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Nanoscale Precision Processing of Semiconductor Materials Using Ultrafast Lasers: Relationships between Pulse Parameters, Surface Quality and Structural Integrity: A Bibliometric Analysis

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ABSTRACT

Ultrafast laser processing enables semiconductor materials to undergo nanofabrication. To this dimensional precision requires simultaneous control of surface quality and structural integrity. This paper presents and examines relationships among various parameters such as pulse parameters and material transformations through a descriptive analysis. Publications were categorized using overlapping themes covering processing parameters, surface quality and structural integrity. Burst/repetition regimes showed the highest processing-related coverage, followed by wavelength and processing environment. Machining operations and micro-nanostructures accounted respectively. Phase transformation dominated structural themes, followed by amorphization. These findings support integrated Semiconductor Materials Using Ultrafast Lasers performance.

1. Introduction

Ultrafast laser processing has emerged as a versatile technique for fabricating semiconductor structures that require precise dimensional control, tailored surface functionality, and preservation of material integrity. Femtosecond and picosecond laser pulses facilitate highly localized energy deposition, enabling precision micromachining and controlled surface modification with minimal thermal effects under appropriately optimized processing conditions. These capabilities make ultrafast laser processing particularly attractive for applications in microelectronics, photonics, and advanced sensing technologies [49]. Early comparative investigations of femtosecond, picosecond, and nanosecond laser ablation demonstrated the advantages of ultrashort laser pulses in achieving precise material removal and reducing undesirable thermal damage [16]. However, laser processing of semiconductor materials involves complex interactions between electronic excitation, energy transfer, and structural transformation rather than simple instantaneous evaporation. Experimental investigations of dense electron–hole plasma generation in silicon have demonstrated that intense

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femtosecond laser excitation significantly alters the optical properties of the material during irradiation [48]. These transient electronic responses influence energy absorption and subsequent material transformations, creating opportunities for highly localized modifications that extend beyond the capabilities of conventional machining techniques. For example, Kiani et al. [27] demonstrated that femtosecond laser-induced amorphization followed by selective chemical etching could produce a silicon line approximately 150 nm wide, corresponding to approximately 1/67 of the 10 µm focused laser spot diameter, as illustrated in Figure 1. Nevertheless, the successful fabrication of nanoscale features should not be interpreted as direct evidence of reproducible dimensional accuracy or complete preservation of the underlying crystalline structure.

Laser processing parameters play a critical role in determining the balance between desirable material modification and unintended structural damage. Investigations of femtosecond laser irradiation of silicon have identified amorphization, melting, recrystallization, and ablation as possible outcomes depending on the applied laser fluence, demonstrating that shorter pulse durations do not necessarily guarantee superior processing quality [10]. Experimental and theoretical investigations have further established that laser pulse duration significantly influences the ablation threshold of silicon, reflecting the complex relationship between energy deposition and material response [25]. Similarly, multiple-pulse ablation experiments have demonstrated that pulse duration and cumulative laser exposure jointly affect ablation thresholds through incubation effects, whereby repeated irradiation progressively modifies the material's response to subsequent pulses [36].

Consequently, laser fluence, wavelength, repetition rate, pulse number, polarization, and spatial pulse overlap must be considered collectively when evaluating ultrafast laser processing performance. Furthermore, surface morphology alone is insufficient to provide a comprehensive assessment of processing quality. Raman spectroscopic investigations combined with surface microscopy have revealed the formation of amorphous layers and recrystallized regions in femtosecond laser-modified silicon, highlighting the importance of examining subsurface and structural transformations alongside visible surface features [11]. Therefore, a reliable evaluation of semiconductor laser processing should integrate structural characterization with quantitative measurements of feature dimensions, surface roughness, material removal efficiency, and crystalline integrity.

Beyond individual pulse characteristics, temporal pulse organization has attracted increasing attention as a strategy for improving processing efficiency and productivity. Ablation-cooled material removal using ultrafast laser pulse bursts has demonstrated that carefully controlled pulse sequences can enhance material removal efficiency while limiting residual thermal effects under suitable processing conditions [26]. Meanwhile, the formation of laser-induced periodic surface structures (LIPSS) introduces additional opportunities for engineering functional semiconductor surfaces. Theoretical investigations indicate that LIPSS formation involves complex interactions between electromagnetic excitation and material redistribution mechanisms, including processes associated with surface energy absorption and thermally driven material movement [7]. Despite substantial progress in understanding these mechanisms, important questions remain regarding the fundamental processes governing LIPSS formation, the reproducibility of the resulting structures, and their practical implementation in advanced manufacturing applications [8].

The diversity of laser processing mechanisms, experimental parameters, characterization techniques, and semiconductor applications highlights the need for a systematic examination of the development and emerging directions of this research field. Bibliometric analysis provides a quantitative framework for evaluating scientific publications, identifying influential contributions, examining collaboration networks, and mapping the intellectual and conceptual structures of a defined research literature corpus [17]. By integrating bibliometric approaches with an

understanding of the underlying laser–material interaction mechanisms, it becomes possible to identify established research themes, emerging technological developments, and knowledge gaps that may guide future investigations into ultrafast laser processing of semiconductor materials.

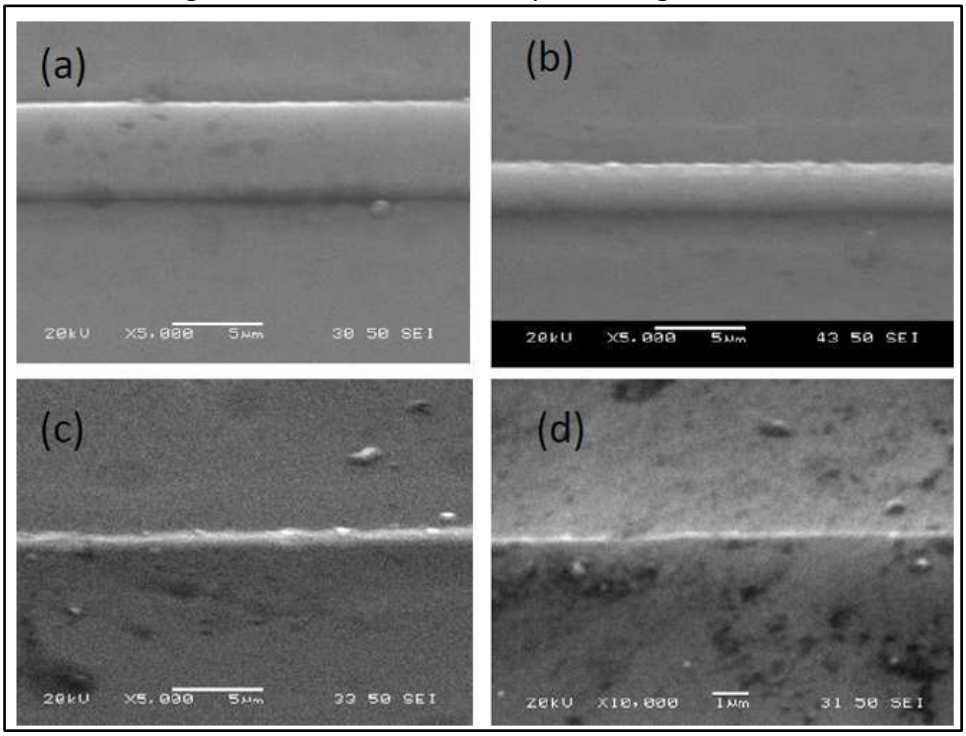


Fig. 1. Silicon line widths produced by femtosecond laser-induced amorphization followed by selective chemical etching. The narrowest line measures approximately 150 nm, corresponding to approximately 1/67 of the 10 µm focused laser spot diameter. Source: Adapted from Kiani et al. [27, p. 16524, Fig. 7]

Citation, bibliographic coupling, and keyword co-occurrence analyses provide valuable approaches for identifying the intellectual foundations, research relationships, and thematic structures of a scientific field that may not be readily apparent through conventional narrative reviews. VOSviewer facilitates the construction and visualization of bibliometric networks, including citation, co-authorship, bibliographic coupling, and keyword co-occurrence networks [51]. Similarly, Bibliometrix provides an integrated framework for quantitative science mapping, enabling comprehensive analyses of publication trends, intellectual structures, and thematic development [2]. These approaches are consistent with established bibliometric methodologies for examining scientific knowledge structures and research evolution [60]. Nevertheless, citation prominence primarily reflects scholarly attention and influence rather than experimental reliability or methodological validity. Likewise, keyword co-occurrence patterns reveal conceptual associations but cannot independently establish causal relationships between laser processing parameters and material performance.

Against this background, the present study addresses the need for an integrated bibliometric perspective that explicitly examines the relationships among laser pulse parameters, surface quality, and structural integrity in semiconductor processing. Specifically, the study aims to characterize publication trends, identify influential contributors and collaborative networks, map the intellectual and conceptual structures of the research field, and investigate the evolution of major research themes. Accordingly, four research questions guide the analysis:

1. How has scientific publication activity in ultrafast laser processing of semiconductor materials evolved over time?

2. Which publications, authors, institutions, and countries have contributed most significantly to the development of this research field?
3. How are laser pulse parameters associated with surface quality and structural integrity within the identified bibliometric research networks?
4. Which emerging research themes and insufficiently connected topics represent potential directions for future investigations?

By integrating bibliometric findings with selected technical studies, this research seeks to identify major research priorities, knowledge gaps, and emerging technological directions in ultrafast semiconductor laser processing. Importantly, the analysis does not attempt to establish experimentally validated operating conditions or infer direct causal relationships from bibliometric associations. Instead, it provides a systematic assessment of knowledge development and a conceptual foundation for subsequent experimental investigations focused on semiconductor processing performance.

2. Literature Review

The interaction between ultrafast laser pulses and semiconductor materials involves complex, highly transient physical processes governed by electronic excitation, energy transfer, and subsequent structural transformations. When an ultrafast laser pulse interacts with a semiconductor surface, photon absorption initially excites electrons before the electronic and lattice subsystems reach thermal equilibrium. The dominant absorption mechanisms depend on the incident photon energy, electronic band structure, and density of photoexcited charge carriers. Consequently, the temporal evolution of laser-induced material modification is strongly influenced by the coupling between electronic excitation, carrier transport, and lattice heating.

Experimental investigations of silicon below its melting threshold have employed transient reflectivity measurements to distinguish the contributions of carrier diffusion and energy transport to the observed optical response [23]. Under stronger excitation conditions, time-resolved reflectivity measurements have revealed the evolution of laser-induced electron–hole plasma formation and subsequent material expansion following irradiation with a single 300 fs laser pulse [18]. Similar investigations of germanium have demonstrated the temporal evolution of melting, ablation, and solidification within laser-irradiated regions, highlighting the complexity of ultrafast phase transformations in semiconductor materials [9]. Furthermore, ultraviolet femtosecond laser experiments involving silicon and germanium have shown that transient optical responses vary with laser fluence, emphasizing the importance of measurement timing when identifying and interpreting laser-induced phase transitions [41].

The influence of laser wavelength becomes particularly important when considering the mechanisms through which absorbed optical energy is transferred to the semiconductor lattice. For silicon irradiated with 50 ps laser pulses, experimental investigations have attributed energy deposition near the ablation threshold predominantly to band-to-band absorption at wavelengths of 343 and 515 nm, whereas absorption by laser-generated free carriers becomes more significant at 1030 nm [47]. These findings demonstrate that the dominant absorption mechanism can vary considerably with irradiation wavelength, even when pulse duration remains unchanged. Further investigations have distinguished the thresholds associated with laser-induced amorphization and ablation across different pulse durations and wavelengths, demonstrating that permanent structural modification can occur before measurable material removal [21].

Figure 2 illustrates the progression from ultrafast laser energy absorption to structural modification in crystalline silicon. The fluence interval between amorphization and ablation

thresholds is particularly relevant to precision semiconductor manufacturing because it provides a potential processing window in which the crystalline structure can be modified without substantial material removal. Nevertheless, the practical applicability of this processing window depends on the stability and reproducibility of the resulting material transformations under repeated irradiation.

During multipulse laser processing, the interaction between successive pulses introduces additional complexity because subsequent pulses may encounter material with altered optical absorption, thermal properties, and crystalline structure. Therefore, an ablation or modification threshold determined from a previously unexposed semiconductor surface may not adequately represent the response of the same material after repeated laser irradiation. These considerations highlight the importance of evaluating cumulative exposure effects when interpreting experimental processing thresholds.

Laser fluence, defined as the incident pulse energy per unit irradiated area, is a fundamental parameter governing the magnitude of energy delivered to the semiconductor surface. Pulse duration also influences the peak laser intensity for a given fluence, thereby affecting the relative contributions of nonlinear absorption, carrier excitation, and subsequent energy transfer processes. In addition, laser wavelength and temporal pulse arrangement may interact to influence energy deposition and material removal efficiency. For example, dual-wavelength femtosecond laser experiments involving silicon have demonstrated enhanced ablation efficiency when a 515 nm pulse precedes a 1030 nm pulse, indicating that the temporal sequence of different wavelengths can significantly influence laser–material interactions [12].

In scanning laser processing, the spatial distribution of successive laser pulses is another important factor determining material removal characteristics and surface morphology. The distance between consecutive pulse centers along a scanning trajectory is determined by the ratio of scanning speed to pulse repetition rate. For a fixed laser spot diameter and repetition rate, increasing the scanning speed reduces the spatial overlap between successive pulses. Meanwhile, the spacing between adjacent scanning tracks independently determines the transverse overlap. These relationships influence cumulative energy deposition, surface modification uniformity, and the resulting topographical characteristics.

Experimental investigations of single-crystal 4H-SiC have demonstrated the formation of laser-induced surface ripples with periodicities ranging from approximately 145 to 196 nm under the reported higher-repetition-rate processing conditions [52]. Similarly, studies involving femtosecond laser planarization of SiC ceramics have shown that variations in spot overlap ratio influence material removal depth, surface roughness, and oxidation behavior [29]. These findings indicate that pulse overlap must be considered alongside fluence, repetition rate, and scanning conditions when evaluating processing performance, particularly where surface quality and structural preservation are critical requirements.

Beyond conventional single-pulse and multipulse irradiation, ultrafast laser burst processing introduces an additional temporal dimension through the controlled delivery of closely spaced pulses. Investigations of silicon ablation using gigahertz-repetition-rate laser sources have demonstrated that material removal efficiency depends on both the energy distribution and the number of pulses within each burst [34]. Systematic comparisons involving crater formation, laser scribing, and cavity milling have further demonstrated that processing efficiency and material response depend on the specific machining operation, emphasizing the need to distinguish among different experimental geometries when comparing reported results [6].

Recent investigations have extended burst-processing approaches to terahertz intraburst pulse repetition rates, as well as megahertz and gigahertz burst regimes, including ultrafast laser processing at repetition rates reaching 15 GHz [22, 33, 4]. Collectively, these developments demonstrate the

increasing importance of temporal pulse engineering in semiconductor laser processing. However, improvements in material removal efficiency must be evaluated together with surface morphology, thermal accumulation, and crystalline integrity to determine whether enhanced processing productivity is accompanied by acceptable material quality.

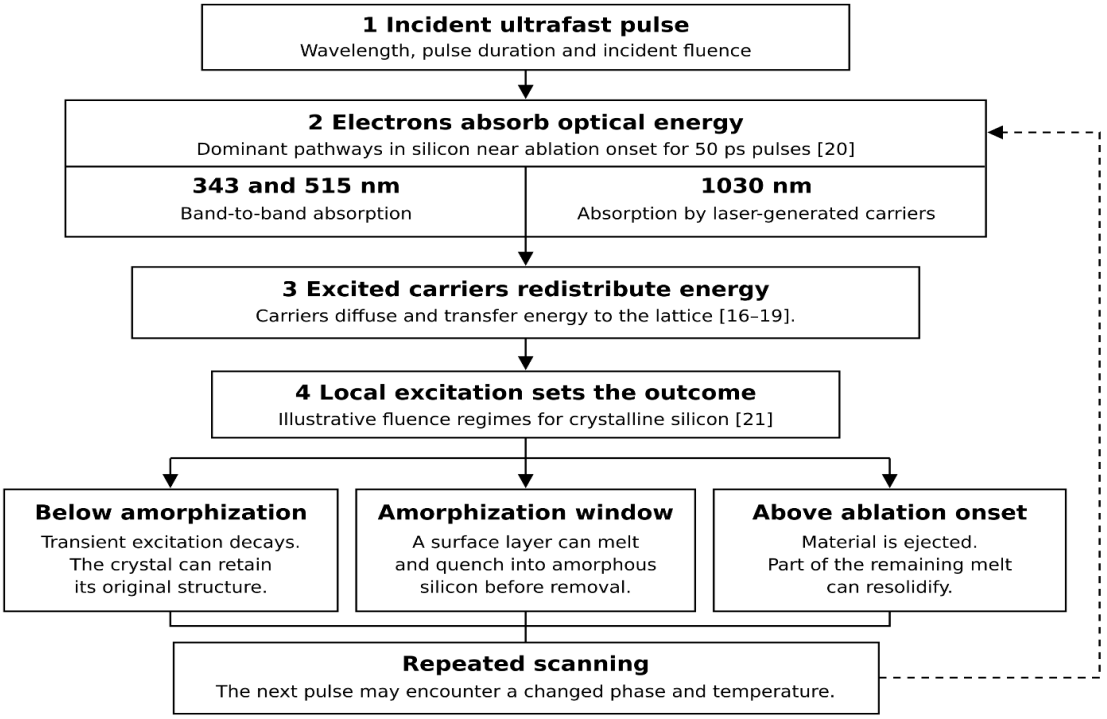


Fig. 2. Ultrafast laser absorption to structural modification in crystalline silicon

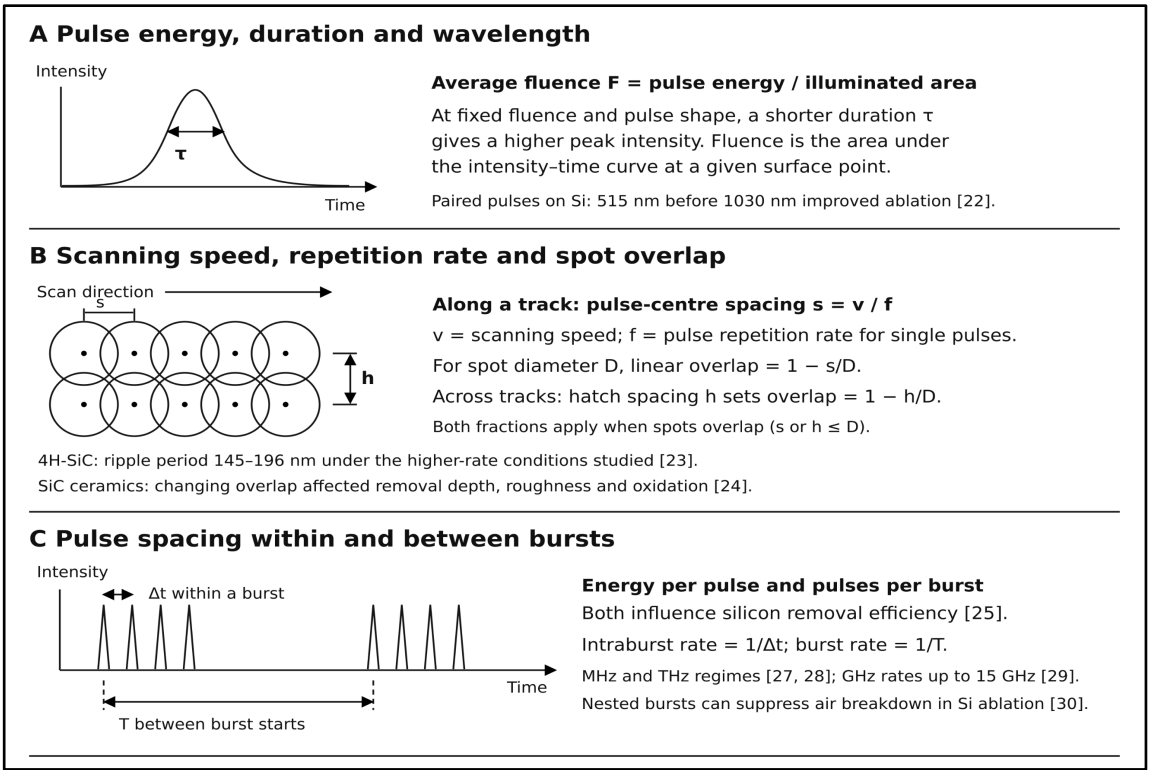


Fig. 3. Principal laser processing parameters in ultrafast semiconductor machining

These investigations highlight the importance of distinguishing the temporal separation between individual pulses within a burst from the interval between successive bursts, as both timescales can influence laser–material interactions, energy accumulation, and material removal efficiency. Further advancements in burst-mode processing have demonstrated that distributing laser energy across nested pulse bursts can suppress air ionization during silicon ablation, thereby facilitating more efficient energy delivery to the target material [37].

Surface quality is a critical factor in determining whether laser-fabricated semiconductor structures satisfy their intended functional and dimensional requirements. Important quality indicators include feature width, groove depth, edge definition, and surface roughness measured over a clearly specified sampling area. The interpretation of these parameters depends on the intended application, particularly when surface roughness is deliberately introduced as a functional characteristic. For example, periodic surface ripples may enhance the performance of textured optical surfaces, whereas similar surface irregularities along a laser-diced wafer edge may compromise dimensional accuracy and cutting quality. Consequently, reliable comparisons of laser processing outcomes require clearly defined measurement procedures and consistent evaluation criteria.

In addition to surface topography, debris formation and material redeposition can significantly influence the overall quality of laser-processed semiconductor surfaces. Redeposited material may extend beyond the intended processing region, increasing the effective area affected by laser irradiation. Experimental investigations of femtosecond laser ablation of silicon have reported debris deposits extending approximately 40–300 μm around laser-generated craters under the investigated fluence conditions [45]. The surrounding processing environment also plays an important role in determining debris formation and surface contamination. Studies have demonstrated that ambient air influences debris generation during femtosecond laser ablation, whereas processing silicon under water can reduce oxidation and redeposition under suitable experimental conditions [38, 44]. More recently, assisted femtosecond laser surface structuring using a thin frost layer has been investigated as an alternative approach for improving micro- and nanoscale surface quality while reducing undesirable debris and recast material [20].

These observations emphasize the importance of distinguishing surface contamination and redeposited material from subsurface structural damage. Unlike debris deposits, which accumulate on or around the processed region, subsurface damage involves changes in the material that remains beneath the surface, including amorphization, recrystallization, residual stress, and defect formation. Accordingly, surface morphology measurements should be complemented by structural characterization techniques to provide a more comprehensive evaluation of laser processing quality.

Raman spectroscopy is particularly useful for identifying laser-induced phase transformations and evaluating changes in crystalline structure under different processing environments [1]. Meanwhile, cross-sectional transmission electron microscopy provides direct information regarding the thickness and morphology of structurally modified layers. For example, investigations of single-pulse femtosecond laser irradiation of silicon have identified an amorphous layer approximately 42–44 nm thick at a selected measurement location, demonstrating that substantial structural modification can occur beneath a laser-processed surface [19]. Other investigations have reported dislocations and additional silicon phases surrounding laser-induced microcraters, indicating that localized laser irradiation can generate complex structural transformations beyond the visibly ablated region [31].

Similar considerations apply to silicon carbide, where internal laser modification can produce complex residual stress distributions and subsurface defects. Investigations of femtosecond laser-induced internal stress adjustment zones in 4H-SiC have revealed compressive stress concentrated

within modified regions and surrounding tensile stress distributions. Microscopic observations have also identified lateral cracks and nanovoids, highlighting the relationship between localized energy deposition, microstructural damage, and macroscopic wafer deformation [28]. These findings demonstrate that microcracking and residual stress must be assessed independently of conventional surface roughness measurements because a geometrically smooth surface does not necessarily indicate the absence of internal structural damage.

For semiconductor devices, material integrity may also require evaluation through electrical characterization. In photovoltaic wafer manufacturing, for instance, femtosecond laser ablation is employed to selectively remove dielectric layers and create electrical contact openings. However, excessive laser energy can damage the underlying silicon substrate, potentially affecting device performance. Consequently, the evaluation of laser processing quality should consider both the accuracy of dielectric removal and the preservation of the electrical properties of the semiconductor material [56].

Previous reviews have examined semiconductor laser processing from different manufacturing and material perspectives. Reviews of laser ablation and wafer dicing have emphasized the influence of processing parameters on kerf width, cutting speed, cut-edge quality, and material damage during wafer separation [32, 13]. These studies provide valuable insights into the technological requirements and challenges associated with precision semiconductor manufacturing.

More specifically, investigations of femtosecond laser processing of silicon carbide have examined the relationships among laser parameters, material removal mechanisms, surface morphology, and processing performance [55]. Recent reviews of laser-assisted silicon carbide wafer exfoliation have further highlighted the importance of controlling subsurface fracture initiation and propagation to achieve precise material separation while minimizing structural damage [39]. These investigations emphasize that localized laser energy deposition must be carefully controlled to balance manufacturing efficiency, dimensional precision, and preservation of material integrity.

Similarly, studies of femtosecond laser-assisted etching for microelectronic chip fabrication have examined laser–material interaction mechanisms, material removal characteristics, and process integration requirements [40]. Such investigations demonstrate the growing importance of ultrafast laser technologies in semiconductor manufacturing, particularly for applications requiring high precision and controlled material modification.

At a broader research level, bibliometric investigations have provided quantitative insights into the development of laser processing technologies. For example, Chen et al. [15] examined 3,958 publications related to laser processing, identifying influential contributors, research trends, and major thematic areas across different applications. Although these studies provide valuable perspectives on technological developments and scientific contributions, an important research gap remains concerning the extent to which laser pulse parameters, surface geometry, and subsurface structural integrity are investigated collectively for the same semiconductor material and manufacturing operation.

The present study addresses this gap by integrating bibliometric mapping with a focused examination of selected experimental investigations. Specifically, the analysis distinguishes conventional surface roughness measurements from periodic surface structure characteristics, differentiates surface texturing from internal material modification, and identifies studies that combine morphological observations with structural or electrical characterization techniques. This integrated approach enables the identification of influential research contributions, emerging methodological combinations, and insufficiently explored relationships among processing parameters, surface quality, and structural integrity.

Nevertheless, bibliometric associations do not independently establish the physical condition of laser-processed materials or demonstrate causal relationships between processing parameters and material performance. Therefore, the findings are interpreted as indicators of research development and knowledge gaps rather than direct experimental evidence of optimal processing conditions.

3. Bibliometric Methodology

This study employs a bibliometric approach to systematically examine the development, intellectual structure, and emerging research priorities of ultrafast laser processing of semiconductor materials, with particular emphasis on the relationships among laser pulse parameters, surface quality, and structural integrity. The analysis provides a quantitative framework for evaluating scientific publication trends, identifying influential research contributions, examining collaboration networks, and mapping the conceptual relationships that characterize the field.

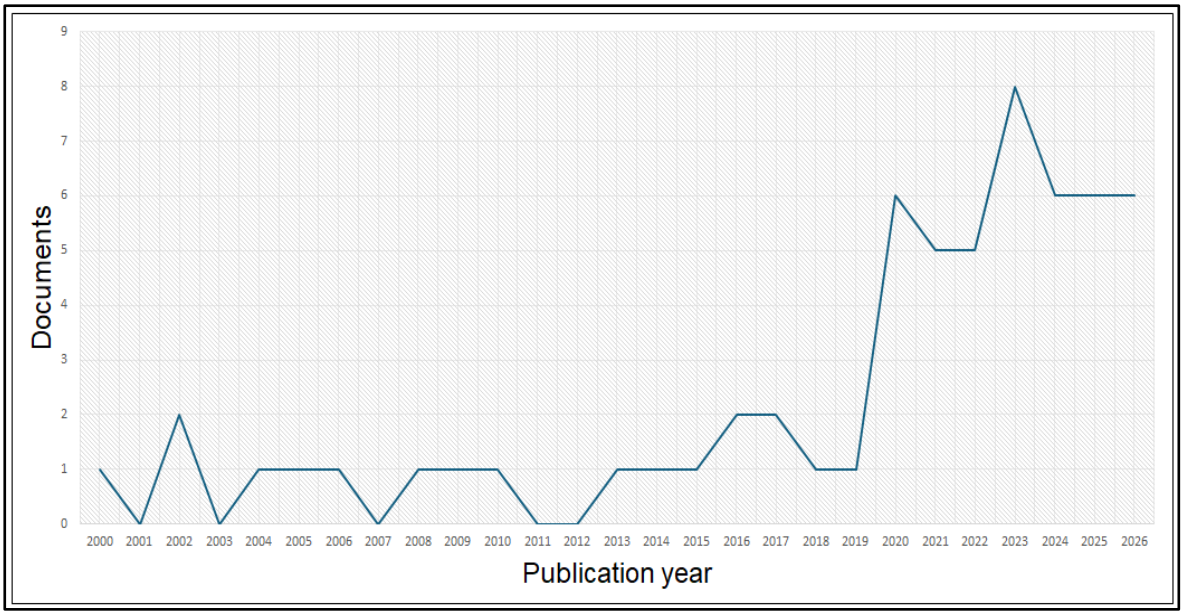


Fig 4. Laser processing parameters versus number of publications

Performance analysis with mapping of technical will follow bibliometric supporting statistical analysis. Scopus will serve as the primary database, covering publications from 2000 to the actual retrieval date in 2026. The retrieval date, complete search expression, applied filters and exported record count will be documented to ensure reproducibility. Publications from 2026 will be treated as partial-year data. The search will combine three concept groups such as ultrafast irradiation, semiconductor materials and processing operation within current titles and keywords. The figure-4 shows the annual distribution of documents concerning ultrafast laser processing of semiconductor materials from 2000 to 2026. Document counts remain low during 2000–2015 years. Output reaches two documents in 2016 and 2017, before declining to one in 2018 and 2019. A marked increase occurs in 2020 with six documents, followed by five annually during 2021–2022. The highest count appears in 2023 reaching eight documents, while 2024–2026 each show six. These values describe the plotted dataset; database provenance and the completeness of 2026 coverage require verification before interpreting the pattern as field-wide research growth. Eligible records are included with research articles, reviews and conference papers addressing ultrafast semiconductor processing. Studies involving exclusively metals, nanosecond processing will be excluded unless they provide directly relevant comparative semiconductor evidence. Duplicate records will be identified using DOIs and normalized titles. A thesaurus will harmonize equivalent terminology while preserving distinctions between semiconductor compositions, pulse regimes and characterization methods.

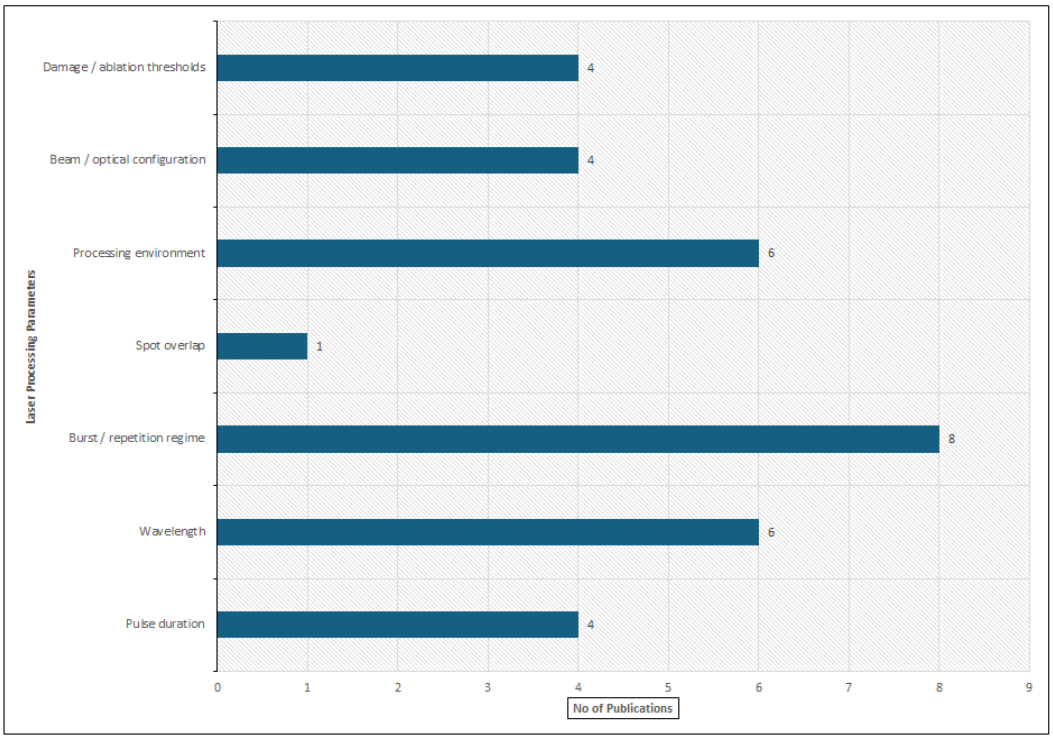


Fig. 5. Laser processing parameters versus number of publications

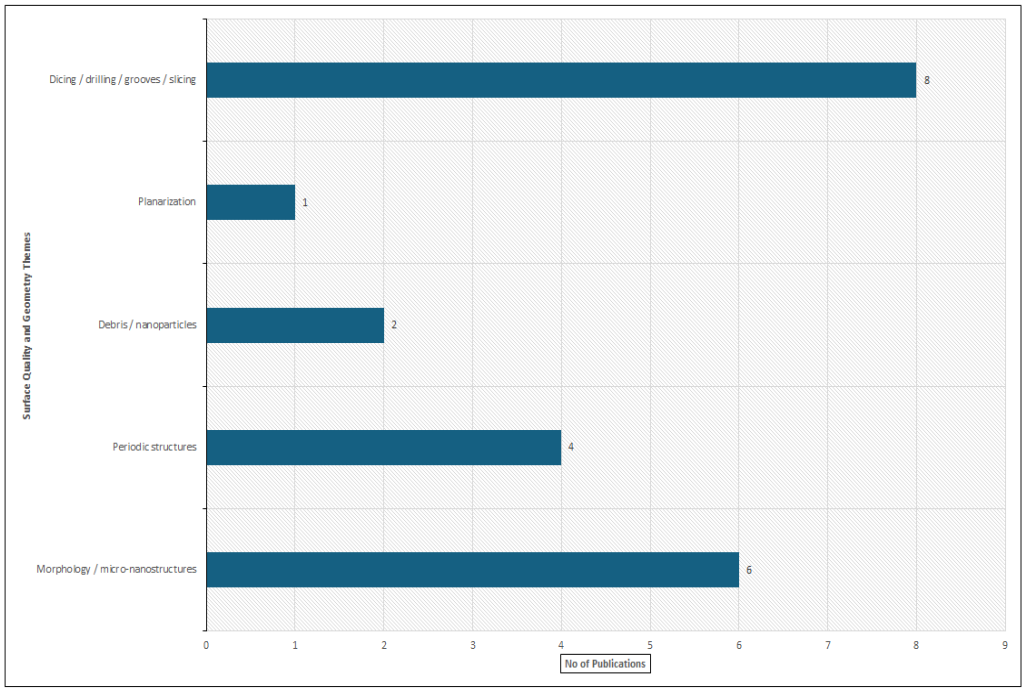


Fig. 6. Surface Quality and geometry themes versus number of publications

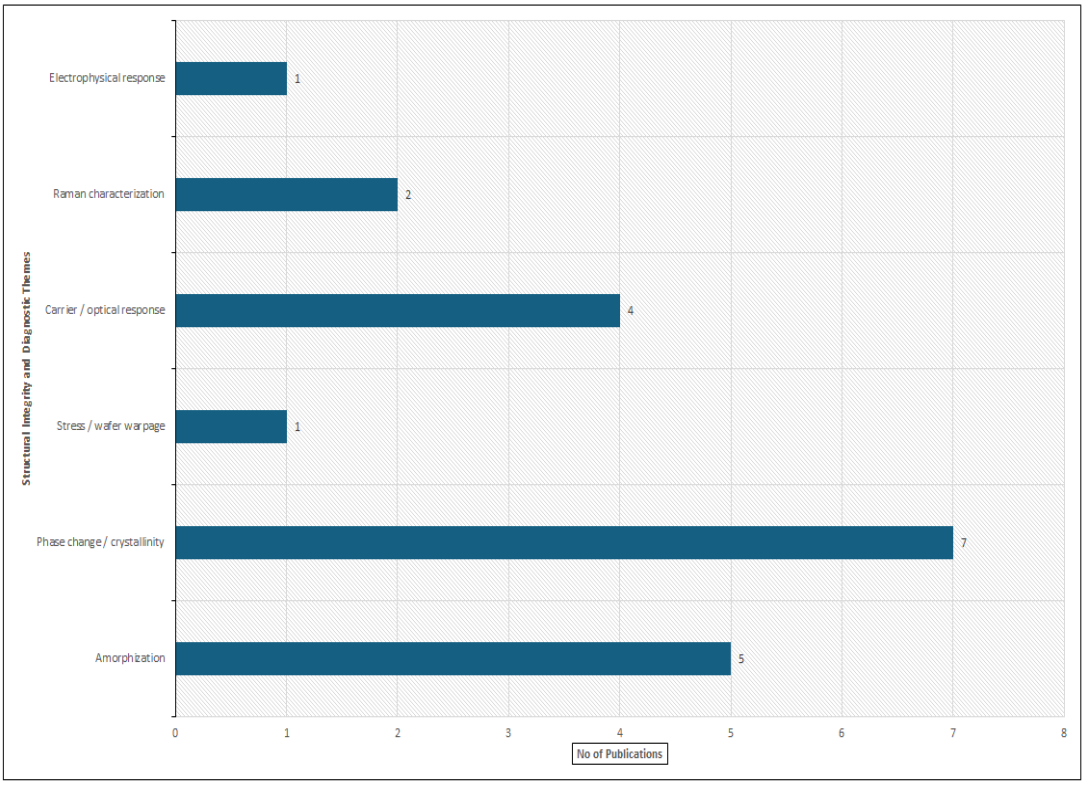


Fig. 7. Structural integrity and diagnostic themes versus number of publications

The interpretation of bibliometric networks considers several interconnected research areas, including carrier dynamics and phase transformations [48, 23, 18, 9, 41], wavelength- and pulse-duration-dependent material responses [47, 21, 12], ultrafast laser burst processing [34, 6, 22, 33, 4, 37], and surface morphology and crystallinity [53, 50, 43, 35, 14, 46]. These research areas provide a technical foundation for examining the relationships among irradiation conditions, semiconductor material responses, surface characteristics, and structural integrity.

Figure 5 presents the distribution of selected references according to laser processing parameters, including externally controlled irradiation conditions and experimentally determined material-response thresholds. Burst and repetition-rate regimes constitute the most frequently represented category, accounting for eight references, followed by irradiation wavelength and processing environment, with six references each. Pulse duration, beam and optical configuration, and damage or ablation thresholds each account for four references, whereas spatial pulse overlap is represented by one reference. This classification distinguishes independently controlled laser processing variables from experimentally determined material-response characteristics, providing a structured basis for interpreting the technical focus of the selected literature.

Figure 6 illustrates the distribution of references associated with surface quality and geometrical characteristics. Machining operations represent the largest category, comprising eight references, followed by surface morphology and micro/nanostructures with six references, periodic surface structures with four, debris and nanoparticle formation with two, and planarization with one. For quantitative comparisons, the analysis distinguishes between profile and areal surface roughness parameters, lateral feature dimensions, and ablation depth. Where available, the corresponding measurement units, characterization techniques, and sampling conditions are retained to facilitate consistent interpretation of reported processing outcomes.

Figure 7 presents the distribution of references related to structural integrity and diagnostic characterization. Phase transformations and crystallinity constitute the most frequently represented

category, with seven references, followed by amorphization with five and carrier dynamics or optical response with four. Raman characterization is represented by two references, whereas residual stress and wafer warpage, as well as electrophysical response, are each represented by one reference. The classification distinguishes characterization techniques from the structural states and functional properties they are intended to evaluate. Subsequent keyword co-occurrence analysis is intended to examine conceptual associations among laser irradiation parameters, surface characteristics, and structural integrity indicators.

3. Results and Discussion

The descriptive findings indicate increasing research attention to ultrafast laser processing of semiconductor materials within the selected bibliography. However, the publication distribution should not be interpreted as a comprehensive representation of publication growth across the entire research field. As illustrated in Figure 4, the selected publications show relatively limited annual representation before 2016, followed by an increase to six documents in 2020. Five documents were recorded annually in 2021 and 2022, while the highest annual count of eight publications occurred in 2023. The reported distribution subsequently shows six publications annually from 2024 to 2026. Nevertheless, the 2026 count requires reconciliation with the underlying bibliographic records, particularly because the available coverage represents an incomplete publication year. Therefore, these observations should be interpreted as descriptive characteristics of the selected literature rather than evidence of broader publication trends.

The classification of laser processing parameters presented in Figure 5 demonstrates that burst and repetition-rate regimes receive the greatest attention within the selected references, accounting for eight publications. Irradiation wavelength and processing environment follow, with six references each. Pulse duration, beam configuration, and damage or ablation thresholds are each represented by four references, while spatial pulse overlap appears in only one. This distribution suggests that temporal energy delivery and irradiation conditions are prominent research themes within the selected literature. However, the frequency of references associated with a particular parameter does not necessarily indicate its relative importance in determining experimental processing performance.

The physical mechanisms underlying ultrafast laser–semiconductor interactions further support the need to interpret these processing parameters collectively. Laser-induced electronic excitation modifies carrier populations and optical absorption characteristics, while subsequent energy transfer and phase transformations determine whether irradiation results in structural modification, melting, or material removal [23, 18, 9, 41]. Wavelength-dependent absorption mechanisms and pulse-duration-dependent modification thresholds provide a physical basis for understanding the relationships between irradiation settings and semiconductor processing outcomes [47, 21, 12]. Consequently, the combined effects of laser fluence, pulse duration, wavelength, and temporal pulse arrangement must be considered when evaluating material responses.

Burst-mode laser processing introduces additional complexity because material removal characteristics depend on several interconnected temporal parameters. Experimental investigations have demonstrated the importance of distinguishing intraburst pulse spacing, burst repetition rate, pulse number, and energy distribution when assessing processing efficiency [4, 37]. Although burst and repetition-rate regimes represent the most frequently identified processing category, their prominence does not establish the superiority of any particular burst configuration. Instead, processing performance remains dependent on semiconductor composition, machining geometry, irradiation conditions, and the specific quality requirements of the intended application.

Figure 6 indicates that machining operations constitute the largest surface-related category, with eight references, followed by surface morphology and micro/nanostructures with six, periodic surface structures with four, debris and nanoparticle formation with two, and planarization with one. These categories encompass both manufacturing operations and resulting surface characteristics and therefore should not be interpreted as equivalent indicators of processing quality. For example, periodic surface structures may provide desirable optical or functional properties, whereas similar topographical variations along a precision-machined edge may adversely affect dimensional accuracy and geometrical conformity. Accordingly, surface ripple periodicity, groove depth, profile roughness, and areal roughness should be evaluated and reported as distinct parameters.

The fabrication of nanoscale silicon structures further illustrates the distinction between feature dimensions and comprehensive manufacturing quality. Kiani et al. [27] demonstrated the formation of a silicon line approximately 150 nm wide using femtosecond laser-induced amorphization followed by selective chemical etching. Although this feature dimension was substantially smaller than the focused laser spot diameter, its successful fabrication does not independently establish dimensional repeatability, processing consistency, or preservation of the surrounding crystalline structure. Therefore, nanoscale feature formation should be evaluated alongside structural characterization and reproducibility measurements before conclusions regarding manufacturing precision are established.

The processing environment also influences surface quality through its effects on debris generation, material redeposition, oxidation, and surface contamination. Comparative investigations of silicon laser ablation under different environmental conditions have demonstrated that processing media can alter material removal behavior and the characteristics of the resulting surface [44, 20, 1]. These findings emphasize that the relationship between laser processing parameters and surface quality extends beyond direct irradiation conditions to include environmental interactions that may influence the final morphology and material integrity.

Figure 7 identifies phase transformations and crystallinity as the most frequently represented structural integrity category, comprising seven references. Amorphization follows with five references, while carrier dynamics and optical response account for four. Raman characterization is represented by two references, whereas residual stress and wafer warpage, together with electrophysical response, are each represented by one. These distributions suggest that mechanical and electrical integrity receive comparatively limited explicit representation within the selected reference titles. Nevertheless, this observation should not be interpreted as evidence that these characteristics are insufficiently investigated across the broader research field.

Experimental investigations demonstrate that surface morphology alone cannot provide a comprehensive assessment of semiconductor material integrity. Laser-induced amorphous layers, recrystallized regions, residual stresses, dislocations, and subsurface defects may coexist with apparently well-defined surface geometries [19, 31, 28]. Consequently, surface microscopy should be complemented by appropriate structural characterization techniques to identify material transformations that may not be visible through conventional topographical measurements. Furthermore, electrical characterization provides an additional criterion for evaluating processing quality in semiconductor device applications, particularly where laser irradiation may alter the electrical properties or functionality of the underlying material [56].

Collectively, these findings support a processing–structure–property framework in which laser irradiation conditions influence energy deposition and material transformations, which subsequently affect surface geometry, structural integrity, and functional performance. Within this framework, the principal research opportunity lies in integrating these measurements for the same semiconductor material and machining operation. Future comparative investigations should therefore report

material composition, pulse characteristics, laser fluence, spatial overlap, processing environment, characterization methods, and measurement uncertainty to enable more reliable interpretation of processing outcomes.

Nevertheless, the present findings must be interpreted within the limitations of the adopted classification approach. Because the thematic categories may overlap and are derived primarily from reference-title screening, their frequencies cannot establish causal relationships, quantify the relative experimental importance of individual processing parameters, or identify statistically validated operating windows. Furthermore, comprehensive assessments of author influence, institutional collaboration, citation impact, and keyword-network relationships require complete bibliographic metadata and systematic network analysis. Accordingly, the current results provide a descriptive foundation for subsequent bibliometric network assessment and targeted synthesis of experimental evidence rather than a definitive evaluation of processing performance.

4. Conclusion and Future Research Directions

This study presents a descriptive synthesis of research examining the relationships among ultrafast laser pulse parameters, surface quality, and structural integrity in semiconductor processing. The findings indicate that burst and repetition-rate regimes represent the most frequently identified processing-related category within the selected bibliography, followed by irradiation wavelength and processing environment. This distribution highlights research attention to temporal energy delivery and irradiation conditions, although the relative frequency of these themes does not necessarily reflect their experimental significance. Within the surface-related categories, machining operations and surface morphology constitute the most frequently represented research areas, whereas phase transformations, crystallinity, and amorphization dominate the structural integrity classifications.

The findings emphasize that successful nanoscale feature fabrication should not be evaluated solely on the basis of feature dimensions. Instead, comprehensive assessment of semiconductor laser processing requires consideration of dimensional repeatability, surface morphology, material redeposition, subsurface damage, residual stress, and functional performance. A small fabricated feature does not independently demonstrate manufacturing precision or preservation of semiconductor material integrity. Therefore, reliable processing evaluation requires the integration of geometrical measurements with structural and, where relevant, electrical characterization.

The comparatively limited representation of residual stress, wafer warpage, electrophysical response, and spatial pulse overlap within the selected reference titles suggests potential priorities for further investigation. However, these observations identify gaps within the analyzed literature selection rather than establishing deficiencies across the entire research field. Future investigations should therefore extend the bibliometric analysis through comprehensive citation, co-authorship, bibliographic coupling, and keyword co-occurrence networks to establish a more systematic understanding of influential research contributions and emerging thematic relationships.

Further experimental research should distinguish intraburst pulse repetition frequency from the repetition rate of successive bursts and systematically examine their combined effects on material removal efficiency, surface quality, and structural integrity. Comparative studies should jointly report laser fluence, wavelength, pulse duration, pulse number, spatial overlap, semiconductor composition, and processing environment. Integrating these parameters within consistent experimental frameworks would improve the interpretation of laser–material interactions and facilitate more meaningful comparisons across different semiconductor systems and machining operations.

In addition, coordinated characterization using surface and cross-sectional microscopy, Raman spectroscopy, residual stress mapping, and electrical measurements should be employed to establish stronger relationships among surface geometry, subsurface transformations, and device functionality. Standardized measurement definitions, transparent uncertainty reporting, and comparable processing conditions are essential for improving experimental reproducibility and supporting reliable process optimization. Ultimately, integrating bibliometric insights with systematic experimental characterization can provide a stronger foundation for developing precise, efficient, and structurally reliable ultrafast laser processing technologies for advanced semiconductor manufacturing.

Declaration

The authors declare that they have no conflicts of interest regarding the publication of this article. The authors further affirm that the manuscript represents their original work and that all sources have been appropriately acknowledged and cited.

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