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Review article

Directional heat rectification in electronic logic circuits via near-field radiative heat transfer

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ABSTRACT

As electronic devices become increasingly compact and integrated, conventional heat dissipation techniques are proving insufficient, posing challenges to device longevity and performance. In this review, the state-of-the-art approach to nanoscale temperature management, near-field radiative heat transfer (NFRHT), is examined to explore the emerging concept of heat rectification in electronic logic circuits. Despite growing interest in NFRHT, most studies have primarily focused on geometric refinement and heat flux amplification, with limited attention to its functional integration within logic circuits. This review synthesizes recent advancements in leveraging NFRHT for directional control of heat flow, providing a comprehensive perspective on strategies for transforming nanoscale heat regulation. NFRHT performance can be significantly enhanced through strategic material selection, structural asymmetry, and nanoscale gap control, enabling its integration into advanced logic components such as phononic gates, rectifiers, switches, and thermotronic diodes. Representative studies report rectification efficiencies of up to 93% using materials such as Bi_2Se_3, vanadium dioxide (VO_2), gold, and doped silicon in sub-100-nm gaps. With its capacity to regulate heat currents, NFRHT offers promising avenues for mitigating localized overheating and improving the energy efficiency of logic devices. The review concludes by highlighting how NFRHT-driven heat rectification can address challenges related to materials variability and gap control while proposing future research directions for advanced carbon-based thermo-logic devices.

1. Introduction

With the increasing power and compactness of electronic logic circuits, effective cooling has become a crucial design concern. Significant heat generation occurs during the operation of integrated circuits due to the continual decrease in transistor size and higher component density. Excessive heat can shorten the lifespan and durability of electronic devices by accelerating material degradation and reducing performance. Localized heat dissipation in nanometer-scale designs is frequently not effectively addressed by conventional cooling techniques like heat sinks, fans, and interface materials for heat control. For next-generation electronics to maintain temperature stability, reliability, and durability of device performance, innovative heat management techniques are therefore required to control high heat flux [1,2]. Based on the 2004 International Electronics Manufacturing Initiative (iNEMI) technological roadmap, by 2020, high-performance microprocessor chips were projected to have a maximum power dissipation of 360 W and a heat flux of 190 W/cm^2, respectively, as depicted in Fig. 1 [3].

Notwithstanding the realization that these predictions have mostly come to pass, current trends reveal the net effect that processor power requirements will likely exceed 700 W by 2025 [4], with further thermodynamic design challenges arising from next-generation technologies like two-and-a-half-dimensional (2.5D) and three-dimensional (3D) advanced semiconductor packaging. Given the rapid advances in radiative and thermotronic control technologies, there is still no cohesive perspective that ties circuit-level logic implementation with nanoscale rectification techniques. This gap drives the current review to investigate the effective translation of near-field radiative phenomena from material-level optimization to functional circuit architectures. By establishing this linkage, the review aims to facilitate informed decisions for the rational design of thermally driven electronic logic components.

A viable strategy is to utilize heat rectification, which is the thermodynamic counterpart of electrical rectification. The directional asymmetry in the transmission of heat (via conduction, radiation, or other mechanisms), when heat preferentially travels in one direction more effectively than the opposite, is commonly referred to as heat rectification. In this context, Fig. 2 illustrates a thermo-rectifier that may regulate directional heat transfer by permitting heat conduction in a

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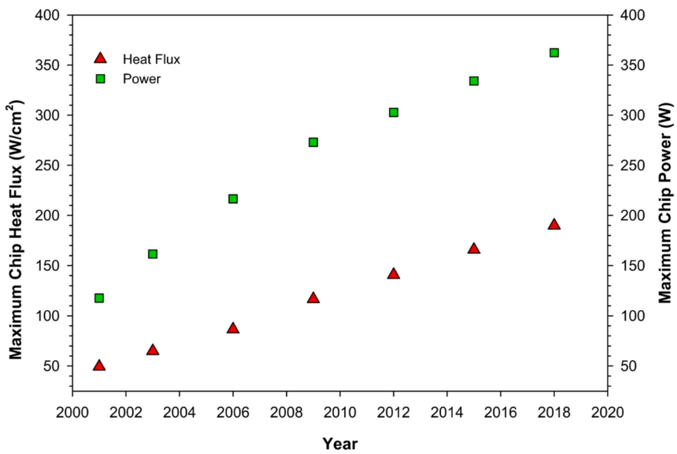

Fig. 1. Projected peak heat flux and power dissipation for microprocessor chips based on the 2004 iNEMI technology roadmap [3], demonstrating the overall trend that has been observed and continues to escalate beyond 2025, which underscores the necessity of sophisticated heat control innovations.

single direction (Q_{fwd}) while obstructing it in the opposite direction (Q_{rev}). This enables the rectifier to dissipate excess heat, while also functioning as an insulator to prevent heat influx. Moreover, direct control of temperature differential (ΔT) between two system sides can be accomplished, which is a crucial practical capability for managing heat [5]. The working principle of heat diodes is further demonstrated in Fig. 3, which also distinguishes them from electrical diodes and emphasizes how the sign of the temperature gradient or heat current dictates heat transport along a specific axis [6]. Transistors, switches, regulators, and thermo-diodes may regulate heat in a similar way to how their electrical equivalents manage electricity [7]. When applied to electronic logic circuits, this concept enables dynamic heat routing and even heat-based logic gates that function by using radiative ionizing radiation or phonons rather than electrons. The aforementioned abilities have the potential to revolutionize heat control in micro- and nano-electronics, particularly in instances where passive or active control of heat flow is desired.

An innovative approach to improve heat rectification in the systems in question is the application of near-field radiative heat transfer (NFRHT) [8]. In contrast to far-field radiative transfer (FFRT), which is constrained by the blackbody radiation law, NFRHT relies on the electromagnetic coupling between surfaces that are in extremely close proximity to one another, typically on the order of 10 μm or less than the typical wavelength of emitted heat radiation. At its core, NFRHT can be quantified by evaluating the radiative heat flux between two surfaces as a function of their temperature difference, emissivity, and the separation gap. The interaction includes contributions from both propagating and evanescent modes, with the latter dominating at sub-wavelength distances, enabling energy transfer rates far exceeding classical predictions. The energy exchange is often expressed in terms of the spectral transmission coefficient integrated over all frequencies and parallel wavevectors, accounting for the material dielectric functions and geometric configuration of the gap.

The radiative heat flux between two surfaces in the near field can be expressed as:

$$q = \int_0^\infty \Phi(\omega) \quad \Delta T \, d\omega$$

In this expression, $\Phi(\omega)$ is the spectral transmission coefficient accounting for both propagating and evanescent modes, and $\Delta T = T_2 - T_1$ is the temperature difference between the surfaces. This formulation highlights the frequency-dependent nature of NFRHT and emphasizes the dominant role of evanescent modes at sub-wavelength separations.

In the near field, the heat flux increases sharply as the separation d decreases, often scaling approximately as $1/d^2$ or faster in extreme near-field regimes. The magnitude of NFRHT is strongly influenced by the dielectric properties of the interacting surfaces, where resonant excitations can lead to orders-of-magnitude enhancement compared to far-field radiation.

For two parallel planar surfaces in the quasi-static limit, the near-field heat flux can be approximated as:

$$q_{NF} \approx \frac{C}{d^2}\Delta T$$

In this formulation, C is a coefficient determined by material properties and mode coupling. This simplified form captures the essence of NFRHT: a dramatic enhancement of heat transfer as the gap approaches nanoscale dimensions.

Table 1 outlines the key differences between NFRHT and FFRT, highlighting the superior heat transfer rates, spectral selectivity, and potent directional control potential of NFRHT, thereby rendering it especially ideal for infrared logic and heat rectification applications in electronic circuits. Significant heat exchange can be mediated in this domain by evanescent waves, among which are surface phonon-polaritons or surface plasmon-polaritons, whose transfer rates exceed classical bounds by far. Recent studies have demonstrated that supported multilayer graphene structures can further enhance NFRHT by up to ∼1129× at nanoscale gaps (∼55 nm), with coupled surface plasmons

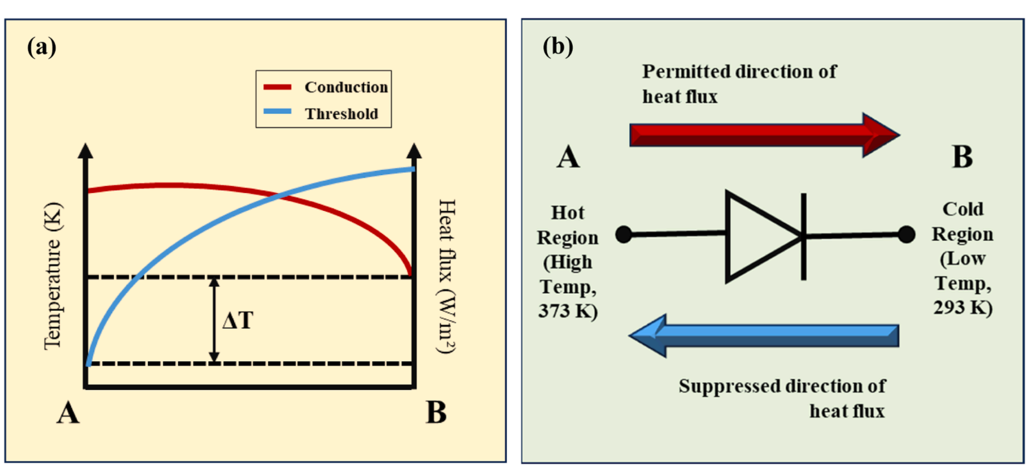

Fig. 2. Illustrative representation of a thermo-rectifier: (a) distinct temperature gradients generated by directional heat transfer, demonstrating that heat flows preferentially in one direction, and (b) a rectifier functioning analogously to an electric diode, where diode-like electrical rectification is replicated by thermo-transport.

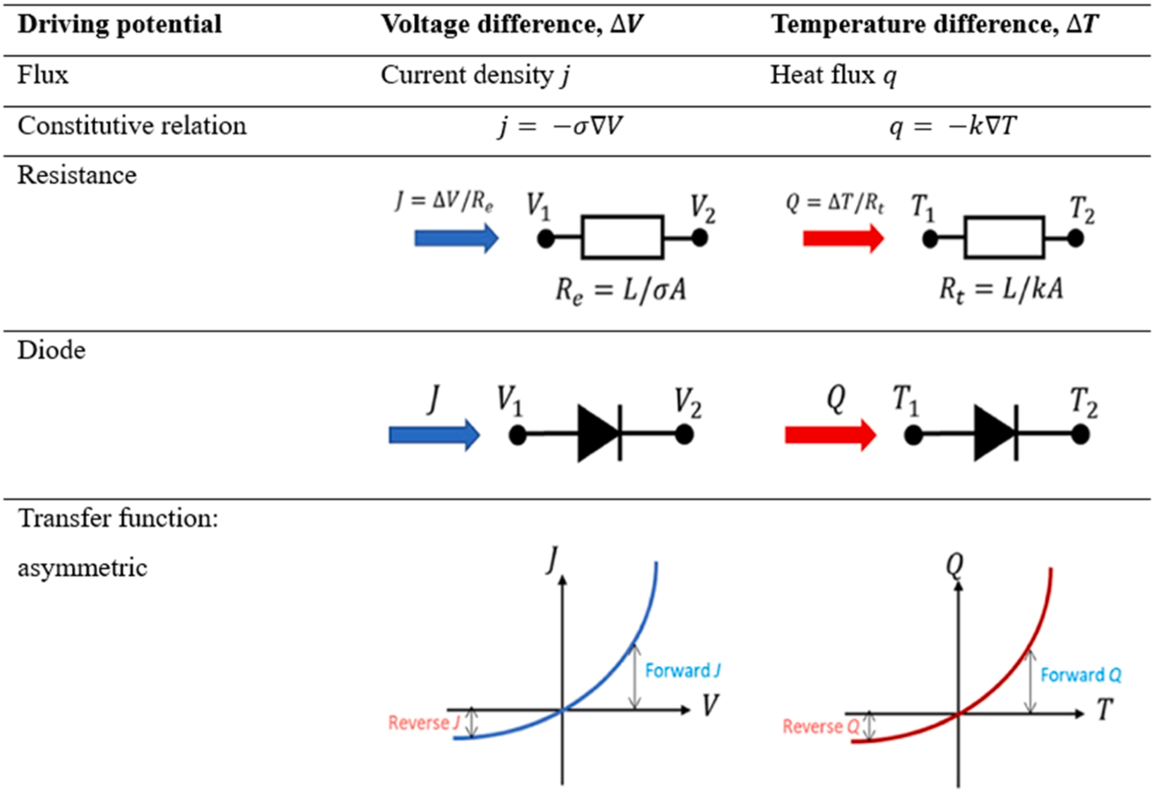

Fig. 3. Analogies between linear (a) electrical and (b) thermo-components, where σ denotes electrical conductivity, k represents heat conduction, R_e signifies electrical resistance, R_t indicates heat impedance, L refers to the Lorenz number, and A corresponds to the surface area. Heat flow Q depends on the temperature difference ΔT, electric current J varies according to the voltage difference ΔV, current density j is governed by the voltage gradient ∇V, and heat flux q is determined by the temperature gradient ∇T [6].

and phonon polaritons enabling near-unity photon tunneling and tunable heat transfer through Fermi-level adjustments [9]. By pairing surface plasmon polaritons across numerous metal-dielectric interfaces, Lim et al. [10] demonstrate an important spike in heat transfer by NFRHT between metallo-dielectric multilayers at nanoscale gaps.

Another study measured NFRHT in graphene/hBN heterostructures and graphene/hBN/graphene multilayer membranes, yielding increases of 3 and 6 times higher than the blackbody limit, respectively [13]. Similar findings were reported by Yang et al. [14], who observed heat radiation emanating from two macroscopic graphene sheets on an insulated silicon carrier separated by a 430 nm vacuum gap with an efficiency of 4.5 times above the blackbody limit. Inducing rectifying behavior through asymmetric near-field interactions and modifying the radiative heat flux can be achieved by meticulously designing the materials and interface geometry. Unlike traditional heat management methods, this combination of heat rectification with near-field effects presents an exciting new paradigm for ultra-compact, non-invasive heat regulation in electronic circuits. For the purpose of providing a systematic transition from basic theory to practical design, this study is structured to relate fundamental mechanisms, material architectures, and their integration into circuit-level functionality, ensuring logical consistency across these advancements.

The existing literature on NFRHT has presented fundamental interactions and improvements in mechanisms across a wide range of nanoscale structures, such as periodic arrays, plasmonic surfaces, and natural hyperbolic materials [15]. Studies have validated the notable amplification of radiative heat flow in configurations including silicon carbide (SiC) deep gratings [16], in addition to those that exploit nanohole and nanowire patterns that enable thermophotovoltaic activities [17]. Moreover, demonstrating controllable heat-associated performance through designed photonic states, NFRHT coupled with doped-silicon nanostructured metamaterials [18] has contributed another potential material platform to the expanding field. NFRHT has also been observed between dielectric nanoparticle clusters in a recent study by Dong et al. [19], indicating increased coupling and collective effects at nanoscale separations. In a similar vein, numerical investigations, such as those employing the Finite Difference Time Domain (FDTD) approach [20], have offered an extensive understanding of the mechanisms of energy exchange in nano-gaps. Taken together, these studies highlight significant progress in material platforms, photonic effects, and modeling approaches; however, the majority of work has remained focused on material optimization and transfer efficiency rather than operational device-level applications.

To contextualize these developments, FFRT adheres to the classical framework of propagating modes established by blackbody radiation theory, whereas NFRHT is primarily defined by the role of evanescent electromagnetic modes that dominate at sub-wavelength distances. This distinction underscores how tunneling and near-field coupling effects enable NFRHT to achieve energy exchange rates far exceeding the conventional limits of FFRT. Despite these advances, studies translating NFRHT principles into functional electronic architectures remain limited, particularly with respect to heat rectification in electronic logic circuits.

$$q_{BB} = \sigma(T_2^4 - T_1^4) \tag{1}$$

Definition:

q_{BB} = Radiative heat flux between the plates

σ = Radiative heat transfer constant

T_2, T_1 = Temperatures of the two surfaces

$$\varepsilon = \frac{q}{q_{BB}} = \frac{q}{[\sigma(T_2^4 - T_1^4)]} \tag{2}$$

Table 1
Key Differences Between NFRHT and FFRT. Data sourced from Yang et al. [11] and Králík et al. [12].

Feature	NFRHT	FFRT
Radiative Heat Flux	Strongly enhanced due to tunneling and evanescent waves	Limited to classical blackbody radiation
Maximum Power Density	Above three times that of far-field	Much lower than that of NFRHT; suitable as baseline comparison
Cell Temperature Rise at Maximum Power Density	+14.7 K compared with FFRT	Baseline (lower cell temperature)
Sensitivity to Heat Transfer Parameter	Highly affected. At 1.5 W/(cm^2·K), cell temperature ↑126 K and power density ↓5.43 W/cm^2	Less affected. At 1.5 W/(cm^2·K), cell temperature ↑40 K and power density ↓0.68 W/cm^2
Effect of Voltage and Emitter Temperature	Performance heavily depends on emitter temperature and voltage tuning	Performance also depends on both voltage and emitter temperature, but the overall impact is less
Strategies to Boost Performance	Increase emitter temperature, reduce cell temperature	Same strategies apply, but yield minor improvements
Distance (gap, d)	Occurs when $d \lesssim$ characteristic wavelength (typically < 10 μm)	Dominant when $d \gg$ characteristic wavelength
Thermal Conductance (K_t)	High dependence on d, universal scaling for identical metals (e.g., copper, tungsten)	Low dependence on d; determined by temperature difference and surface emissivity
Material Dependence	Strong influence of both residual resistance ratio and electron scattering	Less pronounced; mainly emissivity and reflectivity
Relevance to Heat Rectification	High potential; strong sensitivity to d and temperature gradient, particularly useful for diodes	Low potential; low sensitivity to d; relatively symmetric heat transfer
Relevance to Logic Circuits	Enables strong flux contrast; essential for logic functionality	Low flux contrast; hampers logic use

In the far field, ε is less than 100%, whereas in the near field, it can be orders of magnitude higher than the "blackbody" value. Even between highly reflective metallic surfaces, near-field heat transfer can exceed this value significantly due to strong dependence of intensity on the gap d. The transmitted heat approaches a saturated value at extremely small d, typically below approximately 10 nm [12].

Heat rectification based on NFRHT has garnered increasing attention [21–24]. Compared with broader reviews that provide classification-oriented overviews of NFRHT and discuss challenges and prospects [25], the present study aims to be both comprehensive and unbiased, while placing a particular emphasis on heat rectification mechanisms specifically within electronic logic circuits, an area that has remained underexplored in prior reviews. Instead of translating these concepts into logical or computing architectures, earlier reviews have primarily emphasized augmentation tactics and fundamental limits. Innovative approaches to improving performance are highlighted by recent developments, such as the isotope design of radiative diodes to increase rectification by modulating the electromagnetic local density of states (LDOS) [26]. However, these advancements continue to be mostly limited to material-level optimization, which leaves a gap in the translation of these approaches into functional computing and information processing applications. This distinction highlights an essential branch of research that extends beyond structural optimization and heat transfer enhancement toward functional implementations such as thermo-logic gates, heat-based electronic components, and radiative computing architectures.

Accordingly, this review emphasizes NFRHT not only as a mechanism for efficient heat transfer, but also as a functional catalyst enabling scaled, programmable, and circuit-level heat-controlled devices. Building upon established mechanisms, this study develops a conceptual taxonomy aimed at unifying and steering the design and implementation of NFRHT-based rectifiers in logic circuits. The objective of this review is hence twofold: (i) to offer a comprehensive, structured, and unbiased overview of the material platforms, procedures, and guiding principles of NFRHT across its various dimensions and (ii) to rigorously assess the specific potential of NFRHT in enabling electronic logic circuits to benefit from heat rectification. To achieve this, the review covers the fundamental principles of heat rectification, the physical mechanics underlying near-field heat transfer, and the integration of these concepts into nanoscale electronic circuit architectures. By synthesizing findings from conceptual, computational, and experimental-based studies, this article seeks to provide a structured and balanced perspective on how near-field phenomena may transform heat control strategies and computing approaches in micro- and nano-electronics; ultimately, it offers directional knowledge to guide the development of heat-driven, programmable elements for thermotronic circuits of the future.

2. Methods

This section presents a structured and sequential description of the systematic review methodology, progressing from study identification to data synthesis to ensure alignment with the overall manuscript flow. This methodological framework is designed to logically follow the conceptual discussions in the preceding sections and to support the synthesis and analysis presented in the subsequent sections. This methodological approach ensures that the selected studies directly support the review's objective of analyzing heat rectification under NFRHT conditions in electronic logic circuits.

In this review, four main stages were employed, guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol: identification, which included searching for relevant studies via manual reference screening and electronic database searches; screening, involving the initial filtering of titles and abstracts to remove duplicates and irrelevant works; eligibility, involving full-text evaluation against predetermined inclusion and exclusion criteria; and inclusion, representing the final selection of studies synthesized in the review. Studies that did not meet methodological or relevance criteria were excluded at the screening and eligibility stages. Exclusions at each stage ensure a transparent, reproducible, and rigorously documented selection process.

To provide clarity and logical continuity, the following subsections detail each stage of the methodology in the same sequence as the PRISMA framework, from literature search to data synthesis.

2.1. Literature search strategy

A systematic literature search was conducted to identify articles relevant to the study of heat rectification under NFRHT in electronic logic circuits, corresponding to the identification phase of the PRISMA framework. This stage establishes the foundation for subsequent screening and selection procedures.

In compliance with PRISMA 2020 guidelines, the search adhered to a systematic review procedure to ensure reproducibility and transparency. Electronic databases searched included Scopus, Web of Science, Google Scholar, and ScienceDirect, covering peer-reviewed journal articles, review articles, and other relevant high-impact studies. Keywords used included combinations of: “near-field radiative heat transfer,” “NFRHT,” “heat rectification,” “electronic logic circuits,” “heat-based logic gates,” “thermotronic,” “thermal diode,” "thermal rectifier," “radiative computing,” “nanoscale thermal management,” and their variations. Boolean operators (AND/OR) were applied to optimize search results. An example query string is: (“near-field radiative heat transfer" OR "NFRHT") AND ("heat rectification" OR "thermal diode") AND ("electronic logic circuits" OR "thermotronic"). To identify additional relevant studies, reference lists of key articles were manually screened. The search was restricted to publications from 2013 to 2025 to ensure coverage of recent developments.

2.2. Screening process

Titles and abstracts were screened to assess relevance to the study objectives. This stage represents the screening phase, where irrelevant and duplicate studies were systematically removed prior to full-text evaluation. Articles discussing heat rectification techniques, NFRHT, or their incorporation into nanoscale electronic or logic systems were considered for full-text review. Studies irrelevant to electronic or nanoscale heat management, duplicates, and non-English publications were excluded. Screening was independently performed by two reviewers, with discrepancies resolved through discussion or consultation with a third reviewer, ensuring consistency and objectivity.

2.3. Inclusion criteria

Studies specifically focusing on NFRHT with an emphasis on heat rectification were included in this review. These criteria guide the eligibility phase by defining the scope and relevance of studies selected for detailed assessment. Eligible studies investigated fundamental NFRHT mechanisms and their integration into electronic or thermologic circuits, including functional deployments in nanoscale/microscale electronic systems, design approaches, and performance optimization. Only articles published between 2013 and 2025 were considered. Additionally, included studies were required to report experimental, computational, or analytical evidence relevant to NFRHT-based rectifiers or associated electronic architectures. To qualify for inclusion, each study had to: (i) report a detectable heat rectification ratio (HRR) or comparable measure; (ii) specify gap separation and temperature difference ΔT; and (iii) include adequate details on materials and device configuration.

2.4. Exclusion criteria

Studies were excluded if not relevant to thermal management, heat rectification, or radiative transfer. Complementing the inclusion criteria, these exclusions ensure methodological rigor and thematic consistency. Additional exclusion included: articles lacking sufficient context to assess experimental, computational, or conceptual validity; editorials, opinion pieces, preliminary reports, conference proceedings, outdated studies, or non-English publications; studies that did not provide new insights into device operation, heat rectification mechanisms, or integration with electronic architectures; and studies lacking material/geometry details, ΔT values, or rectification parameters.

2.5. Eligibility assessment

Full-text publications satisfying the screening criteria were evaluated for methodological rigor, relevance to circuit-level heat rectification, and quality of results. Beyond the inclusion criteria, this stage further evaluates the quality, applicability, and robustness of the selected studies to ensure consistency and reliability in the synthesis stage. This stage finalizes the eligibility phase, ensuring that only high-quality and relevant studies proceed to data synthesis. Priority was given to studies that advanced understanding at the material level and demonstrated translation into electronic structures. Scalability, reproducibility, and potential integration into NFRHT-based devices were key considerations. Eligibility was assessed independently by two reviewers, with disagreements resolved by discussion or third-party consultation, ensuring consistency and objectivity.

2.6. Data extraction and synthesis

After final inclusion, data extraction and synthesis were conducted to ensure a seamless transition from study selection to analytical interpretation, aligning with both prior methodological procedures and subsequent results and discussion sections. This stage represents the inclusion phase of the PRISMA framework and directly supports the development of the comparative analysis and discussion presented in the following sections. Data extraction involved systematically compiling key parameters, experimental conditions, and findings from eligible articles. A standardized extraction framework was used and cross-checked for consistency. Extracted information included device type, primary findings, measurement or simulation techniques, temperature range, gap distance, material system/structure, HRR, and significant rectification observations. This process allowed identification of trends in rectification performance across materials, temperature regimes, and nanoscale gaps. Synthesized data illustrated relationships between material properties, structural design, and rectification efficiency. Comparative analysis assessed the impact of phase-change media, temperature-responsive dielectric properties, and nanoscale geometries on HRR. The synthesized results are presented through comparative analysis, trend identification, and performance evaluation to ensure consistency with the subsequent Results and Discussion sections. The synthesis highlighted the potential for scalable, programmable, and energy-efficient circuit designs, emphasizing translation of material and geometric improvements into functional thermologic systems. Both quantitative and qualitative synthesis were conducted to identify avenues for further investigation and ensure coherence of findings.

3. Fundamentals of heat transfer in nanoscale electronic circuits

This section provides a focused foundation on heat generation, management, and transfer mechanisms in electronic circuits, with explicit emphasis on the implications for NFRHT and heat rectification in nanoscale electronic logic systems. The discussion links conventional heat generation mechanisms directly to the limitations of traditional cooling approaches at the nanoscale, framing the need for advanced, precision heat management techniques. This section establishes the motivation for integrating NFRHT by connecting conventional heat generation and dissipation to the challenges posed by miniaturized, high-density circuits, creating a seamless transition from traditional heat management strategies to advanced mechanisms enabling directional and localized thermal control.

3.1. Heat generation, thermal effects, and nanoscale hotspot challenges in electronic circuits

Transistors, resistors, capacitors, and various other active or passive components all undertake energy conversion processes during operation, which inevitably results in the generation of heat in electronic circuits. Due to power consumption, resistive losses, and switching losses, these components lose electrical energy as heat while performing their designated operations. Heat is generated primarily in transistors, for example, during the switching operations that trigger the device to change between conducting and non-conducting modes. Bipolar Junction Transistors (BJTs) [27] and Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) [28] produce significant heat owing to their switching activity, resulting in both static and dynamic losses. A recent study by Liu et al. [29] has demonstrated that a $BiFeO_3$ (BFO) ferroelectric capacitor mounted in series with a commercial power MOSFET's gate sharpens the drain current (I_{DS}) switching between the OFF and ON states. This reduces the voltage range necessary for switching and maintains the I_{DS} in the OFF state at extremely low levels. This behavior of ultralow subthreshold swing (SS) substantially reduces the heat released during switching, in addition to dynamic power dissipation.

This principle is represented in Fig. 4. Overall, Table 2 summarizes the temperature and heat dissipation aspects of the diverse electronic components.

Generation of heat has inevitably emerged as a crucial issue in circuit development and functioning, particularly as electronic circuits' power densities increase due to component miniaturization. The challenge is amplified in nanoscale circuits, where surface area for heat dissipation is limited, and conventional heat sinks cannot effectively address localized hotspots. This clearly motivates the need for advanced heat management techniques, including NFRHT, which can precisely control localized heat flow in densely packed circuits. Therefore, mitigating the heat generated by these components has become critical for ensuring the longevity and operational effectiveness of electronic systems. By using ferroelectric MOSFETs with ultralow SS [29], localized hotspot formation can be minimized, which is essential for enabling efficient NFRHT-based heat rectification in densely packed circuits. Localized hotspots might arise from heat accumulation in closely spaced circuits. Exposure to elevated temperatures can eventually deteriorate the material properties of semiconductors, expedite structural changes, and induce electrolyte decomposition in the cathode [30], and insulating layers in high-performance CPUs and power electronics, potentially causing component breakdown.

Heat has a profound effect on the efficiency and durability of electronic circuitry. Increased resistance in conductive elements, reduced charge carrier mobility in semiconductors, and degradation of the dielectric attributes of insulating materials are among the adverse effects that may result from high temperatures. Such heat impacts can lead to performance deterioration, including slower integrated circuit processing rates or reduced efficiency in power conversion systems. Prolonged exposure to high temperatures can accelerate component wear and cause premature failures. For example, thermal stress induced by temperature fluctuations can cause materials to undergo mechanical deformations, leading to integrated circuit package fractures or solder joint fatigue. In severe cases, excessive heat may trigger uncontrolled heating [31], a phenomenon in which the rate of radiant energy generation increases uncontrollably, often resulting in device malfunction.

Table 2
Heat Generation in Electronic Components and Reduced Dissipation in MOSFETs with a BFO Capacitor (Ultralow SS) [27 –29].

Component	Key Heat Generation Mechanism	Temperature / Heat Aspect
BJT	Switching losses, resistive losses	Produces significant heat during operation
MOSFET	Switching losses, resistive losses	Produces significant heat; dynamic and static losses
MOSFET + BFO capacitor	Ultralow subthreshold swing reduces switching losses	Maintains very low I_{DS} in the OFF state; reduces heat during switching

A recent study by Endo et al. [32] demonstrates that such heat effects can be visualized using thermoreflectance imaging techniques such as phase and I/Q mapping (Fig. 5). Phase images display delays from a trigger signal, while I/Q images show reflectance deviations, with blue dots appearing in phase images and white dots in I/Q images, highlighting regions of notable thermal irregularity. Thermoreflectance imaging provides critical, spatially resolved insights into the temperature distribution of nanoscale components, thereby identifying potential hotspots where NFRHT can be effectively applied for precise, directional, and localized heat rectification. This directly underscores the significance of Fig. 5 in demonstrating the necessity of advanced heat management strategies that integrate NFRHT principles into electronic logic circuits. Large deviation regions along leakage routes are visible in failure samples, correlating well with thermography findings. Therefore, regulating heat in electronic circuits is crucial not only for maintaining efficiency but also for ensuring the robustness, safety, and longevity of electronic systems. Sustaining the functionality of modern electronic devices requires precise, nanoscale heat management approaches, particularly as continued miniaturization pushes the limits of heat accumulation in increasingly compact and powerful circuits. In

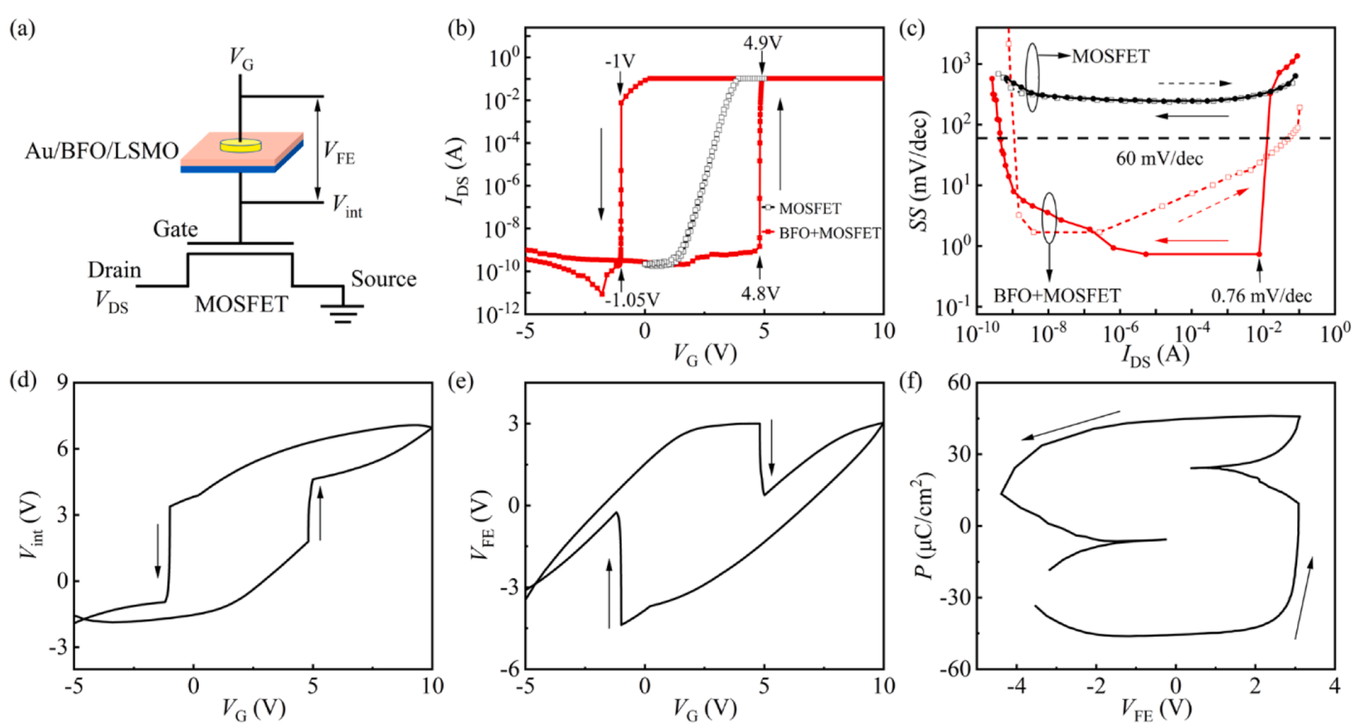

Fig. 4. A MOSFET with a BFO ferroelectric capacitor integrated exhibits ultralow SS. (a) Diagram of a commercial power MOSFET's gate coupled in series with a BFO ferroelectric capacitor. The MOSFET paired with and without the ferroelectric capacitor are compared using (b) I_{DS} against gate voltage (V_G) characteristics and (c) the corresponding subthreshold swing (SS) relative I_{DS} curves. (d) internal gate voltage (V_{int}) compared to V_G. (e) Complementary ferroelectric voltage (V_{FE}) vs V_G, and (f) The BFO capacitor's polarization-voltage (P–V_{FE}) loop with the V_{FE} waveform introduced. The directions of the voltage sweep are marked by arrows [29].

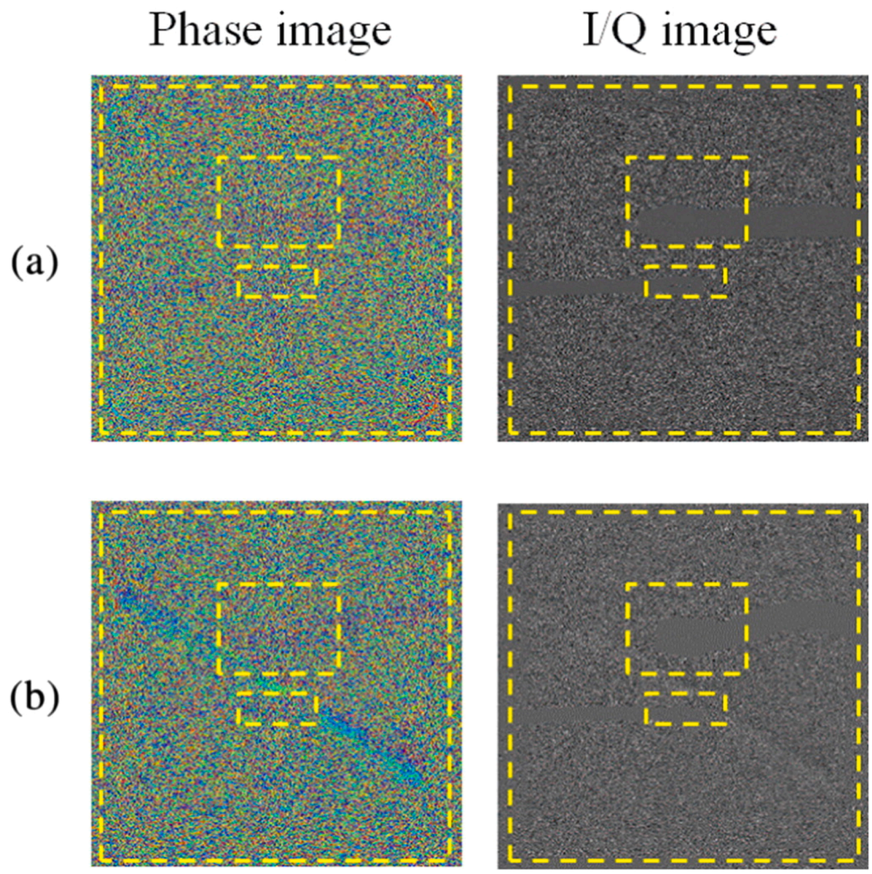

Fig. 5. Electronic Component Thermoreflectance Imaging: (a) a typical device displaying a consistent temperature distribution, and (b) a device exhibiting leakage failure, indicating localized hotspots and heat buildup [32].

summary, the limitations identified in conventional heat management and the heat distribution patterns revealed by nanoscale imaging establish a clear rationale for the subsequent discussion on NFRHT, bridging Sections 2 and 3, and guiding the transition to directional heat rectification strategies in electronic logic circuits.

3.2. Conventional heat management techniques and their limitations in nanoscale electronic circuits: bridging to NFRHT

To ensure proper operating temperatures and dissipate excess heat energy generated in electronic circuits, traditional heat management approaches have been implemented for decades. Air-cooled heat sinks, fans (e.g., solid-state [33] or piezoelectric [34]), and liquid cooling systems represent some of the most commonly utilized techniques. By expanding the surface area that interfaces with the surrounding air, heat sinks, which are usually composed of high-conductivity metals like copper or aluminum, facilitate passive convective heat transmission. By actively circulating air across heat sink surfaces to speed up convective cooling, fans enhance this process. Liquid cooling systems serve their purpose in areas with higher heat demands, including power electronics and high-performance devices. In contrast with air-based systems, these systems employ circulating coolants to draw heat away from the

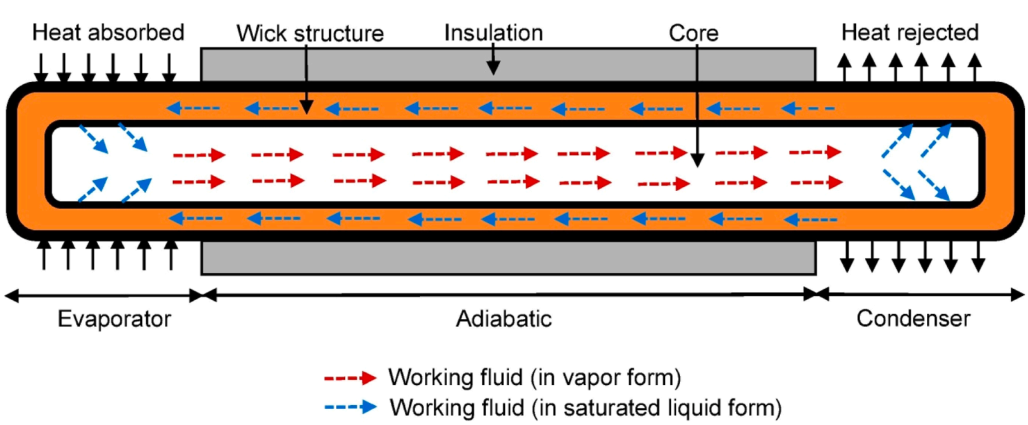

Fig. 6. Schematic of a typical heat pipe showing the cycle of fluid flow. Within the evaporator portion, the working fluid absorbs heat and turns into a vapor. The vapor then moves through the adiabatic section and into the condenser, where it releases heat and turns back into a liquid. The cycle completes when the liquid is transported back to the evaporator by capillary action [39].

electronic components and transmit it to exterior radiators or heat exchangers, delivering an improved means of heat dissipation.

Cooling systems, which are generally divided into passive and active techniques [35], can additionally be categorized into various types based on the materials and techniques used for electronic device heat management. These include liquid-based cooling systems [36], heat pipes [37–39] (Fig. 6), spray cooling [40], thermoelectric cooling [41], and air-based cooling [42]. Moreover, there are several different types of microchannel heat sinks (MCHSs) and their associated heat transfer performance, which have been deemed effective approaches for electronic device cooling. Fig. 7 displays various geometries of MCHSs, spanning from straightforward to manifold channels [43]. Nevertheless, these conventional cooling approaches are limited when applied to nanoscale and high-density circuits, where localized hotspots and rapid thermal fluctuations occur. NFRHT offers extremely effective, non-contact, and spatially localized heat dissemination at micro- and nanoscale dimensions, hence significantly surpassing these traditional methods. By facilitating directional and localized thermal control, NFRHT addresses the limitations of conventional conduction- and convection-based cooling, making it highly relevant for heat rectification in modern electronic logic systems.

When deployed on contemporary miniature electronic circuits, these conventional cooling techniques pose major shortcomings despite their extensive use. Bulky temperature control components, such as fans and heat sinks, are growing increasingly challenging to incorporate due to the tremendous reduction in physical space brought on by perpetual device scaling down. Moreover, localized hotspots that are difficult to treat with traditional methods are caused by the higher power density, bulk volume, high heat flux, and fluctuating temperature on the electronic chip surface [44]. A significant temperature gradient and heat stress have been observed throughout the chip as a result of the power dissipation density at the hotspots, which was estimated to be up to eight times greater than the background [45]. The capacity of heat sinks and fans to regulate heat at the micro- and nanoscale, where conduction routes and airflow are constrained, is intrinsically limited since their functions depend on macroscopic heat transport systems. Comparably, although liquid cooling enhances performance, it imposes complications such as elevated system weight, potential leakage hazards, and higher costs, which render it unfeasible for small or portable electronic equipment. Although performance improvement has been demonstrated by electrospray cooling with both finned and smooth heat sinks, greater flow rates enhance cooling by 15–44%, while finned versions cool 1.3–1.6 times better [46]. However, it has limitations in fluid management, spray stability, and scalability. In contrast, NFRHT enables localized, non-contact, and ultrafast heat dissipation at the nanoscale, circumventing these limitations and allowing for heat rectification in

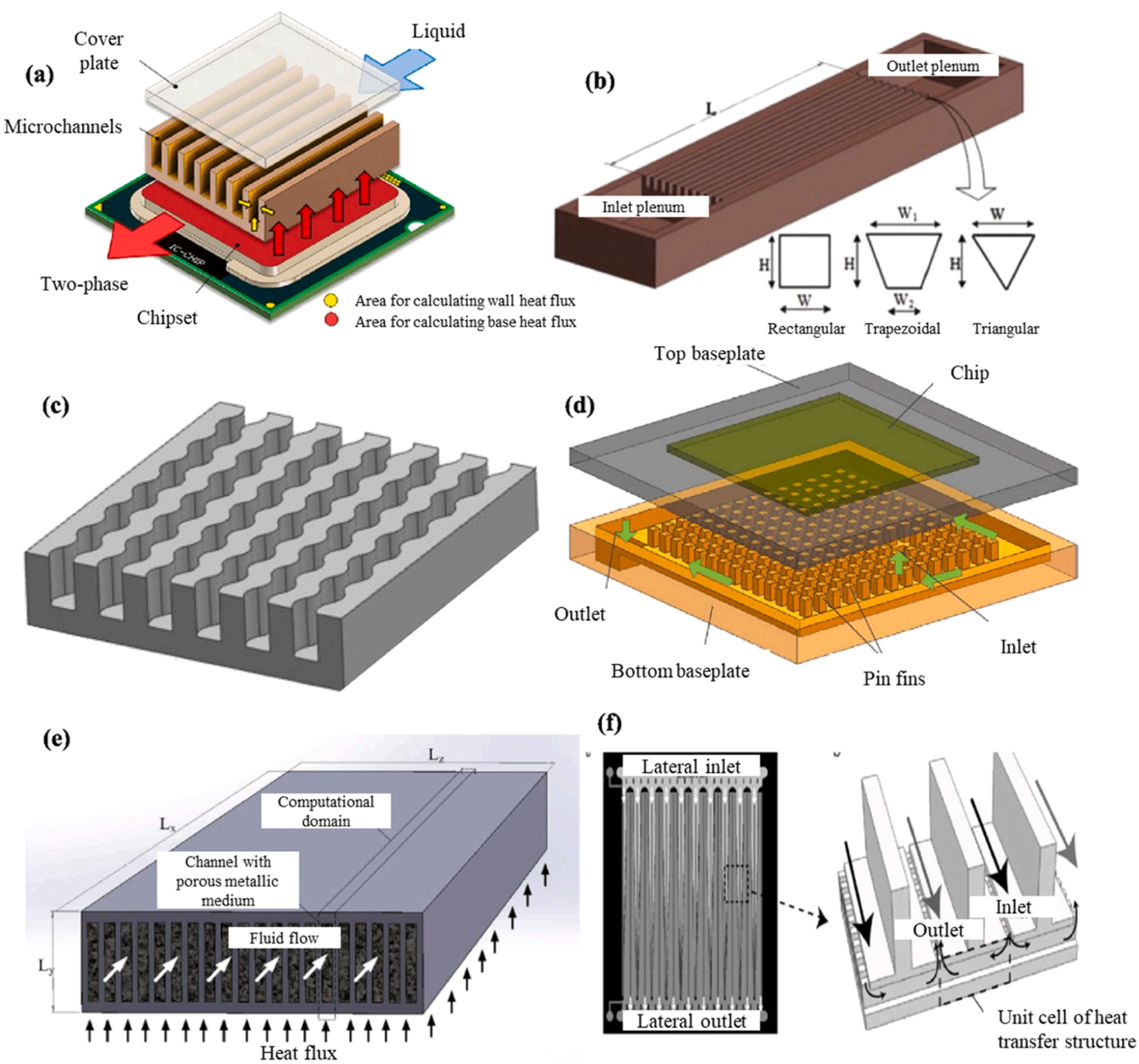

Fig. 7. Different configurations of MCHSs include the following: (a) simple straight, (b) rectangular, trapezoidal, or triangular, (c) wavy or undulating, (d) pin fins, (e) porous materials, and (f) manifold-type structures [43].

densely packed circuits.

Furthermore, directional or dynamic regulation of heat flow, which has become progressively more desirable in sophisticated circuit architectures, is impractical with conventional cooling techniques, which typically offer uniform cooling. Advanced heat management approaches, particularly NFRHT-based solutions, provide adaptive, spatially controlled thermal regulation, enabling targeted cooling of hotspots while maintaining overall circuit efficiency. Innovative approaches that can operate effectively at a smaller scale and provide localized, adaptive heat control are vital as electronic gadgets continue to advance towards greater integration and multifunctionality. These disadvantages highlight the importance of alternative heat management paradigms that are better suited for the thermal constraints of future electronics and overcome the limitations inherent in conventional cooling systems. Even though the deployment of nano-enhanced phase-change materials (NePCMs) [47] can possibly further enhance heat management in electronic devices through the mechanisms of heat transfer and base temperature reduction, NFRHT offers highly localized and ultra-efficient heat energy exchange, which NePCMs cannot provide. While copper foam heat sinks yielded the highest temperature drop (up to 36.2%), as reported by Zahid et al. [48], incorporating RT54HC/Al_2O_3 NePCMs, their reliance on phase-change and conduction limits their scalability and reaction speed in intricate or densely packed devices. By comparison, NFRHT circumvents these difficulties, enabling precise nanoscale heat control, avoiding material degradation, and supporting rapid thermal rectification, making it an indispensable solution for next-generation miniaturized electronic devices. The summary of both advantages and disadvantages of a variety of the discussed conventional cooling approaches is presented in Table 3 for an overview.

Overall, while conventional cooling techniques provide valuable approaches to manage heat, their limitations in terms of spatial scalability, localized hotspot mitigation, and dynamic heat regulation underscore the necessity of advanced heat management methods such as NFRHT. In high-density and miniaturized circuits, these limitations highlight the need to examine fundamental heat transfer mechanisms—conduction, convection, and radiation—at micro- and nanoscale dimensions. While Sections 2.1 and 2.2 highlighted the sources of heat generation and traditional dissipation strategies, it becomes evident that localized hotspots, high power density, and limited physical space necessitate advanced approaches. NFRHT leverages evanescent electromagnetic interactions to surpass the constraints of conventional conduction and convection, enabling directional and highly localized heat flow. By integrating the principles of conduction, convection, and radiation with NFRHT, electronic circuits can achieve precise thermal management and heat rectification at the nanoscale. This discussion directly bridges traditional heat management strategies with the fundamental heat transfer mechanisms analyzed in the following section, emphasizing their relevance for modern nanoscale electronic logic systems. This sets the stage for Section 2.3, where the mechanisms of heat transfer are analyzed in detail with explicit consideration of their roles in enabling efficient thermal control in modern nanoscale electronic systems.

Table 3
Summary of pros and cons of conventional cooling methods.

Cooling Method	Pros	Cons / Limitations
Air-cooled heat sinks	Simple, passive, low cost; increased surface area necessary for heat dissipation	Bulky; struggles with hotspots; reduced effectiveness at micro and nanoscale
Fans (solid-state or piezoelectric)	Enhances convective cooling; promotes active air circulation	Increase in bulk; consumes power; limited efficiency at micro and nanoscale
Liquid cooling systems	Efficient heat dissipation for high-power electronics	High system weight; high cost; leakage risk; not ideal for portable devices
Heat pipes	High thermal conductivity; facilitates heat spreading	Complexity in design; low effectiveness when used for very localized hotspots
Spray / Electrospray cooling	Significantly enhances cooling; more efficient when finned versions are employed	Fluid management challenges; limited scalability; spray stability issues
Thermoelectric cooling	Precise temperature control; enables active cooling	Limited cooling capacity; high energy consumption; bulky
Microchannel heat sinks (MCHS)	Ideal for compact devices; enhanced overall heat transfer	Design and fabrication complexity; clogging issues; performance depends on flow rate
Nano-enhanced PCMs (NePCMs)	Base temperature reduction; boosts heat management through phase change	Limited scalability; material degradation ; limited response speed

3.3. Fundamental heat transfer mechanisms in electronic circuits: conduction, convection, radiation, and the role of NFRHT

Motivated by the need to overcome the limitations of conventional heat management methods in miniaturized and high-density circuits, this section analyzes the fundamental mechanisms of heat transfer—conduction, convection, and radiation—to enable a clear comparison of their characteristics, advantages, and constraints in electronic systems. Building upon the sources of heat generation and limitations of conventional heat management discussed in Sections 2.1 and 2.2, it is essential to examine the fundamental mechanisms by which heat is transferred in electronic circuits. Conduction, convection, and radiation are among the three principal modes by which heat is transferred inside electronic systems. The basic mechanism of heat transmission in solid materials is conduction, which involves transmitting heat energy from a hotter region to a colder one via free electrons or lattice vibrations (phonons). In electronic circuits, conduction generally takes place through semiconductor substrates, encapsulating materials, and metallic interconnects. The heat transfer capacity of the constituent materials has a significant impact on their efficiency. In light of their inherent conductivities and cost-effectiveness, metals such as copper (Cu) [49] and graphene nanoplatelets (GnPs) [50,51] are widely reported among the metal matrix materials suitable for use as heat sinks [52] and interconnects.

Interfacial resistances can hinder the overall efficacy of transmission, and the conduction path length is streamlined as devices become more compact. Strategies including surface modification and customizable interface design have been emphasized in recent developments as ways to enhance heat conduction efficiency across material boundaries and reduce interfacial thermal resistance [53]. Convection, in contrast, involves heat transfer through fluid motion, which may include gases or liquids. In conventional cooling systems, it is frequently used in conjunction with conduction. Air circulates to transmit heat away from hot surfaces via forced convection, as in fan-based systems. Natural convection is less efficient and depends upon buoyancy-driven fluxes, especially within enclosed or closely packed electrical systems. Given the boundary layer effects and restricted fluid flow, the convective process is less effective at the microscale, impeding the transfer of heat energy away from hotspots. By contrasting conduction and convection, it becomes evident that conduction dominates in solid components, while convection is more relevant for fluid-assisted cooling but is limited in miniaturized devices.

The phenomenon of radiative energy transfer arises when any substance at a temperature greater than absolute zero emits electromagnetic waves, primarily in the infrared range. In contrast to conduction and convection, radiation can occur across a vacuum and does not require a medium. This attribute renders it particularly useful in isolated or vacuum-sealed conditions, such as microelectromechanical systems (MEMS). Micro heat pipes (MHPs) integrated with micro-structured pillars, specifically circular copper pillars with zigzag patterns, have demonstrated superior wettability and heat transfer performance, helping to address issues of flow instability and low critical heat flux within confined geometries [54]. This supports efforts to further optimize heat control in MEMS environments. The performance of MEMS in such environments can be further enhanced by materials such as poly (vinylidene fluoride) (PVDF), which is renowned for its exceptional heat and radiation resistance, and electroactive attributes [55]. This is especially valuable for applications that require energy harvesting capabilities. The blackbody radiation law governs radiative transfer in typical applications, and due to its low power density, it often contributes only partially to the overall heat dissipation at ambient temperature. Radiation may nonetheless become fundamental at elevated temperatures or within systems where convection and conduction are minimal. This comparison highlights the distinct operational conditions and relative effectiveness of conduction, convection, and radiation in electronic circuits.

NFRHT extends the capabilities of conventional radiation by enabling highly localized and directional heat flow, directly addressing the limitations highlighted in Section 2.2. NFRHT is a significant contributor to radiation variation found in miniaturized devices. It is most apparent when two surfaces are brought extremely close together, usually closer than their specific infrared wavelength, which is around 10 μm at ambient temperature. Surface phonon-polaritons and surface plasmon-polaritons are illustrations of evanescent waves that enhance heat transmission in this domain, when conventional blackbody radiation principles are surpassed. By facilitating electromagnetic coupling across minuscule gaps, such waves enable heat transfer rates that exceed many orders of magnitude beyond far-field radiation. In nanoscale and miniaturized technologies, NFRHT serves an increasingly important role. NFRHT presents a scalable, non-invasive alternative that can precisely control temperature, while traditional cooling techniques underperform at sub-micrometer scales due to material and physical constraints. It is also a strong contender for heat rectification, in which heat flows preferentially in a specific direction due to its intrinsic directionality and sensitivity to surface geometry and material properties. By integrating NFRHT with the conventional mechanisms of conduction, convection, and radiation, next-generation electronic circuits can achieve efficient, adaptive, and localized thermal management, enabling innovative heat management topologies such as infrared logic gates and thermo-diodes. Overall, the discussion in this section clarifies the motivation for considering all three conventional heat transfer mechanisms while highlighting the superior advantages of NFRHT for nanoscale thermal management and directional heat control. Table 4 summarizes the four primary heat transfer modes—conduction, convection, radiation, and NFRHT—highlighting their mechanisms, advantages, limitations, and relevance in nanoscale electronics, with NFRHT enabling highly localized and directional thermal management for miniaturized, high-density circuits.

4. NFRHT: principles, mechanisms, and implications for nanoscale electronics

Building on the foundational understanding of heat generation and conventional management strategies in nanoscale circuits, this section delves into NFRHT as an advanced mechanism for precise, directional, and high-intensity thermal control. By exploring the fundamental principles, underlying mechanisms, and material- and geometry-dependent modulations, Section 4 establishes the conceptual and practical framework for leveraging NFRHT to overcome the limitations of traditional cooling approaches, enabling efficient heat rectification and logic-level thermal management in ultra-dense electronic systems.

4.1. Fundamental concepts and physical mechanisms of NFRHT

The accelerated exchange of thermal radiation between two separate surfaces that are divided by a very small gap is known as NFRHT. This phenomenon is fundamentally distinct from conventional far-field radiative heat transfer based on blackbody radiation. Radiative transfer is predominantly isotropic and exhibits limited intensity in the far-field domain because it is determined by the geometry of radiating bodies and the heat emission properties of surfaces. However, the far-field assumptions break down, and near-field phenomena become dominant when the distance between two surfaces reduces to subwavelength dimensions. The occurrence and contribution of evanescent waves, which are non-propagating electromagnetic waves that decay exponentially with distance from the surface, are key distinctions in near-field radiative transfer. Since these waves attenuate rapidly in space, they are usually disregarded in far-field models. Nevertheless, evanescent waves can tunnel across a diminutive vacuum or dielectric gap when two elements converge into nanometric closeness, introducing

Table 4
Comparison of Heat Transfer Mechanisms in Electronic Systems.

Heat Transfer Mode	Mechanism	Key Advantages	Limitations / Constraints	Relevance in Nanoscale Electronics	Schematic / Visual Concept
Conduction	Heat transfer via free electrons or lattice vibrations (phonons) in solids	High efficiency in solid materials; dominates in interconnects and substrates; cost-effective with metals and conductive materials	Limited by interfacial resistances; efficiency decreases with minimal contact or long conduction paths; less effective for localized hotspots in miniaturized devices	Primary mode for solid components and heat sinks; critical for managing heat within compact substrates and interconnects	Heat moves along a solid medium from hot to cold, e.g., a metal wire or substrate
Convection	Heat transfer via motion of fluids (air or liquid)	Enhances heat removal from surfaces; can be passive (natural) or active (forced)	Less efficient at microscale due to boundary layer effects; dependent on fluid flow; constrained in tightly packed devices	Used in conjunction with conduction; limited utility in miniaturized or high-density circuits where fluid flow is restricted	Fluid (air or liquid) carries heat away from surfaces; arrows indicate flow moving heat away from hot regions
Radiation	Emission of electromagnetic waves, primarily infrared	Non-contact heat transfer; can occur across a vacuum; useful in isolated or enclosed systems	Low power density at ambient temperature; contributes partially to overall heat dissipation; less effective when conduction or convection dominate	Important for isolated or high-temperature applications; complements conduction and convection in nanoscale devices	Heat radiates outward as waves from a hot surface; can cross gaps without a medium
NFRHT	Heat transfer via evanescent electromagnetic waves across sub-wavelength gaps	Highly localized; directional; non-invasive; can exceed far-field radiation rates; enables heat rectification	Requires precise surface proximity; highly sensitive to surface geometry and material properties	Ideal for nanoscale and miniaturized circuits; enables adaptive, localized thermal management, directional heat flow, and advanced thermal components	Heat flows across extremely small gaps via evanescent waves; arrows indicate strong directional transfer between closely spaced surfaces

energy transfer mechanisms that would not otherwise be conceivable in the far field. This technique makes it feasible to achieve radiative heat transfer rates that are multiple orders of magnitude higher than the blackbody limit [56,57].

Total internal reflection at a dielectric material's interface generates evanescent waves, which are especially potent at surface resonances such as surface plasmon-polaritons within metals or surface phonon-polaritons in polar dielectrics. The likelihood of photon tunneling across the gap is enhanced by these associated excitations between electromagnetic fields and either free-electron oscillations (plasmons) or lattice vibrations (phonons), which significantly boost the local electromagnetic density of states. In light of this, NFRHT becomes highly sensitive to temperature, gap size, and material properties, establishing a solid foundation for localized and tunable heat management. The unique properties of near-field radiative transfer exhibit profound implications for electronics, especially in applications demanding high-intensity, directional, and non-invasive heat transfer. In comparison with standard conduction or convection mechanisms, NFRHT can be employed in vacuum conditions, MEMS, and nanoelectromechanical (NEMS), where conventional cooling techniques are insufficient. As a result, NFRHT is a crucial component in the development of heat control strategies for high-density electronic systems.

4.2. Mechanisms of NFRHT: phonon, plasmon, and photon interactions

The intricate interactions between phonons, plasmons, and photons essentially regulate heat transmission in the near-field region. Unlike far-field radiation, these interactions yield evanescent electromagnetic fields, which enable energy to travel over nanometric gaps. Surface phonon-polaritons (SPhPs) [58] are formed when phonons, which are quantized lattice vibrations in solids, interact with electromagnetic waves in polar dielectrics. When materials consisting of SiC [59,60] or silicon dioxide (SiO_2) are applied, these hybrid modes, which are strongly bound at the surface, dominate near-field heat propagation. Parallel to this, surface plasmon-polaritons (SPPs) [9] emerge when photons come into proximity with plasmons, which are collective oscillations of free electrons in conductive materials. This is especially prevalent in metals like gold, silver, or doped semiconductors. By virtue of its function in augmenting near-field heat radiation, semiconductor-supported SPPs and their coupling modes have garnered a lot of attention lately [61].

Effective radiative heat exchange between two closely spaced surfaces is rendered attainable by the potent localized electromagnetic fields that result from SPhPs and SPPs, which tunnel over a narrow gap but dissipate exponentially away from the interface. A key process in near-field heat transfer is photon tunneling [62], in furtherance of phonon and plasmon coupling. These include evanescent photons that reside adjacent to material surfaces and transfer energy with no direct contact, as opposed to propagating photons in the far field. At small separation distances, the density of these evanescent states expands drastically, enabling a massive amplification of the local radiative heat flow. Multilayered metamaterials consisting of graphene and InSb can be employed to actively regulate NFRHT. In these materials, the surface magneto-plasmon polariton behavior is significantly enhanced or modulated by an external magnetic field and graphene's chemical potential. A magnetic field applied along the z-axis, with graphene/indium antimonide (InSb) multilayers separated by a vacuum gap is shown in a schematic diagram (Fig. 8) [63]. Since these modes combine to circumvent the blackbody limit, near-field systems are very appealing for controlling heat in nanoscale devices.

4.2.1. Role of strategic material selection in modulating NFRHT

The capacity to tune near-field heat transmission through shape and materials constitutes a key feature. By carefully selecting appropriate material combinations and designing surface geometries, radiative heat transfer's magnitude and spectral properties may be accurately modulated. In this context, advanced thermo-interface materials, such as nano-enhanced phase-change materials (NePCMs), play a crucial role in enabling effective heat dissipation as electronics become smaller and more powerful [64], complementing the use of phase-change and anisotropic materials in NFRHT control. To optimize the coupling of evanescent waves, materials with strong surface mode resonances can be integrated, such as metals with adaptable plasmonic characteristics or polar dielectrics for phonon-polariton coupling.

Additionally, the heat transfer behavior can be dynamically altered by including phase-change materials [65–68] or anisotropic materials. For instance, heat rectification could be modulated over time, enabling time-dependent heat flow control when the insulator-to-metal transition of vanadium dioxide (VO_2) is utilized [69], where the heated phase promotes active regulation of near-field radiation. Recent studies show that the total thermal rectification of asymmetric n-type doped silicon–VO_2 near-field radiative thermal rectifiers (NFRTRs) can be significantly enhanced by coating both plates with graphene, with the rectification factor increasing from 4.38 to 7.79 at a 10 nm gap for a silicon doping of 10^{19} cm^{-3} and a graphene chemical potential of 0.25 eV [70]. The emissivity hysteresis of VO_2 thin films can be modulated by substrate choice, with VO_2 on silicon exhibiting a wider hysteresis ($\sim 3\times$) and a slower insulator-to-metal transition than on sapphire,

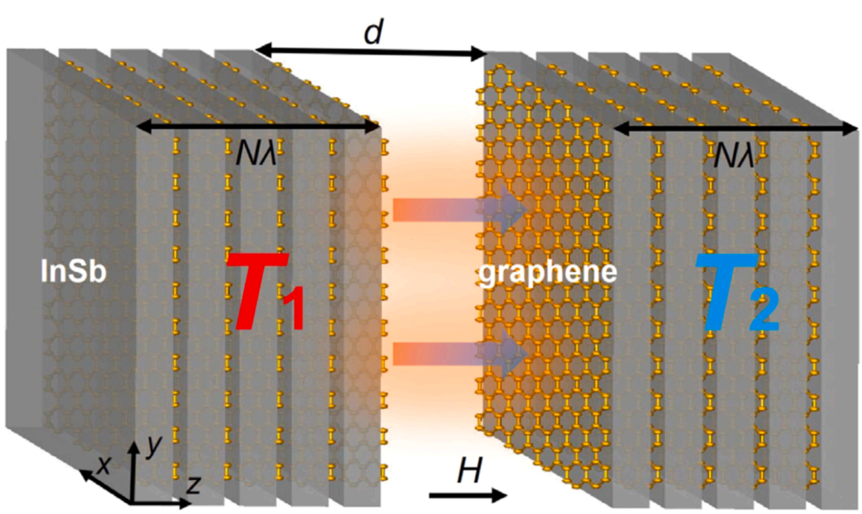

Fig. 8. Two magneto-optical multilayer metamaterials composed of alternating InSb and graphene layers with *N* periods each are exposed to a static magnetic field *H* oriented along the z-axis and separated by a vacuum gap *d* [63].

enabling radiative thermal diodes with rectification factors up to 87% [71].

Several other candidate materials include intrinsic Si + SiO_2 (ideal for ultra-tight gaps, sub-20 nm), intrinsic Si + doped Si (suitable for sub-10 nm), and intrinsic Si + Au (suitable for wider gaps, 100–500 nm), with high (R ≈ 9.9), moderate (R ≈ 2.7), and lower (R ≈ 0.85), respectively [72]. These materials have shown promise for enhancing rectification efficiency, highlighting the critical role that material selection plays in nanoscale heat control. Recent advancements in photoluminescent materials, including perovskites, quantum dots (QDs), metal–organic frameworks (MOFs), and carbon-based nanostructures across optoelectronic applications [73], further broaden this design landscape as they show potential for sophisticated near-field heat regulation and rectification by providing strong light-matter interaction and controllable emission for selective photon-mediated energy exchange.

4.2.2. Influence of structural asymmetry on directional heat rectification

Another significant variable in near-field interactions is geometry. Features such as curvature, surface roughness, and nanostructures (such as gratings or metasurfaces) affect the coupling efficacy between surfaces and influence the spatial arrangement of the local electromagnetic field. In an effort to facilitate rectification, in which heat travels preferentially in one direction, directional bias in heat transfer can be accomplished through the addition of asymmetrical geometries. Heat-based diodes and logic circuits that solely employ radiative phenomena are developed on the basis of this geometrical asymmetry. As an illustration of its potential for environmentally conscious structures and heat management applications, a macroscopic thermo-diode with asymmetrically integrated copper and polystyrene layers within a stainless-steel backdrop achieved a normalized rectification ratio of about 1.6 at ambient temperature [74]. Similarly, structural asymmetry can increase heat transmission by up to 18.3% in convective systems [75], while maintaining tolerable pressure drops. In the context of micro-/nanoscale implementations, rectification performance has been shown to correlate with the dominant physical mechanism: directional heat flow modulation is achieved in asymmetric nanograting or conical geometries; metasurfaces utilize dielectric tuning to control energy transfer; and phase-change materials such as VO_2 exhibit rectification through intrinsic material asymmetry and heat-induced transitions. Structural asymmetry leads to both performance enhancements and manufacturability restrictions from a figure-of-merit (FoM) standpoint, where the geometric accuracy and reproducibility that can be achieved via fabrication must be weighed against the enhanced directional coupling efficiency.

4.2.3. Impact of nanoscale gap control on heat transfer enhancement

Heat transmission may be enhanced by numerous orders of magnitude via narrowing the vacuum gap between two surfaces to a few nanometers, as this improves the tunneling of evanescent waves. In contrast to conventional far-field behavior, evanescent wave coupling facilitates heat transfer rates that are many orders of magnitude higher than the blackbody limit in the near-field domain, when separations are below λ_{th} [76]. When the separation is less than the wavelength of photons, NFRHT occurs, enabling the coupling of SPhPs and enhancing electromagnetic energy transfer by up to 100 times compared to the blackbody limit at nanometer-scale gaps [77]. Therefore, it is essential to maintain sub-100-nm gaps for maximized near-field radiative heat transmission. In sophisticated electronic systems, NFRHT becomes a highly controlled and efficient method for localized heat management through the careful design of nanoscale gaps, material selection, and structural asymmetry. Advanced logic devices, including switches, rectifiers, phononic gates, and thermotronic diodes, are rendered possible by this integration, which ensures enhanced effectiveness and operational reliability. Reliability margins are decreased by fabrication and alignment restrictions, although rectification efficiency is maximized from a FoM perspective when gaps are maintained below 100 nm. To ensure stability and integration feasibility, a high-performance FoM device must therefore balance excessive coupling enhancement with practical gap-control tolerances.

4.3. Recent advances in NFRHT for nanoscale thermal management

The intriguing prospect of NFRHT for non-invasive, ultrahigh-efficiency thermal management in nano- and microscale gadgets has garnered a lot of attention in recent years. By enabling exceptionally high heat flux densities over nanometric gaps, far above the conventional blackbody radiation limit, NFRHT proposes an excellent alternative. This feature becomes particularly desirable for high-density logic circuits, NEMS, and MEMS, where the viability of traditional approaches is restricted by size constraints and sensitivity to mechanical disturbance. A prime instance of this sort is a metal–insulator–metal (MIM) structured emitter and receiver system featuring fixed temperatures of 1000 K and 300 K, respectively, housed in a 4400 × 4400 × 2000 nm^3 vacuum domain for simulations of near-field radiation transmission, as illustrated in Fig. 9 [78]. Recent advances in graphene-based metasurface lenses illustrate how the tunable optical characteristics of graphene enhance NFRHT for microscale temperature management through enhanced electromagnetic field control [79].

There has been an extensive repository of studies devoted to the experimental validation of the NFRHT mechanism, as well as hypothetical modeling. The empirical foundation for modeling near-field energy exchange typically stems from the framework of fluctuational electrodynamics. Using this model, the electromagnetic field distributions that develop in close proximity are projected, and stochastic variations in temperature in materials are taken into account. To model NFRHT across different materials and geometries, computational tools, which include the boundary element method (BEM), fluctuational surface current approaches, and the finite-difference time-domain (FDTD) simulations, have been commonly adopted. These models have been useful for identifying the combination of material and structural configurations that enhance the coupling effectiveness of evanescent modes, such as surface phonon-polaritons and surface plasmon-polaritons, with the current focus on heterostructures such as graphene-covered SU8 films on SiO_2/Si substrates. As an innovative NFRHT-based system, Fig. 10 illustrates a tunable heat-transfer platform in which back-gated bias voltages (V_1 and V_2) are employed to control the net radiative heat flux along nanometric vacuum gaps [57]. This voltage-controlled arrangement represents a major leap forward for electrically reconfigurable and programmable thermal logic systems, exhibiting an unparalleled degree of dynamic modulation in NFRHT.

Fresh developments in the experimental realm have enabled highly accurate measurements of NFRHT at sub-micron and nanometer distances. Advanced configurations have been used for detecting near-field heat exchange over vacuum gaps with dimensions as small as a few tens of nanometers. These setups may include MEMS cantilevers and microfabricated probes. The discovery that radiative heat fluxes in systems constituted of materials like graphene, gold, and SiC may surpass the blackbody limit by multiple orders of magnitude was one notable milestone. This may be largely due to photon tunneling [62] or strong coupling of evanescent waves. The emitter and receiver are operated at slightly varying temperatures in a standard setup that consists of periodic graphene and vacuum layers, with a precisely determined central vacuum gap between graphene sheets, representing an innovative multilayer NFRHT configuration, as demonstrated in Fig. 11 [61]. By improving spectrum selectivity and photon tunneling routes, this multilayer architecture renders it possible for evanescent modes to be coupled more strongly and opens up possibilities for small, highly efficient NFRHT devices that can manipulate heat at the logic level. In addition to validating hypothetical predictions, these analyses have uncovered subtleties, including spectrum selectivity, the influence of material anisotropy and phase variations, and the non-monotonic

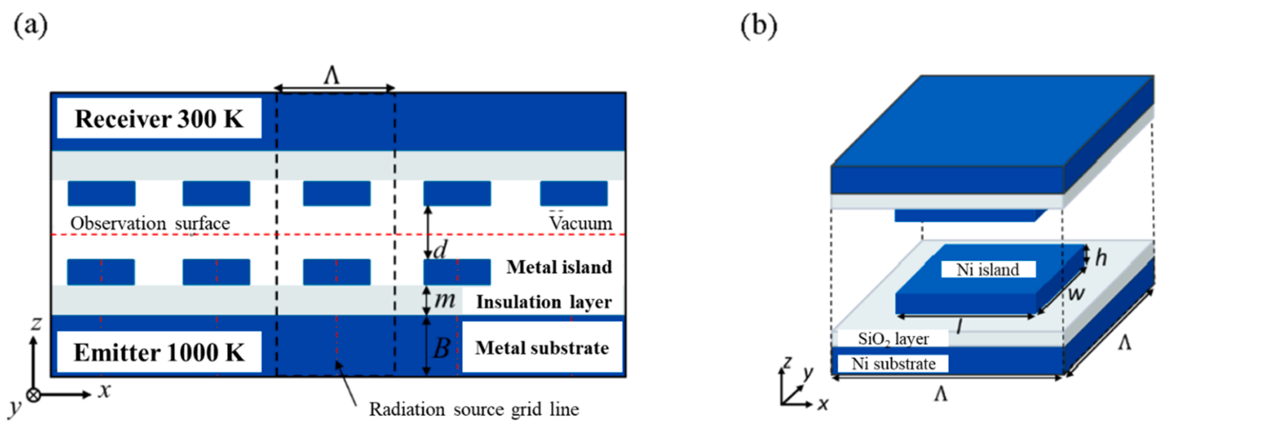

Fig. 9. A MIM emitter–receiver system with both (a) a cross-sectional view and (b) a top-down view, with the simulation domain measured along the x, y, and z axes [78].

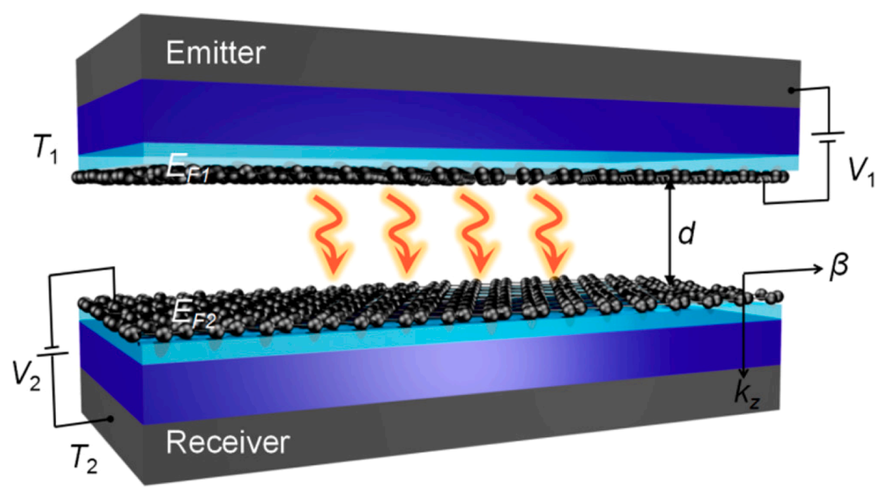

Fig. 10. A simplified representation illustrating two graphene-coated SU8 heterostructures on SiO_2/Si substrates separated by a vacuum gap [57].

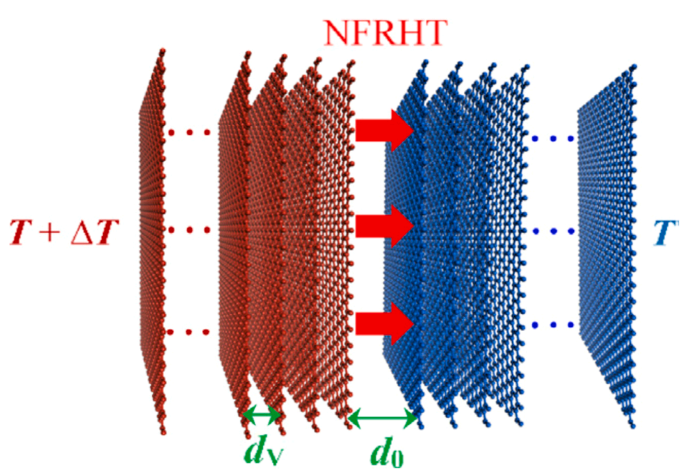

Fig. 11. Configuration of a dual periodic graphene/vacuum multilayer system, showing the central vacuum gap (d_0) and the separation distance between adjacent graphene sheets (d_v). The emitter and receiver are maintained at temperatures $T + \Delta T$ and T, respectively [61].

distance dependence of the heat flux. Pushing beyond the boundaries of traditional two-body frameworks, recent findings have examined many-body configurations, such as three-grating systems, where asymmetric modulators between absorbers and emitters greatly enhance heat flux while providing more control by manipulating the evanescent wave coupling in a specific direction [80].

On top of that, phase-changing materials like VO_2, which display drastic shifts in both optical and heat conduction properties with temperature, are now viable options for constructing thermo-rectifiers, diodes, and transistors, thanks to innovations in the field of materials.

There is currently an array of approaches to enhance the NFRHT, including incorporating grating structures, coating heat-exchange surfaces with either sheets or films [81], doping heat-exchange surfaces [10], and adding multilayer structures to heat exchangers [82]. By integrating these dynamic materials into near-field systems, asymmetric conveyance of heat can simulate the behavior of electrical diodes in heat transfer systems. These advancements represent an important leap towards the development of radiative heat flow-based electronic logic circuits and information processing. Collectively, these conceptual and experimental discoveries highlight the revolutionary potential of NFRHT for next-generation heat management systems for compact devices.

5. Directed heat flow in electronic logic circuits: principles and advanced applications

Building upon the principles and mechanisms of NFRHT (Section 4), this section explores directed heat flow and heat rectification in electronic logic circuits. By leveraging structural asymmetry, material nonlinearity, and near-field interactions, heat can be preferentially guided, enabling unidirectional thermal transport analogous to electrical diodes. Section 5 examines the underlying mechanisms, key materials, geometrical considerations, and integration strategies for micro- and nanoscale heat rectification, highlighting how these approaches enable active thermal control, protect sensitive components, and pave the way for innovative thermo-logic systems in next-generation electronics.

5.1. Heat rectification: principles, mechanisms, and metrics

Analogous to the means by which an electrical diode permits current to flow preferentially in one direction, heat rectification is the phenomenon in which heat flows more efficiently in one specific direction than in the other. The orientation of the temperature gradient determines the magnitude of heat transfer within systems exhibiting this directional asymmetry. This aspect is particularly advantageous in instances where unidirectional heat flow is preferred, such as in dynamically regulating heat currents or preventing heat from recirculating into delicate areas of an electronic system. Various models have been laid out to simulate the heat rectification effect for bulk materials [65,67,83–85]. Bi-segment thermo-rectifiers, which are composed of two segments with varied temperature-dependent conduction coefficients, represent a basic model for achieving the heat rectification effect [86,87]. The conductivity distributions applicable to such a system under a broad range of temperature boundary conditions are qualitatively described [66]. This system may be regarded as an amalgamation of linear systems, where fluctuations in the conduction coefficients of the phase-change material occur when the temperature bias is reversed.

Heat rectification bases its operation on the nonlinear dependence of heat transmission parameters on structural asymmetry or temperature. This rectifying behavior might arise from a variety of mechanisms. A widely used approach is to develop structures with temperature-dependent material characteristics or asymmetric conductivity, which respond distinctively when the temperature gradient is reversed. The use of phase-change materials, for example, can provide a large directional bias in heat flow because these materials undergo substantial fluctuations in heat transport capabilities or emissivity at specific temperatures. In addition, advancements demonstrate that, by modulating the geometric and dielectric properties of metasurfaces, which serve as uniaxial films with adaptable optical responses, NFRHT may be dynamically regulated [88]. Through the directed manipulation of radiative heat flow under fluctuating circumstances, this dynamic control enhances the potential for heat rectification. A valuable metric for measuring the effectiveness of such rectification is the rectification coefficient, which is the ratio of the absolute values of heat fluxes in the two opposing directions. The rectification effect is commonly described by the heat rectification ratio RR (or sometimes denoted as γ), expressed as a percentage difference normalized by the reverse flux [89] with an equivalent ratio form [7].

$$RR = \frac{q_{\mathrm{fwd}}}{q_{\mathrm{rev}}} \tag{3}$$

$$RR = \frac{q_{\mathrm{fwd}} - q_{\mathrm{rev}}}{q_{\mathrm{rev}}} \tag{4}$$

$$RR = \frac{\left|q_{\mathrm{fwd}}\right| - \left|q_{\mathrm{rev}}\right|}{\left|q_{\mathrm{rev}}\right|} \mathrm{x}100\% \tag{5}$$

$$RR = \frac{\left|q_{\mathrm{fwd}}\right|}{\left|q_{\mathrm{rev}}\right|} - 1 \tag{6}$$

Here, the direct heat flux is denoted by q_{fwd} (typically the higher magnitude of heat flux), whereas the heat flux in the opposing direction is denoted by q_{rev} (lower magnitude of heat flux), when an equal temperature gradient along the electronic device in both directions is applied. A stronger rectifying effect corresponds to larger positive values of this coefficient, with RR $= 0$ indicating no rectification.

A further approach is asymmetric interface development, which manipulates heat carriers like phonons or electromagnetic radiation through the use of geometrical asymmetries (such as conical forms, nonuniform gaps, or layered composites). When coupling efficiency is directionally dependent, near-field phenomena, like evanescent waves, including surface phonon-polaritons and surface plasmon-polaritons, may qualify for heat rectification in the context of radiative heat transfer. Sub-10-nm gaps, layered or phase-change materials, and strong temperature-dependent emissivity or phase-change behavior often exhibit higher rectification, while larger gaps and temperature-insensitive dielectrics result in lower rectification efficiency. For enhanced rectification behavior, deliberate mismatches or gradients within surface textures, material properties, or electromagnetic responses are critical. Insightful data may be gained without direct numerical normalization by linking rectification performance across various systems to specific mechanisms and device types, such as logic gates, diodes, or thermotronic devices. In general, heat rectification entails various kinds of physical mechanisms that encompass material nonlinearity, structural asymmetry, and wave-matter interactions; it is not merely the heat equivalent of electrical rectification. Developing thermo-diodes and other heat management devices in sophisticated electronic logic circuits requires an understanding of these principles and the ability to effectively apply them.

5.2. Micro- and nanoscale heat rectification: materials, geometry, and near-field effects

The mounting challenge of temperature regulation at micro- and nanoscale length scales renders near-field heat rectification increasingly essential in these systems. At these scales, traditional conduction and convection gradually give way to emerging mechanisms, such as NFRHT. Similarly, integration restrictions, including signal degradation and limited logic gate scaling, are observed in on-chip iontronic circuits that employ ions as charge carriers via bipolar polyelectrolyte diodes, underscoring the demand for unconventional techniques to sustain performance [90]. Together, these factors highlight unique opportunities to leverage and induce NFRHT-based heat rectification for improved heat management in next-generation micro- and nanoscale systems. In small-scale systems, heat rectification can be accomplished by meticulously crafting the geometrical design and material properties. Leveraging materials with thermodynamic characteristics, such as conductivity or emissivity, which shift dramatically with temperature, is one of the most accessible approaches. Since the rate of heat transfer varies when the temperature gradient is reversed, the total heat flow becomes directionally dependent when two of these materials are connected asymmetrically (for example, in a bilayer structure).

Phase-change materials like VO_2 underscore their crucial near-infrared (NIR) energy modulation capability [91], as they transition from insulating to metallic states at certain temperatures and are highly beneficial. As observed in Fig. 12, recent work has examined the impact of stoichiometry on the structural phase shift within suspended single-crystalline VO_2 nanobeams by constructing a pseudo-T–δ phase schematic with both temperature and stoichiometry dimensions [92]. Whether triggered by temperature changes, electrical impulses, or optical excitation, this reversible phase shift enables multifunctional smart material behavior, allowing a wide variety of device applications. Its integration potential in heat-regulating systems is facilitated by the close proximity of VO_2's phase shift to ambient temperature as well as scalable thin-film fabrication techniques like chemical vapor deposition. Benefits of this approach include a high energy storage density (50–100 times greater than sensible heat) and reduced temperature swings, which have the ability to minimize heat loss [93]. These materials also exhibit significant rectifying behavior due to their rapid shift in heat transfer efficiency, notably when combined with materials that have relatively constant properties.

Micro/nanoscale heat rectification likewise relies largely on geometrical asymmetries. Heat carriers like phonons or radiative waves can be impacted by structures with different cross-sections, tapering forms, or asymmetrical surface patterns. As an illustration, conical or pyramidal designs can efficiently direct heat flow in a single direction by facilitating direction-dependent mode conversion or scattering. Roughness gradients, gratings, and metasurfaces are examples of surface nanostructures that may alter the local density of states for photons or phonons, enhancing the efficacy of heat transmission in one direction while decreasing it in the other. In particular, AZO nanostructured pillar arrays, when arranged a few hundred nanometers away under the influence of a 1000 K to 300 K temperature gradient, can significantly enhance near-field radiation transmission by over 30 times relative to far-field blackbody radiation [94].

Moreover, at the nanoscale, where component separation becomes smaller than the heat wavelength, near-field radiative effects become exceedingly significant. In this domain, radiative heat transmission that exceeds the blackbody limit is deemed achievable through evanescent waves, including surface phonon-polaritons or surface plasmon-polaritons, which can tunnel between surfaces. Specifically, for vacuum gaps below 20 nm, near-field photon transport between materials such as intrinsic silicon and doped silicon or SiO_2, exhibits significant heat rectification, with rectification factors normalized across comparable temperature differences reaching as high as 9.9 [72]. By employing material asymmetries and vacuum gap alterations, these near-field infrared rectifiers allow for directed heat transfer in the absence of physical contact. To generate powerful rectifying effects without tangible contact, asymmetries are created in the material interface or in the spatial distribution of these near-field modes, allowing for non-invasive control of heat.

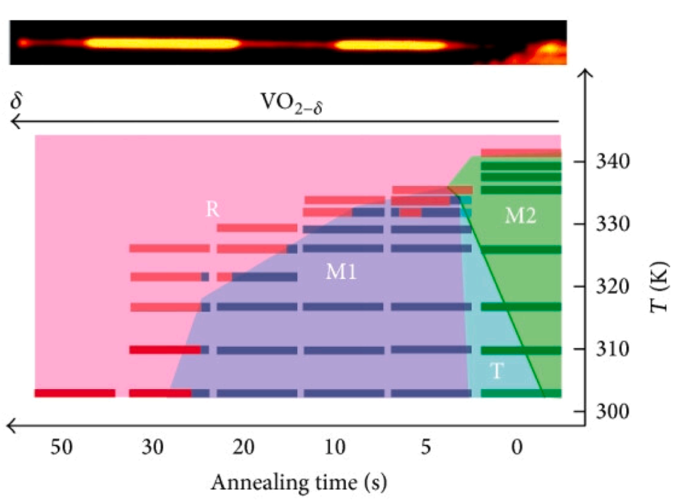

Fig. 12. $VO_{2-\delta}$ structural phase mapping as a function of annealing time and temperature. A pseudo-*T*–*δ* phase diagram is represented by the shaded region. Brighter regions represent the insulating phase, whereas darker areas suggest the metallic phase, determined by confocal reflectivity measurements conducted with a 532 nm laser [92].

With all factors considered, inducing NFRHT-based heat rectification at the micro- and nanoscale is an elaborate challenge that necessitates precise control over geometry and materials. The use of thermo-diodes and logic circuits that rely on directed heat transfer is becoming substantially more practical due to advancements in material science and nanofabrication. These innovations pave the way for advanced heat control systems in future-oriented microelectronics, where energy efficiency is crucial and capacity is at a premium. As a means to assess these implementations from the perspective of the FoM, rectification efficiency is correlated with fabrication feasibility, gap uniformity, and phase stability pursuant to cyclic operation, all of which together define the near-field heat-based logic architectures' practical viability.

5.3. Integration of heat rectification in electronic logic circuits and thermal logic systems

A potentially lucrative path in contemporary micro- and nanoelectronics is the integration of heat rectification into electronic logic circuits, particularly as devices continue to shrink and operate at higher power densities. The main priority of conventional electronic design has been controlling electrical impulses, while heat has been treated as a byproduct and dissipated through the use of external cooling devices. Temperature effects, however, can no longer be regarded as secondary when circuit dimensions approach the nanometer scale and functional densities rise. Uncontrolled and excessive heat can reduce device lifespans, affect performance, and even cause malfunction. In vacuum, microfabricated hotplates divided by nanometric gaps display up to a 6.4-fold enhancement of radiative heat transfer, demonstrating that placing bodies within close proximity at sub-micron distances may substantially improve radiative heat transfer and generate heat fluxes higher than the blackbody limit [77]. In this respect, heat rectification offers an innovative strategy, allowing not only for heat removal but also for the active control of temperature gradients within the circuit.

Heat rectification may be incorporated directly into circuit design to dynamically regulate temperature profiles by facilitating directional control of heat flow. This implies that heat generated in a specific region of a chip can be steered towards heat sinks or more heat-resilient components, while avoiding heat-sensitive areas completely. By boosting operational stability and efficiency, this localized control enables better protection of sensitive transistors, logic gates, and memory units. Heterogeneous systems, where various chip components may perform under different heat conditions or require temperature isolation to be functional, render this feature extremely valuable. In addition, the use of rectifying components and heat diodes can be designed to behave similarly to electrical logic parts. Scalable radiative infrared logic gates [95], for example, have been proposed in which data is transmitted by heat instead of electric current. Controllable hybrid plasmonic integrated circuits (CHPICs), with nano-antennas and graphene-based power splitters, are examples of advanced configurations that demonstrate how photonic and plasmonic waveguides can be coupled to support effective inter/intra-chip wireless transmission and sensing applications [96]. The establishment of hybrid circuits that integrate electrical and temperature signal processing is made viable by this temperature computation paradigm, which could minimize energy consumption for specific tasks such as low-power sensing or data storage in temperature-volatile settings.

The design of energy-efficient electronics is further enhanced through the integration of heat rectification into logic circuits, especially in systems that do not contain active cooling devices. The ability to dynamically control heat flow may reduce the necessity for large cooling equipment in fanless or passively cooled gadgets, such as wearable technology or components with small dimensions. Furthermore, the emergence of contactless heat pathways, which may be effortlessly integrated into circuit topologies featuring a high density, is enabled by the seamless integration of heat rectification and NFRHT mechanisms. Essentially, heat management shifts from an adjunct difficulty to a fundamental design principle when heat rectification becomes interwoven into electronic logic circuits. Along with supporting device miniaturization and fostering heat resilience in contemporary computing systems, it makes possible a new degree of functional control that enhances electronic performance.

6. Integration of NFRHT and heat rectification in electronic circuits: technical challenges and design strategies

Building on the principles of heat rectification and directed thermal transport outlined in Section 5, this section examines the integration of NFRHT and heat rectification into electronic circuits, highlighting both technical challenges and design strategies. The integration of NFRHT-based rectification promises precise, nanoscale thermal control, enabling enhanced device stability, energy efficiency, and novel thermologic functionality. However, realizing these advantages requires careful consideration of material selection, thermal isolation, fabrication constraints, and circuit design, as well as the interplay between heat and electrical performance.

6.1. Challenges in integrating NFRHT-based heat rectification with electronic circuits

Section 6.1 specifically addresses challenges, detailing the difficulties of maintaining temperature gradients, achieving material compatibility, and co-optimizing thermal and electrical domains at the micro- and nanoscale, thereby setting the stage for effective design strategies and functional integration in Section 6.2.

6.1.1. Material selection and thermal isolation challenges

Significant potential for localized temperature control is presented by the integration of heat rectification and NFRHT in electronic circuits; however, this approach additionally poses a multitude of material and technical challenges that require attention. Establishing accurate heat isolation between component parts that require different temperature profiles is one of the most important challenges, especially as the development of beyond-binary and multiple-valued logic (MVL) systems increases circuit density and material complexity at the micro- and nanoscale [97]. Similarly, sophisticated device topologies that enable reconfigurable binary/ternary logic inverters, such as heterojunction non-volatile memory transistors (H-MTRs), emphasize the necessity of precise heat management because of their high integration density and localized current fluctuations [98]. Maintaining different temperature zones becomes progressively difficult as electronic logic circuits become denser and more complex at the micro- and nanoscale. The high radiative coupling promoted by NFRHT over short distances makes it exceedingly difficult to prevent undesired heat leakage into heat-sensitive regions, despite its effectiveness across nanometer-scale gaps.

6.1.2. Material compatibility, fabrication constraints, and structural stability

Effective near-field infrared radiation harvesting additionally requires integrating high-quality, low-bandgap (0.8 eV) materials [99], maintaining sub-wavelength gaps, and sustaining substantial temperature differentials under steady cooling. Fabricating two large-area surfaces separated by a relatively small distance while retaining a large temperature differential makes the realization of a scalable platform for near-field heat transfer energy harvesting even more challenging [100]. Furthermore, rectification frequently necessitates spatially variable heat transfer properties, making it challenging to fabricate seamless transitions across infinitesimal areas of the medium [101]. It is also crucial to ensure material homogeneity, mechanical stability, and resistance to heat cycling, since any flaws or deviations at the nanoscale may drastically lower device efficiency and restrict its practical implementation in real-world applications.

Compatibility of materials remains another fundamental challenge. The phononic and optical properties of the materials significantly impact the efficiency of heat rectifiers and near-field interactions. Materials such as polar dielectrics and plasmonic metals are commonly employed as they can sustain surface phonon- and plasmon-polaritons, respectively. However, material behavior can be complex, tensile strain in graphene/h-BN heterostructures may increase interfacial heat conductance by aligning phonon modes, yet tensile strain in graphene and graphene nanoribbons can reduce conductivity due to phonon softening [102]. Due to conflicting phonon effects, heat conduction efficiency in graphene/h-BN superlattices varies with strain, and conductivities shift from coherent to incoherent phonon transport. Graphene/h-BN superlattice monolayers exhibit non-monotonic behavior with periodic length, first descending and then increasing, exhibiting a conductivity minimum at a defined periodic interval [103].

Integrating these materials into conventional semiconductor manufacturing adds further challenges. The selection of materials is limited by critical factors such as stability during extended temperature cycling, compatibility with complementary metal-oxide-semiconductor (CMOS) circuitry, and resistance to degradation under the influence of strong electromagnetic fluxes. Additionally, rectification often requires asymmetric material couplings or patterned interfaces, complicating multilayer assembly and fabrication. A descriptive FoM approach contextualizes these fabrication and reliability limits in terms of performance to support these qualitative discussions. While maintaining reasonable gap uniformity, minimal surface roughness (<5 nm RMS), and stable performance across $>10^4$ heat cycles, a high FoM device offers great rectification efficiency (η or HRR). The most practicable thermotronic systems balance rectification strength with CMOS-compatible development and production resilience, as indicated by this viewpoint, which unifies efficiency, reliability, and manufacturability.

6.1.3. Circuit design constraints and coupled heat–electrical performance

Heat rectification and NFRHT performance are further significantly impacted by circuit design. Conventional electronic circuit designs prioritize signal integrity and electrical productivity above radiative heat control. Adding features such as surface gratings, nanoscale gaps, or asymmetric geometries to facilitate directional heat flow and near-field coupling may complicate fabrication or obstruct electrical pathways. While advanced fabrication techniques like atomic layer deposition (ALD) [104] and atomic layer etching (ALE) [105] allow for precise control at the atomic scale, they also add design constraints that make it harder to achieve uniform thin films, high-aspect-ratio structures, and minimal surface damage while incorporating heat-control features. Achieving a balance between heat control management and electronic performance often requires co-optimization of electrical and heat-control domains. Design restrictions are also imposed by the requirement to maintain precise nanometric separation between interacting surfaces while ensuring mechanical stability during the device's lifespan, particularly in dynamic or portable systems where near-field coupling may be affected by vibrations and heat-induced expansion.

6.2. Strategies for effective integration of NFRHT and heat rectification in electronic systems

Innovative design approaches that adequately account for the components' electrical and heat demands are necessary for integrating heat rectification and NFRHT into electronic systems. The target is to efficiently control heat without compromising the performance of electrical circuits. The selection of material designs, geometrical arrangements [106], and integration strategies that enable effective directed heat flow and accurate heat control are among the main focuses of several types of design methods that may be implemented to maximize heat management. Complementing this, heat recovery in complex batch processes can be significantly enhanced by process-level approaches such as pinch analysis and energy storage. Up to 85 GJ/day can be achieved through heat exchangers and 17 GJ/day via storage systems, highlighting the importance of integrated heat management that goes beyond material-focused solutions [107].

Leveraging asymmetric material pairings designed to promote heat rectification has emerged as one of the main strategies. The underlying concept behind heat rectification is that heat can preferentially flow in one direction, just as electrical current flows in a diode, resulting in more effective heat management. Through the inclusion of materials with different optical and phononic properties, including semiconductors, plasmonic metals, or polar dielectrics, it is feasible to create interfaces that display asymmetric heat transmission. Since two-dimensional (2D) materials have atomic thickness, rapid carrier mobility, and adaptable electrical properties, they are being applied progressively more in sophisticated applications [108]. These materials may be used for nanoscale heat management as well as miniaturized transistors. This ensures that heat produced within a device's high-power parts, such as logic gates or power transistors, may be diverted away from delicate parts, preserving stability and operation.

Additionally, geometric design is essential for enhancing the efficiency of heat rectifiers and NFRHTs. For example, the efficiency of heat redirection can be boosted by positioning heat rectifying materials nearest to the circuit's heat-sensitive regions. Designs like surface or rectangular gratings [109] and nanoscale gaps between surfaces where, as the gap distance decreases in the vicinity of the distinctive heat wavelengths ($\lambda_{th} = \frac{\hbar c}{k_B T}$), radiative heat transfer can surpass the blackbody limit by many orders of magnitude [14,110], have the potential to strengthen near-field coupling by encouraging robust interactions between radiative fields. Heat may be effectively diverted from the chip's vital regions thanks to these arrangements. To further optimize the heat dissipation process, curvature and surface roughness of the materials are factors that must be taken into account since they may influence the magnitude of near-field heat transfer. Implementing dynamic heat routing mechanisms could enhance the heat management approach even further. Combining active control components, such as phase-change or thermoelectric materials that respond to shifts in environmental temperature, can potentially accomplish this. Depending on the real-time heat distribution, these systems may adaptively channel heat into various zones of the device, preserving the circuit's stable operation and prolonging the component lifespan.

Heat transmission is commonly mediated through surface phonon-polaritons or plasmon-polaritons in cases of heat rectifying material arrangements near electronic components. To enable the coupling of NFRHT, these setups typically involve coating semiconductor surfaces with thin layers of polar dielectric materials or metals that have precisely controlled gaps. For efficient heat rectification, the heat conduction of the materials is carefully selected to showcase notable anisotropic behavior. For example, a thin film of silicon carbide applied next to a semiconductor surface might reroute heat flow away from sensitive regions or towards heat sinks, maintaining the system as a whole within ideal temperature ranges. Heat rectifiers must be precisely fabricated at the micro- and nanometer scales in order to be integrated into nanoscale circuitry. The small gaps, patterns, and surface properties sought for effective near-field interactions are commonly produced using methods such as electron-beam lithography [111] and molecular beam epitaxy [112]. Additionally, these complex geometries may be precisely created using advanced techniques such as directed self-assembly or nanoimprint lithography [113], ensuring that the system functions within the desired temperature limits. Effective heat management and enhanced device performance may be attained by fusing these cutting-edge manufacturing processes with precisely designed materials and geometries.

By mapping each rectification mechanism to its corresponding functional role within logic circuits, a preliminary integration framework may be established to connect the dots between mechanism-level insights and circuit-level design. Spectral selectivity regulates the frequency-dependent radiative channels essential for logic-level signal isolation, as illustrated by temperature- and wavelength-dependent optical properties of ceramics and semiconductors [114]; phase-change media enable adaptive or switchable routes ideal for reconfigurable heat logic, as evidenced in VO_2-based thermochromic phase-change behavior [91]; material asymmetry controls directional heat flow and can be coupled with diode-like thermal elements, as demonstrated in asymmetric nanobeam structures [115]; and nanoscale gap control fine-tunes coupling strength and response speed, as proven in graphene-assisted NFRHT. This taxonomy emphasizes that, for effective thermotronic computation, an NFRHT-based circuit design should inherently integrate these physical principles with circuit functions, such as gating, amplification, or signal routing, rather than considering material or geometric asymmetry in isolation. The incorporation of NFRHT rectification goes beyond incremental material optimization by articulating this structure, moving closer to a design philosophy that draws upon logic architecture and physical mechanisms.

The FoM paradigm, which holds that the most desirable designs maintain high rectification ratios under practical fabrication tolerances and integration restrictions, is consistent with such an integration philosophy. The FoM approach bridges the gap between idealized optimization and practical thermotronic systems by establishing a correlation between feasible rectification performance and gap uniformity, material stability, and switching reliability. This qualitative FoM assessment guides practical logic-level implementation by integrating manufacturing feasibility, reliability, and performance measures across nanoscale rectification architectures.

6.3. Performance enhancement in logic circuits via near-field heat rectification

Electronic logic circuit heat management is revolutionized by near-field heat rectification, which offers notable advantages in device longevity and performance. By employing the nanoscale directional control of radiative heat flow, heat can actively be diverted from vital components, including logic gates, memory units, and transistors. Recent molecular dynamics simulations by Jiang et al. [116] demonstrated that kinks in silicon nanowires may reduce thermal conductivity by up to 70% at ambient temperature. Driven by phonon interchanging and pinching mechanisms, the resulting reduction presents an alternative means to control heat transmission in nanoscale structures. Localized overheating is a typical cause of performance decline and early malfunction in dense integrated circuits, and thus tailored heat removal supports its prevention. The rising complexity and shrinking size of logic circuits make it impractical to dissipate heat effectively and uniformly using conventional cooling techniques. On the flip side, near-field rectification provides a compact, non-invasive way to control heat precisely at its source, ensuring operational stability even under heavy workloads.

High-density circuits and cutting-edge technologies like quantum computing further amplify the advantages of near-field heat rectification. Temperature isolation and homogeneity are particularly critical in these systems. For instance, in qubits used for fundamental logic operations, excessive heat can introduce noise or decoherence, and reduce computing efficiency. By isolating temperature-sensitive zones and redirecting waste heat into regions that are either more heat-resilient or equipped with specialized dissipation structures, near-field heat rectifiers can be designed to meet these demanding specifications. Furthermore, these rectifying devices can be integrated into circuit layouts without compromising performance or capacity due to their small size. Key metrics relevant to logic circuits are taken into account when evaluating the performance of these devices, including switching time, energy per switching event, thermal gain, resistance to thermal noise, and durability under repeated thermal cycles. These metrics are directly mapped to logic primitives such as thermal diodes, thermal switches, and thermal gates, providing guidance for design decisions. Recent advances in carbon-based nanomaterials, including carbon nanotubes, graphene, and hybrid nanocomposites, exhibit unique physicochemical properties and robust structural stability, which have been widely utilized in advanced energy storage systems [117], suggesting their suitability as high-performance materials for applications that demand efficient and stable nanoscale energy or heat management. Ultimately, near-field heat rectification enables the next generation of micro- and nanoelectronics to achieve higher reliability, energy efficiency, and functional sophistication by offering unparalleled heat management.

7. Advances and comparative insights in heat rectification under NFRHT

Building on the integration strategies and design considerations discussed in Section 6, this section focuses on the latest advances and comparative insights in near-field heat rectification within electronic circuits. By systematically synthesizing experimental and computational studies, it highlights performance trends, material innovations, and device architectures that drive effective rectification. Section 7 emphasizes how factors such as gap distance, material composition, phase-change properties, and nanoscale geometries jointly influence rectification efficiency and device functionality. The comparative framework presented here, including quantitative performance metrics and mechanistic analyses, provides practical, context-sensitive benchmarks for thermotronic devices such as diodes, transistors, and logic gates, translating mechanism-level insights into design guidance for next-generation nanoscale heat management.

Building upon the systematic data extraction and synthesis framework outlined in the Methods section, this section also presents a structured comparative analysis, trend identification, and performance evaluation of key studies. Many recent studies have substantially augmented the understanding of heat rectification performed under NFRHT conditions within electronic logic circuits. Near-field effects can presently be validated more readily due to laboratory techniques, which allow for precise evaluation of heat flow at the nanoscale. Significant experimental studies have shown that heat rectifiers could potentially be used in electronic circuits, providing useful details on asymmetric heat transfer along a specific direction [89,118] and efficient design techniques. In support of this, computational models [72,83,119,120] have led to in-depth simulations of near-field radiative heat flow and how it affects circuit performance. This has made it possible to include heat rectification concepts directly into the design of next-generation micro- and nano-electronic devices.

The studies selected provide a range of perspectives for enhancing heat rectification and NFRHT performance in various material systems, gap distances, temperature bands, and measurement techniques. Consistent with the standardized extraction parameters defined in the Methods section, a crucial point of comparison is the composition and structure of the material, either in solid-state [84] or liquid-state, which has a significant effect on normalized HRR. To demonstrate whether topological insulator materials could enhance radiative heat transmission, Odebowale et al. [120] studied a layered system including indium antimonide (InSb) and SiC combined with bismuth selenide (Bi_2Se_3). Their modeling findings indicate remarkable performance under moderate temperature environments, with a high rectification effectiveness normalized over ΔT reaching up to 93% ($\eta = 0.93$) at 500 K and 75% at 350 K within an enclosed 20 nm gap. Comparatively, Bernardi et al. [56] implemented a custom-built device with adaptable gaps between intrinsic silicon planar surfaces and found that a 150 nm vacuum gap under a temperature gradient of approximately 120 K could result in a significant NFRHT enhancement of 8.4 times the blackbody limit, even without the use of topological materials. Collectively, the findings of Odebowale et al. [120] and Bernardi et al. [56] provide a basis for heat computing systems and scalable logic devices, particularly in NFRHT-based designs operating at moderate to high temperatures. Moreover, these studies further confirm that the amplification of evanescent-wave tunneling and the achievement of effective heat rectification in sophisticated thermotronic systems depend on both material properties (such as phase and topological behavior) and precise control of nanoscale gaps.

Employing fluctuation-based electrodynamics modeling, Wang & Zhang [72] examined prospective combinations of intrinsic silicon, doped silicon, SiO_2, along with gold over extremely narrow gaps (5 to 500 nm). With the greatest rectification factor normalized for comparable ΔT ($R = 9.9$) between intrinsic Si and SiO_2 at a 5 nm gap and exceptional performance ($R = 2.7$) for both intrinsic and doped Si, these findings underscore the significance of gap-dependent rectification. At a broader 500 nm gap, the rectification factor decreased sharply to 0.85 for Si-Au, demonstrating that near-field effects may decline with increasing gap separation. A distinctive feature of the study of Gu et al. [83], compared with the finding of Wang & Zhang [72], is its reversal of heat flux, which can be achieved by manipulating the VO_2 film's phase and position. As a result, an overall power density of 7.5×10^3 to 3.2×10^4 W/m^2 was obtained. Given its reversible behavior near the metal–insulator transition temperature, this implies that VO_2 is an ideal fit for switchable devices such as logic gates or heat transistors, especially in the terahertz (THz) frequency range [121], electromagnetic (EM) shielding [122], and absorbing applications [123].

Across studies, Wen et al. [119], who evaluated intrinsic silicon nanoparticles combined with different materials, reported the highest HRR, surpassing record-high values of over 10^4. Their efficacy was explained by temperature-induced dielectric shifts in silicon, allowing for a dynamic and tunable thermo-diode effect, governed by fluctuation electrodynamics. Although the investigation encompasses a broader temperature spectrum (300–1000 K) and larger gaps (<1000 nm), it reveals that tailored dielectric properties [124] can significantly enhance nanoscale heat control, either through compositional or structural tailoring [125]. Through comparative trend identification and performance evaluation, the studies conclude that measurement method, gap distance, and material selection are crucial elements that influence heat rectification performance. Due to idealized conditions, simulation-based analyses [83, 119−120] generally suggest higher efficiency. In general, harnessing temperature-sensitive dielectric attributes or integrating phase-change materials is the most effective approach for generating ultrahigh heat rectification in near-field heating systems.

Many studies examine near-field heat radiation in numerous types of devices and applications related to nanoscale information processing and heat control. In alignment with the device-level classification extracted during the synthesis stage, in a study of phononic logic gates, Odebowale et al. [120] used a Bi_2Se_3-coated InSb/SiC system's superior radiative flux and heat rectification to facilitate energy-efficient temperature logic operations. By using a combination of intrinsic and doped silicon, Si–SiO_2, and Si–Au instead of Bi_2Se_3-coated InSb/SiC system, Wang & Zhang [72] analyzed near-field heat rectifiers and diodes and demonstrated rectification effects normalized for consistent ΔT, compatible with thermo-diode applications that regulate directional heat flow over nanoscale gaps. The potential for thermo-switching in adaptive temperature circuits is highlighted by Gu et al. [83], who demonstrated a switch and rectifier device by adding a VO_2 layer between SiO_2 plates, allowing reversible adaptation of heat flow direction. Wen et al. [119] emphasized thermotronic devices like diodes and transistors by enabling active heat control similar to electrical transistors but for the transfer of heat via ultrahigh, normalized heat rectification. Meanwhile, Bernardi et al. [56] presented feasible devices that use evanescent wave tunneling to surpass blackbody heat transfer in their planar silicon-based rectifiers through substantial near-field enhancements. These devices might serve as a basis for future heat rectification innovations. When taken as a whole, these studies underscore a wide range of applications, from active phononic logic gates and transistors to passive diodes and switches, demonstrating the rapidly developing field of nanoscale semiconductors that function by leveraging heat rather than electric charge to mimic electronic components.

For the purpose of offering actionable design guidance and consolidating insights gathered from multiple investigations, this segment compiles representative near-field heat rectification devices into a single overview. Consistent with the structured data extraction and synthesis approach outlined in the Methods section, Table 5 and Table 6 collectively serve as the central comparative framework for this synthesis. Table 5 provides a concise overview of the main selected studies on near-field heat rectification, highlighting their material systems and structures, geometries and mechanisms, gap distances, applied and operating temperature ranges, device footprints, and measurement methods. Every quantitative indicator was standardized to use the same reporting units: temperature variations (ΔT) in kelvin (K), gap lengths in nanometers (nm), and rectification metrics (HRR, R, or η) in their original formats as reported. Complementarily, Table 6 expands upon this, which gathers the quantitative performance characteristics of the same representative devices, including rectification efficiency, switching ratios, on/off conductance, and operating functionality.

Together, these two tables provide an integrated view: key device stack parameters, including material systems, geometrical configurations, gap lengths, operating temperature ranges, rectification performance, and pertinent device types, are presented in Table 5 and Table 6 to enable direct qualitative comparison across diverse experimental and simulation regimes. It is crucial to recognize that different studies use different formulations of the rectification factor, such as R, η, or HRR, depending on their conceptual or experimental frameworks, such that the definition is not universal throughout the literature. The present review therefore adopts a consistent interpretative basis, where the standard expression for rectification is defined as the ratio of forward to reverse heat flux, $R = \frac{q_{\text{forward}}}{q_{\text{reverse}}}$, to maintain clarity while preserving each study's original context and definition. By combining structural data (Table 5) with performance data (Table 6), the tabular synthesis provides a comprehensive framework for cross-study evaluation through the consolidation of all pertinent design parameters and rectification trends, resulting in an effective, context-consistent comparison across devices. This synthesis demonstrates how specific material combinations, gap sizes, and temperature dependencies affect the efficiency of heat rectification, thereby offering practical benchmarks for optimizing thermotronic switches, diodes, and logic circuits.

The overall trend suggests that heat rectification is continuously enhanced in phase-change or layered materials and in nanoscale gaps, highlighting its promise for thermotronic devices and near-field thermal diodes. Consistent with the qualitative and quantitative synthesis strategy defined in the Methods section, by placing significance on qualitative comparisons, categorizing studies under comparable experimental or simulation regimes (e.g., gap size, switching mechanism,

Table 5

Device structure, material configurations, and operating parameters of representative near-field heat rectification studies.

Reference	Material System/ Structure	Geometry / Mechanism	Gap Distance (nm)	ΔT (K) (Applied temperature difference)	Temperature Range (K) (Operating temperature window)	Device Footprint	Measurement Method
Odebowale et al. [120]	InSb, SiC coated with Bi_2Se_3	Planar multilayer stack; temperature-dependent InSb and Bi_2Se_3-coated 3 C−SiC near-field thermal radiation; passive asymmetry via Fermi energy tuning and material contrast	20	~150 (ΔT between 350 K and 500 K)	350−500	Not specified	Simulation; numerical modeling
Wang & Zhang [72]	Intrinsic silicon (Si), doped Si, SiO_2, gold	Planar multilayer near-field radiative setup; surface mode coupling for photon-mediated thermal rectification	5 nm for Si–SiO_2, sub-10-nm for Si−doped Si, 100–500 nm for Si−Au	700 K (Si–SiO_2); 700 K (Si–doped Si); 300 K (Si–Au)	1000 K and 300 K for Si−SiO_2, 600 K and 300 K for Si−Au	Nanoscale planar structure	Fluctuational electrodynamics; Poynting vector; Green's function; fluctuation-dissipation theorem
Gu et al. [83]	Two SiO_2 plates with a 50- nm-thick VO_2 film in between	NFRHT, thermal switching, and phase transition-controlled rectification	150	100	300−400	Not specified	Fluctuational electrodynamics; numerical modeling
Wen et al. [119]	Near-field radiation between nanoparticles of intrinsic Si and a dissimilar material	Configuration of nanoparticles; photon tunneling through temperature-dependent modification of the dielectric function; change in Si's ε" generated from thermally excited carriers	<1000	~700 K (between 300 K and 1000 K)	300−1000	Theoretical nanoscale arrangement; dipole discretization yielded the effective particle radius (~tens of nm).	Fluctuational electrodynamics; combined with Discrete Dipole Approximation; Green's function formalism
Bernardi et al. [56]	Intrinsic silicon planar surfaces (5 × 5 mm²)	Tunneling between planar Si surfaces using evanescent modes for near-field radiative transmission	150–3500	~120 K	~300–420 K	5 × 5 mm² planar plates	Fluctuational electrodynamics; piezo-controlled nanoscale vacuum gap in a custom-built device

Table 6
Quantitative rectification performance, switching characteristics, and device functionalities of corresponding studies.

Reference	HRR / R / η	On/Off Conductance	Key Findings	Application / Device Type	Heat Rectification Remark
Odebowale et al. [120]	Up to 0.93 (η = 93%)	Bi_2Se_3-induced surface mode coupling enhances forward heat flow; strong on/off modulation is estimated from η = 75–93%.	Bi_2Se_3 layer has the ability to improve radiative flux and heat rectification significantly; achieved η of 75% at 350 K and as high as 93% at 500 K.	Phononic logic gates	High rectification efficiency enhanced by Bi_2Se_3 layer
Wang & Zhang [72]	$R = 9.9$ (Si–SiO_2) $R = 2.7$ (Si–doped Si) $R \approx 0.85$ (Au–Si)	≈ 10.9 (Si–SiO_2), ≈ 3.7 (Si–doped Si), ≈ 1.85 (Si–Au), calculated from $R = \frac{Q_{on}}{Q_{off}} - 1$	Heat rectification is observed with intrinsic Si and doped Si ($R = 2.7$) and intrinsic Si and SiO_2 ($R = 9.9$) at 5- nm gap; rectification factor of 0.85 is achieved for Si–Au at 600 K and 300 K; higher rectification is observed in sub-10-nm gaps for Si–SiO_2 and sub-20-nm gaps for Si-doped Si.	Near-field heat rectifiers, diodes	Heat rectification enhances sharply within nanoscale gaps
Gu et al. [83]	7.5×10^3 to 3.2×10^4 W/m²	$G_{on} \approx 320$ W·m^{-2}·K^{-1} , $G_{off} \approx 75$ W·m^{-2}·K^{-1} , $G_{on}/G_{off} \approx 4.27$ ($R \approx 3.27$)	Direction of heat flux is found to be reversible via VO_2 film positioning.	Switch, rectifier	Phase-change VO_2 enables directional heat flow
Wen et al. [119]	$> 10^4$ (record-high)	$G_{on}/G_{off} \gtrsim 1 \times 10^4$ (derived from reported $R > 10^4$); absolute G_{on} and G_{off} not reported	Demonstrated ultrahigh heat rectification attributed to temperature-induced variations in Si's dielectric properties; likely applicable for heat-based diodes/transistors.	Diodes, transistors, and other thermotronic devices	Temperature-sensitive dielectric improves overall heat rectification
Bernardi et al. [56]	8.4 × blackbody (at 150 nm gap)	On/Off ratio ≈ 8.4 ($G_{on} \approx 8.4\ G_{bb}$; $G_{off} \approx G_{bb}$)	Demonstrated significant near-field enhancement in HRR; confirms evanescent wave tunneling enhances heat transfer	Rectifiers	Evanescent wave tunneling substantially enhances heat rectification

temperature range, and material composition), and reporting rectification trends as ranges, qualitative patterns, and mechanisms instead of absolute values to account for variability in definitions, formulations (e.g., R, η, HRR), and operating conditions (gap, ΔT, material pair), this review presents context-sensitive and "apples-to-apples" comparisons across studies. Such a strategy preserves contextual consistency among investigations while enabling cross-referencing across mechanisms and device designs. Consistent performance trends can be identified through this approach, such as the finding that efficiency decreases with increasing separation distance or low dependence on temperature-dependent emissivity, while higher rectification is typically achieved in sub-20-nm gaps, phase-change or strongly asymmetric materials, and circuits with tailored dielectric responses. Additionally, rather than relying exclusively on numerical normalization, this synthesis provides a mechanistic and application-oriented interpretation by relating rectification performance to functional device types such as thermotronic diodes, transistors, and heat-based logic gates as well as to underlying physical mechanisms like material nonlinearity, interfacial asymmetry, and near-field photon tunneling. These mechanism-linked, group-based insights enable valuable comparisons across devices, such as logic gates, thermal switches, and thermotronic diodes, without having to account for direct numerical normalization.

8. Fundamental challenges and frontier gaps in near-field thermal rectification

Direct benchmarking of heat rectification performance becomes increasingly challenging when a rigorous comparison of the reported studies is subjected to limitations and variabilities stemming from material systems, gap lengths, temperature ranges, and methodological techniques. Although Odebowale et al. [120] exhibited exceptionally high HRR for phononic logic gate applications, the implemented simulation-based method could not precisely represent nonlinear conductive behavior, such as that driven by transient phenomena or temperature-dependent thermophysical characteristics [126]. As for Wang & Zhang [72], even though the silicon-based systems showed moderate rectification, without empirical validation, their dependence on modeling based on fluctuation-dissipation imposes an analytical constraint, especially when it comes to the challenges in accurately capturing nonequilibrium, high-dimensional behavior without the presence of substantial data or empirical validation [127]. Even though directional heat flux control was found by Gu et al. [83] using a VO_2 interlayer, the near-field enhancement potential is inherently limited by the comparatively wider 150 nm gap, as fabrication challenges make sub-10-nm systems, where near-field effects are far more powerful, exceedingly hard to attain in real-world nanoscale systems [128]. Among the studies, Wen et al. [119] reported exceptionally high HRR values above 10^4; nevertheless, reproducibility issues arise due to the absence of specific geometrical and material specifications. While Bernardi et al. [56] presented a viable, tunable system featuring silicon plates that demonstrated better heat transfer at 150 nm gaps, rectification efficiency was, however, not measured directly; instead, the emphasis was merely on near-field radiative transfer amplification. With every aspect considered, despite each study offering insightful understandings of thermotronic device design, variations in gap regimes, experimental conditions, and rectification metric nuances restrict the generalizability of a particular study to another and warrant the use of standardized methodologies for precise performance comparison.

9. Emerging frontiers and strategic innovations in NFRHT-enabled heat rectification

To enable credible benchmarking and reproducibility in near-field heat rectification research, enhanced fabrication techniques capable of achieving sub-20-nm gap uniformity and high-throughput replication are essential, alongside extensive empirical validation protocols. In addition to material innovations, future progress will rely on the establishment of open-access databases for cross-comparison of NFRHT performance, development of standardized reporting metrics for rectification efficiency and device reliability, and unified experimental protocols. Future advances in near-field heat rectification suggest that sophisticated carbon-based materials like graphene and carbon nanotubes (CNTs) [129,130] could potentially be integrated into electronic logic circuits. These materials are excellent for enhancing radiative heat management due to their remarkable heat transfer efficiency, adaptable optical properties, and suitability for nanoscale device development. When integrated into circuit components, graphene, for instance, can enable surface plasmon polaritons within the infrared spectrum, facilitating dynamic regulation of near-field heat transfer while enabling tunable heat absorption [131]. Heat conduction anisotropy is a further notable characteristic of CNTs that may be exploited strategically for directional heat rectification.

A feasible hybrid strategy for overcoming heat constraints in high-density electronics is the combination of near-field radiative rectification with conventional cooling strategies, such as hybrid nanofluids, which enhance overall thermal management through improved heat transmission and latent heat storage capacities [132]. Higher heat management performance may be attained through the latent heat absorption of phase-change materials and the rapid heat propagation of carbon-based materials, as shown in the demonstration of carbon-fiber-oriented composite phase-change materials that maintain high latent heat capacity while improving thermal conductivity [133]. Future research should explore combinatorial design frameworks that integrate carbon-based nanomaterials with phase-change media to achieve multi-modal, tunable rectification under variable thermal loads.

The proposed taxonomy expands upon these materials and processes by providing a coherent structure that incorporates the concepts of NFRHT rectification, material asymmetry, phase-change media, spectral selectivity, and nanoscale gap control, into a design philosophy that will guide the development of thermo-logic circuits in the future. By associating nanoscale photon tunneling mechanisms with circuit-level functionality, this design philosophy promotes multi-objective optimization across scales and allows researchers to formulate testable hypotheses regarding performance limits and scaling effects in hybrid NFRHT devices. This framework particularly guides strategic decisions on the deployment of particular rectification techniques within circuit architectures and offers a systematic approach to developing NFRHT-enabled thermo-logic devices. It encourages iterative experimental validation of predictive models to reconcile discrepancies between simulated and real-world heat rectification performance. A fresh perspective on NFRHT-based circuits is encouraged by this taxonomy, which prioritizes system-level integration above isolated material or geometric optimization. This encourages the advancement of multi-modal, energy-saving, and reconfigurable heat-controlled circuitry.

When taken as a whole, these insights serve as a roadmap for the exploration of next-generation thermo-logic devices, offering actionable guidance for experimental design, device optimization, and integration strategies into high-density, high-performance electronic systems. Beyond material-level enhancements, the taxonomy promotes creative solutions by offering a structured relation between NFRHT mechanisms and circuit-level functionality. It constructively draws attention to the significance of co-design frameworks that integrate machine learning-based optimization with NFRHT modeling, enabling predictive performance tweaking and adaptive design iteration for scalable applications in thermal logic, green computing, and nanoscale energy routing. Targeted hypotheses for future research include: (i) quantifying the role of anisotropic thermal conductivity in carbon nanotube arrays under NFRHT conditions, (ii) investigating VO_2 switching speed and fatigue limits under repeated cycling, and (iii) optimizing hybrid metasurface–carbon architectures for tunable rectification across 300–600 K. The development of thermo-logic systems that are scalable, adaptable, and energy-efficient is encouraged by the opportunity it presents for multimodal and reconfigurable device designs.

9.1. Advanced design strategies and implementation framework for NFRHT thermotronic devices

Representative material stacks including VO_2/SiO_2 diodes under transient conditions [134], low-temperature SiC/SiO_2 bonding with nanoscale interfaces [135], and doped-Si/Au architectures [136] emerge as attractive possibilities for thermotronic switching devices and near-field heat rectification when the aggregate insights from comparative investigations are translated into practical design techniques. In order to effectively modulate near-field radiative heat flow within gap ranges of 20–100 nm, where rectification or switching efficiencies are markedly enhanced relative to the far-field regime, these systems take advantage of unique optical and phase-change properties.

In these operating windows, material and structural reliability are still crucial; dielectric breakdown and cyclic stress accumulation within multilayered systems, thermal drift and dopant diffusion in doped-Si, and hysteresis and phase-transition fatigue in VO_2, which arise from its reversible phase transition and associated structural changes, are the main failure modes [137]. Maintaining consistent gap uniformity across the active device region, maintaining surface planarity below 1 nm Root Mean Square (RMS) roughness, ensuring encapsulation integrity and vacuum stability to minimize contamination or outgassing, and precisely calibrating near-field probes or interferometric gap control systems are all necessary for ensuring reproducible and highly efficient device operation. Future studies should systematically quantify how each of these fabrication tolerances affects rectification performance to establish actionable fabrication guidelines. These design and manufacturing factors taken together provide the fundamental framework for the development of reliable, highly effective near-field heat rectification devices that may be integrated into thermotronic logic and nanoscale energy management applications.

Looking ahead, adaptive fabrication feedback systems, NFRHT test-bed integration with MEMS platforms, and the development of modular thermal circuit libraries for fast prototyping will all be advantageous for practical application. Despite significant progress, several critical challenges remain for the NFRHT community. These include achieving wafer-scale devices with gap control on the order of tens of nanometers, developing high-speed VO_2 switches capable of enduring more than 10^6 cycles without fatigue or hysteresis, realizing low-loss metasurface rectifiers operable at moderate temperatures (300–500 K), integrating hybrid NFRHT-carbon materials such as graphene into dense circuit architectures, and reliably fabricating complex geometries and asymmetric structures at sub-100-nm scales with repeatable rectification performance. Proposed research directions include: (i) experimentally verifying VO_2 fatigue thresholds under cyclic NFRHT conditions, (ii) modeling photon tunneling enhancements in sub-20-nm hybrid gaps, and (iii) exploring artificial intelligence–driven predictive design of NFRHT metasurfaces for scalable thermal logic networks. Addressing these challenges is vital for realizing efficient, scalable, and robust performance of NFRHT-enabled thermo-logic devices in next-generation computing and energy systems. Collectively, such perspectives motivate the NFRHT network to pursue the realization of intelligent, thermally adaptable electronics through a coordinated, data-driven, and design-focused approach.

10. Conclusion

In conclusion, this review demonstrates that NFRHT can be an indispensable tool for tackling the growing heat management challenges in increasingly integrated and compact electronic systems. Beyond traditional heat dissipation strategies, NFRHT provides an innovative framework for directed heat rectification in electronic logic circuits by utilizing precise nanoscale gap control, structural asymmetry, and strategic material selection. Across different parameters and factors, Bi_2Se_3, VO_2, gold, and doped silicon represent promising avenues for integrating NFRHT into advanced logic components. With sub-100-nm gaps, this capability to precisely control heat flow could substantially reduce localized overheating and improve the reliability and energy efficiency of future logic devices. Ultimately, this study advocates for further research into the integration of advanced carbon-based materials such as graphene and carbon nanotubes, to enhance thermo-logic technologies, paving the way for the next generation of compact, efficient, and versatile electronic systems.

CRediT authorship contribution statement

Aaron Edward Sheng Jye Teo: Supervision. **Stephanie Yen Nee Kew:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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