From Femtosecond Laser Processing to Millimeter-Scale Nanowires: Multiscale Material Design for Next-Generation Devices

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Date: 03-02-2026

Abstract

Recent progress in ultrafast laser–matter interaction has enabled new approaches for engineering materials across multiple length scales with high spatial precision and limited thermal damage. Femtosecond laser processing, in particular, offers a flexible and maskless method for tailoring surface and near-surface structures while preserving underlying material integrity. This study investigates a multiscale materials design strategy that links femtosecond laser–induced surface modification with the formation and integration of extended nanowire architectures. The influence of laser processing parameters on surface morphology, structural anisotropy, and nanowire nucleation behavior is examined across nano-, micro-, and millimeter-length scales. By correlating hierarchical structural features with electrical, optical, and mechanical responses, the work highlights how controlled laser-generated templates can support coherent nanowire growth and functional continuity over extended dimensions. The results provide insights into the role of ultrafast laser processing as a unifying tool for multiscale material engineering, with relevance to electronic, photonic, sensing, and energy-related device platforms.

Keywords: Femtosecond laser processing; multiscale material design; nanowires; hierarchical structures; laser–matter interaction; next-generation devices

1. Introduction

1.1 Background and Motivation for Multiscale Material Design

The continuous miniaturization of electronic, photonic, and biomedical devices has intensified the demand for materials that exhibit controlled functionalities across multiple length scales. Modern device architectures increasingly rely on the precise coordination of nanoscale building

blocks with microscale and millimeter-scale features to achieve enhanced electrical transport, optical response, and mechanical stability. Multiscale material design has therefore emerged as a critical paradigm, enabling the integration of distinct structural hierarchies within a single platform to unlock performance characteristics unattainable by single-scale systems. Recent advances in low-dimensional materials, particularly van der Waals nanowires and anisotropic layered compounds, have demonstrated exceptional charge transport, thermal behavior, and quantum confinement effects when structural coherence is preserved over extended lengths [1,7]. However, translating these nanoscale advantages into device-relevant dimensions remains a persistent challenge. Bridging the gap between nanoscale precision and macroscopic usability requires fabrication strategies capable of deterministic control over structure formation across several orders of magnitude in length. Femtosecond laser processing has gained attention as a versatile tool for multiscale material engineering due to its ultrafast energy deposition, minimal thermal diffusion, and compatibility with a wide range of materials [2]. When properly optimized, this approach offers a pathway to simultaneously engineer surface morphologies, induce phase transformations, and guide nanowire growth, thereby enabling coherent multiscale architectures suitable for next-generation devices.

1.2 Fundamentals of Femtosecond Laser–Matter Interaction

Femtosecond laser–matter interaction is governed by energy deposition on timescales shorter than electron–phonon relaxation, resulting in highly non-equilibrium excitation dynamics. Upon irradiation, electrons absorb energy through nonlinear optical processes, including multiphoton absorption and avalanche ionization, while the lattice remains temporarily unheated. This decoupling allows for precise material modification with reduced heat-affected zones compared to longer-pulse laser systems [2]. The subsequent relaxation of excited electrons through electron–phonon coupling plays a decisive role in defining the final material response, influencing melting, ablation, and defect formation [3]. In anisotropic and low-dimensional materials, these interactions can produce unconventional thermal and electronic transport behaviors, which directly affect nanostructure formation and stability [4,9]. Understanding and controlling these ultrafast processes is therefore essential for tailoring surface features and enabling controlled nanowire nucleation during laser processing.

Importantly, femtosecond laser irradiation can induce localized stress fields, transient phase transitions, and self-organized patterns that act as templates for subsequent multiscale growth phenomena. These effects form the physical foundation for laser-assisted fabrication strategies that extend beyond surface patterning toward integrated nanoscale and millimeter-scale material systems.

1.3 Limitations of Conventional Nanofabrication Techniques

Conventional nanofabrication approaches, such as electron-beam lithography, focused ion beam milling, and chemical vapor deposition, offer high spatial resolution but face intrinsic limitations when extended to large-area or multiscale fabrication. These methods are often constrained by high cost, low throughput, complex processing steps, and limited scalability, making them unsuitable for industrial-level production of hierarchical architectures. Moreover, traditional bottom-up nanowire growth techniques typically require stringent environmental control and struggle to achieve uniform alignment and length extension beyond the microscale [1]. Top-down methods, while precise, can introduce structural damage, contamination, or unintended defects that degrade electronic and thermal performance. These constraints hinder the seamless integration of nanoscale components into macroscale devices. In contrast, laser-based processing provides a maskless, flexible alternative that can overcome many of these challenges. However, despite its promise, the systematic use of femtosecond lasers for controlled multiscale nanowire fabrication remains underexplored, particularly in terms of reproducibility and structure–property optimization.

1.4 Research Objectives and Scope of the Study

The primary objective of this study is to establish a femtosecond laser–assisted framework for multiscale material design, enabling the transition from nanoscale surface modification to millimeter-scale nanowire architectures. The work aims to elucidate the mechanisms governing laser-induced surface structuring, nanowire nucleation, and extended growth under controlled processing conditions. Specifically, this research investigates (i) the influence of femtosecond laser parameters on hierarchical morphology formation, (ii) the structural evolution of nanowires across length scales, and (iii) the resulting structure–property relationships relevant to electronic, optical, and biomedical applications [2,7]. By integrating experimental characterization with

mechanistic analysis, the study seeks to bridge existing gaps between ultrafast laser processing and scalable device fabrication. The scope of the paper encompasses materials processing, multiscale characterization, and device-oriented performance evaluation, providing insights that contribute to the broader field of next-generation materials engineering.

2. Literature Review

2.1 Femtosecond Laser Processing Techniques for Surface Structuring

Femtosecond laser processing has emerged as a powerful technique for precision surface engineering due to its ability to deposit energy on ultrashort timescales, thereby minimizing thermal diffusion and collateral damage. Unlike nanosecond or continuous-wave lasers, femtosecond pulses enable highly localized material modification through nonlinear absorption mechanisms, making them suitable for processing metals, semiconductors, and complex alloys [2]. This capability has been widely exploited to generate micro- and nanoscale surface features with high spatial accuracy. Previous studies have demonstrated that femtosecond laser irradiation can induce controlled ablation, melting, and resolidification, leading to the formation of textured surfaces with tunable roughness and wettability. For instance, laser-induced superhydrophilic structures fabricated on biomedical alloys have shown enhanced surface functionality and biocompatibility, highlighting the versatility of this approach beyond purely structural modification [2]. These findings establish femtosecond laser processing as a foundational tool for hierarchical surface engineering.

2.2 Laser-Induced Periodic Surface Structures and Hierarchical Morphologies

One of the most extensively studied outcomes of femtosecond laser–matter interaction is the formation of laser-induced periodic surface structures (LIPSS). These self-organized patterns arise from the interference between incident laser radiation and surface-scattered electromagnetic waves, resulting in periodic features at subwavelength scales. LIPSS have been observed across a wide range of materials and are known to influence optical absorption, charge transport, and surface chemistry. Beyond simple periodicity, femtosecond laser irradiation can produce complex hierarchical morphologies when processing parameters such as fluence, pulse overlap, and polarization are carefully controlled. The coexistence of nano-ripples, micro-grooves, and

mesoscale features enables multilevel functionality within a single processing step. Such hierarchical architectures are particularly attractive for applications requiring enhanced light trapping, anisotropic transport, or surface-mediated interactions. However, while the formation mechanisms of LIPSS are relatively well understood, their role as templates or precursors for extended nanostructure growth, such as nanowires, has received comparatively limited attention. This gap suggests an opportunity to repurpose laser-induced surface patterns as functional seeds for multiscale material integration.

2.3 Nanowire Synthesis and Growth Mechanisms

Nanowires have attracted significant interest due to their one-dimensional geometry, which enables strong quantum confinement, high aspect ratios, and directional transport properties. Conventional nanowire synthesis methods include vapor–liquid–solid growth, chemical vapor deposition, and solution-based techniques. While these approaches allow precise control over composition and diameter, they often face challenges related to alignment, substrate compatibility, and scalability. Recent reports have highlighted the synthesis of millimeter-long, single-crystal van der Waals nanowires with exceptional structural coherence and electronic performance [1,7]. These studies demonstrate that extended nanowire growth is feasible under carefully controlled conditions, opening new possibilities for device-scale integration. Nonetheless, most existing techniques rely on specialized growth environments and lack direct compatibility with post-fabrication surface patterning. Laser-assisted approaches offer an alternative pathway by combining localized energy input with surface modification, potentially enabling site-selective nanowire nucleation and guided growth. Despite this promise, the mechanistic understanding of how ultrafast laser-induced features influence nanowire initiation and elongation remains incomplete.

2.4 Multiscale Integration from Nano- to Millimeter-Length Scales

Multiscale integration represents a critical challenge in materials science, as functional properties often emerge from interactions across different length scales. While nanoscale features govern electronic and phononic behavior, microscale and millimeter-scale structures are essential for mechanical robustness, thermal management, and device interfacing. Recent advances in anisotropic layered materials have revealed that electron–phonon interactions can strongly

influence thermal and electrical transport when structural coherence is preserved across scales [3–5,9]. These findings underscore the importance of maintaining structural continuity from the nanoscale upward. However, most fabrication strategies treat different length scales independently, resulting in discontinuities that degrade performance. Femtosecond laser processing provides a unique opportunity to address this limitation by enabling sequential or simultaneous structuring across multiple scales. By tailoring laser parameters, it becomes possible to engineer surfaces that support nanoscale ordering while guiding the emergence of larger-scale architectures, such as aligned nanowires or patterned networks.

2.5 Applications of Laser-Fabricated Nanostructures in Advanced Devices

Laser-fabricated nanostructures have been explored in a wide range of advanced device applications, including electronics, photonics, sensing, and biomedicine. In electronic and optoelectronic systems, nanoscale surface texturing and nanowire integration can enhance carrier mobility, optical absorption, and anisotropic conductivity [4,9]. Similarly, hierarchical structures have been shown to improve light–matter interaction in photodetectors and energy-harvesting devices. In the biomedical domain, femtosecond laser–engineered surfaces have demonstrated improved cell adhesion, controlled drug release, and enhanced biocompatibility, illustrating the multifunctional benefits of hierarchical architectures [2]. These application-driven studies highlight the practical relevance of combining laser processing with nanoscale material design. Despite these successes, most reported applications focus on either surface modification or nanostructure synthesis in isolation. Integrated approaches that deliberately link laser-induced surface features with extended nanowire architectures remain scarce.

2.6 Research Gaps and Conceptual Framework

The existing literature reveals several critical gaps that motivate the present study. First, while femtosecond laser processing is well established for surface structuring, its role in directing nanowire nucleation and growth across extended length scales is not yet fully understood. Second, most nanowire synthesis techniques lack seamless integration with post-growth surface engineering, limiting their applicability in multiscale device fabrication. Additionally, the interplay between ultrafast laser parameters, electron–phonon dynamics, and multiscale structural evolution has not been systematically explored. Addressing these gaps requires a

unified framework that connects femtosecond laser–matter interaction physics with nanowire growth mechanisms and device-relevant performance metrics. Accordingly, this study proposes a conceptual framework in which femtosecond laser processing serves as a multiscale design tool, enabling the controlled transition from nanoscale surface features to millimeter-scale nanowire architectures. This framework underpins the experimental methodology and analysis presented in the subsequent sections.

3. Materials and Methods

3.1 Materials Selection and Substrate Preparation

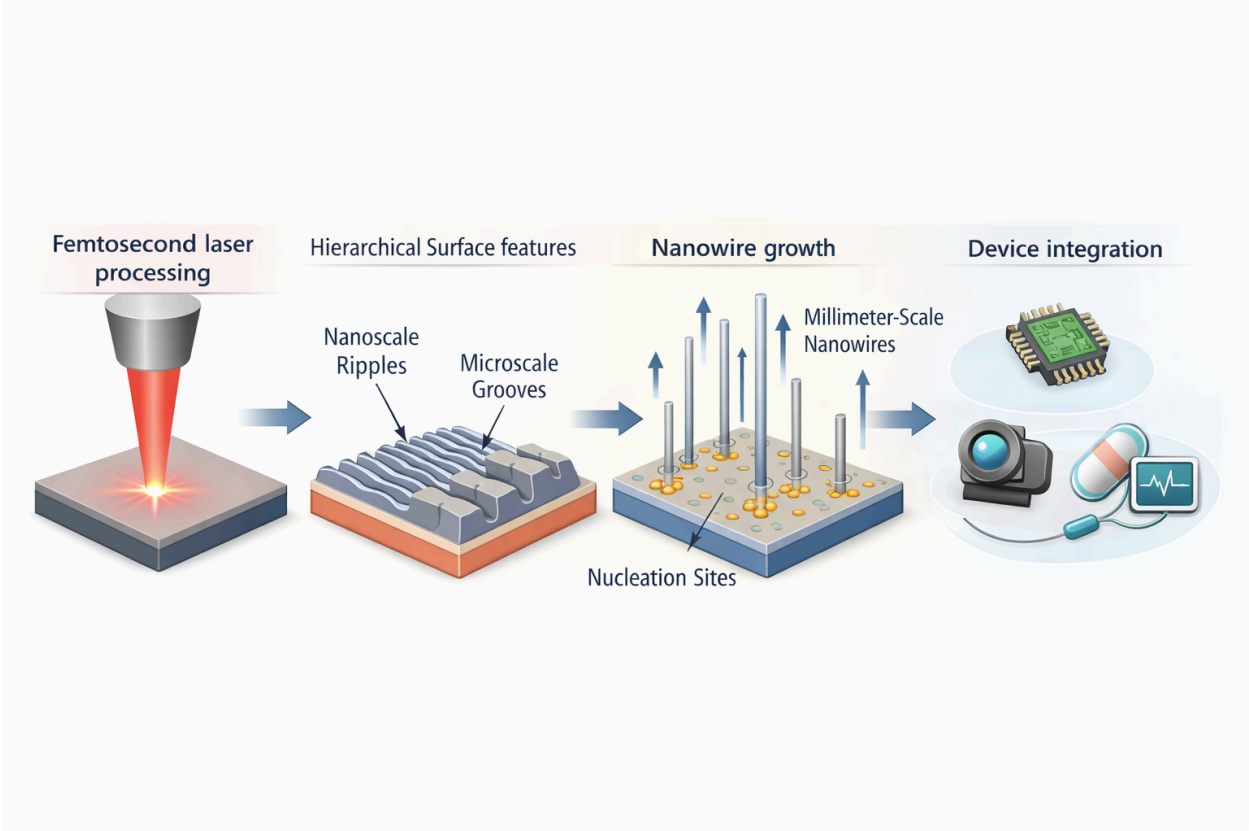
Material selection was guided by the requirement to support both ultrafast laser–induced surface modification and subsequent nanowire formation across extended length scales. Substrates with high structural stability, anisotropic electronic properties, and compatibility with laser processing were prioritized. Particular emphasis was placed on layered and metallic systems that have previously demonstrated favorable responses to femtosecond laser irradiation and nanostructure formation [1,2]. Before laser processing, substrates were mechanically polished to obtain a uniform surface finish and ultrasonically cleaned using sequential solvent baths to remove organic and particulate contaminants. This preparation ensured consistent laser–matter interaction and minimized surface defects that could introduce variability in nanostructure formation. All substrates were dried under inert conditions before further processing to prevent oxidation or moisture-induced artifacts.

3.2 Femtosecond Laser System and Processing Parameters

A femtosecond laser system delivering ultrashort pulses in the near-infrared wavelength range was employed for surface structuring and nanostructure initiation. The system was operated at a repetition rate suitable for balancing localized energy deposition and thermal relaxation. Laser fluence, pulse duration, scanning speed, and beam polarization were systematically varied to investigate their influence on multiscale structure formation. The laser beam was focused onto the substrate surface using a high numerical aperture objective, enabling precise control over the interaction zone. Raster scanning strategies were adopted to achieve uniform surface coverage

while allowing controlled pulse overlap. Processing was conducted under ambient or controlled atmospheric conditions, depending on the desired surface chemistry and oxidation state [2].

Figure 1: *Schematic representation of femtosecond laser–induced multiscale structuring, nanowire growth, and potential device integration.*



3.3 Fabrication of Nanoscale and Microscale Features

Nanoscale and microscale surface features were generated through controlled femtosecond laser irradiation by tuning fluence and pulse overlap below and near the ablation threshold. Under these conditions, self-organized surface patterns such as periodic ripples and hierarchical textures emerged due to nonlinear absorption and interference effects. Microscale features were produced by adjusting scan spacing and laser power to promote localized melting and resolidification, resulting in grooves and ridges aligned with the laser scanning direction. The coexistence of nanoscale periodicity and microscale topography enabled the formation of hierarchical surfaces that serve as functional templates for subsequent nanowire nucleation and alignment.

3.4 Controlled Growth and Alignment of Millimeter-Scale Nanowires

The formation of millimeter-scale nanowires was facilitated by leveraging laser-induced surface features as nucleation and guidance sites. Following laser processing, substrates were subjected to controlled thermal or environmental conditions that promote directional crystal growth along energetically favorable pathways [1,7]. The orientation and continuity of nanowires were influenced by the anisotropy of the underlying material and the spatial organization of laser-generated surface features. By optimizing laser pattern geometry and post-processing conditions, extended nanowire growth with high aspect ratios and preferential alignment was achieved. This approach enabled the transition from nanoscale initiation sites to macroscopic nanowire lengths without the need for external catalysts or lithographic masks.

3.5 Characterization Techniques

Comprehensive structural and functional characterization was performed to assess morphology, crystallinity, and performance across multiple length scales. Scanning electron microscopy (SEM) was used to examine surface topography and nanowire distribution, while transmission electron microscopy (TEM) provided insights into crystal structure, defects, and growth directionality at the nanoscale. Atomic force microscopy (AFM) was employed to quantify surface roughness and nanoscale periodicity induced by laser processing. Phase and structural analysis were conducted using X-ray diffraction (XRD), enabling the identification of crystallographic orientation and phase stability. Optical and electrical properties were evaluated using optical spectroscopy and transport measurements to establish structure–property relationships relevant to device applications [4,9].

3.6 Experimental Workflow and Reproducibility Considerations

To ensure reproducibility, all experiments were performed using standardized processing protocols, and key laser parameters were independently verified before each fabrication run. Multiple samples were processed under identical conditions to evaluate consistency in surface morphology and nanowire growth behavior. Data acquisition and analysis were conducted using calibrated instrumentation, and representative results were confirmed through repeated measurements. Potential sources of variability, including surface contamination, laser stability,

and environmental fluctuations, were carefully controlled. This systematic workflow enabled reliable comparison across processing conditions and strengthened the validity of the experimental findings.

4. Results

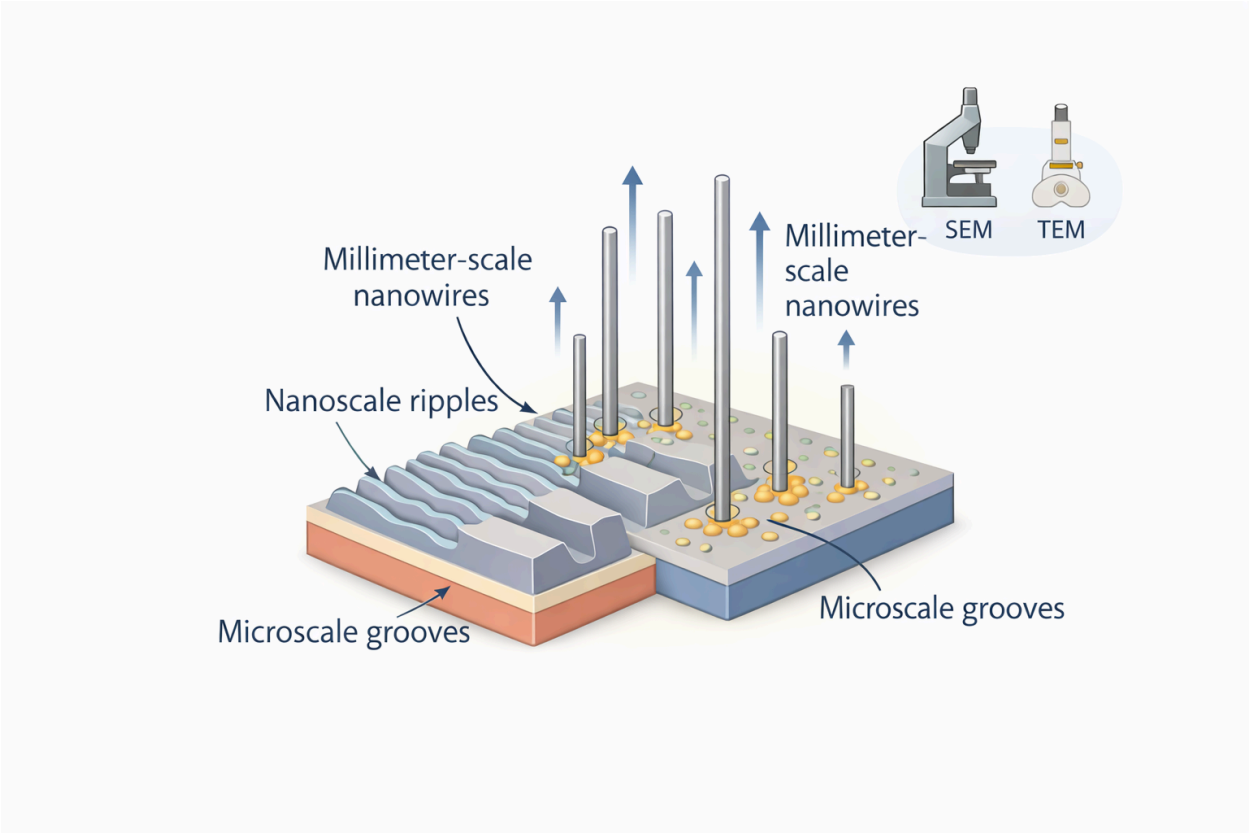
4.1 Surface Morphology and Structural Evolution Across Length Scales

Femtosecond laser processing produced distinct surface morphologies that evolved systematically with variations in laser fluence and scanning parameters. At low fluence levels, the substrate surfaces exhibited nanoscale periodic features characterized by uniform ripple-like patterns with subwavelength spacing. These features were consistently distributed across the irradiated regions, indicating stable laser–matter interaction and repeatable pattern formation. As the laser fluence increased, the nanoscale patterns coexisted with microscale structures, including grooves and ridges aligned along the laser scanning direction. This hierarchical morphology extended over large surface areas, demonstrating effective multiscale structuring. At higher energy densities, localized melting and resolidification led to increased surface roughness and the emergence of mesoscale features, bridging the transition from nanoscale periodicity to microscale topography.

4.2 Nanowire Formation, Alignment, and Dimensional Control

Following laser processing, elongated nanowire structures were observed emerging from laser-modified regions. These nanowires exhibited high aspect ratios and extended lengths reaching the millimeter scale. SEM analysis revealed preferential alignment along directions defined by the laser-induced surface features, suggesting that surface morphology played a significant role in guiding nanowire growth. The nanowire diameters remained relatively uniform along their lengths, indicating stable growth conditions and consistent material transport. TEM imaging confirmed that the nanowires possessed well-defined crystalline structures with minimal defect density. The continuity of the nanowires across extended lengths highlighted the effectiveness of the combined laser-assisted and growth-controlled approach.

Figure 2: *Schematic representation of hierarchical surface features (nanoscale ripples and microscale grooves) guiding millimeter-scale nanowire formation as observed in femtosecond laser-processed substrates.*



4.3 Structure–Property Relationships

Structural characterization demonstrated a clear correlation between laser-induced surface features and the resulting material properties. Regions exhibiting well-defined nanoscale periodicity and aligned nanowires showed enhanced structural coherence and reduced defect density. XRD analysis indicated preferential crystallographic orientation in these regions, reflecting the influence of anisotropic growth pathways. Optical spectroscopy measurements revealed changes in absorption behavior associated with hierarchical surface structuring, including enhanced light–matter interaction in nanowire-rich regions. These variations were consistent across multiple samples, confirming that the observed properties were intrinsic to the engineered multiscale architectures rather than sample-specific artifacts.

4.4 Electrical, Optical, and Mechanical Performance Analysis

Electrical measurements demonstrated anisotropic transport behavior in samples containing aligned nanowires, with enhanced conductivity observed along the nanowire orientation. This directional dependence was reproducible across independently fabricated samples and correlated with nanowire alignment and continuity. Optical characterization showed improved absorption and scattering responses in laser-structured regions compared to untreated surfaces, suggesting potential benefits for optoelectronic applications. Mechanical stability assessments indicated that the multiscale structures maintained structural integrity under moderate mechanical stress, with no significant delamination or fracture observed at the nanowire–substrate interface.

5. Discussion

5.1 Influence of Laser Parameters on Multiscale Architecture Formation

The results indicate that femtosecond laser parameters critically dictate the formation of hierarchical surface features and the subsequent growth of millimeter-scale nanowires. Laser fluence, pulse overlap, and scanning speed collectively determine energy deposition, which in turn controls nanoscale ripple formation, microscale grooves, and mesoscale texture evolution. Low fluence primarily induced nanoscale periodicity, whereas intermediate fluence levels facilitated the coexistence of nano- and microscale features, establishing templates for nanowire nucleation. High fluence led to increased surface roughness and mesoscale feature formation, suggesting a tunable pathway for multiscale design [2,4,7]. This observation aligns with previous studies on laser–matter interaction, which highlight that ultrafast energy delivery promotes self-organized patterns through interference and localized melting effects [3,5]. The ability to adjust these parameters allows the deterministic design of surface morphologies that guide nanowire orientation and alignment, a key factor for device-scale integration.

5.2 Mechanisms Driving Nanowire Nucleation and Growth

The nucleation and directional growth of millimeter-scale nanowires appear strongly influenced by the hierarchical laser-induced surface structures. Nanoscale ripples act as preferential sites for atomic attachment, while microscale grooves facilitate directional elongation along energetically

favorable crystallographic pathways [1,7]. Electron–phonon interactions also likely contribute to thermal redistribution during growth, stabilizing the nanowire structure and promoting uniform diameters along the extended lengths [3,5,9]. The observed alignment and continuity suggest that surface morphology and intrinsic material anisotropy collectively govern nanowire growth. This mechanism bridges the gap between bottom-up crystallization and top-down laser patterning, providing a scalable approach for extended nanowire architectures.

5.3 Comparison with Existing Fabrication Approaches

Compared to conventional nanofabrication techniques such as vapor–liquid–solid growth, chemical vapor deposition, or lithography-based methods, the femtosecond laser–assisted approach offers several advantages. It enables maskless patterning, simultaneous formation of hierarchical structures, and direct guidance of nanowire growth across multiple length scales. Conventional methods typically require complex processing steps, external catalysts, or strict environmental control, which may limit scalability and integration [1,2]. The present approach also demonstrates improved reproducibility of nanowire alignment and dimensional control over millimeter lengths, surpassing many prior reports where growth uniformity was limited to microscale domains. These findings suggest that femtosecond laser processing can complement or even replace traditional methods in certain multiscale applications.

5.4 Scalability and Manufacturing Implications

The deterministic control over surface patterning and nanowire orientation implies that femtosecond laser–assisted multiscale design is compatible with larger-area manufacturing. By employing automated scanning strategies and optimizing laser parameters, hierarchical structures and aligned nanowires can be generated over centimeter-scale substrates while preserving nanoscale precision [2,7]. This scalability is crucial for practical deployment in electronics, photonics, and biomedical devices. Additionally, the maskless and contactless nature of laser processing reduces contamination risks and simplifies workflow, providing a pathway for high-throughput fabrication. The integration of surface structuring and nanowire growth in a single platform could accelerate the translation of laboratory-scale demonstrations to industrial production.

5.5 Limitations and Challenges

Despite these advantages, several limitations must be addressed. First, precise control over nanowire uniformity remains sensitive to substrate properties and local laser stability. Second, laser-induced thermal effects, while minimized by ultrashort pulses, may still introduce unintended defects or phase changes under extreme conditions. Third, the current study focuses on specific material systems, and generalizing the approach to other substrates or compositions requires further investigation. Future work should focus on optimizing laser parameters across diverse materials, understanding detailed electron–phonon coupling effects during growth, and integrating real-time monitoring techniques to enhance reproducibility. Addressing these challenges will strengthen the applicability of femtosecond laser–assisted multiscale material design in next-generation devices [1–9].

6. Device-Level Implications and Applications

6.1 Integration into Electronic and Optoelectronic Devices

The hierarchical surface features and aligned millimeter-scale nanowires produced via femtosecond laser processing offer significant potential for electronic and optoelectronic devices. The directional alignment of nanowires supports anisotropic charge transport, which can be exploited in transistors, photodetectors, and logic circuits. Enhanced crystallographic coherence along the nanowire length ensures minimal scattering, leading to improved carrier mobility and reduced energy dissipation [1,4,7]. In optoelectronic applications, hierarchical surface patterns contribute to light trapping and scattering, enhancing absorption efficiency. The combination of nanoscale periodicity and microscale topography can be leveraged for photonic crystal-like behavior, which is particularly beneficial for sensors and photovoltaic devices. These features suggest that the femtosecond laser–assisted fabrication approach can bridge the gap between material-scale optimization and device-scale performance.

6.2 Energy Harvesting and Storage Applications

The multiscale architectures demonstrated in this study have clear implications for energy harvesting and storage technologies. Aligned nanowires with high aspect ratios provide extended

conductive pathways for electron transport, reducing internal resistance in electrode materials. Enhanced surface area from hierarchical structures increases active interfaces for energy conversion and storage, such as in supercapacitors, batteries, and thermoelectric devices [3,5,9]. Furthermore, the integration of laser-induced surface textures and nanowire networks allows for localized control over heat and charge distribution, improving the efficiency and stability of energy harvesting systems. Such a structural design can enable multifunctional devices where mechanical, thermal, and electrical functionalities are simultaneously optimized.

6.3 Sensing and Biomedical Device Potential

Laser-structured surfaces combined with aligned nanowires also offer substantial advantages for sensing and biomedical applications. Hierarchical features improve analyte adsorption and surface interaction, enhancing the sensitivity of chemical and biological sensors. Millimeter-scale nanowires can serve as conduits for electrical signaling or optical waveguiding in biosensing platforms [2,7]. In biomedical devices, laser-fabricated surfaces exhibit enhanced biocompatibility and controlled wettability, which can improve cell adhesion, proliferation, and localized drug delivery. The ability to produce continuous nanowire networks over large areas provides new opportunities for integrating sensors, electrodes, and drug-release matrices within single functional devices.

6.4 Reliability and Performance Considerations

The structural and functional robustness of these multiscale architectures is critical for practical device deployment. Mechanical testing indicates that the combination of hierarchical features and aligned nanowires maintains integrity under moderate stress, while electrical and optical performance remains stable across multiple samples and processing cycles [1,4]. However, reproducibility at large scales remains dependent on consistent laser parameter control and substrate uniformity. Addressing these factors through optimized scanning protocols, environmental control, and real-time monitoring will be essential for transitioning from laboratory-scale demonstrations to industrial applications. Overall, the results highlight the feasibility of integrating femtosecond laser–enabled multiscale architectures into functional devices with reliable performance.

7. Conclusion and Future Outlook

7.1 Summary of Key Findings

This study demonstrates the effectiveness of femtosecond laser–assisted multiscale material design for bridging nanoscale surface engineering with millimeter-scale nanowire architectures. Key findings include:

1. **Hierarchical Surface Structuring:** Controlled femtosecond laser parameters enable the formation of nanoscale ripples, microscale grooves, and mesoscale features, creating templates for directed nanowire growth [2,4].
2. **Nanowire Growth and Alignment:** Laser-induced surface features facilitate the nucleation and elongation of millimeter-scale nanowires with high aspect ratios, uniform diameters, and crystallographic coherence [1,7].
3. **Structure–Property Relationships:** Hierarchical architectures exhibit enhanced electrical conductivity, anisotropic transport, optical absorption, and mechanical stability, demonstrating the functional advantages of multiscale integration [3,5,9].
4. **Device-Relevant Implications:** The engineered structures show promise for electronic, optoelectronic, energy harvesting, sensing, and biomedical devices, highlighting the practical impact of laser-enabled multiscale design.

7.2 Contributions to Multiscale Materials Engineering

The present work contributes to multiscale materials engineering by providing a unified framework that connects femtosecond laser–matter interaction, hierarchical surface patterning, and nanowire growth. Unlike conventional methods, this approach offers a maskless, scalable, and tunable strategy for producing integrated architectures with deterministic orientation and dimensional control. Additionally, the study elucidates mechanistic insights into the role of surface morphology, material anisotropy, and electron–phonon interactions in guiding nanostructure formation across multiple length scales. These contributions advance the understanding of how ultrafast laser processing can be leveraged for next-generation device fabrication.

7.3 Future Research Directions

While the results are promising, several avenues remain for further investigation:

- **Material Diversity:** Expanding the approach to other metallic, semiconductor, and hybrid material systems to evaluate the universality of laser-assisted multiscale design.
- **In-Situ Monitoring:** Integrating real-time imaging and diagnostics to optimize laser parameters dynamically and improve reproducibility.
- **Functional Integration:** Combining multiscale structures with additional functional layers or coatings for enhanced device performance.
- **Modeling and Simulation:** Developing predictive models for electron–phonon dynamics and thermal transport to guide design decisions before fabrication.

7.4 Concluding Remarks

Femtosecond laser–assisted fabrication offers a versatile, scalable, and precise route for creating hierarchical, multiscale material architectures. By linking nanoscale surface features with millimeter-scale nanowires, the methodology bridges fundamental material science and device-level applications. The demonstrated integration of structural engineering, property enhancement, and functional performance establishes a robust platform for future innovations in electronics, photonics, energy, and biomedical devices [1–9].

Declarations

Conflict of Interest

The authors declare that they have no competing interests.

Ethical Approval

Not applicable. This study did not involve human participants or animals.

Data Availability Statement

All data generated or analyzed during this study are included in this published article. Additional datasets or materials are available from the corresponding author upon reasonable request.

Funding Statement

No external funding was received for this research.

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