Ultrashort Pulse Lasers Deliver Cleaner Cuts for Semiconductor Packaging

The semiconductor packaging industry faces numerous manufacturing challenges in the production of next generation designs for advanced, miniaturized, microelectronic devices. The singulation of multiple circuits produced on a single substrate into individual devices is a standout example of this. In many instances, the cutting requirements for singulation already surpass the capabilities of mechanical cutting. Specific examples are System-in-Package (SiP) circuitry used in wrist-worn devices and the fingerprint sensors found in many phones, tablets or even smart watches. This leaves laser cutting as the only viable method, and both nanosecond and picosecond (called ultrashort pulse) lasers are currently employed for these processes. This article compares these two approaches, and provides some detail on the characteristics and implementation of USP picosecond lasers for both SiP and fingerprint sensor singulation.

Background

SiP is rapidly emerging as an important semiconductor packaging technology which enables a high degree of functionality in a very small volume. Smart wrist-worn devices were the first widely available consumer products to take advantage of this advanced level of miniaturization.

SiP devices typically consist of active and passive electronic components, all mounted on a substrate, which contains copper traces on its surface to act as connectors and ground planes. This entire assembly is encapsulated in molding compound. In turn, the molding compound may then be coated with a conductive layer which acts as an electromagnetic shield. The entire SiP device is usually around 1 mm thick, and the mold compound typically accounts for a little more than half this total.

In volume production, multiple SiP devices are fabricated on a single substrate, typically FR4 or ceramics, which is then cut singulated to yield individual devices. Furthermore, in some cases, trenches are cut into the molding compound in individual devices (before singulation) all the way down to the ground plane. This is done before coating in order to completely enclose a sub-region of the SiP when the conductive coating is subsequently applied. This then shields one area of the SiP's circuitry from another.

For both singulation and trenching, the cuts have to be precise in both location and depth, and free of debris. Additionally, any thermal effects and related damage can pose unacceptable risks for these devices which will be integrated into high-end smartphones, tablets or wearable electronics. Potential damage includes delamination of multilayered substrates and micro-cracks in the ceramic layer from the cutting process

The traditional method used for singulation employs diamond-enriched saw blades. However, mechanical sawing presents several significant limitations in the context of SiP singulation. One of these is chipping and delamination of the substrate, and the creation of significant debris. All of these effects can ultimately lead to device failure. The removal of cutting debris can be accomplished using additional post-processing techniques, but, depending upon chip size and quantity, it's possible for residual material to remain on the component after this cleaning.

Another drawback to saw cutting is that it can only be used to produce straight line cuts. It cannot deliver curves, contours or cutouts in the device. Since SiP devices are almost universally intended for highly space-constrained applications, they often have complex, non-rectangular shapes, and sometimes cutouts.

Mechanical cutting also has economic drawbacks because it reduces process utilization. Specifically, saw cutting produces a relatively large kerf and process affected area adjacent to the cut. This, in turn, requires that the individual components be spaced sufficiently far apart in order to avoid damage from the cutting process. However, the greater the street spaces between components, the fewer that can be packed into a given area. This increases the cost per device.

Laser Singulation

Lasers represent the only cutting technology currently available that meets all of the requirements for SiP singulation, trenching and fingerprint sensor singulation. Water jet cutting may cause package failure due to water intrusion between the package layers during cutting.

Up to now, solid-state lasers with nanosecond regime pulsewidths have been the primary tools utilized for SiP cutting. This class of lasers removes material via a photothermal interaction (figure 1). Here, the focused laser beam acts as a spatially confined, intense heat source. Targeted material is heated rapidly, eventually causing it to be vaporized (essentially boiled away). This processing mechanism produces some peripheral heat affected zone (HAZ) damage (e.g., delamination of surface coatings, microcracking, or changes in the bulk material properties) and can lead to the creation of some recast material and debris fragments.

Nanosecond lasers are available with infrared, green and ultraviolet (UV) output wavelengths. UV is often the preferred laser for these singulation applications, because the size of the HAZ can often be minimized by utilizing UV output, compared to the longer (green, infrared) wavelengths. This is because UV light is strongly absorbed by most materials, and therefore doesn’t penetrate as far into the substrate.

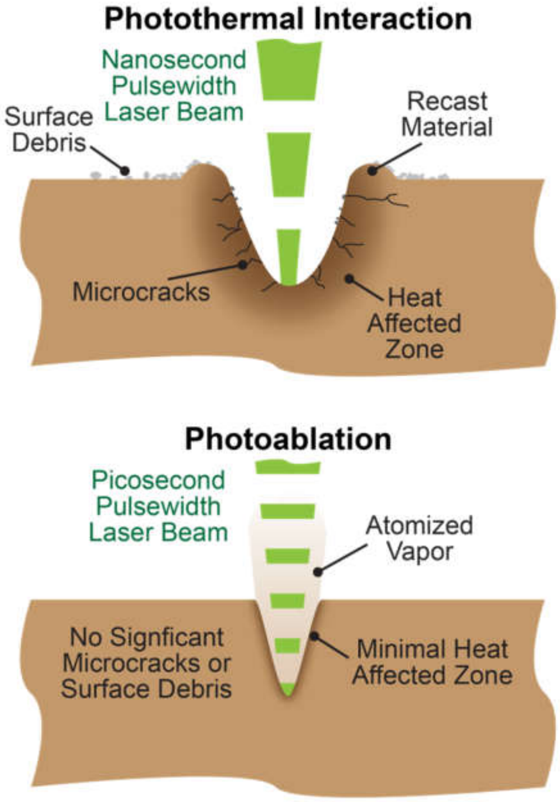

Figure 1: *Schematic illustrating the major differences between ultrafast processing and processing with longer pulsewidth lasers.*

Picosecond regime, ultra-short pulse (USP) lasers operating at 532 nm (green) are now emerging as alternative technology to UV nanosecond lasers in package cutting applications because they often deliver superior processing results. This is because their extremely short pulsewidths lead to very high peak powers (megawatts and above). These high peak fluences can cause immediate bond breaking in a material. Plus, because the laser is only on for such a brief time period, electrons in the material don't have time to transfer their energy into lattice vibrations and produce bulk heating. This combination of effects yields a cold process called *photoablation* that is characterized by minimal HAZ (figure 2). Plus, green USP laser processing creates a reduced amount of microscopic debris that is easily eliminated by cost-effective cleaning methods.

Why green? Like traditional nanosecond lasers, the newer USP lasers are available with output in the infrared, green and UV. In the case of package singulation, green output is preferred over IR because the longer wavelength can cause burning or charring in many of the composite substrates (e.g. FR4) commonly utilized. And while UV lasers actually delivers a higher quality cut than green lasers, the only commercial USP lasers with UV output currently available offer lower powers and therefore reduced throughput. Thus, green represents the best combination of quality and speed.

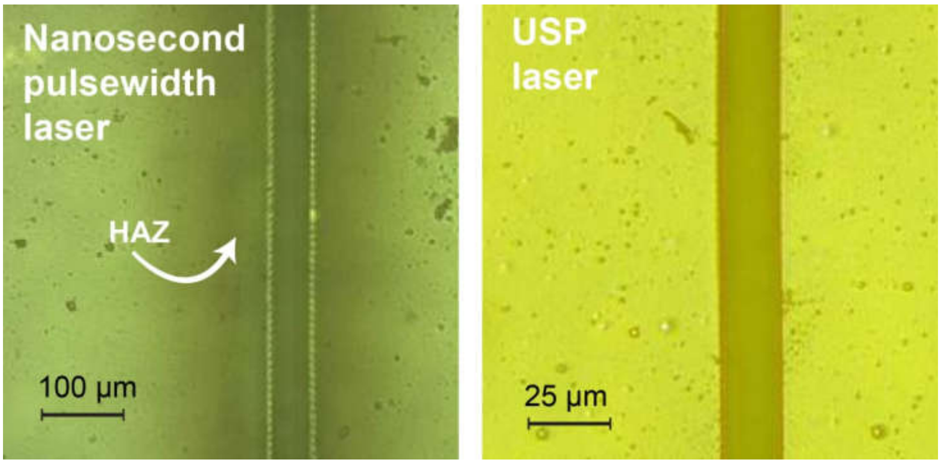

Figure 2. *"Dark Yellow," 30 µm thick polyimide sheets scribed with a nanosecond and USP laser (in the UV). The nanosecond laser processed at 66 mm/sec, while the USP laser cut at 193 mm/sec. The nanosecond laser produced a substantial HAZ – seen as a darkening in this image – while the USP laser produced none, and also delivered a substantially smaller cut width. Note the difference in scale between the two images.*

Practical Lasers for Singulation

Coherent offers both nanosecond and USP lasers with the requisite output power for these singulation applications. The 40W Coherent AVIA NX is a nanosecond pulsewidth, UV solid- state laser that is already widely employed for semiconductor package cutting. Coherent also offers higher power AVIA NX lasers than this (up to 50W), and these can deliver higher cutting speeds due to this additional power. However, there is trade-off in terms of speed versus cut quality due to the thermal component of the laser/material interaction. Specifically, higher power enables increased cutting speeds, but also produces greater debris formation.

The Coherent HyperRapid NX (figure 3) is a picosecond USP laser available with 50W of output in the green (532 nm). This delivers the same cutting speed as the 40W UV nanosecond laser on thick (1.2 mm) SiP devices – typically a value of around 10 mm/s. For thinner structures (0.45 mm), such as used in fingerprint sensors, the green USP laser demonstrates significantly higher cutting speeds. In particular, it can reach over 75 mm/s of throughput, while the 40W UV nanosecond laser operates at about a third of this value.

While USP lasers generally offer better results than nanosecond sources in many advanced packaging applications, they are only now being adopted throughout the microelectronics industry. This is because companies such as Coherent have substantially improved the performance and reliability of these lasers over the past few years thereby lowering the cost of ownership. Moreover, Coherent's HyperRapid NX series of USP lasers incorporate a number of sophisticated output control options that enable a high degree of process optimization and process flexibility, further maximizing customers' return on their capital investment.

Particularly important features in this context are pulse gating, continuous energy control of individual pulses, and the ability to alter repetition rate on the fly. These are necessary to support a high degree of synchronization between the scanner, motion stage, and the laser pulses, enabling optimum cutting of curves and contours. A laser beam travels slower around the curves than it does when cutting straight lines (because the stage or galvanometer mirrors must decelerate/accelerate). So, the time spacing between pulses must be varied on the fly in order to maintain constant laser power delivery at any given point, and therefore a consistent laser/material interaction. A key benefit of this advanced synchronization scheme is the ability to always able to cut at the maximum speed of the scanner, therefore delivering shortest cycle time, while maintaining perfect quality. The alternative is to work at a constant slower speed, equal to the minimum speed imposed by the shape of the component. The architecture of Coherent HyperRapid lasers, which feature a pulse jitter of ~10 ns, supports this functionality particularly well.

Figure 3. *The Coherent HyperRapid NX represents the new generation of USP lasers that deliver the performance and reliability necessary for cost sensitive, high throughput manufacturing applications.*

USP laser technology is more complex than older laser technologies. And, with complexity comes potential failure modes. Coherent has improved product reliability and lifetime of USP lasers by employing Highly Accelerated Life Testing (HALT) and Highly Accelerated Stress Screening (HASS) protocols (and is currently the only company in the laser industry to do so). HALT is a proven approach that takes initial component and system designs and makes them better through pushing components and systems to failure, analyzing the failure mechanism(s), designing out the failure cause, and then iteratively repeating the harsh testing until all identifiable failure mechanisms are eliminated. HASS is a complementary screening protocol applied to every manufactured unit. It enables the detection of potential manufacturing weaknesses before delivery, without affecting the useful life of the units, therefore dramatically improving open-box quality. HASS also enables continuous improvement of the manufacturing processes, which is a major contributor to product quality.

Finally, operational flexibility is important because device structure is both diverse and fast evolving. Operational flexibility enables display manufacturers to adapt seamlessly as device structure changes, as well as to address different market segments. A laser which supports a wide range of operating modes can more readily deliver the right process recipes for these various needs.

Of course, cost is always a consideration, and USP lasers are still more expensive than a nanosecond pulsewidth laser of the same output power. Thus, a USP laser such as the HyperRapid NX is likely to be employed when it offers clear advantages in the context of a given application. For package singulation, this crossover occurs when:

- The HAZ requirement is <50 µm
- Cutting through transparent solder masks (because these darken when heated)
- Cutting through brittle layers, such as ceramics, glass or composite (including glass fibers), and when there is a requirement to keep any chips formed smaller than a few tens of microns
- Cutting through copper layers of a few tens of microns in thickness

Process Optimization

While USP processing is inherently superior to nanosecond methods, USP requires a more comprehensive process optimization to fully exploit this potential and to minimize, or even eliminate, the production of any debris. Coherent has conducted an advanced optimization study for fingerprint sensor and SiP singulation with the specific target of minimizing the amount of debris generated during cutting, but without decreasing the cutting speed. Our application team has optimized all the aspects pertaining to the process, beyond just the laser beam. These include the exhaust system (position, pressure), the blowing system (geometry, position, pressure, process gas type), laser synchronization with the galvanometer scanners (speed, triggering, jumps, timing) and overall processing strategy. Before this work, despite optimization of the laser parameters, cutting produced an asymmetrical HAZ, some burns and some debris.

For fingerprint sensor cutting, the best results were an essentially perfect cut, which produced a sufficiently small amount of debris to potentially open the way to cleaning-free manufacturing processes (figure 4). This high quality cut was achieved at the highest available pulse energy setting on the laser (125 µJ). At this power level, the laser can cut a 0.45 mm thick substrate at speeds of >75 mm/s. This speed can be maintained regardless of substrate composition (copper, epoxy, etc.). For a typical fingerprint sensor with a 42 mm perimeter, this yields a cycle time of 0.55 s.

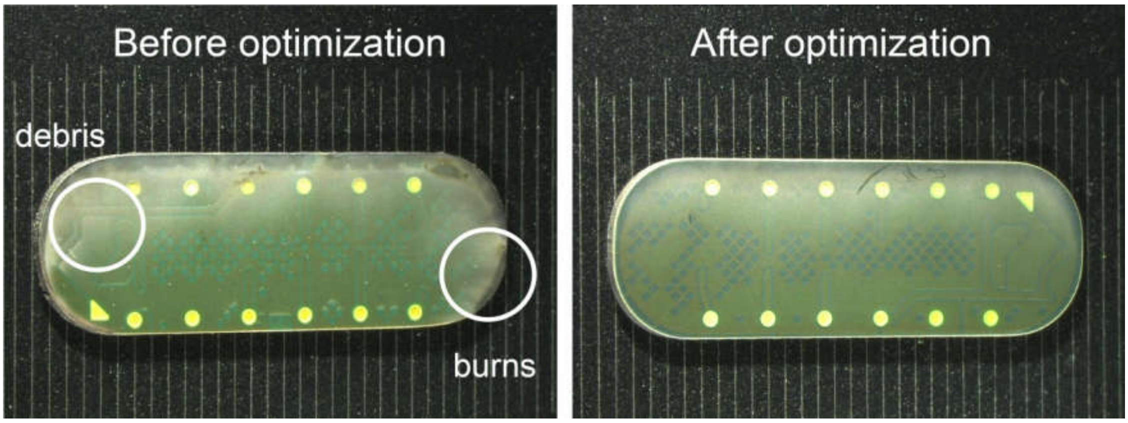

Figure 4. *Green USP laser singulation of a fingerprint sensor, before and after process optimization. Process optimization virtually eliminated burns and debris (whitish layer). Samples shown are uncleaned.*

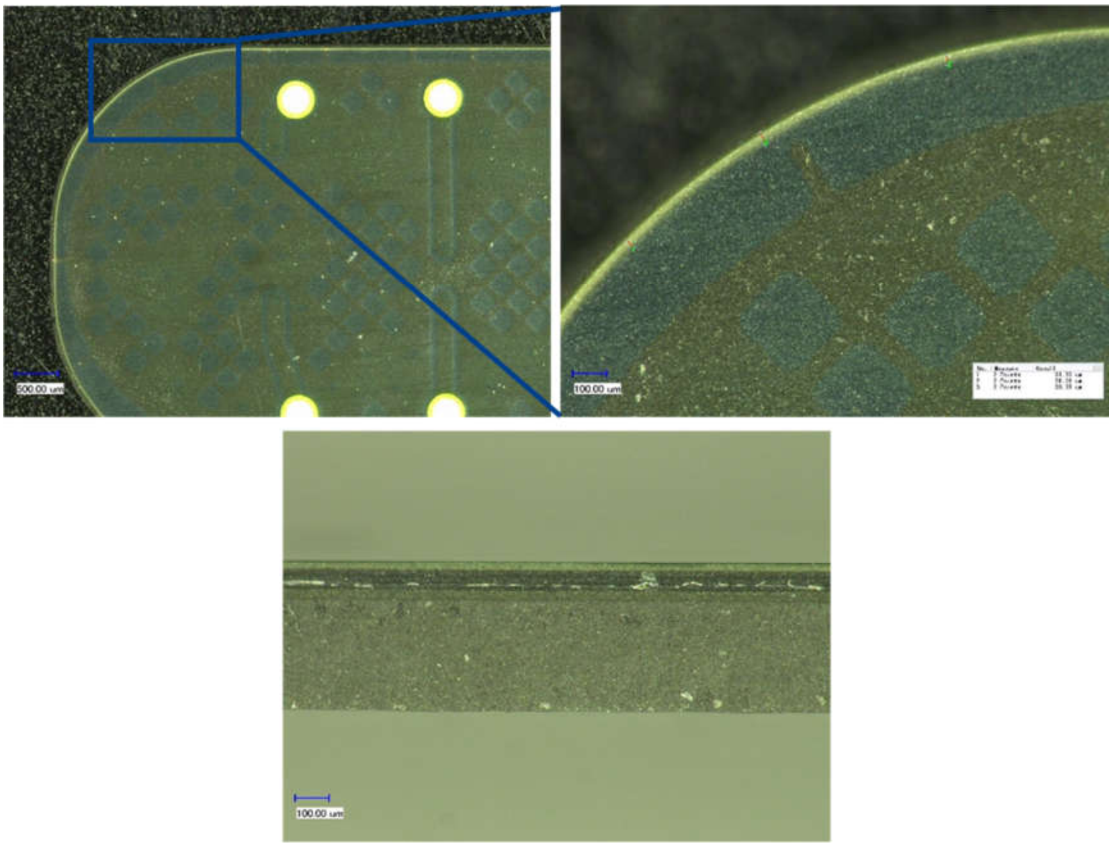

Figure 5. *Edge and cross section detail of a green USP laser singulated fingerprint sensor after process optimization showing a very clean, high quality cut. Samples shown are uncleaned.*

Similar results were obtained in process optimization of SiP singulation. Specifically, the best results were obtained at the highest pulse energy setting (125 µJ). This enabled a cutting speed of >10 mm/s for a substrate thickness of 1.2 mm. This yields a cycle time of 10.3 s on a SiP sample. Once again, the cut quality was nearly perfect, producing a sufficiently small quantity of debris to simplify cleaning or potentially avoid the need for any subsequent cleaning.

For many industrial processes, optimization requires trade-offs and compromises, e.g., speed versus cut quality. Yet in both these singulation examples using a USP laser, process optimization required no lowering of laser power or repetition rate whatsoever, i.e., no speed trade-off. This demonstrates the critical importance and value of comprehensive process development at the machine level in order to get the best results from ultrafast laser processing.

Coherent has an experienced application development team that is able to optimize the laser/matter interaction for any new application variation, as well as other process components to achieve the best results. This is part of the total value package that we offer to our customers: the most reliable and high performance laser source, the optimum processing parameters, and the best machine configuration to unleash the full benefits of USP processing.

Conclusion

Testing at Coherent proves that the green USP laser is capable of delivering very high cut quality in various semiconductor advanced packaging singulation tasks. And, the optimum quality appears to coincide with the highest power and energy regime in the green. Therefore, it is reasonable to expect that cycle time per part will be even further reduced when higher power USP lasers become available. This should make the technology increasingly attractive to end users, as it will continue to become more economical over time.

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