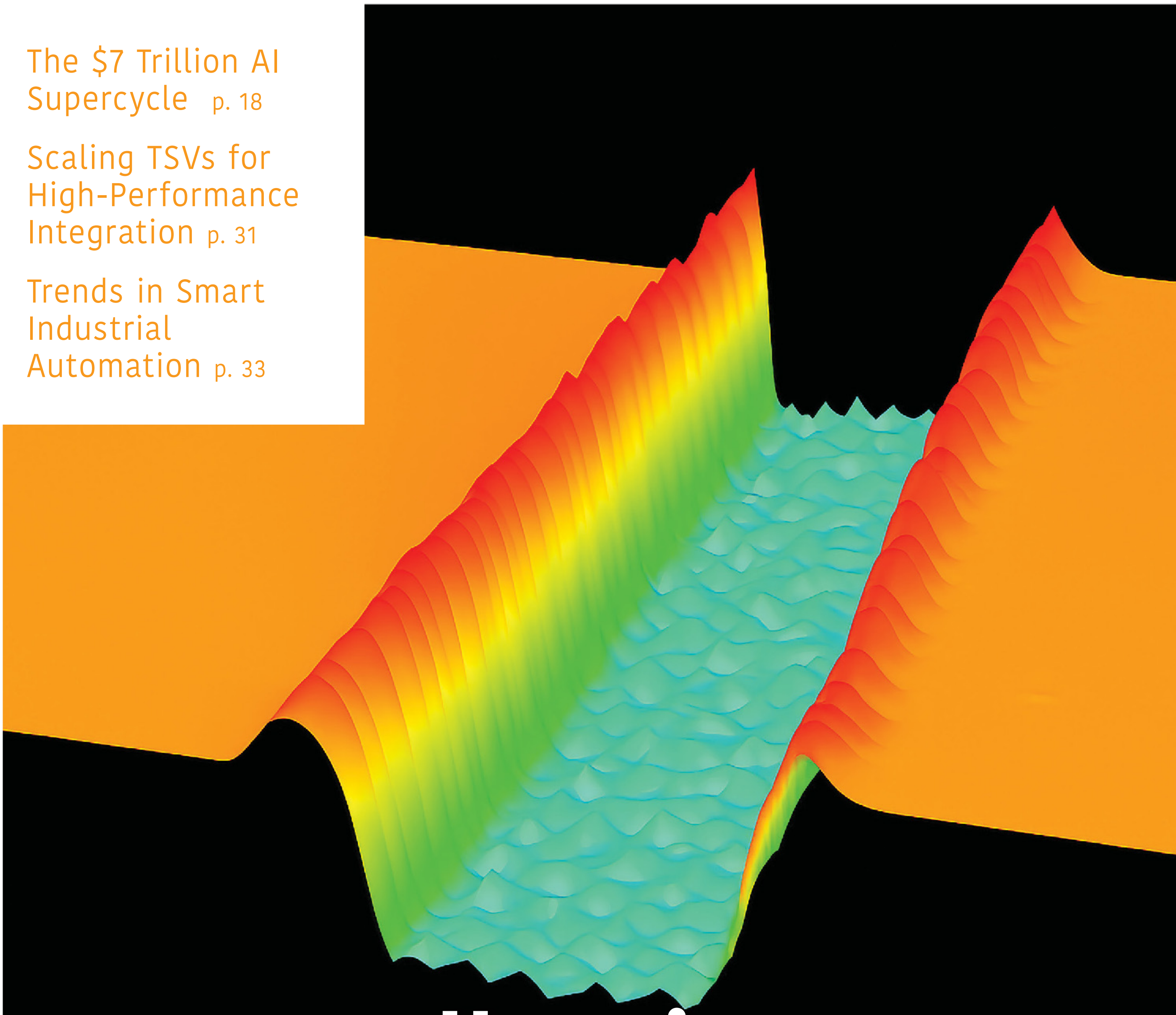

# Lasers Illuminate

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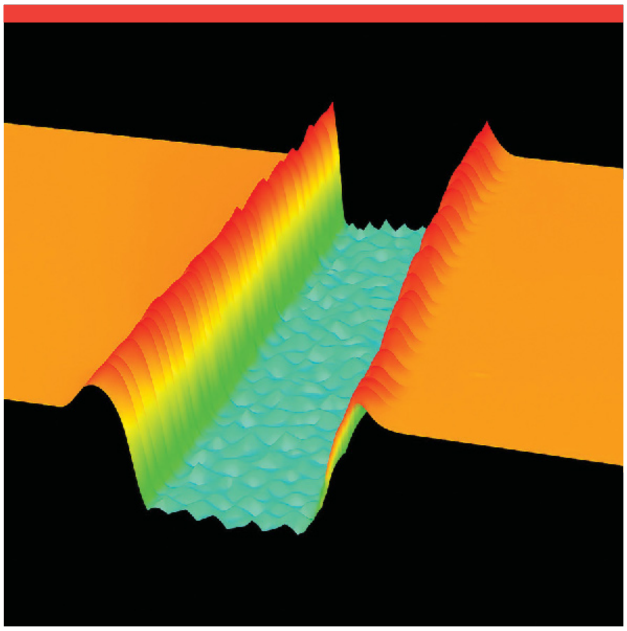

COVER: Scribes in a dielectric film on a silicon substrate made with a UV USP laser results in a narrower scribe with smoother walls and a higher aspect ratio than a UV nanosecond laser. *Source: MKS*

# Features

# Lasers Illuminate the Roadmap for Advanced Packaging

**DR. VICTOR MATYLITSKY**, Senior Product Marketing Manager, MKS Inc.

*Ultrashort pulse lasers enable stress-free material removal in the low-κ substrates that are increasingly essential to advanced packaging.*

Advanced packaging began as a way to shrink electronics into smartphones, wearables, and other space-constrained devices. But as the benefits of Dennard scaling and multi-core architectures taper off, the semiconductor industry has turned to heterogeneous integration as the next engine of innovation. As a result, a range of advanced packaging approaches — including 2.5D and 3D integration, fan-out wafer-level packaging, and chiplet-based architectures — have now become essential for sustaining the pace of performance improvements envisioned by Moore's Law (**FIGURE 1**).

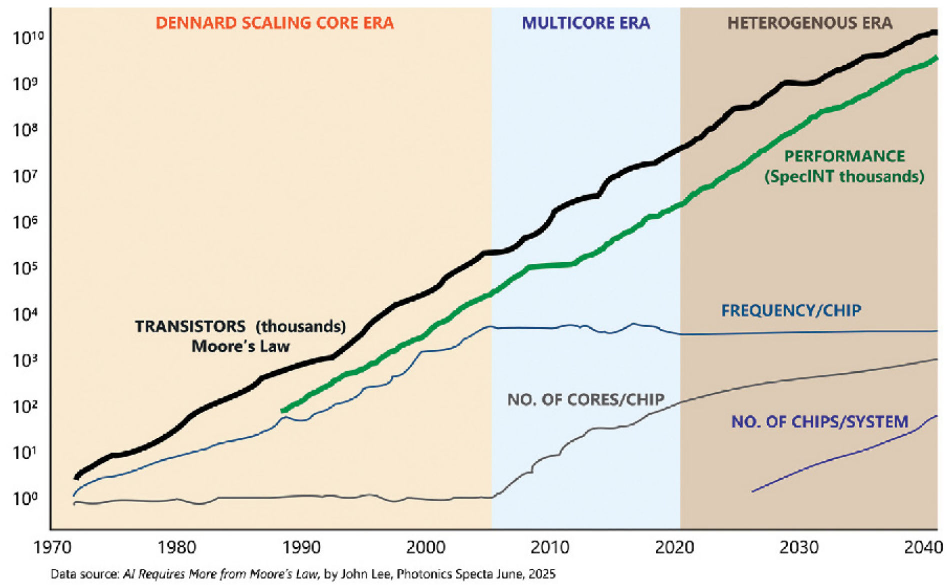


**Figure 1.** Historic trends in microprocessor transistor density, performance, and architecture from 1970 to the present, and projected through 2040. As the benefits of transistor scaling and multi-core architectures have diminished, heterogenous computing has become the means to maintaining Moore's Law.

This shift has brought a new class of process challenges to the forefront, especially in wafer singulation, scribing, drilling, and marking. Dies are getting smaller. Streets are narrowing. Substrates are thinning. And, perhaps most critically, the material stacks — including redistribution layers (RDLs), interposers, package substrates, and on-die BEOL layers — are becoming more fragile. This is largely due to the increasing use of low-κ and ultra-low-κ dielectric materials throughout modern packaging architectures.

Most traditional processing technologies struggle to deliver the spatial precision and material selectivity required to create next-generation structures in these increasingly delicate materials. Here we explore how lasers — and ultrashort pulse lasers, in particular — offer a high-precision, damage-free solution to some of the most difficult production challenges presented by low-κ materials.

## The promise and perils of Low-κ materials

Key enablers of heterogeneous computing include redistribution layers (RDLs), interposers, and on-die BEOL interconnects. These are undergoing significant material and structural evolution to support continued gains in performance and integration.

At the center of this shift are low-dielectric-constant (low-κ) and ultra-low-κ dielectrics. Once limited to traditional logic BEOL processes, these materials are now widely adopted across fan-out wafer-level packaging, 2.5D interposers, and chiplet-based architectures.

The primary advantages of low-κ materials are well established. By reducing the dielectric constant of insulating layers between metal traces, designers can significantly lower parasitic capacitance. This, in turn, reduces RC delay, improves signal integrity, and supports higher bandwidths at lower power. For high-performance computing (HPC), AI accelerators, and 5G applications (where high-density interconnects and wide memory interfaces dominate) these electrical benefits have become absolutely essential.

Low-κ dielectrics also enable tighter routing densities by minimizing crosstalk and signal loss in increasingly compact interconnect layouts. In multi-die configurations with high I/O counts, the ability to maintain performance at tight pitches is critical. As line widths and spacing drop below 5 µm (in some cases approaching 1 µm) the insulating materials between metal layers become not just electrically relevant, but also mechanically and thermally consequential.

And this is where the tradeoffs begin to surface. While low-κ and ultra-low-κ materials offer excellent electrical performance, they are mechanically weaker, more brittle, and often more porous than traditional dielectrics. Their lower density and chemical characteristics can lead to increased moisture uptake, reduced adhesion to surrounding materials, and greater susceptibility to cracking or delamination under stress.

These properties introduce new vulnerabilities in manufacturing. These are particularly pronounced during post-passivation processes such as singulation, trenching, or via drilling.

Thin-film stacks that include low-κ layers are less tolerant of mechanical stress, thermal cycling, and surface damage. As a result, process windows are narrowing, and conventional tooling methods are under increasing pressure to deliver clean, damage-free results.

Thus, while low-κ materials have transitioned from a niche enabler to a packaging cornerstone, their integration introduces complexity that ripples across the entire manufacturing flow. At every process stage, the use of low-κ materials demands more precise, lower-impact process technologies than ever before.

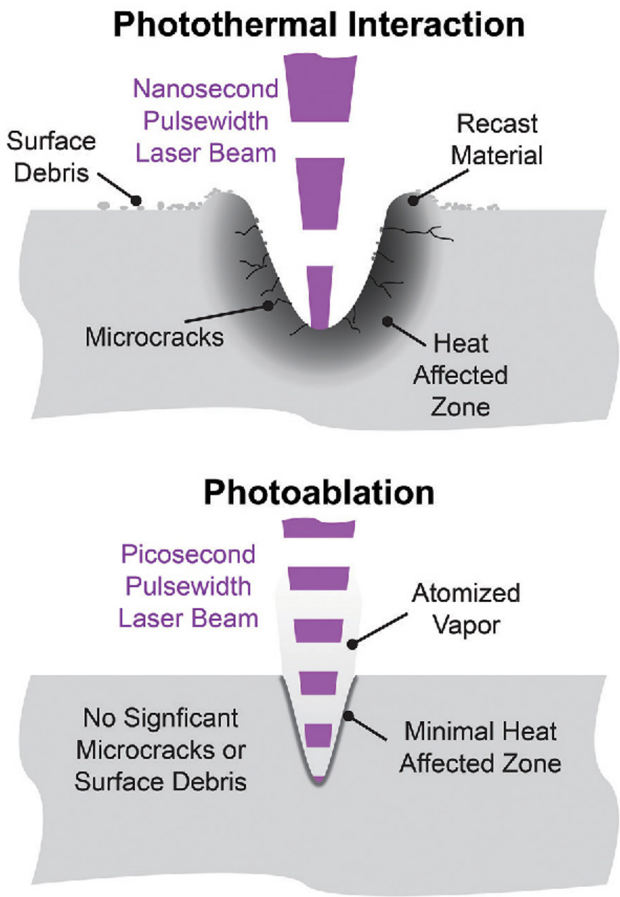


**Figure 2.** The short time duration of ultrashort pulses minimizes heat transfer into the bulk material and produces significantly better cut quality than longer pulse duration lasers.

## Current process limitations

Mechanical dicing with blade saws has been the standard method for wafer singulation for decades. The process is fast, familiar, and well-optimized for volume manufacturing. High speed diamond blades separate dies with impressive precision and throughput. This is particularly true on traditional silicon substrates with robust passivation.

But the transition to advanced packaging materials has exposed the limitations of blade-based dicing. The key issue is mechanical stress. As the blade cuts through increasingly fragile layers, it introduces vibration, flexure, and lateral force.

These can lead to chipping, cracking, or delamination. This is particularly problematic when dealing with fragile low-κ dielectrics, copper redistribution layers, or ultra-thin substrates. And the thinner the substrate and the more delicate the BEOL stack, the more pronounced these issues become.

In some applications, mechanical dicing can trigger catastrophic failures. But, even if the die survives the cut, residual stress can compromise long-term reliability or trigger failures downstream.

To reduce these risks, some manufacturers have adopted hybrid approaches. A common example is laser grooving followed by blade dicing. Most commonly, this employs a pulsed ultraviolet (UV) laser operating at 355 nm.

The laser removes the top layers from the saw lane, clearing a path through passivation, metal, and dielectric layers. The blade then completes the silicon cut with less load on the structure.

However, current hybrid processes utilizing nanosecond lasers still face limitations. This is because nanosecond lasers operate through thermal interaction. Their relatively long pulse durations (typically between 10 and 100 nanoseconds) allow some heat to spread into surrounding layers. In fragile packaging stacks, this can cause edge delamination, discoloration, or microcracks. It can also generate recast debris that interferes with bonding or contaminates nearby dies.

Consider what all this means for a typical advanced package. These often include porous low-κ dielectrics, copper RDLs, polyimide films, passivation, and solder bumps, all on a thinned silicon or glass substrate. Many of these materials have low thermal budgets, weak adhesion, or mismatched CTEs. Even modest thermal or mechanical loads can lead to cracks, voids, or delamination.

Taken together, these factors define a clear threshold: a class of packaging applications where neither blade dicing nor conventional laser tools can deliver the precision and material control needed. And as the push for higher density, higher reliability, and thinner form factors continues, that threshold is being crossed more often.

Thus, a better tool is needed. One that delivers high precision without introducing mechanical or thermal stress.

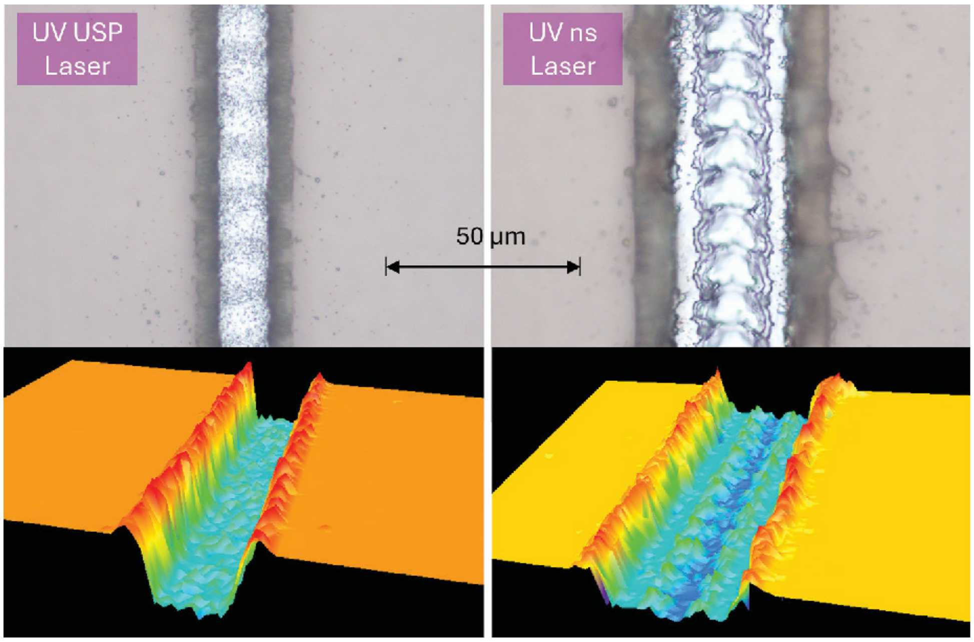


**Figure 3.** Tests at MKS Applications Labs of scribes in a dielectric film on a silicon substrate made with a UV USP laser (left) and a UV nanosecond laser (right). Both the white light microscope (top) and 3D profile images (bottom) show that the USP laser creates a narrower scribe with smoother walls and a higher aspect ratio.

## The laser/material interaction

The ideal scribing and drilling tool would preserve all the benefits of existing laser technology, including non-contact, zero force processing, extremely high mechanical precision, and wide material compatibility. But it would eliminate the thermal and related side effects that damage sensitive structures.

Ultrashort pulse lasers are this technology. To understand why, it's necessary to briefly review the laser/material interaction.

There are three basic mechanisms by which lasers can remove material from a solid substance. The first is photothermal interaction. Here, the laser light is absorbed and converted into heat. When the temperature rises high enough, the material melts, vaporizes, or ablates.

The second method is photochemical interaction. This involves using a laser with enough photon energy to directly break atomic or molecular bonds within the material. Thus, material is removed nearly instantaneously because the bonds holding it together are directly dissociated. In most solid materials, this requires ultraviolet (UV) photons or even shorter wavelengths

Both the photothermal and photochemical mechanisms just described depend on linear absorption of the laser light. The third mechanism relies on nonlinear absorption (particularly multiphoton absorption). It is called "cold" ablation.

In nonlinear absorption, a bond in the material absorbs the energy of two or more photons simultaneously. Even if a single photon lacks the energy to break a bond, their combined energy can. This nonlinear process requires extremely high peak pulse power, typically achievable only with ultrashort pulse (USP) lasers. These have pulse durations in the picosecond ($10^{-12}$ s) or femtosecond ($10^{-15}$ s) range.

Because the energy is delivered in such an extremely short time window, there's no opportunity for heat to spread into the surrounding material (**FIGURES 2** and **3**). Most of the absorbed laser energy goes directly into breaking molecular bonds, and the ejected ablated material carries most of the residual heat energy away. This makes the process effectively athermal. There's minimal melting, no recast layer, and no heat-affected zone. The shorter the pulse duration, the more athermal the process becomes.

Of course, there are negatives to USP processing. First, these lasers invariably represent a higher capital cost than nanosecond lasers. Also, they typically operate with lower material removal rates. This tends to correspond to pulse duration, with picosecond pulses often removing material faster than femtosecond pulses (although this is not universally true). Together, this means that USP technology will only be applied when it offers results that can't be obtained through other means.

## Practical Benefits of Cold Ablation

The value proposition of cold ablation with USP lasers is particularly attractive for some of the most pressing limitations in advanced packaging. This is because cold ablation enables selective removal of dielectric material without triggering delamination, chipping, melting, or stress fractures at the interface between layers.

Cold ablation allows for precise structuring of low-κ films, even when deposited on thermally sensitive substrates or layered with dissimilar materials like

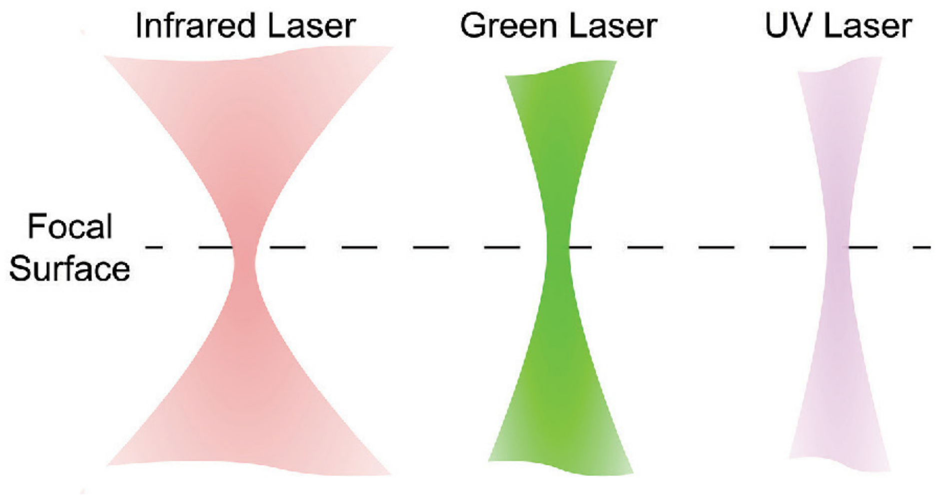


**Figure 4.** When all are focused to the same spot size, the depth of focus of a UV laser is larger than that of a green or infrared laser. This enables creation of higher aspect ratio features and also reduces system sensitivity to variations in material surface height or slight misalignments. This increases process stability and consistency.

copper or polyimide. Because energy is deposited faster than it can propagate, adjacent layers remain unaffected. This preserves interfacial adhesion, avoiding voids or moisture pathways, and enabling clean transitions across complex material stacks. Whether processing porous dielectrics, conductive metals, or delicate polymers, USP lasers maintain fidelity without introducing mechanical stress, thermal distortion, or debris.

These benefits are further enhanced when USP operation is combined with UV wavelengths. UV light enables a smaller diffraction-limited spot size and is more readily absorbed by most dielectrics, enabling even finer resolution at lower energy input. Together, USP and UV support the formation of narrow, high-aspect-ratio features with minimal taper and extremely clean edges (**FIGURE 4**). This is essential for the sub-5 µm geometries now common in redistribution layers and interposer routing.

The benefits compound further at the edges of the die, where even microscopic flaws can propagate into major failures during downstream assembly or thermal cycling. By avoiding edge damage entirely, cold ablation reduces latent defect rates and extends the overall reliability of advanced packages.

This approach also opens up the process window in several ways. Tighter saw lanes, thinner films, and higher aspect ratios all become feasible when the risk of thermal or mechanical damage is removed. And because cold ablation doesn't rely on tool contact or bulk heat transfer, it can be used to machine advanced structures like trenches, vias, and isolation cuts without the typical side effects: no carbonization, no melt redeposition, no stress cracking.

For low-κ materials in particular, this means higher yields, greater design flexibility, and fewer downstream failures. And this all occurs without sacrificing precision or throughput.

## Integration and adoption

USP lasers are already in production across MEMS, photonics, photovoltaics, and medical device manufacturing. Now they are gaining ground in advanced packaging. One reason for this is that they don't require a wholesale replacement of existing infrastructure.

Currently, a hybrid cutting process is the most popular approach, but with the USP laser replacing a nanosecond laser. The USP laser pre-cuts the fragile top layers including copper, low-κ dielectrics, and passivation. Then, a blade completes the silicon cut. This approach minimizes the mechanical stress on delicate materials, reducing edge damage while preserving the throughput advantages of mechanical dicing.

In more demanding applications, such as ultra-thin wafers, 3D ICs, or high-reliability MEMS, full laser singulation is being used to cut the entire stack. Here, ultrashort pulse processing eliminates mechanical contact entirely, enabling crack-free edges, narrower street widths, and cleaner interfaces.

Other fabs are using USP systems for highly localized processes such as via drilling and wafer marking. Because the energy can be tightly confined and controlled, vias can be formed directly through redistribution layers without damaging adjacent structures, and IDs can be marked cleanly even near sensitive areas.

## Conclusion

As advanced packaging features shrink and material stacks grow more delicate, legacy tools are reaching their limits. Long-pulse lasers and mechanical saws were never designed for today's fragile dielectrics, thin substrates, and narrow features.

USP lasers offer a more precise, lower-impact solution. Their ability to remove material without thermal or mechanical damage makes them a good fit for scribing and many other steps in advanced packaging. Especially those involving low-κ materials and other materials that are "challenging" to structure with other methods.

The transition won't happen overnight. Hybrid flows that combine USP lasers with existing tools will likely remain common in the near term. But for high-value or high-risk applications, full USP laser-based processing is already viable. Its adoption will accelerate as the need for precision continues to grow.

## Author contact

victor.matylitsky@mks.com