

REVIEW ARTICLE

Heat-Induced Morphological Changes in Silver Nanowires: A review

Noor Zulfiqar^{1*}, Muhammad Arsalan², Fawad Inam³

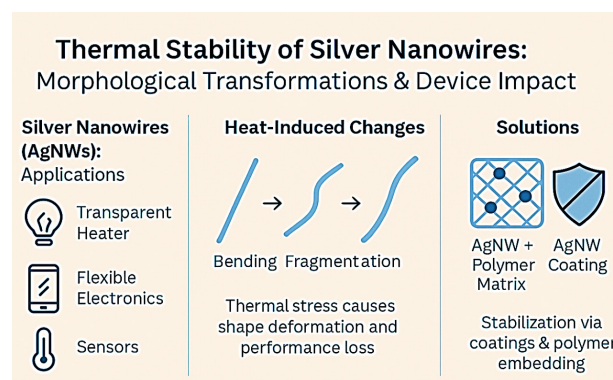
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Abstract

Silver Nanowires (AgNWs) are gaining widespread attention for their remarkable electrical, optical, and mechanical properties, which make them ideal for a variety of cutting-edge applications such as flexible electronics, transparent conductive films, and sensors. However, their stability and performance when exposed to high temperatures are crucial for their practical use. This review sightsees into how heat affects the shape and structure of AgNWs, exploring the mechanisms behind these changes and what they mean for real-world applications. We cover topics like the melting behavior of tiny metallic wires, the role of surface atoms moving around, and how environmental factors can influence their stability. Additionally, we discuss how these heat-induced changes can impact the efficiency of devices that use AgNWs, like transparent heaters. This review uniquely contributes by bridging nanoscale morphological transformations with macroscale functional consequences in devices, offering a

consolidated analysis of critical temperature thresholds, degradation modes, and stabilization strategies. It further distinguishes itself through the inclusion of green synthesis perspectives and comparative data on other metallic nanowires, providing a holistic view of AgNW thermal behavior that is currently lacking in existing literature. By bringing together findings from recent research, this review aims to provide a clear understanding of how AgNWs behave under heat and offer insights into improving their design and use in high-temperature situations.

Graphical Abstract



Key Words: Silver Nanowires (AgNWs); Heat-induced morphological changes; Thermal stability; Rayleigh instability; Surface atom diffusion; Transparent conductive films; Flexible electronics; Device performance

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Introduction

Silver Nanowires (AgNWs) have attracted considerable interest due to their unique properties and diverse applications in fields such as electronics, optics, and biomedical engineering. Their remarkable electrical conductivity, optical transparency, and mechanical flexibility make them ideal candidates for next-generation devices, including flexible electronics, transparent conductive films, and sensors. However, the thermal stability and behavior of AgNWs under elevated temperatures are critical factors that significantly influence their performance and functionality. Understanding how heat affects the morphology and structure of AgNWs is essential for optimizing their synthesis, processing, and practical application [1,2]. This review aims to comprehensively analyze the existing research on heat-induced morphological changes in AgNWs. We will elucidate the mechanisms underlying these transformations and discuss their implications for the practical utilization of AgNWs. By examining the thermal behavior of metallic nanowires, particularly focusing on AgNWs, we can gain valuable insights into the fundamental principles that govern their structural stability and performance under thermal stress.

This review offers a novel framework by classifying heat-induced morphological changes in Silver Nanowires (AgNWs) based on temperature thresholds, environmental conditions (e.g., vacuum, air, inert gases), and nanowire dimensions. Unlike previous studies, which primarily describe individual mechanisms in isolation, we provide comparative insights across different metal nanowires (Ag, Au, Cu, Zn) and correlate observed morphological changes such as fragmentation, coalescence, and

surface diffusion with functional consequences in real-world devices. A unique contribution of this review is the integration of device-level performance metrics (e.g., resistance increase, loss of optical transparency, structural failure) with thermal exposure parameters, offering practical correlations for sensor, heater, and film applications. Additionally, we incorporate green synthesis approaches and their influence on the thermal resilience of AgNWs—an area rarely explored in earlier reviews. Summary matrices, comparative tables, and mechanism-based flow diagrams are included to visually represent the synthesis-to-failure continuum, making this review not only comprehensive but also analytically instructive for material scientists and device engineers [3-7].

Green synthesis and its influence on thermal morphology

The advancement of nanotechnology has highlighted the pressing need for environmentally benign synthesis routes. Among these, green synthesis methods have garnered significant attention for their potential to reduce the environmental and biological hazards traditionally associated with chemical synthesis. These methods typically utilize biological entities such as plant extracts, microbial agents, biopolymers, or naturally derived reductants like ascorbic acid to fabricate nanomaterials, including Silver Nanowires (AgNWs). In addition to environmental benefits, these green routes also impart distinct physicochemical properties to the resulting nanostructures, particularly influencing their morphological response under thermal stress.

Unlike conventional methods that often rely on harsh chemicals and high-temperature

conditions, green synthesis proceeds under milder, aqueous conditions and at lower temperatures. For instance, the use of plant extracts such as Aloe vera, green tea, or neem introduces a diverse array of phytochemicals such as flavonoids, terpenoids, and polyphenols that can act simultaneously as reducing and stabilizing agents. These biomolecules often yield thinner and more labile capping layers on AgNWs in comparison to synthetic surfactants like Polyvinylpyrrolidone (PVP), which forms a dense, polymeric sheath around nanowires. This distinction in surface chemistry is critical when evaluating the thermal morphology of AgNWs. The organic capping layer not only determines the interfacial diffusion and sintering behavior under heat but also plays a role in oxidation resistance and structural integrity. AgNWs synthesized using green agents such as ascorbic acid has shown enhanced thermal mobility due to weaker surface binding, which can lead to earlier onset of morphological transformations, such as necking, fragmentation, or spheroidization, upon exposure to elevated temperatures [8-12].

Moreover, green-synthesized nanowires often exhibit lower defect densities and more uniform crystalline structures, as evidenced by Transmission Electron Microscopy (TEM) and X-ray Diffraction (XRD) analyses. This crystallinity can contribute to improved thermal stability, as fewer grain boundaries and dislocations are available to act as initiation sites for thermal degradation. In contrast, AgNWs prepared via conventional polyol routes tend to exhibit heterogeneous grain structures, making them more susceptible to thermally induced deformations at defect-rich sites. Another advantage of green synthesis lies in its tenability the pH, temperature, and extract concentration can be varied to modulate nucleation and growth

rates, which in turn affect nanowire diameter, length, and aspect ratio. These parameters are directly linked to thermal conduction and morphological evolution, especially under stress conditions like Joule heating in electronic or optoelectronic applications [13,14].

Melting behavior of metallic nanowires

The melting behavior of metallic nanowires is a complex phenomenon influenced by their reduced dimensions and high surface-to-volume ratios. Unlike their bulk counterparts, metallic nanowires exhibit significantly lower melting points due to the increased significance of surface atoms, which possess lower binding energies than those in the bulk. This section reviews the melting behavior of metallic nanowires, with a particular focus on silver nanowires, utilizing insights from various studies. The relationship between nanowire dimensions and melting temperature, as well as the influence of the Gibbs-Thomson effect, will be discussed to understand why metallic nanowires melt at lower temperatures compared to bulk materials.

Thermal behavior of metal nanostructures under high temperatures

The thermal stability and morphological changes of metal nanostructures under high temperatures provide significant insights into their practical applications. Studies utilizing in situ Environmental Transmission Electron Microscopy (E-TEM) have revealed that the thermal stability of metal nanostructures is highly dependent on their initial shape, crystallographic defects, and the surrounding gas environment. For instance, Pd@SiO₂ nanostructures exhibit different behaviors based on their shape and environmental conditions,

highlighting the importance of particle structure and external factors in determining thermal stability.

Limits of analogy between core–shell and pure metal nanowire systems: While core–shell architectures such as Pd@SiO₂ or Pd@CeO₂ provide valuable thermal behavior insights, they are not directly transferable to uncoated AgNWs. In situ TEM studies on Pd@CeO₂ and Pd@SiO₂ show that the oxide shell suppresses sintering and atom diffusion up to high temperatures (>1000 K), thanks to mechanical confinement and oxidation resistance provided by the shell [15]. However, bare AgNWs lack such encapsulation, making them significantly more vulnerable to surface diffusion, Rayleigh instability, and oxidation at much lower temperatures (~200–300°C). Consequently, core–shell systems often display much higher thermal thresholds and slower degradation rates compared to naked metallic nanowires. Any direct extrapolation from encapsulated systems to pure AgNWs could therefore misestimate their melting and fragmentation behavior. A clear distinction should be maintained core–shell studies are insightful models, but pure AgNW behavior requires separate, material-specific investigation.

Heat-induced fragmentation

Heat-induced fragmentation of AgNWs is primarily attributed to Rayleigh instability, a fundamental concept in fluid dynamics. This phenomenon describes the breakup of a fluid jet into smaller droplets due to surface tension forces, and in solid nanowires, it manifests as the tendency to minimize surface energy, leading to fragmentation under thermal stress.

The diameter of the nanowires plays a crucial role in this process, with thinner wires being more susceptible to instability and subsequent breakup. The surrounding environment, including the presence of other materials and ambient conditions, also significantly influences the rate and pattern of fragmentation.

Beyond rayleigh instability: Alternate fragmentation mechanisms: Although Rayleigh instability is a primary mechanism explaining heat-induced fragmentation in AgNWs, particularly under uniform heating, alternative mechanisms have been observed under specific experimental conditions. For instance, grain boundary sliding, electromigration, and substrate-induced stress gradients have been identified as contributors to non-Rayleigh fragmentation. In particular, in-situ TEM studies have reported localized necking and asymmetric void formation at grain boundaries rather than evenly spaced breakup, which deviates from the classic sinusoidal Rayleigh model. Furthermore, when AgNWs are subjected to non-uniform thermal gradients or electrical biasing, fragmentation can initiate at defect sites or junctions due to enhanced local atom mobility and current-induced stress. These anomalies suggest that fragmentation is a multivariate process, where Rayleigh instability is dominant under idealized conditions, but real-world behaviors also involve surface defects, inhomogeneous heating, and external fields that drive alternative breakdown pathways [16,17]. A scientific diagram illustrating Rayleigh instability in silver nanowires, showing how periodic surface perturbations grow under thermal stress, leading to fragmentation is shown in (Figure 1).

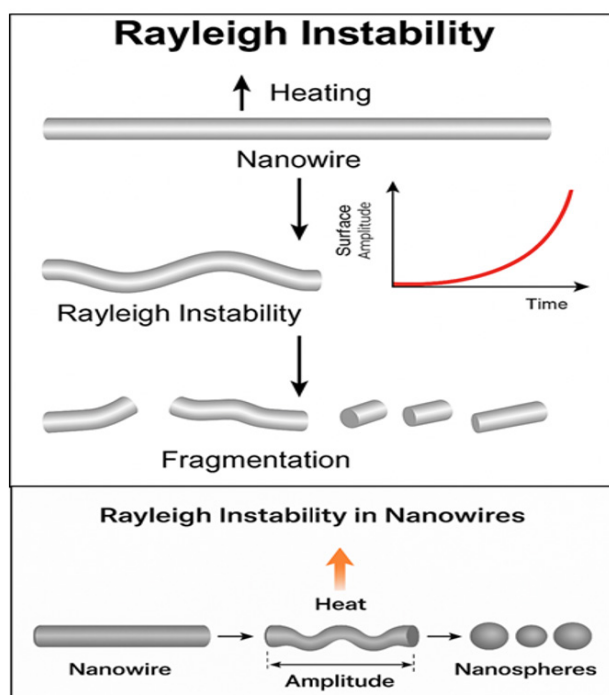


Figure 1) A scientific diagram illustrating Rayleigh instability in silver nanowires, showing how periodic surface perturbations grow under thermal stress, leading to fragmentation. The amplitude increases and necking regions represent the onset of morphological instability due to surface energy minimization.

Morphological changes and surface atom diffusion

Heat treatment can induce significant morphological changes in AgNWs, including fragmentation, elongation, bending, and merging. These changes are often driven by mechanisms such as surface atom diffusion, thermal expansion, and Rayleigh instability. Surface atom diffusion, in particular, plays a critical role in the morphological stability of AgNWs, with elevated temperatures facilitating the movement of atoms on the surface of nanowires, leading to changes in shape and potentially coalescence or breakage. Understanding these processes is essential for optimizing the design and application of AgNWs in various high-temperature environments.

Morphological transformations in Silver Nanowires (AgNWs) induced by thermal stress

are largely irreversible under normal cooling conditions. Once processes like Rayleigh instability, surface diffusion, fragmentation, or coalescence occur, the structural changes such as thinning, necking, or bead formation are typically permanent due to atomic rearrangement and energy minimization. Upon cooling, the nanowires do not return to their original shape because the atoms have diffused to new equilibrium positions or have formed energetically favorable aggregates. However, limited reversibility can be achieved through reprocessing techniques such as re-annealing in controlled atmospheres, chemical regrowth, or surface refunctionalization, which may partially restore electrical conductivity or mechanical integrity. Still, these methods do not truly reverse the original morphology but rather repair or reconstruct functionality. Thus, from a device reliability perspective, it is critical to design AgNW-based systems with preventive thermal management rather than relying on post-degradation recovery. Figure 2 visually summarizes the dominant morphological changes in Silver Nanowires (AgNWs) under varying thermal conditions. The x-axis represents temperature ranges (e.g., $<150^{\circ}\text{C}$, $150\text{--}300^{\circ}\text{C}$, $>300^{\circ}\text{C}$), while the y-axis denotes exposure duration (short-term, medium-term, long-term) across different environments (air, vacuum, inert gas). Color intensity reflects the severity of observed transformations such as surface roughening, fragmentation, coalescence, and complete melting. This matrix aids in identifying critical thresholds for AgNW thermal degradation, supporting better thermal design and application-specific material selection.

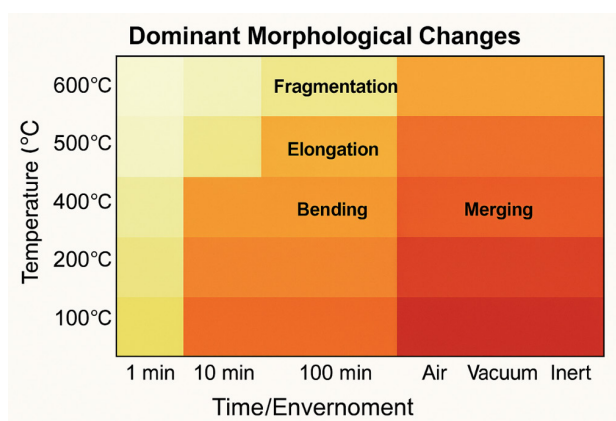


Figure 2) Visual summarization of the dominant morphological changes in Silver Nanowires (AgNWs) under varying thermal conditions.

Thermal cycling and long-term performance of AgNWs: Morphological changes such as fragmentation, necking, and coalescence in Silver Nanowires (AgNWs) significantly degrade their long-term cyclic performance under repeated heating and cooling cycles by increasing electrical resistance, inducing microstructural fatigue, and disrupting conductive pathways. These transformations reduce the mechanical integrity and electrical stability of AgNW-based devices, leading to performance failure over multiple thermal cycles. Studies have shown that repeated thermal stress accelerates degradation, especially in systems lacking effective surface passivation or reinforcement layers [18].

Influence of synthesis methods on thermal behavior: The synthesis route of silver nanowires has a profound impact on their thermal behavior, oxidation resistance, and dimensional uniformity all of which indirectly govern their response to heat. Techniques such as polyol synthesis, hydrothermal methods, and green chemistry approaches produce AgNWs with varying surface chemistries, crystallinities, and aspect ratios. These factors influence not only their initial structural integrity but also their susceptibility to Rayleigh instability, surface diffusion, and oxidation under thermal stress.

For example, wires synthesized with surfactants like PVP show different degradation thresholds compared to those with inorganic or bio-based stabilizers. Therefore, a thorough understanding of synthesis-structure-property relationships is essential for designing thermally robust AgNWs suitable for high-performance applications.

Optical and electronic property shifts due to thermal morphological changes: Heat-driven morphological changes in AgNWs such as necking, fragmentation, and coalescence lead to significant shifts in both surface plasmon resonance (SPR) behavior and electrical conductivity:

- **Optical/Spectroscopic effects:** Thermal annealing around 350°C causes the SPR peak to red-shift (e.g., shifting from ~380 nm to ~445 nm) and broaden due to morphological changes and reshaping of the nanowires [19].
- **Electrical conductivity:** In situ X-ray diffraction (XRD) studies show that resistance begins increasing sharply over a ~25°C thermal window, tied to crystalline distortion and atom migration [20]. These morphological disruptions result in loss of connectivity within the nanowire network, raising sheet resistance and diminishing plasmonic field enhancement thereby degrading overall device performance.

These findings highlight the critical interplay between morphological integrity and functional stability in AgNW-based devices under thermal stress.

Linking surface atom diffusion to functional property shifts

Surface atom diffusion plays a pivotal role in the thermal behavior of AgNWs, driving morphological changes such as neck formation, thinning, and eventual fragmentation. These structural transformations have direct implications on the functional performance of AgNW-based devices. For instance, atomic rearrangements disrupt the continuous conductive pathways, leading to increased electrical resistance, especially in transparent electrodes and heaters. Simultaneously, the reshaping of nanowire geometry alters their Surface Plasmon Resonance (SPR) characteristics, often resulting in redshifts and peak broadening in UV-V is spectra due to changes in aspect ratio and surface roughness. These optical shifts degrade the performance of plasmonic sensors and optoelectronic devices. Additionally, diffusion-driven coalescence or breakage diminishes network connectivity, compromising both optical transparency and charge transport efficiency. Therefore, surface diffusion is not just a structural issue but a key mechanism governing electronic, optical, and thermal reliability in AgNW-integrated technologies [21].

Implications for device performance

The morphological changes in AgNWs directly impact the performance of devices such as TransparentFilmHeaters(TFHs). Fragmentation and surface diffusion can lead to increased resistance and reduced heating efficiency, while strategies such as coating AgNWs with protective layers or embedding them in stable polymer matrices can enhance thermal and mechanical stability. These improvements are

crucial for applications requiring consistent heating performance, such as automotive window defrosting and wearable electronics. By comprehensively reviewing the existing literature on heat-induced morphological changes in silver nanowires, this article aims to provide a detailed understanding of the mechanisms involved and their implications for practical applications. Such knowledge is vital for advancing the development and optimization of AgNW-based devices, ensuring their reliable performance and longevity under thermal stress.

Device-level correlations with heat-induced morphological changes:

Several studies have established clear quantitative links between thermal exposure of AgNW networks and device failure. For example, in transparent heaters, Joule heating above $\sim 250^{\circ}\text{C}$ leads to detectable nanowire fragmentation and an $\sim 80\%$ increase in sheet resistance, resulting in significant performance loss [22,23]. In flexible sensor applications, thermal annealing at 200°C enhances contact welding at NW junctions (reducing resistance by up to 85%), but prolonged exposure beyond this threshold causes junction breakdown, causing irreversible resistance spikes [24]. Additionally, SEM/TEM analyses revealed nanowire necking and void formation after 180°C – 200°C exposure for 1 hour, correlating with a 40–60% reduction in device optical transparency and an approximately fourfold increase in resistance. Thermal cycling (30°C – 200°C over tens of cycles) further induces cumulative resistance drift of $\sim 10\%$ – 30% , attributed to progressive network [24]. These findings quantitatively illustrate how nanoscale morphological degradation under thermal stress translates to macroscopic failure in AgNW-based devices.

Thermal stress ranges for AgNW based devices

AgNW networks display well-defined thermal tolerance limits, often correlating directly with device performance and lifetime:

- **Transparent conductive films / touchscreens:** Stable below $\sim 200^{\circ}\text{C}$; annealing at 200°C for tens of minutes induces Rayleigh-instability fragmentation and $\sim 80\%$ sheet resistance increase [25].
- **Transparent heaters:** Designed to operate in the $100\text{--}250^{\circ}\text{C}$ range. Exposure above $\sim 250^{\circ}\text{C}$ triggers wire breakage and sharp resistivity increase due to morphology changes. For example, AlOx-protected AgNWs achieve stable heating at $\sim 81^{\circ}\text{C}$ under 40 s at 7 V, while Ni-enhanced heaters retain performance at 165°C for 2 h [26,27].
- **Wearable and flexible sensors / electronics:** Typically endure $25^{\circ}\text{C}\text{--}150^{\circ}\text{C}$ thermal stress. Above $\sim 160^{\circ}\text{C}$, junction degradation appears (evidenced by $2\times$ sheet resistance increase), and continuity fails entirely at $\sim 205^{\circ}\text{C}$ [28].
- **High temperature photonic/thermoelectric devices:** With protective coatings (e.g., ALD ZnO or polymers), AgNW composites maintain structure up to $300^{\circ}\text{C}\text{--}450^{\circ}\text{C}$, beyond which coalescence and void formation damage performance [27].

Melting Behavior of Metallic Nanowires

The melting behavior of metallic nanowires is a complex phenomenon influenced by their reduced dimensions and high surface-to-volume

ratios. Compared to their bulk counterparts, metallic nanowires exhibit significantly lower melting points due to the increased significance of surface atoms, which possess lower binding energies than those in the bulk. This section reviews the melting behavior of metallic nanowires with a particular focus on silver nanowires, utilizing insights from the provided references.

The melting temperature of Zn nanowire arrays is highly influenced by the dimensions of the nanowires. It has been found that the melting temperature changes in a curvilinear fashion when plotted against the reciprocal of the nanowire diameter. This relationship is explained by the variations in the heat of fusion that depend on the size of the nanowires [29]. While work of some other researchers primarily discusses gold nanoparticles, their insights into the melting behavior of nanoparticles are applicable to metallic nanowires, including silver. They explain that the melting point depression in nanoparticles and nanowires results from the Gibbs-Thomson effect, where the curvature of the nanostructures leads to a reduction in the melting point. This principle is vital in understanding why metallic nanowires melt at lower temperatures compared to their bulk counterparts [29,30].

Beyond the gibbs–thomson effect: role of ligands and stabilizers

While the Gibbs–Thomson effect is the primary thermodynamic explanation for melting point depression in metallic nanowires, it is not the sole factor influencing their thermal stability. Surface ligands and stabilizers used during synthesis such as Polyvinylpyrrolidone (PVP), oleylamine, or citrate play a crucial role in

defining surface energy, passivating active sites, and altering atom mobility. These organic or inorganic coatings can either enhance thermal stability by preventing atom diffusion or, conversely, promote instability if they decompose or desorb at elevated temperatures. For example, AgNWs synthesized with PVP exhibit earlier morphological transformations when the polymer decomposes around 200–250°C, leaving the nanowires unprotected and prone to Rayleigh-like fragmentation. Moreover, studies have shown that ligand desorption leads to increased surface diffusion rates, effectively lowering the nanowires' thermal degradation threshold compared to bare or core-shell coated counterparts. Therefore, synthesis conditions especially ligand type, coverage density, and thermal decomposition profile significantly impact the observed melting and degradation behavior of AgNWs, in conjunction with classical size effects [31,32].

Experimental evidence of melting temperature depression in AgNWs

Experimental studies have consistently demonstrated that Silver Nanowires (AgNWs)

exhibit significant melting point depression compared to their bulk counterparts and other metallic nanowires [33]. In situ transmission electron microscopy (TEM) investigations have shown that AgNWs begin to exhibit morphological changes such as necking and surface diffusion at temperatures as low as 180°C–200°C, whereas bulk silver melts at 961.8°C [34]. This depression is attributed to the Gibbs–Thomson effect, which relates smaller diameters to reduced melting points due to increased surface-to-volume ratios. Compared to Gold Nanowires (AuNWs), which typically start deforming at ~250°C, and Copper Nanowires (CuNWs) which retain stability until ~300°C, AgNWs are notably less thermally stable [34,35]. Experimental data from Differential Scanning Calorimetry (DSC) and Thermo Gravimetric Analysis (TGA) further confirm the early onset of melting-like behavior in AgNWs, even in protective environments. These findings emphasize the need for structural reinforcement or surface passivation to extend the thermal durability of AgNW-based devices. Comparative Experimental Melting Points of Metal Nanowires vs. Bulk Metals is depicted in (Table 1).

TABLE 1
Comparative experimental melting points of metal nanowires vs. bulk metals.

Metal	Bulk melting point (°C)	Observed melting point for nanowires (°C)	Nanowire diameter (nm)
Silver (Ag)	961.8	~375–500	~30–60
Gold (Au)	1064	~500–650	~10–20
Copper (Cu)	1085	~550–700	~40–70
Zinc (Zn)	419.5	~280–350	~25–50
Aluminum (Al)	660.3	~400–500	~20–50
Nickel (Ni)	1455	~800–1000	~50–100

Thermal Behavior of Metal Nanostructures under High Temperatures

The thermal behavior of metal nanostructures under high temperatures reveals significant insights into their stability and morphological changes. In the study by some previous scientists, the researchers utilized in situ Environmental Transmission Electron Microscopy (E-TEM) to observe the thermal stability of Pd@SiO₂ nanostructures. The core Pd particles exhibited different morphological behaviors based on their initial shapes. Octahedral particles, which were monocrystalline, showed notable instability, with Pd atoms diffusing from the core towards the silica shell, leading to a reduction in particle size. This behavior was attributed to the lower number of crystallographic defects in octahedral particles, which facilitated outward diffusion. On the other hand, icosahedral particles, with higher defect densities, displayed internal atom diffusion, thereby maintaining their morphology and stability even at high temperatures. This indicates that the initial structure of the nanoparticles significantly influences their thermal behavior and stability [18].

Furthermore, the surrounding gas environment plays a crucial role in determining the thermal behavior of these nanostructures. Under reductive conditions, such as in a hydrogen atmosphere, the silica shell densified, effectively preventing significant atom diffusion and maintaining the core-shell structure. Conversely, in oxidative environments, like ambient air, the silica retained its porosity, which enhanced the diffusion of Pd atoms to the external surface at elevated temperatures. This led to the complete expulsion of Pd atoms from the core

at temperatures around 850°C. These findings underscore the complex interplay between particle structure, environmental conditions, and thermal treatments, which collectively determine the stability and morphological evolution of metal nanostructures. Understanding these dynamics is essential for optimizing the design and application of nanostructured materials in various high-temperature environments [18].

Transferability of core-shell insights to bare Ag nanowires

Although Pd@SiO₂ core-shell nanostructures have yielded valuable observations on thermal behavior, their relevance to uncoated AgNWs is limited. In situ environmental TEM studies of Pd@SiO₂ show that the silica shell effectively delays sintering, diffusion, and reshaping up to ~400°C under various gas atmospheres [18]. By contrast, bare AgNWs lacking such encapsulation exhibit accelerated surface atom mobility and fragmentation at much lower temperatures. This fundamental difference arises because the rigid shell in core-shell structures confers mechanical confinement and reduces surface energy-driven diffusion, effects absent in naked AgNWs. Therefore, while Pd@SiO₂ behavior illuminates general thermal transformation trends, it cannot accurately predict the thermal response of unprotected AgNWs, underscoring the need for material-specific studies on pure metal nanowires. Table 2 compares the effectiveness of various stabilization techniques (ZnO, SnO₂, polymers) in enhancing thermal stability, electrical resistance, and device lifetime of silver nanowires under heat stress.

TABLE 2

Comparison between effectiveness of various stabilization techniques (ZnO, SnO₂, polymers) in enhancing thermal stability, electrical resistance, and device lifetime of silver nanowires under heat stress.

Stabilization technique	Thermal stability (°C)	Resistance increase delay	Device lifetime improvement	Additional benefits
ZnO Coating	~300–350	Delayed >250°C	2x–3x longer than uncoated	UV protection, oxidation resistance
SnO ₂ Coating	~320–370	Stable up to ~350°C	2x longer in cyclic tests	Excellent thermal resistance and adhesion
Polymer Coating (PVP, PEDOT:PSS)	~200–250	Starts rising >200°C	Modest improvement; susceptible to degradation	Flexibility, solution processability

Heat-Induced Fragmentation

In a research conducted by previous researchers an in-depth investigation into the fragmentation of silver nanowires under thermal treatment, attributing this phenomenon primarily to Rayleigh instability. This instability, which is a fundamental concept in fluid dynamics, describes the breakup of a fluid jet into smaller droplets due to surface tension forces. In the context of solid nanowires, this instability manifests as the tendency of the nanowire to minimize its surface energy, leading to fragmentation when subjected to thermal stress. The study highlighted that the diameter of the nanowires plays a crucial role in this process. Thinner wires, with higher surface area to volume ratios, are more susceptible to instability and subsequent breakup. Additionally, the surrounding environment, including the presence of other materials and the ambient conditions, significantly influences the rate and pattern of fragmentation. For instance, a vacuum environment might reduce the thermal conductivity away from the nanowire, thereby accelerating the fragmentation process compared to an environment with a higher thermal conductivity medium. The insights from this study are critical for understanding how to

control and manipulate the structural integrity of silver nanowires during thermal processes, which is essential for their application in nanotechnology and materials science [36].

Similarly, in a comparative study on the morphological evolutions of silver nanowires under two different conditions: nanosecond-pulsed laser irradiation and thermal treatment in ambient air. Their research revealed that both methods induce fragmentation through Rayleigh instability, but with markedly different outcomes due to the distinct time scales involved in each process. Under nanosecond-pulsed laser irradiation, the rapid and localized heating caused silver nanowires to fragment into single-crystalline, pure Ag nanospheres. This process leverages the rapid thermal dynamics of the laser, allowing the nanowires to quickly reach the temperatures necessary for Rayleigh instability without significant oxidation, thus preserving the purity and crystalline nature of the resulting nanospheres. On the other hand, thermal treatment in ambient air resulted in the formation of oxidized, polyhedron-shaped particles. The slower heating process in thermal treatment allowed sufficient time for oxidation to occur, leading to a different morphological

outcome where the particles formed were not as uniform or pure as those produced by laser irradiation.

Furthermore, some researchers demonstrated an innovative approach to synthesize bimetallic Ag-Au nanospheres by coating silver nanowires with a thin layer of gold and then subjecting them to nanosecond-pulsed laser irradiation. This method provided a facile route to produce nanospheres with tunable plasmonic properties, leveraging the plasmonic behavior of both silver and gold. The pulsed laser beam facilitated the controlled fragmentation and mixing of the metals, resulting in bimetallic nanospheres that exhibited enhanced and adjustable plasmonic characteristics compared to their monometallic counterparts. This technique showcases the versatility of laser irradiation in manipulating nanowire morphology and composition, offering significant potential for the design and optimization of nanomaterials in various applications, such as in sensors, catalysis, and photonic devices. The comparative insights provided by this study underscore the importance of understanding and selecting the appropriate thermal processing method to achieve desired structural and functional properties in silver nanowires and other nanostructures [37].

Morphological Changes and Surface Atom Diffusion

The morphological changes and surface atom diffusion of Silver Nanowires (AgNWs) were investigated using a facile heat-treatment method. AgNW films, fabricated via spin-coating, were subjected to different temperatures (230°C-280°C) for 30 minutes. The morphology and oxidation degree of the AgNW films were notably sensitive to the

heat-treatment temperature, while transparency remained largely unaffected. Increasing the heat-treatment temperature led to spontaneous fragmentation of AgNWs into finer wires and droplets, accompanied by accelerated oxidation. Furthermore, higher heat-treatment temperatures significantly enhanced the antibacterial activity of the AgNW films. Notably, treatment at 280°C substantially improved antibacterial efficacy. These findings underscore the role of controlled heat treatment in modifying the morphology and surface properties of AgNWs, thereby potentially enhancing their performance for various applications [38].

Elongation

Nanowires, with their nanoscale diameters and high aspect ratios, exhibit unique mechanical properties significantly influenced by their size and shape. A particularly intriguing phenomenon observed in these structures is the elongation of nanowires under heat, primarily driven by surface atom diffusion. In the 2019 study, a scientist demonstrated that this process is especially pronounced in sub 5 nm silver nanowires. As temperatures rise, the increased atomic mobility facilitates the migration of surface atoms along the length of the wire, leading to its elongation. This migration occurs as atoms move from regions of high curvature to areas of lower curvature, minimizing surface energy in the process.

Moreover, some researchers identified that stress-induced slip and diffusion mechanisms are crucial to this elongation process. Under thermal stress, surface atoms experience forces that drive them to migrate, forming atomic-scale steps and terraces which serve as pathways for further atomic movement, effectively stretching the wire. This phenomenon is particularly

significant in nanowires with high aspect ratios and low diameters, where the surface-to-volume ratio is extremely high, making them more susceptible to elongation under thermal conditions. These findings have important implications for the design and application of nanowires in fields like nanoelectronics and photonics, where precise control over nanowire dimensions and properties is essential for developing reliable and efficient devices. Understanding these mechanisms allows for better manipulation of nanowire properties, paving the way for advancements in nanotechnology [39].

Bending

Bending of nanowires is another common morphological change induced by heat. This occurs when differential thermal expansion or localized heating causes a curvature in the nanowire structure. Bending of silver nanowires is a significant morphological change commonly induced by heat. This phenomenon occurs due to differential thermal expansion, where different parts of the nanowire expand at varying rates when exposed to heat, leading to a curvature in the structure. Localized heating, often from Joule heating in conductive nanowires, can further exacerbate this effect. As specific regions of the nanowire heat up more than others, differential expansion induces bending. This change not only affects the physical appearance but also the electrical and mechanical properties of the nanowires, which is critical for applications in flexible electronics and nanoscale devices [40]. By optimizing synthesis and application processes, researchers aim to harness the unique properties of silver nanowires while minimizing unwanted morphological changes caused by heat [40] (Figure 3).

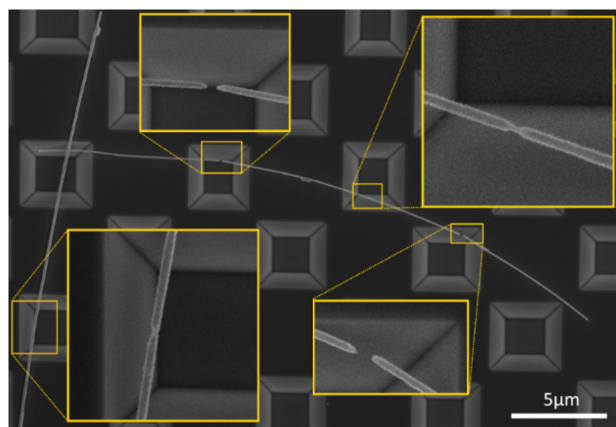


Figure 3) Formation of necking and splitting in Silver Nanowires (AgNWs) was observed in the heating, (heating scheme 1) following exposure to 375°C [40].

Merging

Nanowire merging under heat treatment results from surface atom diffusion leading to the coalescence of adjacent nanowires. This process can improve the electrical conductivity of nanowire networks but may also compromise their structural integrity. In previous studies it was discussed how thermal annealing promotes the merging of metallic nanowires, enhancing their network connectivity and electrical performance. Their study highlights that thermal annealing significantly reduces electrical resistance through local sintering at junctions, optimizing the nanowire networks for applications like transparent electrodes in solar cells and flexible displays. The annealing process involves a careful balance to avoid excessive heat that can lead to spheroidization of the nanowires, which can detract from the network's effectiveness by increasing the resistance once again.

Previous research studies demonstrated that an optimized annealing process can achieve nanowire networks with high transmittance and low sheet resistance, which are desirable for various electronic applications. They provided a model that correlates experimental

observations with theoretical predictions, offering a comprehensive understanding of how thermal treatment impacts the electrical properties of nanowire networks. This research underlines the importance of precise control over thermal annealing conditions to maximize the performance of metallic nanowire-based devices while maintaining their structural integrity [41].

Thermal stability

The thermal stability of nanowires is a critical factor for their application in high-temperature environments. Factors such as nanowire composition, diameter, and surrounding medium significantly influence their stability. Some researchers investigated ways to enhance the physical properties and stability of silver nanowire networks, emphasizing the importance of material selection and fabrication techniques in achieving thermally stable nanowire-based devices. Their research demonstrated that coating silver nanowire networks with thin oxide layers, like ZnO or SnO₂, significantly improves morphological stability under thermal stress, making them more suitable for use in high-temperature applications and ensuring longer device lifetimes.

The study by previous researchers highlighted that applying thin oxide layers, such as ZnO or SnO₂, to silver nanowire networks through Atmospheric Pressure Spatial Atomic Layer Deposition (AP-SALD) significantly enhances their thermal stability. This coating approach reduces morphological instabilities, surface roughness, and adhesion issues, thereby improving the longevity and performance of devices utilizing these networks. The research underscores the importance of advanced

fabrication techniques in optimizing the physical properties of nanowire networks for high-temperature applications [32].

Quantitative thresholds of thermal failure in AgNWs

Numerous studies have quantified critical thermal thresholds for performance degradation in AgNW networks. In one investigation, AgNW films showed optimal reductions in sheet resistance at temperatures below 250°C in air and 300°C in N₂; however, heating beyond these thresholds rapidly reversed this trend, with breakdown and sharp resistance increases observed once structural integrity failed specifically at AgNW fragmentation temperatures of 250°C (air) and 400°C (N₂) [42]. Additionally, annealing 90 nm-diameter AgNWs at 180°C for 30 minutes resulted in a 590% increase in resistance over 60 days, compared to a 137% increase for milder (80°C) treatment demonstrating long-term degradation linked to thermal exposure [43]. Similarly, FeCl₃-treated networks exhibited diameter-dependent turning points between 200–300°C, with resistance sharply rising once these thresholds were surpassed indicating variables like wire diameter and surface treatment control thermal tolerance. This collective data suggests that practical operating limits for AgNW-based devices should fall below ~150°C–180°C to maintain structural integrity and functionality over time.

Silver nanowires as transparent film heaters

Silver Nanowires (AgNWs) have emerged as a promising material for Transparent Film Heaters (TFHs) due to their exceptional electrical and thermal properties. These heaters are constructed by embedding a

network of AgNWs into a flexible substrate, such as Polyethylene Terephthalate (PET) or Polyimide (PI). The AgNW network provides high electrical conductivity and excellent transparency, making these films suitable for applications where both flexibility and optical clarity are essential. Research by previous research scientists demonstrated the large-scale fabrication of AgNW-based TFHs using a slot-die coating method. This method produced heaters with a sheet resistance of less than $20 \Omega/\text{sq}$ and optical transmittance higher than 95% at 550 nm. The resulting heaters exhibited uniform heating capabilities, reaching temperatures of up to 104°C with an applied voltage of 12V, showcasing their potential for applications such as window defrosting and deicing systems [44] (Figure 4).

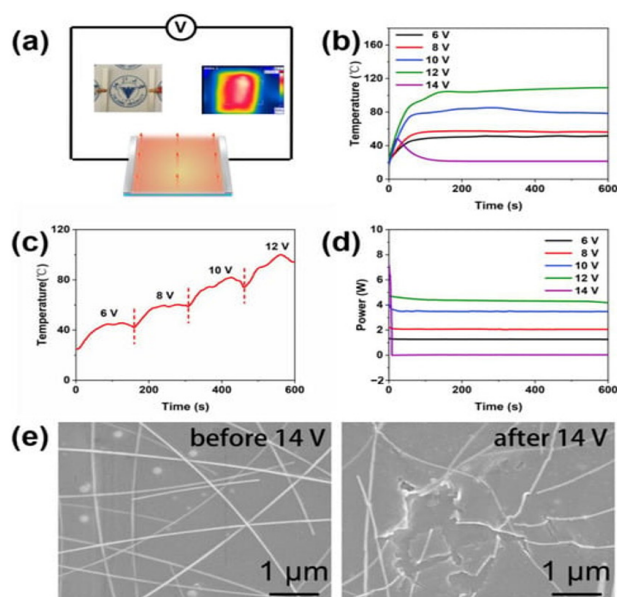


Figure 4) Illustrates various aspects of the AgNW film heater (5 cm × 5 cm). Panel (a) presents a schematic illustration alongside an infrared image. Panels (b) and (c) depict the temperature-time profile under different applied voltages, while panel (d) showcases the power-time profile across varying voltages. Panel (e) displays SEM images of the AgNW heater both before and after applying a voltage of 14 V.

Additionally, a researcher explored the fabrication of highly flexible TFHs using AgNWs embedded in transparent PI films.

Their study highlighted the superior mechanical and thermal stability of these heaters, which achieved heating temperatures of approximately 96°C with a low input voltage of 6V. These AgNW/PI hybrid TFHs also demonstrated excellent resistance to bending and maintained stability after repeated use. The effective embedment of the AgNW network into the PI film not only reduced surface roughness but also enhanced resistance against oxidation and moisture, making them suitable for applications such as window defogging and thermochromic devices [45].

Morphological changes of silver nanowires under heat

Heat treatment induces significant morphological changes in silver nanowires, affecting their electrical and mechanical properties. These changes are often driven by mechanisms such as Rayleigh instability, surface diffusion, and thermal expansion [41]. A previous scientific approach provided an in situ characterization of silver nanowires under high temperature using aberration-corrected STEM, revealing detailed insights into the morphological transformations. They observed that nanowires undergo surface atom diffusion leading to changes in shape and size, which are critical for understanding their behavior in real-world applications. Silver Nanowires (AgNWs) exhibit various morphological changes when subjected to heat. These changes significantly impact their properties and potential applications. Understanding these changes is crucial for optimizing the performance of Ag NW-based devices, particularly those exposed to elevated temperatures during operation or processing [46].

Fragmentation: Understanding the phenomenon of heat-induced morphological changes in Silver Nanowires (AgNWs) is crucial

for improving the durability and performance of AgNW-based Transparent Film Heaters (TFHs). In literature it was highlighted that thermal stress can cause AgNWs to fragment and redistribute atoms on their surfaces, leading to significant degradation in the electrical and mechanical properties of the nanowire network. This fragmentation increases resistance and decreases heating efficiency, while surface diffusion can result in coalescence or breakage, adversely affecting the film's transparency and conductivity.

To mitigate these effects, a previous researcher suggested employing strategies such as coating AgNWs with protective layers and embedding them within stable polymer matrices like Polyimide (PI). These methods enhance the thermal and mechanical stability of AgNWs, preventing significant morphological changes and ensuring the reliability and longevity of TFHs under operational conditions. Such improvements are critical for applications requiring consistent heating performance, such as in automotive window defrosting and wearable electronics, where maintaining the integrity of the AgNW network is essential for the device's functionality [47] (Figure 5).

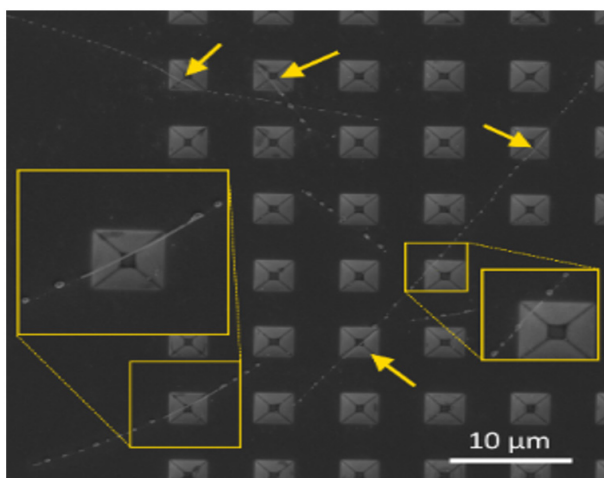


Figure 5) Scanning Electron Microscopy (SEM) was employed to examine the Silver Nanowires (AgNWs) following a one-step heat treatment process (heating scheme 2) at 400°C. Notably, the fragmentation of the nanowires predominantly occurred within the adhered regions [40].

Surface diffusion and atom redistribution:

Surface diffusion plays a critical role in the morphological stability of AgNWs [48]. At elevated temperatures, atoms on the surface of nanowires tend to move, leading to changes in shape and potentially to coalescence or breakage. This atom redistribution can influence the electrical conductivity and optical transparency of the TFHs, as described by [49].

Structural stability: The structural stability of AgNWs in TFHs is essential for their reliable performance. Embedding AgNWs in a polymer matrix, such as Polyimide (PI), enhances their mechanical and thermal stability. Studies have shown that such hybrid structures maintain their integrity under thermal cycling and mechanical stress, crucial for applications in flexible electronics [50].

Implications for device performance:

The morphological changes in AgNWs directly impact the performance of TFHs. Fragmentation and surface diffusion can lead to increased resistance and reduced heating efficiency. Strategies to mitigate these effects, such as using protective coatings or embedding AgNWs in stable matrices, have been shown to improve the operational stability and longevity of TFHs [21,47]. These improvements are critical for applications in automotive and smart window technologies, where consistent and reliable heating performance is required. Figure 6 illustrates flowchart for the progression of Silver Nanowires (AgNWs) from their synthesis through heat exposure, leading to morphological changes such as fragmentation and melting, and ultimately resulting in application breakdown.

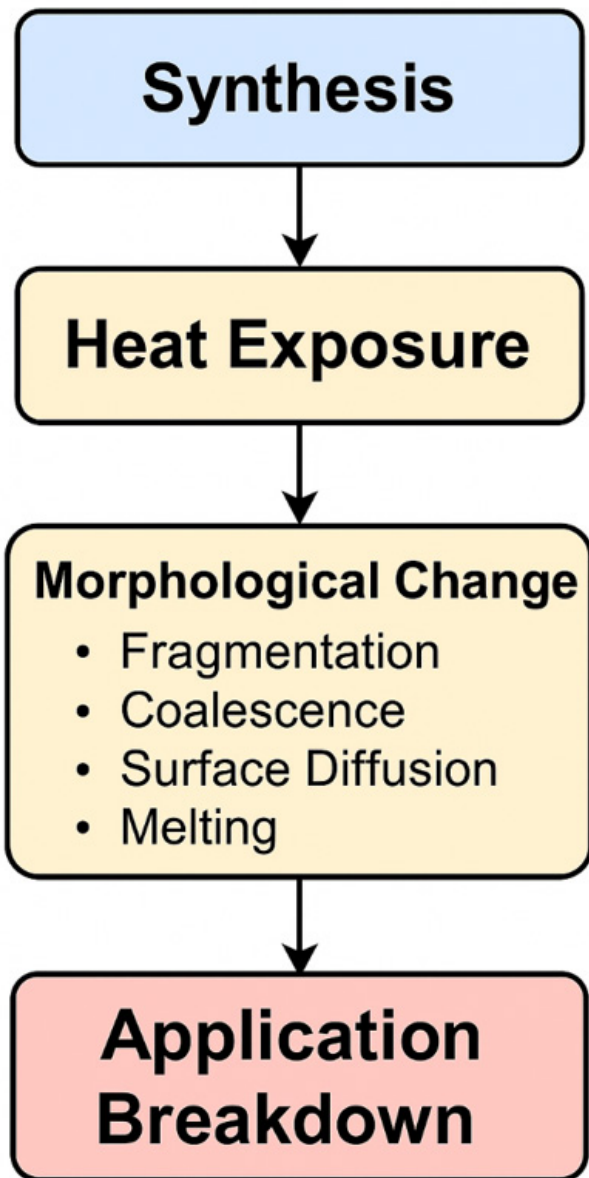


Figure 6) This flowchart illustrates the progression of Silver Nanowires (AgNWs) from their synthesis through heat exposure, leading to morphological changes such as fragmentation and melting, and ultimately resulting in application breakdown. It highlights the critical transitions that affect device stability and performance.

Conclusion

This review analyzed how heat affects Silver Nanowires (AgNWs), emphasizing

morphological changes essential to their application in nanotechnology and electronics.

- Key mechanisms such as Rayleigh instability, surface atom diffusion, and fragmentation were identified as primary drivers of thermal-induced transformations in AgNWs.
- At high temperatures, AgNWs experience significant changes, including fragmentation, bending, and elongation, which directly impact device performance.
- Heat-induced changes in AgNWs result in increased resistance and decreased efficiency, posing challenges for devices like transparent film heaters, flexible electronics, and sensors.
- Stabilization techniques, including protective coatings and embedding AgNWs within stable polymer matrices, have shown effectiveness in enhancing thermal stability, minimizing degradation, and extending device lifespan.
- Further research is necessary to optimize these strategies and explore new solutions for improving the thermal stability of AgNWs. These advancements are crucial for realizing the full potential of AgNWs in high-performance applications such as flexible electronics and transparent conductive films.

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