Carbon-based Microheaters: A Review of Materials, Fabrication, Modelling, and Application

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Abstract: This review evaluates how carbon material selection, fabrication, and multiscale heat transport jointly determine the performance of carbon-based microheaters, with emphasis on graphene, carbon nanotubes (CNTs), amorphous carbon, functionalized carbon fibers, and selected transferable carbon nanostructures. A structured narrative synthesis of 70 Scopus-indexed references spanning 2003-2026 distinguishes direct microheater demonstrations from supporting material, modelling, and adjacent-transfer evidence. Direct evidence shows that graphene and CNT heaters enable rapid, low-power heating and mechanically compliant architectures, while printed or laser-written and functionalized carbon systems broaden flexible and structural applications. Recent process advances include multizone chemical vapor deposition, laser writing, and standardized printed-heater assessment; adjacent evidence on carbon-dot encapsulation and interface engineering is treated as transferable rather than as direct heater performance. Persistent gaps are temperature uniformity, reproducible doping and functionalization, wafer-scale process consistency, and experimentally validated multiscale models. The review contributes an integrated material-fabrication-transport-application framework and an evidence-aware roadmap for future carbon-based microheater design.

Keywords: Carbon nanomaterials, graphene, carbon nanotubes, amorphous carbon.

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Introduction

Micro and nanoscale heating elements, commonly termed microheaters, provide localized, rapid, and energy-efficient thermal actuation for a broad class of miniaturized systems, including gas sensors, point-of-care diagnostic platforms, in situ electron microscopy stages, and thermally activated actuators (Jeroish et al., 2022; Spruit et al., 2017). Traditional metallic resistive heaters such as platinum, nickel, tungsten, and molybdenum have long dominated this space because of their well-characterized temperature coefficients of resistance and compatibility with complementary metal-oxide-semiconductor processing (Bhattacharyya, 2014; Singh et al., 2018). The intrinsic rigidity, relatively high thermal mass, and susceptibility to electromigration and oxidative degradation of metallic films at elevated temperatures have, however, motivated a sustained search for alternative conducting materials capable of combining rapid thermal response, low power consumption, and mechanical compliance (Spruit et al., 2017). Carbon nanomaterials, principally graphene, carbon nanotubes (CNTs), and amorphous carbon (a-C), have emerged over the past decade as compelling substitutes and complements to metallic heating elements (Ghosh & Balandin., 2011; Janas & Koziol., 2014; Shi., 2025). Their appeal originates from an unusual combination of exceptionally high in-plane thermal and electrical conductivity, low areal density, mechanical flexibility, and chemical tunability through doping and functionalization (Renteria et al., 2014; Sun et al., 2026). Beyond the canonical sp2 carbon allotropes, carbon fibers functionalized through metal co-deposition (Ma et al., 2026), carbon dots encapsulated in protective silica shells (S. Zhang et al., 2024), and amorphous monolayer carbon phases (de Moraes et al., 2026) have expanded the materials palette available to microheater designers, while simultaneously raising new questions about interfacial thermal transport, doping uniformity, and long-term mechanical and thermal stability. This carbon-specific focus is justified because carbon allotropes span unusually broad combinations of conductivity, areal mass, flexibility, tunable resistance, and chemical functionality, while their network and interface effects differ substantially from conventional metallic heater films. This review updates and extends earlier syntheses of carbon-based microheater research by incorporating a substantial body of literature published between 2024 and 2026, spanning electrothermal de-icing composites (Ma et al., 2026), multizone chemical vapor deposition reactors for carbon nanotube forest manufacturing (J. Lee et al., 2019), femtosecond laser direct-write metallization for high-resolution patterning (Ha et al., 2025), AI-guided design of low-dimensional carbon materials (Shan et al., 2025), and refined multiscale frameworks for phonon transport across solid-solid interfaces (Norris et al., 2021). Wearable and biomedical sensing applications, an area of rapid growth, are also revisited in light of recent reviews of carbon-based nanomaterials for wearable health monitoring (Erdem et al., 2022) and of translational challenges facing minimally invasive wearable biochemical sensors (Ausri et al., 2023). The objective is to consolidate this expanding literature into a coherent narrative that identifies where genuine novelty has been achieved, where persistent research gaps remain, and which directions are most likely to yield the next generation of carbon-based microheaters. Despite prior reviews of individual carbon materials, general microheater technologies, wearable sensing, and thermal transport, a gap remains in connecting intrinsic carbon properties to fabrication-controlled geometry, interface-limited heat flow, and application-level heater performance within one evidence-aware framework. Accordingly, the present review distinguishes direct microheater evidence from supporting and transferable studies and integrates materials, fabrication, modelling, and application requirements rather than treating them as separate topics.

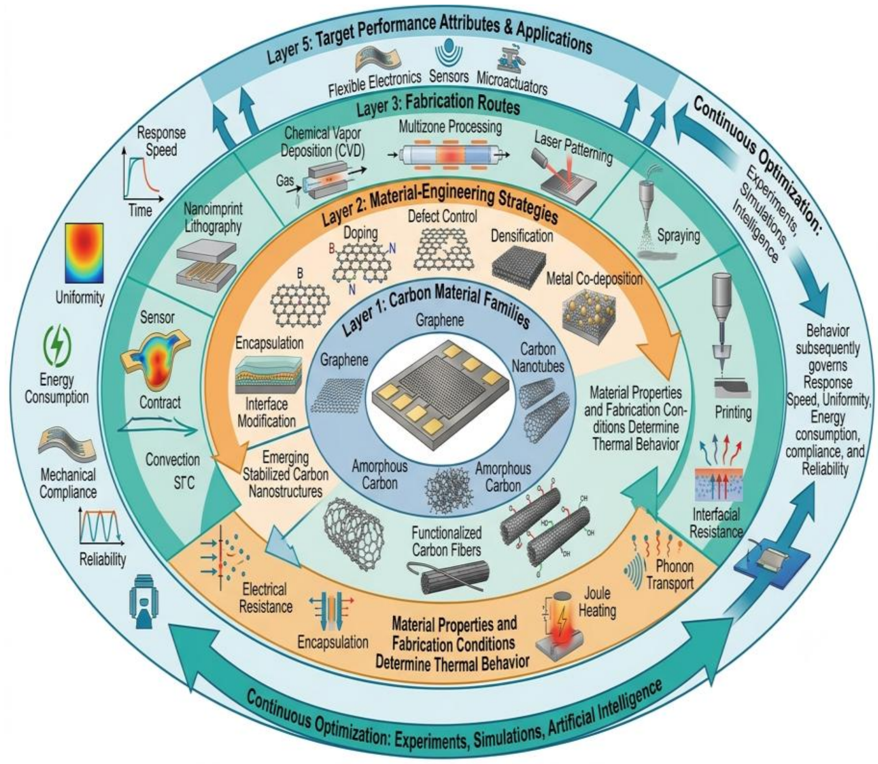

Figure 1 Conceptual scope of carbon-based microheater research, linking material innovation, fabrication engineering, multiscale thermal transport, performance optimization, and multifunctional applications. This figure is an author-generated conceptual synthesis of the reviewed literature and should not be interpreted as a quantitative experimental dataset.

Figure 1 shows the integrated research framework that connects carbon material selection with device fabrication, thermal behavior, and application-specific performance. Graphene, carbon nanotubes, amorphous carbon, functionalized carbon fibers, and stabilized carbon nanostructures provide distinct combinations of electrical conductivity, thermal transport, flexibility, and structural functionality. Their properties can be further adjusted through doping, defect control, densification, metal co-deposition, encapsulation, and interface modification. These engineered materials are subsequently processed using chemical vapor deposition, laser patterning, printing, spraying, multizone processing, or nanoimprint lithography to form functional heater architectures. The resulting electrical resistance, Joule heating, phonon transport, interfacial resistance, and heat dissipation determine response speed, temperature uniformity, power consumption, mechanical compliance, and reliability. Experimental characterization, multiscale simulation, and AI-guided analysis provide continuous feedback for optimizing future multifunctional microheater systems.

The review proceeds as follows. Section 2 compares the structural, thermal, and electrical properties of the principal carbon materials used in microheater construction, including recent additions such as functionalized carbon fibers and carbon dots. Section 3 surveys fabrication strategies, from chemical vapor deposition and multizone rapid thermal processing to laser-based direct writing and printing. Section 4 addresses the modeling of heat transport at the nanoscale, including thermal boundary conductance, nonlocal conduction effects, and multiscale simulation frameworks. Section 5 reviews application domains, and Section 6 discusses outstanding novelty and gaps before the concluding remarks.

Review Methodology

Scope and Literature Identification

This review focuses on carbon-based microheater technologies, with particular attention to material characteristics, material modification, fabrication strategies, thermal transport, modelling approaches, and emerging applications. The literature considered in this review covers major carbon materials used or proposed for electrothermal heating, including graphene, carbon nanotubes (CNTs), amorphous carbon, functionalized carbon fibers, and carbon dots. The review also considers studies addressing doping, defect engineering, densification, metal co-deposition, encapsulation, and interface modification because these approaches influence the electrical, thermal, mechanical, and operational characteristics of carbon-based heating structures. In addition to material-related studies, relevant literature concerning microheater fabrication, device geometry, thermal transport, multiscale modelling, and application-specific requirements was considered to establish an integrated understanding of carbon-based microheater development. The scope was therefore defined across the material, processing, thermal, modelling, and application dimensions reflected in the subsequent sections of this review. The working reference library used for this revision contains 70 Scopus-indexed records spanning 2003-2026, with deliberate emphasis on literature from 2024-2026. The original database-by-database search log and exact Boolean strings were not retained; therefore, this article is presented as a structured narrative review rather than a systematic review and does not claim exhaustive coverage. For transparent scope definition in the present revision, the thematic keyword families were operationalized around carbon microheater, graphene heater, carbon nanotube/CNT heater, amorphous carbon heater, electrothermal carbon, microheater fabrication, thermal boundary conductance, nonlocal heat conduction, and application terms including wearable, point-of-care, in situ TEM, gas sensing, and de-icing. Reference relevance was cross-checked using the title, abstract/metadata, and DOI information retained in the working library.

Literature Selection and Relevance Assessment

The literature was selected based on its relevance to the technological scope of carbon-based microheaters. Studies were considered relevant when they provided substantive information on carbon material properties, material modification, electrothermal behaviour, fabrication processes, thermal transport, modelling, or applications associated with microheater and related heating systems. Literature addressing closely related carbon-based electrothermal technologies was also considered when its underlying material, thermal, or fabrication principles provided transferable insights for microheater development. Particular attention was given to studies that reported measurable material or device characteristics, described fabrication approaches, examined thermal behaviour, or identified technological limitations. Studies whose primary subject was outside the material, fabrication, thermal, modelling, or application scope of carbon-based microheaters were not emphasized in the synthesis.

Inclusion criteria were: (i) direct carbon microheater or electrothermal-heater experiments; (ii) carbon-material studies reporting properties directly relevant to Joule heating, thermal transport, flexibility, doping, or reliability; (iii) fabrication studies with transferable control of heater geometry, contacts, or conductive networks; (iv) thermal-transport or modelling studies applicable to micro/nanoscale heating; and (v) application studies that define operating requirements. Studies were excluded from direct performance claims when they did not demonstrate a heater, used non-carbon systems without a transferable design principle, or lacked substantive material, fabrication, thermal, modelling, or application information. Adjacent studies were retained only where their transfer role is stated explicitly.

Thematic Classification and Comparative Synthesis

Following the relevance assessment, the selected literature was organized into five interconnected thematic areas: carbon materials and their properties, fabrication techniques and device engineering, thermal transport and multiscale modelling, applications and performance considerations, and research gaps and future directions. This thematic organization was used to examine the development of carbon-based microheaters from material selection to device fabrication, thermal behaviour, application requirements, and future technological opportunities. To prevent evidence conflation, the synthesis uses four evidence roles: direct carbon-microheater/heater evidence; supporting carbon-material or fabrication evidence; theoretical/numerical/experimentally constrained modelling evidence; and adjacent-transfer/context evidence. These roles are used throughout the discussion so that intrinsic material values, device-level heater measurements, modelling outputs, and transferable concepts are not treated as equivalent demonstrations. Within the material category, graphene, CNTs, amorphous carbon, functionalized carbon fibers, and carbon dots were examined according to their electrical, thermal, mechanical, and structural characteristics, together with the effects of doping and other material-engineering strategies. Fabrication studies were compared according to processing route, geometrical control, resolution, uniformity, scalability, and integration requirements. Thermal and modelling studies were examined in relation to heat generation, heat dissipation, interfacial thermal transport, and multiscale effects. Application-oriented studies were subsequently compared according to their specific thermal, mechanical, electrical, and operational requirements.

The final synthesis was used to identify recurring limitations, emerging approaches, and research gaps across the reviewed literature. This comparative approach allows the review to move beyond a study-by-study description and instead identify relationships between material selection, fabrication, thermal behaviour, device performance, and application requirements.

Result and Discussion

Carbon Material for Microheaters: Properties, Doping, and Comparative Performance

Graphene, Carbon Nanotubes, and Amorphous Carbon

To avoid conflating intrinsic properties with device performance, this section distinguishes material-level thermal, electrical, and mechanical characteristics from values demonstrated in operating heaters. Graphene and CNT conductivity values therefore describe material potential unless a heater demonstration is identified explicitly; amorphous-carbon coating, carbon-dot encapsulation, sensor, and energy-storage studies are treated as supporting or adjacent evidence.

Graphene remains the benchmark carbon material for thermal management applications, owing to in-plane thermal conductivities that can exceed several thousand watts per meter-kelvin in suspended, defect-free samples, together with high carrier mobility and mechanical strength (Dhumal et al., 2026; Ghosh & Balandin, 2011; Renteria et al., 2014). Its two-dimensional geometry, however, makes graphene sensitive to substrate interactions, wrinkling, and folding, all of which modulate its effective thermal and mechanical response.

Recent molecular dynamics and atomic force microscopy work has shown that suspended and supported graphene sheets can spontaneously fold, inducing tensile pretension in the range of 0.14 to 0.35 newtons per meter, with the magnitude depending on fold morphology (de Moraes et al., 2026). Because pretension alters phonon dispersion and consequently thermal conductivity, this finding has direct relevance to microheater design, where suspended graphene membranes are increasingly used as ultrathin, rapidly responding heating elements, as demonstrated in graphene microheater chips developed for in situ transmission electron microscopy (J. Zhao et al., 2023). CNTs combine many of graphene favorable transport properties with a one-dimensional geometry that simplifies integration into fibers, yarns, and printed patterns (Bulmer et al., 2021; Janas & Koziol., 2014; Khan et al., 2026). Chirality and alignment strongly influence thermal and electrical performance: zig-zag CNTs exhibit systematically higher axial thermal conductivity than armchair tubes of comparable diameter (Gautam et al., 2025; Kotcioglu et al., 2024), a distinction that is increasingly incorporated into the design of resistive elements for microheater chips (Z. Zhao et al., 2024). Doping strategies, including nitrogen incorporation and endohedral metal-halide doping, have pushed CNT fiber conductivity toward, and in some formulations beyond, that of copper, while simultaneously improving environmental stability (Sun et al., 2026). Densification of CNT films by various post-processing methods has also been shown to markedly improve electrothermal performance stability under repeated cycling (S. Wu et al., 2022), while flexible transparent conductive heaters based on multiwalled CNT sheets illustrate the practical translation of these material advances into device form (Jung et al., 2014). Floating-catalyst and conventional chemical vapor deposition (CVD) routes remain the dominant synthesis pathways and continue to be refined for wafer-scale uniformity through nitrogen-doped graphene CVD processes (Deokar et al., 2022) and next-generation CNT synthesis for energy storage electrodes, which share materials-design principles with electrothermal applications (R. Kumar et al., 2026). Amorphous carbon, in contrast to its crystalline counterparts, offers a continuously tunable sp^2-sp^3 bonding ratio that governs its electrical and thermal behavior, enabling memristive switching and reconfigurable resistive states useful in dynamically controlled heaters (Shi., 2025), (J. Wu et al., 2024). Amorphous carbon is comparatively easy to deposit by conventional thin-film methods and integrates well with existing microfabrication infrastructure (Ghosh & Balandin., 2011; Janas & Koziol., 2014). A 2026 study demonstrated that amorphous carbon incorporated at the grain boundaries of tantalum carbide coatings substantially improves thermal shock resistance by lowering the effective coefficient of thermal expansion and forming a compliant, stress-relaxing network; coatings with amorphous carbon content near 29 atomic percent survived fifteen thermal cycles without through-thickness cracking, whereas low-content coatings failed by cracking and partial phase transformation (Hu et al., 2026). This behavior is consistent with broader observations that microstructural disorder and stress evolution in inorganic thin films govern their cyclic thermal durability (H. Liu et al., 2024). Although this work addresses ultra-high-temperature coatings rather than microheaters directly, the underlying mechanism, amorphous carbon acting as a stress-redistributing boundary phase, offers a transferable design principle for mitigating thermal fatigue in carbon-based heating elements subjected to repeated thermal cycling. Functionalization chemistry continues to refine the performance ceiling of both graphene and CNT-based heating elements. Nitrogen-doped graphene grown by chemical vapor deposition has been characterized in detail with respect to defect density, doping level, and resulting electronic structure, providing a foundation for reproducible doping protocols applicable to heater electrode design (Deokar et al., 2022). CNT nanocomposite sensors, reviewed comprehensively across sensing modalities, illustrate how the same conductive nanocomposite architectures used for electrothermal heating can be adapted, with modest compositional changes, for simultaneous strain, gas, or temperature sensing, suggesting a route toward integrated multi-modal microdevices that combine heating and sensing functions on a single carbon platform (Kausar & Ahmad., 2024). Advances in CNT-based conductors for electrical wiring and integrated energy storage further demonstrate that the synthesis, microjoining, and interconnection strategies developed for one application domain transfer readily to microheater electrode and contact engineering, since the underlying requirements, low contact resistance, mechanical robustness, and oxidation resistance, are largely shared across applications (Khan et al., 2026). Continued development of high-performance CNT materials for energy storage electrodes similarly benefits microheater design by providing a steady stream of improved, high-conductivity CNT feedstocks originally optimized for a different end use (R. Kumar et al., 2026).

Carbon fibers and carbon dots as emerging heater materials

Carbon fibers functionalized through electroless, or electrodeposited metal coatings represent an increasingly important materials family for electrothermal applications, particularly de-icing systems that demand both rapid, uniform Joule heating and electromagnetic interference shielding. A 2026 study reported nickel-copper co-deposited carbon fiber achieving a heating rate of 4.38 degrees Celsius per second, a conversion coefficient of 0.0349 watts per degree Celsius, electromagnetic shielding effectiveness of 50.12 decibels, and de-icing times as short as 68.3 seconds, while maintaining stability under repeated electrical cycling and mechanical deformation, including an improved interlaminar shear strength relative to unmodified carbon fiber (Ma et al., 2026) . This dual electrothermal and electromagnetic functionality illustrates how carbon fiber heaters are evolving beyond simple resistive elements into multifunctional composite platforms, a trend echoed in reviews of carbon fiber sensors for healthcare monitoring (Han et al., 2026) and in broader treatments of low-dimensional carbon materials for electromagnetic wave attenuation (Shan et al., 2025). Related nanoengineered glass-fiber-reinforced laminates incorporating carbon nanomaterials have similarly demonstrated integrated multifunctionality, combining structural reinforcement with in situ damage sensing, as visualized through synchrotron computed tomography (Patel et al., 2022). Carbon dots, though more commonly associated with fluorescence and sensing applications, have recently demonstrated thermal stability characteristics of direct relevance to high-temperature carbon-based devices. A multi-core at shell silica-confinement strategy was shown to suppress thermal quenching of carbon dot photoluminescence up to 1000 K and to sustain lasing at that temperature without gas protection, a result attributed to the silica shell dual role in protecting the emissive core and stabilizing its luminescence center (S. Zhang et al., 2024). While not a heater in the conventional sense, this architecture illustrates a generalizable encapsulation strategy, core at shell confinement, that could be adapted to protect thermally sensitive carbon nanostructures integrated within microheater assemblies operating at elevated temperatures. Complementary theranostic uses of carbon nanodots underscore the versatility of carbon based nanostructures across thermal, optical, and biomedical functions within a single

materials family (M. Kumar et al., 2026).

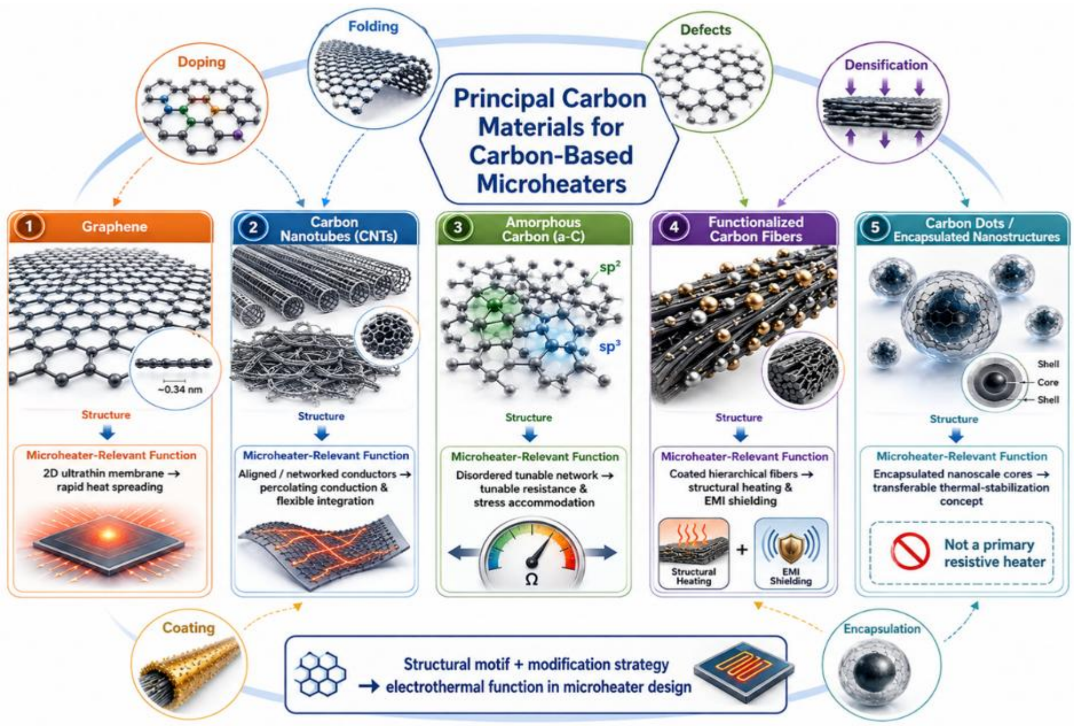

Figure 2 Carbon-material landscape for microheater construction, illustrating the dimensionality, structural characteristics, modification pathways, and functional roles of graphene, carbon nanotubes, amorphous carbon, functionalized carbon fibers, and stabilized carbon nanostructures This figure is an author-generated conceptual synthesis of the reviewed literature and should not be interpreted as a quantitative experimental dataset.

Figure 2 shows how the structural characteristics of major carbon material classes determine their suitability for microheater applications. Graphene provides an ultrathin two-dimensional platform that supports rapid lateral heat spreading, although folding, defects, and substrate interactions can alter its transport behavior. Carbon nanotubes form aligned or percolating networks that combine flexibility, scalable processing, and efficient electrical conduction, while densification and doping improve network continuity. Amorphous carbon offers tunable resistance through its disordered sp^2-sp^3 bonding structure and can accommodate thermally induced stress. Functionalized carbon fibers extend electrothermal performance into structurally integrated systems through metallic coating and hierarchical reinforcement, enabling simultaneous heating and electromagnetic shielding. Encapsulated carbon nanostructures are not primary resistive heaters, but they introduce transferable strategies for thermal protection, interface stabilization, and long-term operation under demanding conditions.

Comparative summary

Table 1 consolidates the structural, thermal, electrical, and stability characteristics of the principal carbon material classes discussed above, together with representative supporting references. Graphene offers the highest thermal conductivity but poses substrate-interaction and folding-related challenges; CNTs provide a favorable balance of conductivity, mechanical robustness, and processability; amorphous carbon and functionalized carbon fibers trade peak conductivity for tunability, stress accommodation, and multifunctional integration; and carbon dots, while primarily optical materials, contribute encapsulation strategies relevant to thermal stability engineering. Broader treatments of carbon materials for micro- and nano-device engineering situate these individual material classes within a unified design space (Sharma., 2024). At the material level, suspended graphene is reported up to approximately 5000 $W\ m^{-1}\ K^{-1}$ and CNTs around 3000 $W\ m^{-1}\ K^{-1}$ depending on chirality and alignment, whereas amorphous carbon is lower in thermal conductivity but offers resistance tunability and stress accommodation. These material values should not be interpreted as heater temperatures or efficiencies; device performance additionally depends on network/contact resistance, substrate heat loss, geometry, and cycling stability.

Figure 3 shows that the selection of a carbon material for microheater construction must be guided by the intended device architecture and operating environment rather than by a single superior property. Graphene favors ultrathin integration and rapid thermal response but remains sensitive to folding, substrate interaction, and contact resistance. Carbon nanotubes offer flexibility, scalable network processing, and electrical tunability, although junction resistance and alignment must be controlled. Amorphous carbon provides deposition compatibility, adjustable resistance, and stress accommodation, whereas functionalized carbon fibers are particularly suitable for structural heating and multifunctional systems. Encapsulated carbon nanostructures occupy a supporting role by improving thermal protection and interface stability. Therefore, application requirements should determine the relative weighting of thermal response, flexibility, processability, multifunctionality, and cycling stability during material selection.

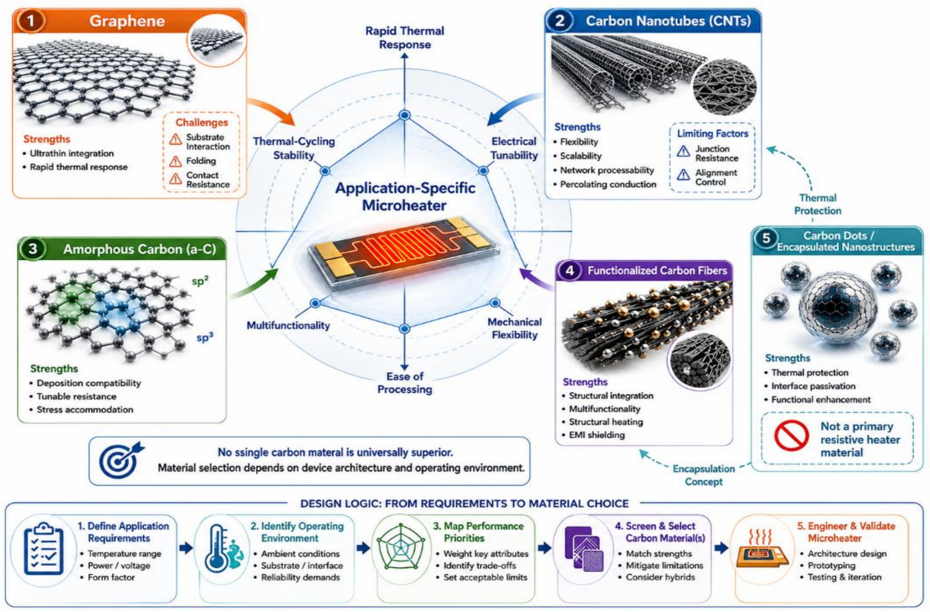

Figure 3 Qualitative structure-property-performance map for selecting carbon materials in microheater design according to thermal response, electrical tunability, flexibility, processability, multifunctionality, and stability requirements. This figure is an author-generated conceptual synthesis of the reviewed literature and should not be interpreted as a quantitative experimental dataset.

Table 1 Comparative properties of principal carbon material classes used in microheater construction

Material	Reported thermal property / context	Electrical / structural property	Microheater relevance / evidence	Ref.
Graphene	Up to ~5000 W m^{-1} K^{-1} (suspended material value)	High carrier mobility	Material + direct heater evidence: rapid response; ultrathin, electron-transparent membranes for in situ h eating	(Ghosh & Balandin, 2011), (Renteria et al., 2014), (de Moraes et al., 2026), (J. Zhao et al., 2023)

Material	Reported thermal property / context	Electrical / structural property	Microheater relevance / evidence	Ref.
Carbon nanotubes (CNTs)	~3000 W m⁻¹ K⁻¹ (material value; chirality/alignment dependent)	High, tunable by doping (approaches or exceeds Cu)	Material + direct heater evidence: fiber/yarn integration, scalable CVD synthe sis, and tunable network re sistance	(Janas & Koziol, 2014), (Bulmer et al., 2021), (Sun et al., 2026), (Gautam et al., 2025), (Kotcioglu et al., 2024), (Z. Zhao et al., 2024)
Amorphous carbon (a-C)	Low to moderate, tunable	Tunable via sp²-sp³ ratio; memristive switching	Supporting/adjacent evidence: thin-film compatibility and stress accommodation are relevant to heater durability	(Shi, 2025), (J. Wu et al., 2024), (Janas & Koziol, 2014), (Hu et al., 2026), (H. Liu et al., 2024)
Functionalized carbon fiber (metal co-deposited)	Moderate, enhanced by met al coating	High (Ni-Cu co-deposition approaches metallic conductors)	Direct electrothermal structural-heater evidence (not microscale): rapid Joule heating plus EMI shielding and rein forcement	(Patel et al., 2022), (Ma et al., 2026), (Han et al., 2026)
Carbon dots (silica-encapsulated)	Not primary function; thermally stable emission	Optically active; not a resis tive conductor	Adjacent/transferable evidence: encapsulation motif for protecting thermally sensitive carbon nanostructures	(M. Kumar et al., 2026), (S. Zhang et al., 2024)

Fabrication Techniques and Device Engineering

Chemical vapor deposition and multizone processing

CVD, in its many variants, remains the workhorse technique for synthesizing graphene and CNT films for microheater applications, building on foundational coating deposition principles established across decades of materials engineering (Choy., 2003). Consistent, wafer-scale production continues to be hindered, however, by coupled, multistep reaction pathways: gas-phase hydrocarbon decomposition, catalyst nanoparticle formation, and catalytic nanotube growth typically proceed simultaneously, complicating independent process control (J. Lee et al., 2019). A custom multizone rapid thermal processing CVD reactor has been developed to decouple these steps, incorporating measures such as air baking between growth runs, dynamic pumping cycles, and low-pressure baking to remove residual oxygen-containing species, alongside in situ videographic monitoring of nanotube forest height kinetics (J. Lee et al., 2019). This decoupled recipe substantially improves run-to-run growth consistency, a persistent bottleneck identified in earlier reviews of CNT forest manufacturing (J. Lee et al., 2019). Complementary substrate-morphology studies have shown that large-scale, well-aligned CNT films depend sensitively on underlying substrate texture, reinforcing the need for tightly controlled deposition environments (P. J. Cao et al., 2006), while nanoimprint lithography approaches have been explored for wafer-scale patterning of vertically aligned CNT arrays (Bu., 2010).

Laser-based direct writing and patterning

Laser-based fabrication has advanced considerably in resolution and materials versatility. Femtosecond laser multiple-pulse irradiation of a surfactant-modified glyoxylic acid copper complex ink enables thermochemical precipitation of copper with minimum feature sizes near 1.6 micrometers and stable reproducibility, achieved through nonlinear, saturable optical absorption effects mediated by nucleated copper nanoparticles (Ha et al., 2025) . Although this technique targets copper microwiring rather than carbon heating elements directly, it demonstrates a scalable, low-thermal-diffusion approach to high-resolution conductor patterning that is directly transferable to microheater electrode and interconnect fabrication, and it complements existing laser ablation and direct-write methods for flexible carbon heaters (Ulieru et al., 2006), (Y. Yang et al., 2022), (Jiaxiang et al., 2025), (Taherian et al., 2025), (C. Yang et al., 2025). Flash lamp annealing combined with laser ablation continues to be used to synergistically improve the electrothermal properties of graphene-CNT composite electrodes through localized structural modification (Myung & Kim., 2024), (Kuhfuß et al., 2026).

Printing, spraying, and hybrid integration routes

Nanomaterial spraying, solution processing, and selective laser treatment allow CNTs and graphene to be patterned onto flexible polymer substrates with fine resolution and mechanical durability (Tavakkoli Gilavan et al., 2025), (Bae et al., 2026). Polymer cross-linking strategies originally developed for responsive hydrogel layers have been adapted to enhance the mechanical flexibility of printed conductive films and to support sub-10-micrometer feature resolution (Kuckling., 2009), while rugged island-bridge architectures mounted on locally strain-isolated substrates further improve device robustness under repeated mechanical deformation (D. H. Lee et al., 2024). Printed electronics approaches, in particular, have matured to the point of systematic performance benchmarking; a 2024 experimental assessment defined global figures of merit for printed carbon- and graphene-based temperature sensors and microheaters on flexible substrates, incorporating power analysis and temperature coefficient of resistance measurements to guide material selection (Barmpakos et al., 2024). This kind of standardized characterization is a notable methodological advance, since prior literature on printed carbon heaters had relied on heterogeneous, difficult-to-compare metrics (Barmpakos et al., 2024). Ultra-long CNT-based flexible transparent heaters extend this printed and coated heater paradigm toward large-area, optically transparent applications (Dubnov et al., 2025).

Geometry, uniformity, and process comparison

Microheater geometry, whether serpentine, S-shaped, or double-spiral, continues to govern the trade-off between thermal uniformity and mechanical compliance (X. Wang et al., 2017), (T.-Y. Zhang et al., 2017) . Wafer-scale uniformity remains constrained by growth dynamics and substrate effects, but multizone reactors, advanced lithography, and post-deposition treatments such as nitric acid doping have measurably improved consistency (P. J. Cao et al., 2006), (Bu., 2010). Table 2 summarizes representative fabrication routes, their achievable resolution, principal advantages, and limitations. Across the principal routes, CVD offers high material quality and wafer integration but relatively high process complexity; multizone CVD improves run-to-run control at the cost of custom equipment; laser/direct-write routes provide local resolution and geometry freedom but can introduce thermal modification; and printing/spraying favor low-cost flexible scaling but require tighter control of network resistance, thickness, and contacts. These process variables act through sheet resistance, current density, contact loss, and lateral heat spreading and therefore directly influence response time, hotspot formation, temperature uniformity, and cycling stability.

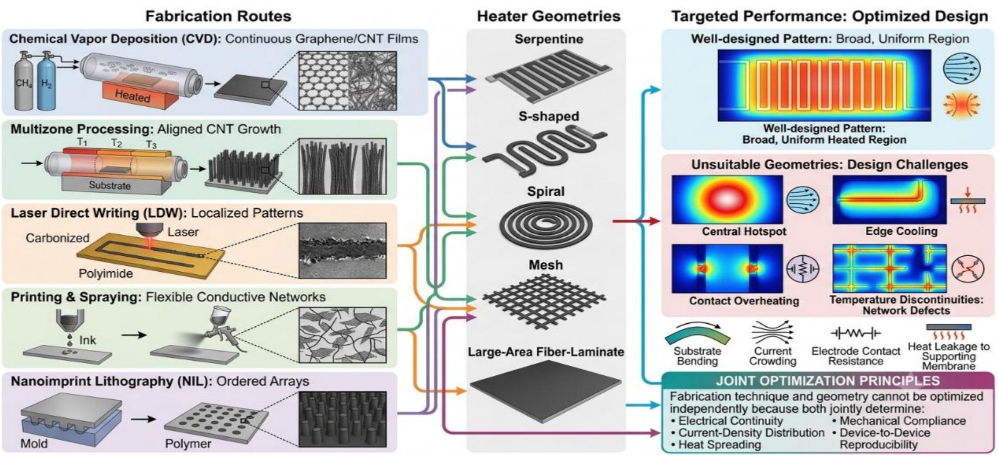

Figure 4 Process-geometry-thermal uniformity framework for carbon-based microheaters, showing how fabrication route, conductive-network formation, heater pattern, substrate configuration, and electrical contacts shape the resulting temperature distribution. This figure is an author-generated conceptual synthesis of the reviewed literature and should not be interpreted as a quantitative experimental dataset.

Figure 4 shows that fabrication route and heater geometry must be optimized as an integrated design problem because both directly influence electrical continuity and thermal uniformity. Chemical vapor deposition, multizone processing, laser direct writing, printing, spraying, and nanoimprint lithography generate different film structures, alignments, resolutions, and defect distributions. These process-dependent features subsequently determine the performance of serpentine, S-shaped, spiral, mesh, and large-area fiber-laminate heaters. Uniform heating is achieved when current density and lateral heat spreading remain balanced across the active region. Conversely, unsuitable geometries or imperfect interfaces can produce central hotspots, edge cooling, contact overheating, and interrupted temperature fields. Substrate bending, electrode resistance, network defects, and heat leakage through the supporting membrane must therefore be considered simultaneously to improve flexibility, stability, and device-to-device reproducibility.

Table 2 Representative fabrication routes for carbon-based microheaters

Fabrication Technique	Typical Feature Resolution	Scalability / key advantage	Processing complexity / limitation	Ref.
Conventional / floating-catalyst CVD	Film-scale, sub-microncontrol	Scalable carbon-film synthesis with maturepro cesscontrol	High-temperature multiste p process; coupled reaction ns can limit run-to-run con sistency	(Janas & Koziol, 2014), (Deokar et al., 2022), (R. Kumar et al., 2026), (Shan et al., 2025)
Multizone rapid thermal processing CVD	Forest-level height control; improved uniformity	Improved uniformity by decoupling catalyst format ion, gas decomposition, an d CNT growth	Custom-reactor complexity; supporting CNT-manufacturing evidence rather than a direct heater benchmark	(J. Lee et al., 2019), (P. J. Cao et al., 2006)
Femtosecond laser direct writing / thermochemical precipitation	~1.6 µm minimum feature size	High-resolution, low-thermal-diffusion metallization with scale-up potential	Adjacent copper-metalliza tion evidence; carbon-spe cific adaptation remains to be demonstrated	(Ha et al., 2025), (Jiaxiang et al., 2025), (Taherian et al., 2025), (C. Yang et al., 2025)
Laser ablation / flash lamp annealing	Sub-20 µm (ablation); localized	Localized patterning and structural/electrothermal modification	Mixed direct/adjacent laser evidence; excessive local heating	(Myung & Kim, 2024), (Ulieru et al., 2006), (Y. Yang et al., 2022),

Fabrication Technique	Typical Feature Resolution	Scalability / key advantage	Processing complexity / limitation	Ref.
			can alter the condu ctive structure	(Kuhfuß et al., 2026)
Spray coating / solution printing	Fine patterning on flexible substrates	Low-cost and scalable for flexible/wearable substrates	Direct/supporting flexible-heater evidence; network thickness, contact resistance, and heterogeneous metrics complicate comparison	(Tavakkoli Gilavan et al., 2025), (Bae et al., 2026), (Kuckling, 2009), (D. H. Lee et al., 2024), (Dubnov et al., 2025), (Barmpakos et al., 2024)
Nanoimprint lithography	Wafer-scale (2-inch demonstrated)	Wafer-scale ordered CNT-array patterning	Adjacent CNT-array fabrication evidence; pattern fidelity depends on imprint and substrate conditions	(Bu, 2010)

Thermal Transport and Multiscale Modelling

For clarity, the reviewed approaches are separated into three levels: theoretical/analytical models such as nonlocal conduction; numerical simulations including MD, DPD, NEMD, NEGF, and continuum/FEM approaches; and experimentally constrained or validated approaches that compare predicted transport with thermoreflectance, infrared/Raman thermometry, or nanoscale scatterometry. Their roles differ: atomistic models resolve phonon, defect, and interface physics; continuum models predict device temperature fields and hotspots; and validation experiments test whether model parameters remain realistic at device scale. Accurate prediction of heat generation and dissipation in carbon-based microheaters requires models spanning atomistic to continuum length scales, since classical Fourier conduction breaks down as characteristic dimensions approach the phonon mean free path (Kutuzov., 2026), (Aydin et al., 2020). A recent two-parameter nonlocal heat conduction analysis under pulsed heating conditions demonstrates that classical diffusion models systematically fail to capture finite-neighborhood and retardation effects that become significant at nanoscale dimensions and short heating pulses, both of which are characteristic operating regimes for microheaters (Kutuzov., 2026). This finding reinforces earlier calls for improved multiscale simulation methods combining molecular dynamics and dissipative particle dynamics techniques to bridge atomistic and mesoscopic descriptions of heat transport (Aydin et al., 2020). Interfacial thermal transport represents a second major modelling challenge. A comprehensive review of measurement, modeling, and manipulation of thermal boundary conductance across solid-solid interfaces shows that vibrational spectral mismatch, harmonic and anharmonic phonon scattering, interfacial disorder, and mixing all jointly determine interfacial thermal resistance, and that no single experimental or computational technique captures all of these factors simultaneously (Norris et al., 2021). The same review demonstrates that introducing an intermediate layer with vibrational properties intermediate between two dissimilar contacts, or employing an exponentially mass-graded interlayer, can measurably enhance interfacial thermal conductance, a strategy with direct relevance to the metal-carbon and carbon-substrate interfaces ubiquitous in microheater architectures (Norris et al., 2021). Time-domain thermoreflectance and nonequilibrium molecular dynamics remain the principal experimental and computational tools for quantifying these effects, while nonequilibrium Green function approaches provide a quantum-mechanical treatment of phonon transmission across atomically resolved interfaces (Norris et al., 2021). Engineered thermal interface materials with one-dimensional vertical architectures further illustrate how directional phonon channeling can be exploited to manage heat flow across dissimilar-material stacks (H. Cao & Sun., 2026).

A third relevant modeling tradition originates in boiling heat transfer research, which, while not concerned with microheaters per se, has produced multiscale frameworks, spanning macroscale two-fluid models, meso-scale interface-capturing methods, and nanoscale molecular dynamics simulations, that are methodologically instructive for microheater thermal design in liquid environments such as microfluidic point-of-care platforms (Ilic et al., 2019). The review argues that dramatically different characteristic time steps across these scales hinder full multiscale coupling and proposes algorithms for identifying sub-domains within macroscale regions that warrant small-scale simulation, a concept that could be adapted to identify localized hotspots in carbon-based microheater arrays requiring atomistic-resolution modeling (Ilic et al., 2019). Finally, nanoscale thermal transport experiments employing extreme ultraviolet scatterometry have quantified size- and spacing-dependent cooling of periodic nanostructures, providing benchmark data against which multiscale simulations of microheater arrays can be validated (Frazer et al., 2019). Porous, foam-like carbon architectures used for ultra-high-temperature thermal insulation offer a further data point on how hierarchical porosity governs effective thermal conductivity at the macroscale, complementing the atomistic and interfacial perspectives discussed above (Qu et al., 2026). Collectively, these modelling advances point toward a converging need: multiscale frameworks that couple nonlocal conduction, interfacial thermal boundary conductance, and array-level thermal management, validated against high-resolution experimental thermal transport measurements. Existing models remain limited by uncertain interface parameters, idealized boundary conditions, computational cost across scales, and sparse device-level validation. Predictions of absolute temperature, response time, and uniformity should therefore be distinguished from experimentally measured heater performance. A practical hierarchy is to use atomistic or nonlocal models for material/interface parameters, continuum simulation for geometry-level behavior, and thermal measurements to close the validation loop.

Figure 5 shows how thermal behavior in carbon-based microheaters emerges from coupled phenomena operating across multiple length scales. At the atomistic level, carbon bonding, defects, doping, nanotube chirality, and graphene folding influence phonon transport and intrinsic conductivity. At interfaces, vibrational mismatch, disorder, contact resistance, and graded interlayers regulate heat transfer between carbon elements, metal electrodes, and supporting substrates (Norris et al., 2021). These effects propagate to the device scale, where Joule heating, lateral heat spreading, substrate conduction, convection, radiation, and hotspot formation determine temperature uniformity. At the system scale, thermal cross-talk and environmental boundaries affect array-level control. Reliable prediction therefore requires bidirectional integration between molecular dynamics, nonequilibrium Green-function methods, nonlocal models, finite-element simulation, and experimental validation using thermoreflectance, infrared imaging, Raman thermometry, and nanoscale scatterometry.

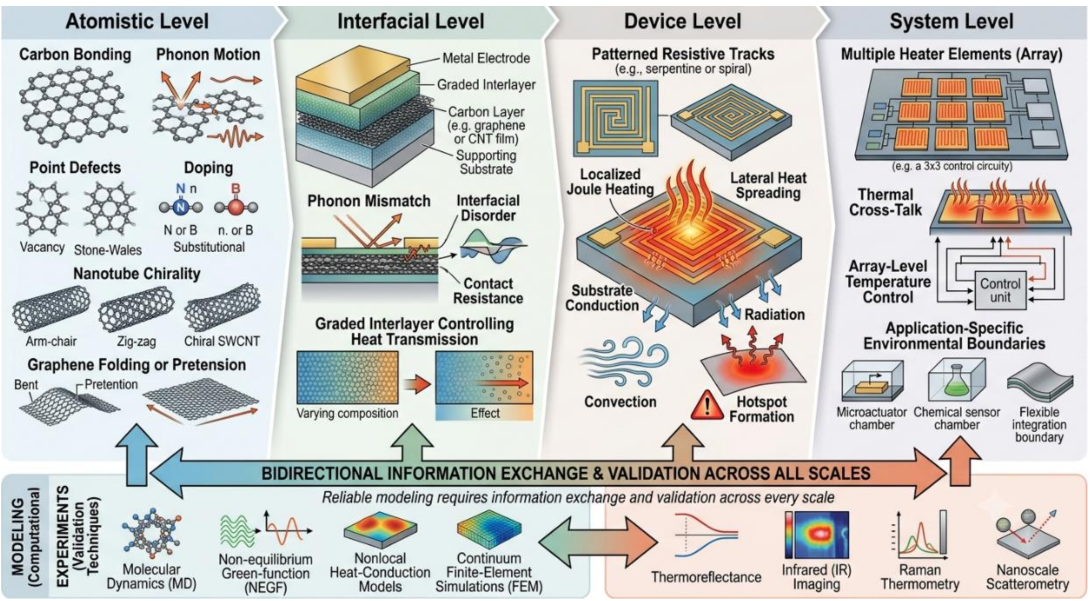

Figure 5 Multiscale thermal transport and validation framework for carbon-based microheaters, spanning atomistic phonon behavior, interfacial heat transfer, device-level Joule heating, nonlocal conduction, and system-level thermal management. This figure is an author-generated conceptual synthesis of the reviewed literature and should not be interpreted as a quantitative experimental dataset.

Applications and Performance Considerations

In this section, direct carbon-microheater/heater demonstrations are separated from enabling or adjacent application evidence. Metallic microheater controls, wearable sensing platforms, wireless subsystems, theranostic carbon dots, and related carbon electrothermal technologies are used only when they define a transferable operating requirement or design principle.

Biomedical diagnostics and wearable health monitoring

Carbon-based microheaters and associated sensing elements are increasingly embedded within microfluidic point-of-care testing platforms, where controlled, localized heating drives nucleic acid amplification, biochemical assays, and thermally activated actuation (Kulkarni & Vyas., 2024), (Mahalakshmi et al., 2025) . A dedicated review of microheater materials, design, fabrication, and temperature control explicitly framed around the COVID-19 pandemic illustrates the urgency with which rapid, low-power, and disposable heating elements have been sought for decentralized diagnostic testing (Jeroish et al., 2022). The broader carbon nanomaterial toolkit for wearable health monitoring, including graphene, CNTs, and carbon fiber-based sensors, has been comprehensively reviewed, with particular attention to its integration with acoustic, optical, electrochemical, and wireless communication subsystems (Erdem et al., 2022) , and complementary surveys emphasize the mechanisms by which carbon materials support flexible wearable sensing more broadly (Hossain et al., 2026). A parallel review of minimally invasive wearable biochemical sensors emphasizes that translating in vitro sensor performance to reliable in vivo operation remains difficult, with sensor design choices, bioreceptor selection, nanomaterial incorporation, and surface modification exerting a profound influence on sensitivity, linear range, and long-term stability; personalized calibration against reference techniques was identified as the most reliable strategy for accurate in vivo biomarker quantification (Ausri et al., 2023). These translational challenges apply directly to implantable or skin-mounted carbon microheaters intended for thermally assisted biosensing or controlled drug release, an application space further enriched by carbon nanodot-based theranostic platforms capable of combined thermal, optical, and therapeutic function (M. Kumar et al., 2026). Except where heater operation is explicitly reported, wearable-sensor and theranostic studies are therefore treated as application-context evidence rather than direct microheater-performance data.

In situ electron microscopy and high-temperature characterization

Graphene microheater chips have been developed specifically for in situ transmission electron microscopy, exploiting graphene low mass, high thermal conductivity, and electron transparency to achieve rapid, spatially localized heating within the microscope column, enabling real-time observation of temperature-dependent structural transformations (J. Zhao et al., 2023). This application places stringent demands on temperature uniformity and response time that differ from those of gas sensors or wearable devices, underscoring the importance of application-specific design optimization rather than a one-size-fits-all microheater architecture.

Gas sensing and precision temperature control

Reliable microheater design for MEMS-based metal-oxide gas sensors continues to depend on the interplay between heater geometry, membrane suspension, and material selection to minimize residual stress-induced deflection while achieving fast, uniform temperature distribution (Bhattacharyya., 2014). Platinum heating electrodes integrated with electrochemically prepared anodic porous alumina membranes illustrate one route to combining thermal isolation with mechanical robustness in suspended heater architectures (Park et al., 2016), while nanoscale thermal management strategies demonstrated for single tin-oxide nanowire sensors show that pico-joule-scale energy budgets are achievable when heater dimensions are pushed toward the nanoscale (Meng et al., 2016). Precision temperature control strategies have also advanced: an open-loop to closed-loop switched proportional-integral controller for platinum microheaters embedded in metal-oxide gas sensors achieved a settling time of three seconds, compared with fourteen seconds for conventional proportional-integral control, by combining the fast initial response of open-loop operation with the steady-state accuracy of closed-loop feedback (Singh et al., 2018). Such control strategies are increasingly relevant as carbon-based heating elements, with their distinct thermal mass and response characteristics relative to metallic heaters, are integrated into existing sensor control architectures. The platinum-heater studies in this subsection are retained as adjacent control and thermal-isolation benchmarks and are not interpreted as direct evidence of carbon-microheater performance.

Electrothermal de-icing and multifunctional structural heating

Electrothermal de-icing represents a rapidly growing application domain for carbon fiber-based heaters, driven by the need for lightweight, rapid-response alternatives to conventional resistive heating elements that also provide electromagnetic interference shielding for co-located avionics (Ma et al., 2026). As discussed in Section 2, nickel-copper co-deposited carbon fiber achieves a favorable combination of electrothermal conversion efficiency, mechanical durability under cyclic loading, and shielding performance, positioning functionalized carbon fiber composites as multifunctional structural heating elements rather than standalone thermal devices (Ma et al., 2026). Adjacent multifunctional applications, such as graphene-carbon composite structures engineered for solar-driven and low-voltage-powered interfacial evaporation, further illustrate how electrothermal carbon architectures are being redeployed across energy and environmental technology domains that share underlying materials and heat-management principles with microheaters (F. Liu et al., 2020). This evidence is a direct carbon-fiber electrothermal demonstration at structural scale rather than a microscale microheater benchmark.

Wireless integration and AI-guided multifunctional design

Wearable and implantable microheater-integrated systems increasingly require co-located wireless power and data transmission. Stretchable radio-frequency systems based on asymmetric three-dimensional microstrip antennas have demonstrated on-body wireless communication combined with energy harvesting, offering a template for powering distributed carbon microheater networks without rigid battery packs (S. Zhang et al., 2022). Graphene and CNT conductive ink-based biomimetic structures have similarly been engineered into self-powered flexible medical monitoring devices (J. Wang et al., 2024), while dual-functional graphene-based self-alarm health-monitoring electronic skins combine sensing, signaling, and thermal management within a single flexible platform (Chen et al., 2019). A 2025 perspective on low-dimensional carbon materials, spanning carbon fibers, CNTs, and graphdiyne, articulates a synergistic relationship between electromagnetic wave attenuation and artificial-intelligence-guided materials design, in which machine learning and in situ characterization accelerate the optimization of impedance matching, defect engineering, and hierarchical architectures (Shan et al., 2025). Although framed primarily around electromagnetic shielding, the AI-driven design methodologies described are directly applicable to microheater optimization, particularly for balancing the competing objectives of thermal uniformity, power efficiency, and mechanical durability that have historically required extensive empirical trial and error. These wireless and multifunctional examples are enabling-system evidence; they define integration requirements but do not by themselves constitute direct carbon-microheater performance measurements.

Economic, environmental, and scalability considerations

Beyond raw performance metrics, the eventual adoption of carbon-based microheaters in commercial products depends on manufacturing cost, environmental footprint, and supply chain resilience. Femtosecond laser thermochemical writing from aqueous, surfactant-stabilized copper complex inks has been explicitly framed by its developers as an affordable, environmentally conscious alternative to vacuum-based metallization, since it avoids high-temperature furnace processing and hazardous solvents while remaining compatible with roll-to-roll manufacturing concepts (Ha et al., 2025). Multizone rapid thermal processing CVD reactors, while more capital-intensive to construct than conventional single-zone furnaces, reduce material waste associated with failed growth runs by improving process consistency, a benefit that becomes increasingly significant as CNT forest and film production is scaled from laboratory to pilot-plant volumes (J. Lee et al., 2019). Printed and sprayed carbon heater routes retain a cost advantage for large-area, disposable, or single-use applications such as point-of-care diagnostic cartridges, but the heterogeneity of reported performance metrics across studies complicates direct techno-economic comparison, reinforcing the value of standardized benchmarking protocols of the kind recently proposed for printed temperature sensors and microheaters (Barmpakos et al., 2024). Electrothermal de-icing composites based on nickel-copper co-deposited carbon fiber further illustrate how multifunctionality, in this case simultaneous heating and electromagnetic shielding, can improve the economic case for carbon-based heaters by displacing multiple single-function components with one integrated structural-thermal-electromagnetic solution (Ma et al., 2026).

A concise comparison of reported heater-level performance further illustrates the evidence hierarchy. The graphene in situ TEM microheater reached 800 °C in 26.31 ms at 0.025 mW per 1000 μm² and showed only ~50 nm membrane bulging at 650 °C (J. Zhao et al., 2023). CNT-resistor microheater chips limited membrane bulging to ~100 nm at 800 °C while retaining rapid high-temperature response (Z. Zhao et al., 2024). Laser-written graphene flexible microheaters achieved 60 μm heating-line widths and temperatures up to 150 °C (Y. Yang et al., 2022). By contrast, Ni-Cu carbon fiber reached 102.8 °C at 4.38 °C s^{-1} with a 68.3 s de-icing time (Ma et al., 2026), representing larger-scale structural electrothermal evidence. These examples show why operating scale and evidence context must accompany performance metrics.

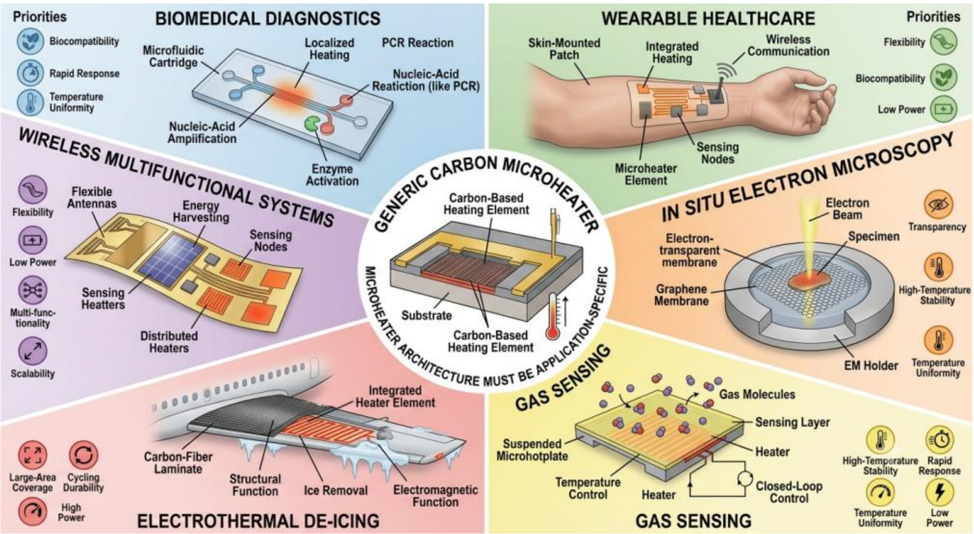

Figure 6 Application ecosystem and design requirements of carbon-based microheaters across biomedical diagnostics, wearable devices, in situ microscopy, gas sensing, structural de-icing, and wireless multifunctional systems. This figure is an author-generated conceptual synthesis of the reviewed literature and should not be interpreted as a quantitative experimental dataset.

Figure 6 shows that carbon-based microheater design must be tailored to the thermal, mechanical, and operational demands of each application. Biomedical diagnostics prioritize localized heating, low power consumption, and temperature uniformity within microfluidic environments, while wearable healthcare additionally requires flexibility, biocompatibility, and wireless integration. In situ electron microscopy demands ultrathin, electron-transparent heaters with rapid response and high-temperature stability. Gas-sensing platforms require suspended architectures, precise closed-loop control, and minimal heat loss. Electrothermal de-icing emphasizes large-area coverage, cycling durability, structural integration, and electromagnetic functionality. Wireless multifunctional systems combine distributed heating with sensing, communication, and energy harvesting. These contrasting requirements demonstrate that material selection, geometry, control strategy, and fabrication route must be optimized according to the intended operating environment rather than through a universal microheater configuration.

Novelty, Persistent Research Gaps, and Future Directions

Table 3 synthesizes the principal novelty claims, unresolved research gaps, and recommended future directions emerging from the literature surveyed in this review, distinguishing between advances already well established prior to 2024 and those introduced by the 2024 to 2026 literature incorporated here. The table now distinguishes direct or demonstrated evidence from transferable evidence and proposed future directions so that emerging opportunities are not presented as already validated microheater technologies.

Table 3 Novelty, research gaps, and future directions across the principal domains of carbon-based microheater research

Domain	Established Novelty (pre-2024)	New advances incorporated / evidence status (2024-2026)	Remaining Gap / Future Direction	Ref.
Materials	Graphene, CNT, and a-C integration for rapid, low-power, flexible heating	Mixed direct/transferable evidence: Ni-Cu carbon fiber for de-icing plus EMI shielding; a-C stress relaxation in TaC coatings; silica-encapsulated carbon dots stable to 1000 K	Proposed/ongoing: atomic-level scalable control of doping and functionalization; heater-specific validation of encapsulation motifs	(Sun et al., 2026), (Ma et al., 2026), (Hu et al., 2026), (S. Zhang et al., 2024)
Fabrication	CVD, laser patterning, additive manufacturing for scalable production	Mixed direct/adjacent process evidence: multizone rapid thermal CVD; femtosecond laser thermochemical writing at ~1.6	Ongoing: wafer-scale run-to-run consistency and unified performance	(Ha et al., 2025), (J. Lee et al., 2019),

Domain	Established Novelty (pre-2024)	New advances incorporated / evidence status (2024-2026)	Remaining Gap / Future Direction	Ref.
		μm; standardized printed-heater benchmarking	metrics across fabrication routes	(Barmpakos et al., 2024)
Modelling	FEM, NEMD, and Boltzmann transport approaches for nanoscale heat transfer	Theoretical/numerical/validation evidence: two-parameter non local conduction; thermal-boundary-conductance frameworks; multiscale coupling concepts	Proposed: computationally tractable and experimentally validated models spanning atomistic to array scale	(Kutuzov., 2026), (Norris et al., 2021), (Ilic et al., 2019), (Frazer et al., 2019)
Applications	Wearable biosensors, microfluidic POCT, tissue engineering	Mixed direct/enabling evidence: in situ TEM graphene microheaters; carbon-fiber de-icing; AI-guided carbon design; wireless integration	Proposed/ongoing: in vivo translation, improved tem perature uniformity, and long-term biocompatibil ity in flexible systems	(Erdem et al., 2022), (Ausri et al., 2023), (J. Zhao et al., 2023), (S. Zhang et al., 2022), (Shan et al., 2025)

Several cross-cutting observations emerge from this synthesis. First, the field is transitioning from single-material, single-function heating elements toward multifunctional composites that simultaneously deliver electrothermal actuation, electromagnetic shielding, and mechanical reinforcement, as exemplified by nickel-copper co-deposited carbon fiber (Ma et al., 2026) and hybrid graphene-CNT composite electrodes (Myung & Kim, 2024). Second, encapsulation and interlayer engineering strategies, whether silica shells protecting carbon dot luminescence at extreme temperatures (S. Zhang et al., 2024) or mass-graded interlayers enhancing thermal boundary conductance (Norris et al., 2021), represent a generalizable design motif for improving the thermal and structural resilience of carbon-based heating elements, even though these specific studies were not conducted within a microheater context. Third, computational and control methodologies, spanning nonlocal heat conduction models (Kutuzov., 2026), multiscale boiling-inspired frameworks (Ilic et al., 2019), AI-guided materials design (Shan et al., 2025), and fast-settling switched proportional-integral temperature control (Singh et al., 2018), are converging toward integrated design pipelines that couple materials selection, fabrication process control, and real-time thermal management. Accordingly, the future directions below separate technically demonstrated enabling approaches from microheater-specific possibilities that still require validation.

Figure 7 shows how future carbon-based microheater development can progress through an integrated and iterative design cycle. Application requirements first define the target temperature, power budget, heating area, substrate flexibility, environmental exposure, and expected service life. These constraints guide AI-assisted selection of carbon allotropes, doping strategies, hybrid compositions, encapsulation systems, and interface layers. Fabrication parameters and heater geometry are then optimized before multiscale simulations predict phonon transport, interfacial resistance, current distribution, thermal uniformity, and mechanical stress. Experimental fabrication and in situ characterization provide electrical, thermal, structural, and process data for reliability evaluation under cycling, bending, oxidation, delamination, resistance drift, and hotspot formation. Measured deviations are subsequently returned to the AI model, creating a closed-loop pathway that addresses limited datasets, insufficient validation, nonuniform heating, and manufacturing inconsistency. In this review, AI is not treated as an already demonstrated end-to-end microheater technology. Its specific near-term roles are materials/composition screening, surrogate modelling, multiobjective optimization of heater geometry and process parameters, parameter-sensitivity analysis, and prioritization of experiments using measured thermal images, resistance drift, and reliability data. Figure 7 is therefore a proposed closed-loop development roadmap whose microheater-specific implementation still requires validated datasets.

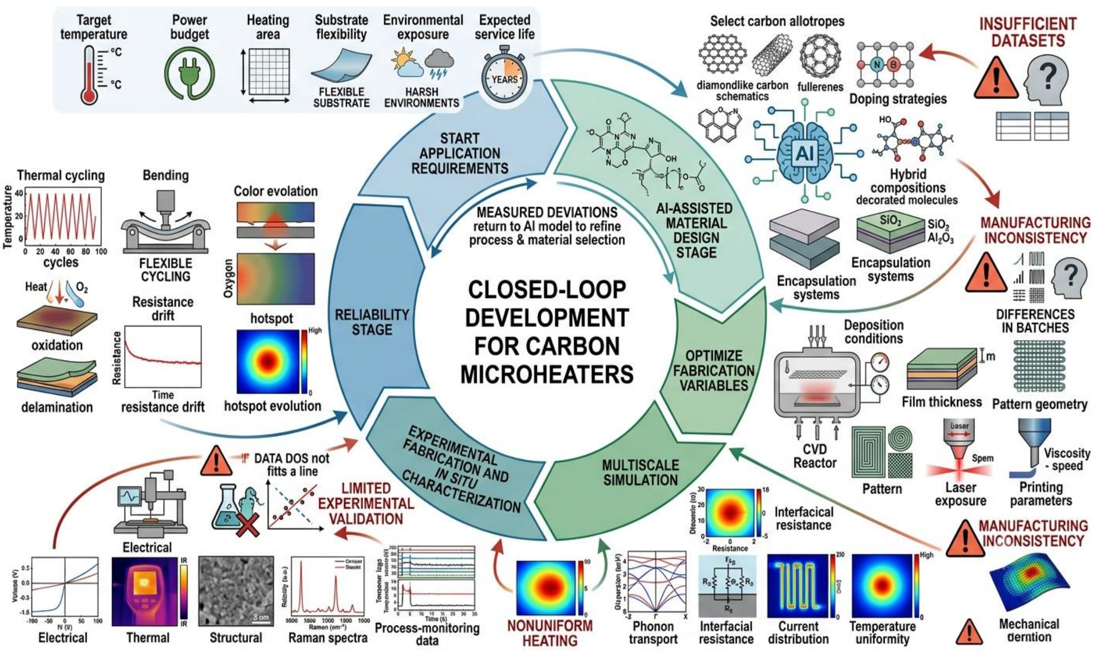

Figure 7 Closed-loop roadmap for AI-guided development of next-generation carbon-based microheaters, integrating material discovery, process optimization, multiscale simulation, experimental validation, reliability assessment, and application-driven feedback. This figure is an author-generated conceptual synthesis of the reviewed literature and should not be interpreted as a quantitative experimental dataset.

Despite this progress, the unresolved gaps identified in earlier literature persist substantively unchanged: achieving uniform, stable heat distribution across flexible and miniaturized geometries; attaining atomic-level control of doping and functionalization at production scale; developing wafer-scale fabrication methods with run-to-run consistency, an issue directly addressed but not fully solved by multizone rapid thermal processing (J. Lee et al., 2019); and constructing multiscale thermal models that are simultaneously computationally tractable and experimentally validated across the full range of relevant length and time scales (Kutuzov, 2026), (Norris et al., 2021), (Ilic et al., 2019), (Aydin et al., 2020). The folding-induced pretension phenomenon recently characterized in suspended graphene (de Moraes et al., 2026) further complicates thermal modelling of ultrathin heater membranes, since fold-induced stress alters phonon transport in ways not yet incorporated into standard microheater design frameworks.

Conclusion

This review finds that carbon-based microheater performance is governed less by any single intrinsic material property than by the coupled selection of carbon architecture, network/contact quality, heater geometry, substrate, and interfacial thermal resistance. Graphene and CNT systems provide the strongest direct microheater evidence for rapid, low-power heating; amorphous carbon offers tunable resistance and stress accommodation; and functionalized carbon fibers extend electrothermal functionality toward structural heating. Adjacent results on carbon-dot encapsulation and interface engineering are useful as transferable design principles rather than direct heater benchmarks. The key unresolved technical challenges are temperature uniformity and hotspot suppression, reproducible doping and network/contact control, wafer-scale process consistency, durability under thermal and mechanical cycling, and multiscale models that are both computationally practical and experimentally validated. The fabrication comparison further shows that higher resolution or intrinsic material quality alone does not guarantee better heater performance because process complexity, substrate compatibility, contact resistance, and thermal losses can dominate device behavior. Future progress should therefore combine evidence-aware material selection, scalable fabrication, hierarchical modelling, and application-specific validation. AI-assisted methods are most credible as tools for screening compositions, optimizing geometry and process variables, building surrogate models, and prioritizing experiments within closed-loop development; end-to-end AI-guided microheater design remains a prospective research direction. This framework provides a practical basis for comparing carbon microheaters without conflating intrinsic material data, direct heater measurements, modelling outputs, and adjacent evidence.

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