ABLATION EFFICIENCY IN SILICON CARBIDE COMPARING UV NANOSECOND AND IR FEMTOSECOND LASER TECHNOLOGIES

The use of silicon carbide (SiC) continues to increase in electric vehicle (EV) systems, power electronics, and clean energy applications. This is due to the material's superior thermal conductivity and wide bandgap characteristics, enabling devices that can withstand higher temperatures, deliver faster switching speeds, and operate with greater efficiency.

Another property of SiC is high mechanical hardness, which poses a problem for traditional mechanical machining methods.

Laser machining can offer a solution. But as with any material, careful consideration must be given to SiC's unique properties and the challenges presented for laser-based processes such as scribing, dicing, and general ablation. Accordingly, careful and methodical process optimization is required to obtain the best results.

A key first step is to investigate material ablation rates and efficiencies under various fluence conditions. These parameters represent the fundamental material removal capability of a particular laser technology for a given material. Thus, comparing them between lasers should help identify the best laser type for specific processes and applications.

This application note presents a comparative study of ablation efficiency in SiC using two different laser platforms –ultraviolet (UV) nanosecond pulse (ns) lasers and infrared (IR) femtosecond pulse (fs) lasers. We explore how fluence, pulse width, and pulse burst tailoring affect efficiency and removal rate, offering valuable guidance for selecting the most suitable laser for precision SiC machining.

UV Nanosecond Laser Ablation

Two different ns UV lasers were tested for ablating 4H crystalline SiC. One laser was an MKS Spectra-Physics® Talon® UV15, a conventional diode-pumped solid state (DPSS) q-switched laser that outputs ~20 ns pulses. The other was an MKS Spectra-Physics Talon Ace™ UV100, a hybrid-fiber laser with TimeShift™ pulse tailoring capability, which can be programmed to deliver single pulse durations from <2 to >50 ns as well as pulse bursts.

In all cases, a pocket milling approach using a 2-axis scanning galvanometer was applied. The scan speed was maintained between 2 and 4 meters per second, with approximately 60% spot overlap, and all experiments were run at a 50 kHz repetition rate. Three different pulse configurations were tested: single 20 ns pulses (Talon), single 2 ns pulses (Talon Ace), and 5×2 ns pulse bursts (Talon Ace).

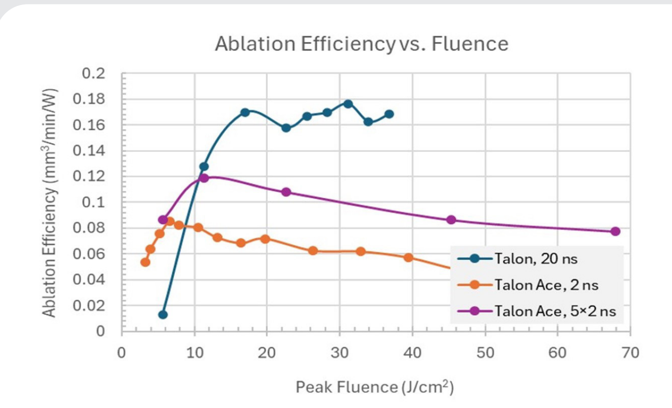

Figure 1. SiC ablation efficiency and optimal fluence vary significantly with the different ns UV pulse outputs tested.

Figure 1 summarizes the results of the UV laser tests, showing ablation efficiency – how much material is removed per unit time, per Watt of laser power – as a function of peak fluence. This data essentially reveals how effectively laser energy is converted into material removal capability is often referred to as the *specific ablation rate*.

The longest pulses – in this case 20 ns – delivered the highest ablation efficiency and maintained it at elevated fluence levels. This result likely reflects the longer interaction time between the laser and the material, which generates some heating that is beneficial to material removal.

The 2 ns pulses demonstrated a lower peak ablation efficiency, but at substantially lower fluences. This should provide a performance (quality) advantage in applications where thermal management is critical, as it is less likely to induce bulk heating of the material.

The 5×2 ns burst mode struck a balance between these two extremes, in terms of both the maximum ablation efficiency as well as the corresponding fluence. This shows that invoking (variable) burst and single pulse output allows tuning of throughput and thermal loading in situations that may require such.

IR Femtosecond Laser Ablation

Ultrashort pulse (USP) ablation processing was conducted with an MKS Spectra-Physics IceFyre® FS IR200 laser. This laser delivers sub-500 femtosecond pulses at output powers exceeding 200 W and operates at repetition rates from single pulses to 50 MHz. This laser implements the Spectra Physics TimeShift programmable pulse feature which enables highly flexible burst-mode operation.

The laser beam was scanned at 5 m/s, which is somewhat faster than the speed used in the UV experiments. However, the higher pulse repetition rate of the IceFyre FS IR200 (1 MHz) resulted in a larger spot overlap – approximately 90%, as compared to 60% overlap in the ns testing.

This high overlap was intentional. Since ultrashort pulses deposit energy so rapidly, they don't produce significant heat build-up in the material. As a result, aggressive overlap can be used without introducing melting or other thermal damage; and higher overlap means fewer scans to remove a given amount of material and therefore less time is wasted on acceleration/deceleration cycles.

Figure 2 shows both ablation efficiency (orange curve) and ablation rate (blue curve) for the IR USP laser, as they vary with increasing number of burst pulses. In all tests, the average laser power was ~200 W. To determine the optimal fluence, the number of burst pulses is simply increased – thus reducing the energy of each pulse – rather than adjusting the overall average power.

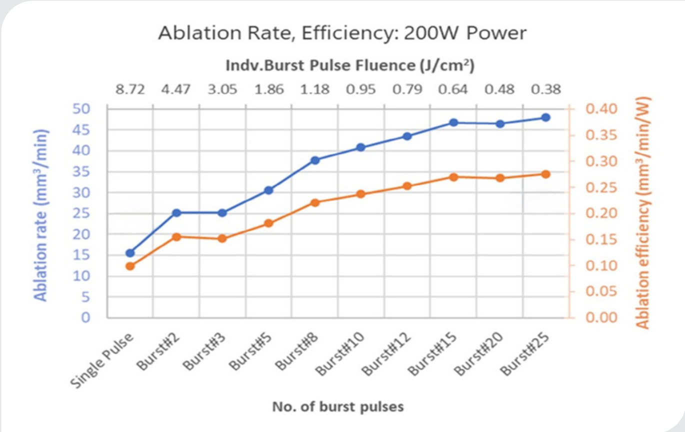

Figure 2. Ablation efficiency can be optimized using increasingly larger pulse bursts, which reduces the fluence of individual pulses applied to the material.

The data reveals a clear benefit of burst operation. Ablation efficiency steadily improves from single pulse operation up to 15 sub-pulses and then essentially levels off. At that point, the process reaches a maximum efficiency of approximately 0.27 mm³/min/W at a sub-pulse fluence of just 0.4–0.6 J/cm². Notably, the single pulse ablation efficiency is ~0.1 mm³/min/W at a fluence of ~9 J/cm². In a previous single-pulse ablation rate study, in which the average power was adjusted, a maximum efficiency of 0.12 mm³/min/W was determined at a fluence of 1-2 J/cm². This is still much higher than the ~0.5 J/cm² optimal fluence that is found to occur with burst mode.

Thus, burst mode more than doubles the ablation efficiency and did so while using far less energy per pulse. This supports the idea that USP burst processing allows more controlled, efficient energy usage by splitting a high-energy pulse into smaller, more manageable sub-pulses. From a broader perspective, the data also demonstrates the benefit of the burst pulse fluence optimization technique, which provides a simple and straightforward method for rapid process optimization.

Quality

For all lasers in this study, the machining quality was excellent. The large pocket-milled features that were processed exhibited smoothly-machined floors without melting, cracking, or other irregularities. In the lower-overlap ns feature sets, individual ablation craters are clearly defined; and for the higher-overlap USP features, smooth and continuous ablated lines are readily apparent.

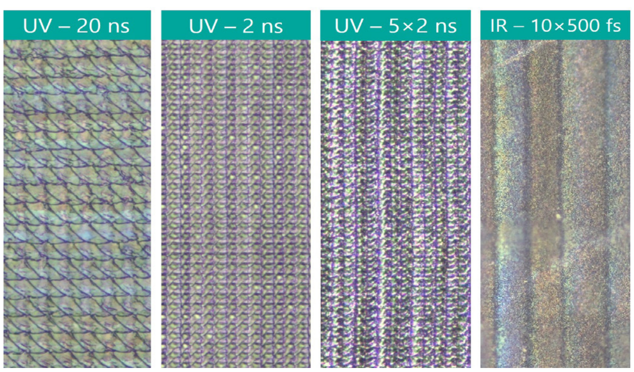

Figure 3. Machined surfaces for all laser output types tested, at their respective optimal fluence conditions, demonstrate excellent surface quality.

Comparison and Takeaways

The ablation efficiency results presented here provide valuable insights, but they tell only a part of the story. This is because actual material removal rates are the product of (ablation efficiency) × (average power), which means higher material removal rates can be achieved with a less efficient – but higher power – laser. Thus, the maximum power available from each laser type must be considered when choosing a source for a specific application. Table 1 summarizes the actual maximum removal rates achievable with some of the lasers available from MKS Spectra-Physics based on their output powers. These products are representative of the nanosecond UV and femtosecond IR lasers currently commercially available.

Laser	Pulse Output	Max. Power (W)	Max. Efficiency (mm^3/min/W)	Max. Removal Rate (mm^3/min)
Talon UV45	20 ns	45	0.17	7.65
Talon Ace UV100	2 ns	100	0.085	8.5
Talon Ace UV100	5×2 ns burst	100	0.12	12
IceFyre FS IR200	500 fs	200	0.12	24
IceFyre FS IR200	25×500 fs burst	200	0.28	56

Table 1. Summary of actual ablation rates achievable when the maximum available average power of the respective laser platforms is considered.

The table reveals how these actual laser sources rank in terms of overall process efficiency. For instance, while the Talon UV15 (20 ns) demonstrated the highest ablation efficiency in the UV laser testing, the comparatively lower maximum power that is available in that platform (45 W, Talon UV45) limits removal to ~7.65 mm^3/min. The Talon Ace, however, can achieve ~12 mm^3/min when operated at 100 W – despite its lower efficiency. Meanwhile, the IR femtosecond IceFyre system, running at ~200 W, could deliver up to 56 mm^3/min, reflecting both its high power and superior burst-mode ablation efficiency.

However, there's another practical process factor not detailed in this chart. Namely, heat affected zone (HAZ). While all lasers performed well – with excellent machined surface quality, no edge chipping, and minimal debris generation – using lower fluences, as well as shorter pulse widths typically yields a smaller HAZ. Therefore, the lasers in this study with the higher overall ablation rates should also be capable of the best overall machining quality due to their shorter pulse widths.

Based on all this information, we can offer the following takeaways from this study of UV ns and IR fs lasers for SiC ablation:

- UV ns lasers are viable, cost-effective tools offering high surface quality and sufficient throughput for many applications. The 20 ns pulse delivers optimal efficiency at high fluence. Shorter pulses (2 ns, 5×2 ns), which are more costly, reduce heat input and therefore provide an advantage for die-level processing or when adjacent circuitry is at risk.
- IR fs lasers, particularly with burst mode, deliver the highest efficiency, throughput, and quality, albeit at greater system complexity and cost.
- Burst control (in any laser) offers a valuable tuning parameter, letting users optimize efficiency without reducing average power or changing spot size.

PRODUCTS

UV Nanosecond and IR Femtosecond Lasers

Talon® UV and Green Lasers

The Talon laser platform is a family of UV and green diode-pumped solid state (DPSS) Q-switched lasers that deliver an unprecedented combination of performance, reliability, and cost. Talon is based on Spectra-Physics' *It's in the Box*™ design, with the laser and controller combined in a single, compact package. Talon exhibits high pulse-to-pulse stability and excellent TEM_{00} mode quality for tens of thousands of operating hours. The Talon laser is designed specifically for micromachining applications in a 24/7 manufacturing environment where system uptime is critical.

Talon® Ace™ UV100 Laser

Talon Ace UV100 is a powerful pulsed nanosecond laser, delivering an industry-leading >100 W UV power with compelling cost-performance in a small form factor. The new laser delivers unprecedented flexibility, including TimeShift™ programmable pulse capability and a wide pulse repetition-rate range, to enable micromachining process optimization. Talon Ace UV100 is ideal for high-speed and high quality manufacturing in micromachining of advanced electronics packaging, PC boards, photovoltaics, ceramics, semiconductors, and other materials and components.

IceFyre® FS UV and IR Femtosecond Lasers

The IceFyre FS family is an extraordinary leap forward in industrial femtosecond laser technology, delivering industry-leading performance, versatility, reliability, and cost-of-ownership. The IceFyre FS femtosecond lasers are ideal for high throughput, highest-quality micromachining of critical materials, including glass, polymers, metals, semiconductors, thin films, and composites for demanding consumer electronics, clean energy, medical device, and industrial applications. Based on Spectra-Physics' *It's in the Box* design, IceFyre FS integrates laser and control electronics in a single, easy-to-install package.

	Talon UV45	Talon Ace UV100	IceFyre FS IR200
Wavelength	355 nm	343 nm	343 ±2 nm
Power	>45 W @ 150 kHz	>100 W	>200 W @ 1–50 MHz
Repetition Rate Range	0–500 kHz	0–5.0 MHz	Single shot to 50 MHz
Pulse Energy	>300 µJ	>500 µJ	>200 µJ
Pulse Width	<35 ns @ 150 kHz	<2 to >50 ns	<500 fs
Pulse-to-Pulse Energy Stability	<2% rms @150 kHz <3% rms up to 300 kHz <5% rms above 300 kHz	<3%, 1 σ	<2% rms

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