

TEMPERATURE SENSING SYSTEM BASED ON FLEXIBLE TEMPERATURE SENSORS FOR IMPLANTABLE GAN POWER DEVICES

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Gallium nitride (GaN) power devices exhibit pronounced self-heating and highly localized hot-spot formation at high power densities, making accurate junction-temperature monitoring essential for reliability management, especially in implantable and weak-convection environments. In this study, a flexible temperature sensor based on a PVA/PANI/CNT ternary composite is developed through a fully low-temperature, MEMS-compatible fabrication process that enables direct lamination onto GaN chip surfaces. The composite material forms a multiscale conductive framework in which hydrogen-bonded PVA, protonation-regulated PANI, and CNT percolation pathways jointly produce a strong negative temperature coefficient and high sensitivity in the low-temperature regime. Three-dimensional thermal-field simulations elucidate the evolution of hot-spot behavior in GaN devices and confirm the necessity of conformal, internally integrated sensing structures for precise thermal monitoring. Experimental characterization demonstrates that the flexible sensor maintains intimate interfacial coupling, captures transient and steady-state junction-temperature variations with high fidelity, and significantly outperforms external NTC sensors, which underestimate the actual junction temperature by 10–20 °C and exhibit substantial response delays. Array-level measurements further visualize spatial temperature gradients across SBD and MOSFET regions, validating the sensor's capability for high-resolution thermal mapping. Beyond device-level integration, the sensor also exhibits stable responses in low-amplitude thermal-disturbance scenarios such as respiratory monitoring, indicating its applicability to broader wearable and implantable systems. These results confirm that flexible, integration-oriented thermal sensing provides an effective pathway for enhancing the thermal management and reliability of implantable GaN power electronics

Keywords: flexible temperature sensor; PVA/PANI/CNT composite; GaN power devices; junction-temperature monitoring; thermal-field simulation; hot-spot detection; MEMS-compatible fabrication

1. Introduction

Gallium nitride (GaN) power devices, owing to their high breakdown electric field, high electron mobility, and excellent thermal stability, are widely regarded as one of the key technological pathways for next-generation high-frequency and high-power-density electronic systems [1]–[3]. In a wide range of high-voltage, wide-bandgap application scenarios – such as radio-frequency communications, automotive powertrains, data-center power management, and power modules operating in extreme environments – GaN devices can maintain stable operation at voltages and power densities far exceeding those of conventional Si devices. However, these performance advantages are accompanied by pronounced self-heating effects [4]. Due to the high carrier concentration localized within the channel region, the limited heat-spreading capability of metal gates, and the thermal boundary resistance at the GaN–substrate interface (on Si or even SiC), GaN devices tend to

develop thermally localized “hot spots” with extremely small spatial dimensions and steep temperature gradients when operating at high power densities [5]–[7]. Numerous studies have demonstrated that the junction temperature is one of the most critical parameters influencing device reliability, lifetime degradation, and breakdown risk [8],[9]. An increase in junction temperature by merely 10–20 °C may cause the device lifetime to decrease exponentially [10],[11]. With the development of monolithically integrated GaN circuits (GaN-ICs) and advanced three-dimensional packaging technologies, the importance of junction-temperature monitoring has become increasingly prominent. Higher integration density, thinner device structures, and stronger thermal coupling within GaN integrated systems render traditional external temperature-measurement techniques ineffective, as they cannot access internal device regions nor maintain calibration stability. Furthermore, thermal cross-talk among closely packed devices contributes to significant temperature differences between functional units, making it difficult for external

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temperature measurements unable to accurately reflect the true thermal state of individual operating blocks [12],[13]. In automotive-grade power systems and implantable electronic platforms where reliability requirements are stringent, real-time thermal management becomes even more essential. Consequently, a highly sensitive flexible temperature sensor capable of being directly attached to, or even embedded within, the GaN chip surface is of critical significance. Real-time and precise monitoring of the true internal junction temperature of GaN devices is thus essential for reliability assessment, power scheduling, and over-temperature protection.

At present, the semiconductor industry still predominantly relies on non-embedded external temperature-sensing methods to estimate the junction temperature of GaN devices [14]-[16]. These include PCB-mounted NTC thermistors, surface-mounted thermocouples, infrared thermography and thermal cameras, and thin-film resistive temperature sensors integrated on the package surface. While these methods offer benefits such as low cost and simple structures, they suffer from inherent limitations in high-power GaN scenarios. First, external sensors are separated from the device junction by multiple intermediate layers (solder, encapsulation resin, dielectric layers, thermal interface materials, PCB copper layers, etc.), and the collective thermal resistance introduced by these interfaces causes the measured temperature to lag significantly behind the actual junction temperature; the response time typically ranges from several hundred milliseconds to several seconds [17]. Second, GaN device hot spots exhibit highly localized spatial characteristics, with typical dimensions below 100 μm , whereas external sensors can only capture the average case temperature or the package-surface temperature. As a result, such sensors inevitably underestimate the steep transient temperature rise associated with hot-spot formation, often leading to an error of 10–30 $^{\circ}\text{C}$ [17]. Additionally, in weak-convection environments such as implantable systems, flexible electronics, or liquid-immersed scenarios, the external sensing approaches are strongly affected by the thermal-diffusion behavior of the surrounding medium, further enlarging the discrepancy between surface temperature and internal junction temperature. In extreme cases, these techniques may completely fail to track rapid junction-temperature variations [18]-[20].

In recent years, flexible temperature-sensing technologies have advanced rapidly. Temperature-sensitive thin-film devices based on polymer conductive composites (e.g., PVA, PDMS, PVP), conductive polymers (e.g., PANI, PEDOT:PSS), and carbon-based materials (CNTs, graphene) have attracted significant interest in wearable systems, electronic skin, and physiological monitoring applications due to their low weight, bendability, and conformal adhesion characteristics [21],[22]. Compared with traditional inorganic materials, flexible temperature-sensing materials can adapt to complex surfaces and form intimate thermal coupling with device interfaces, enabling improved thermal response speed and enhanced

spatial resolution. In GaN implantable scenarios, the device surface typically exhibits stepped topographies formed by metal interconnects, passivation layers, and localized openings. Conventional rigid sensors cannot reliably adhere to such surfaces, whereas flexible films can achieve extremely low interfacial thermal resistance and maintain conformal contact across heterogeneous material boundaries, thereby capturing accurate dynamic temperature information.

Among various flexible materials, ternary composite systems composed of PVA, PANI, and CNTs have shown highly adjustable temperature sensitivity due to the combined effects of CNT-based tunneling networks, PANI protonation-dependent conduction, and PVA hydrogen-bonded flexible frameworks. CNTs provide continuous percolation pathways, PANI enables thermally modulated carrier transport through protonation control, and PVA enhances the temperature-induced resistive response via hydrogen-bond reconfiguration and chain mobility. These mechanisms jointly enable the composite system to exhibit high temperature coefficients (TCRs) in the low-temperature range while maintaining excellent flexibility and stability [23]. Such characteristics offer a promising materials foundation for both epidermal and implantable temperature sensors. However, despite the considerable progress in flexible sensing technologies, their application to real-time junction-temperature monitoring in GaN power devices – particularly for hot-spot detection in weak-convection implantable environments – remains poorly documented.

Moreover, the trend toward miniaturization and high levels of integration in GaN devices imposes stringent requirements on sensor fabrication and packaging. Traditional fabrication processes typically involve high-temperature annealing, electroplating, or sputtering steps, which may damage flexible substrates or compromise the structural stability of conductive polymers. Therefore, developing a low-temperature, GaN-backend-compatible fabrication workflow is essential. Moreover, implantable electronic systems demand mechanical compliance, long-term stability, humidity tolerance, and operational robustness in biological and fluidic environments. As a result, researchers must consider not only TCR and response speed but also how flexible materials behave under the actual thermal fields of GaN devices.

Motivated by these considerations, this work presents a MEMS-compatible flexible temperature sensor that can be directly laminated onto the surface of GaN power chips. The sensor utilizes a PVA/PANI/CNT ternary composite as the temperature-sensitive material and is fabricated through a fully low-temperature, integration-oriented micro-nano processing flow. Real-time monitoring of GaN device hot spots in implantable conditions is thereby achieved. Through three-dimensional thermal-field modeling and multiphysics simulation, we elucidate the thermal-coupling behavior of the composite film under GaN device operation. Experimental measurements and array-level comparisons demonstrate that the flexible sensor

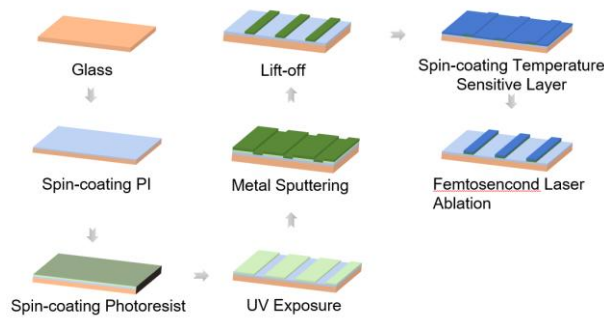


Figure 1: Micro-nano processing flow for flexible temperature sensors of MEMS-embedded gallium nitride devices

achieves high sensitivity, strong conformality, and superior dynamic response in junction-temperature monitoring. Compared with commercial external NTC sensors, we observe that external sensors underestimate the actual junction temperature by 10–20 °C and exhibit significant response delays, whereas the flexible sensor accurately captures the true temporal behavior of hot-spot temperature and maintains high consistency during steady-state operation.

2. Experimental

Building upon the material foundations and application requirements established in the previous section, this section provides a systematic account of the fabrication strategy, structural design, and material characteristics of the flexible temperature sensor. Given the pronounced self-heating behavior and spatially localized thermal gradients inherent in GaN devices operating under weak-convection conditions, the development of an implantable sensing structure necessitates a careful balance between mechanical compliance, interfacial thermal coupling, and microstructural stability of the conductive network. Accordingly, the section begins with a detailed description of the low-temperature microfabrication workflow, including substrate preparation, electrode patterning, and deposition of the ternary sensing composite. This is followed by an analysis of the composite's microstructural features and its thermally modulated conduction mechanisms. Finally, multiphysics simulations are introduced to elucidate the thermal-field distribution and heat-transfer behavior in GaN power devices, thereby establishing the theoretical framework for the subsequent performance evaluation and integration studies.

2.1. Fabrication process of the MEMS-compatible flexible temperature sensor

To achieve direct integration of the temperature sensor with GaN power chips, this study develops a fully low-temperature fabrication process that prevents structural degradation of the functional materials. The overall process includes preparation of the PI substrate,

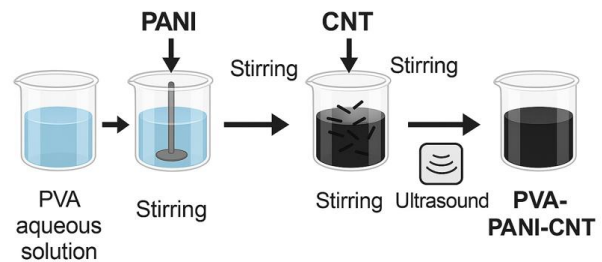


Figure 2: Preparation of the PVA/PANI/CNT ternary composite material

patterning of metal electrodes, deposition of the PVA/PANI/CNT temperature-sensitive film, and femtosecond-laser micromachining. The PI substrate is formed by spin-coating followed by complete curing, ensuring excellent mechanical flexibility. Ti/Au is selected as the metal electrode stack to reduce contact resistance. Femtosecond-laser ablation enables high patterning accuracy and clean edge definition [24].

Figure 1 illustrates the micro-nanofabrication workflow for the flexible temperature sensor used in MEMS-embedded GaN devices. First, a glass substrate is cleaned and dehydrated, after which polyimide is spin-coated and thermally cured according to a predetermined temperature program, forming a uniform and dense flexible supporting layer. Photoresist is then spin-coated on the PI surface and processed by soft baking, UV exposure, development, and post-baking to obtain patterned features. Subsequently, metal thin films are deposited via magnetron sputtering. Lift-off is performed to remove the photoresist and the metal atop it, resulting in metal electrode and interconnect structures with sharply defined boundaries. The temperature-sensitive functional material is then spin-coated over the patterned metal and PI surface and cured at low temperature to form a continuous sensing layer. Lastly, femtosecond-laser ablation is applied to selectively remove excess sensitive material in designated regions, preserving only the sensing channels and electrode-covered regions, thereby producing the final device.

Figure 2 presents the preparation strategy for the PVA/PANI/CNT ternary composite material, in which PVA provides a hydrogen-bonded polymer network, PANI introduces protonation-dependent modulation of thermal conductivity, and CNTs form the conductive percolation framework. The composite ink is formulated in an aqueous solution, avoiding the use of organic solvents that may damage GaN passivation layers. Ultrasonic dispersion and prolonged stirring yield a uniform mixture suitable for spin-coating [25].

During fabrication of the PVA–PANI–CNT composite system, a predetermined quantity of polyvinyl alcohol (PVA) is first dissolved in deionized water to form a transparent and homogeneous PVA solution. Complete dissolution is ensured by magnetic stirring at approximately 90 °C, producing a stable viscous

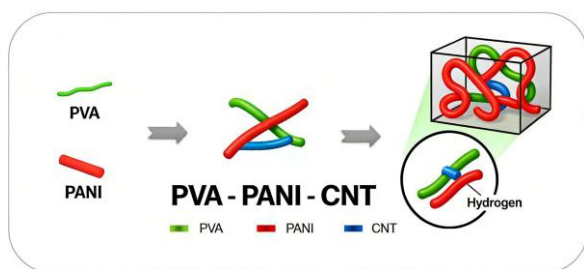


Figure 3: Microstructure and composite mechanism of ternary composite materials

solution. Acid-doped polyaniline (PANI), either synthesized beforehand or subjected to protonation treatment, is then gradually added to the PVA solution. Continuous stirring promotes efficient dispersion of PANI within the PVA matrix and enhances interfacial bonding, forming a stable PVA–PANI binary mixture.

Once the mixture stabilizes, carbon nanotubes (CNTs) are slowly introduced. To improve CNT dispersibility and compatibility with the polymer matrix, stirring is maintained during the addition, with controlled stirring rate and duration to prevent local aggregation. Ultrasonic treatment is subsequently applied; acoustic cavitation breaks CNT agglomerates, further improving uniformity. After sonication, additional stirring ensures that the components achieve homogeneous mixing at both macroscopic and microscopic scales.

The resulting dark, uniform suspension serves as the precursor solution for the composite material. It may be used in subsequent thin-film formation, fiber fabrication, or conductive composite fabrication, providing a stable foundation for both electrical and mechanical properties.

3. Results and discussion

3.1. Microstructural characteristics and material mechanisms of the ternary composite

Figure 3 illustrates the microstructural mechanism of the ternary composite. In the initial slurry stage, PVA molecular chains are dominated by flexible segments containing abundant hydroxyl (–OH) groups. Upon introduction of acid dopants, PANI is converted from its intrinsic state to the emeraldine salt form. Localized positive charges on the benzene rings of PANI form dense hydrogen bonds and electrostatic interactions with the hydroxyl groups of PVA. CNTs, dispersed via ultrasonication, contain a small number of carboxyl or hydroxyl defects on their surface. These defects enable CNTs to form hydrogen bonds with PVA and engage in π – π stacking with PANI, resulting in CNTs being coated with thin PANI layers and progressively interconnected into potential conductive pathways. As solvent evaporates and mild heating is applied, PVA undergoes partial crystallization, forming a mixed network

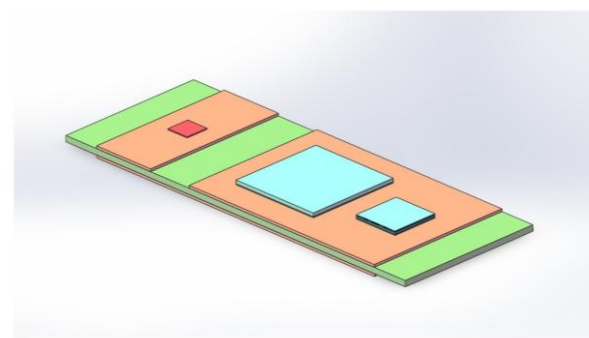


Figure 4: Geometric model diagram of GaN device

consisting of crystalline and amorphous regions. Hydrogen bonds at the crystalline–amorphous interfaces “anchor” the PANI–CNT fragments at multiple points. During subsequent stretching or drying, increased chain alignment in PVA draws the CNT/PANI segments into continuous percolation networks. These networks span across amorphous PVA regions, reducing tunneling distances to the nanometer scale.

Under temperature variation, this microstructure exhibits a coupled response: near the glass-transition temperature of PVA’s amorphous regions, chain mobility increases, enabling reversible hydrogen-bond breakage and reformation, while interfacial distances and tunneling barriers change accordingly. The protonation level of PANI fluctuates slightly with temperature and trace moisture migration, continuously adjusting the electrical conductivity of the PANI-coated CNT network. Macroscopically, the composite film operates as a coupled system consisting of a “hydrogen-bond-constrained conductive skeleton” and a “thermally responsive flexible matrix.” Temperature elevation increases the percolation-path spacing and modifies carrier hopping probabilities, generating stable and reproducible thermoresistive signals.

Overall, CNTs provide high-mobility transport pathways, PANI modulates electrical conduction through thermally induced protonation changes, and PVA contributes mechanical flexibility and structural compliance. These synergistic effects collectively yield pronounced temperature-dependent variation of resistance.

3.2. Multiphysics simulation and analysis of GaN hot-spot behavior

To investigate heat-source distribution in GaN devices under implantable conditions, this study developed three-dimensional steady-state and transient thermal models in COMSOL, incorporating GaN, SiC substrates, metal electrodes, and the flexible sensor film.

Figure 4 presents the geometric model of the GaN-based flexible temperature sensor. From top to bottom, the multilayer stack consists of the device layer, a top copper layer with a central opening, an AlN insulating/heat-spreading layer (green), and a bottom copper layer. The device layer contains three functional units from right to left: a MOSFET, a Schottky barrier

diode (SBD), and a Pt-based NTC sensor. The MOSFET structure includes a Si_3N_4 passivation cap, tungsten gate and aluminum source/drain metal layers, GaN epitaxy, a SiC carrier wafer, and a bottom AlN transition layer. The SBD comprises Si_3N_4 and AlN layers, whereas the NTC uses a thin-film platinum sensing element. The top copper layer provides routing and partial heat spreading; openings are implemented to achieve interconnect isolation and stress relief. The third-layer AlN thin film offers both electrical insulation and high thermal conductivity, enhancing heat dissipation without compromising mechanical compliance.

The simulation incorporates several critical factors: the temperature-dependent thermal conductivity of GaN [26]–[28], heat-diffusion limitations under weak convection (e.g., within bodily fluids) [29], Joule heating associated with metal electrodes, and thermal-boundary resistance at interfaces [30]. Results indicate that at power densities of $10\text{--}20\text{ W}\cdot\text{cm}^{-2}$, pronounced local hot spots develop in the GaN gate region, with temperature gradients reaching $25\text{--}40\text{ }^\circ\text{C}$ per $100\text{ }\mu\text{m}$.

Hot-spot formation originates primarily from high electron-density localization in the channel region, non-uniform heat spreading of gate metals, thermal resistance at the GaN–SiC interface, and significantly restricted convection in implantable environments [31]. These effects yield hot spots with high temperature and extremely limited spatial extent, imposing stringent sensing requirements on microscale flexible sensors.

Figure 5 presents the steady-state thermal field of the flexible temperature sensor – based on the PVA/PANI/CNT composite – when the GaN device operates continuously in an implantable environment. As shown in Figure 5a, the three-dimensional temperature distribution reveals the characteristic thermal-diffusion behavior of power devices under weak-convection conditions: a distinct hot spot first emerges in the high-power-density region on the right side, and subsequently spreads along the device surface toward the sensing window and interconnect routing, forming a directionally pronounced temperature gradient. The top-view distribution in Figure 5b further emphasizes this feature; the densely packed and steep temperature contours near the hot-spot region contrast with the more gradual color changes near the sensing window, indicating that the latter region remains at a relatively uniform temperature. This uniformity facilitates stable measurement baselines and reduces drift-related errors.

Figure 5c visualizes the heat-dissipation pathways through three-dimensional isothermal surfaces. Heat generated at the hot spot propagates along the composite-film layer and the metal interconnects toward the cooler regions. The subtle, finger-like low-temperature structures observed near the device edges reflect the cooling contribution provided by the package and substrate. Figure 5d shows the corresponding isothermal-line morphology, wherein the isotherms near the hot spot appear densely concentrated but gradually expand and become parallel farther from the center. This combined in-plane diffusion and cross-plane conduction behavior is consistent with the highly restricted convection

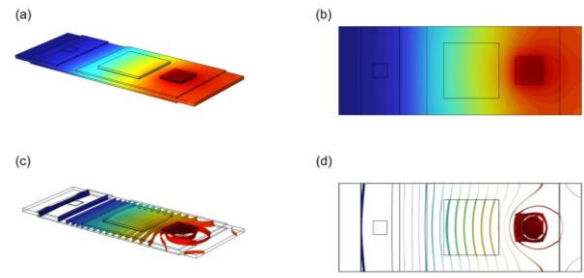


Figure 5: Three-dimensional view of the surface thermal field under steady-state operation of GaN devices (a), xz plane view (b), three-dimensional isosurface thermal-field view with axes view (c), and xz axis view (d)

environment characteristic of implantable systems. The observed distribution also verifies that the present structural design effectively regulates the thermal field in the sensing region.

The ability of the composite material to maintain high sensitivity in such complex thermal environments arises from the cooperative action of multiple internal physical processes. Protonated PANI exhibits thermally activated electrical behavior; as temperature increases, chain segments become more flexible, facilitating proton migration, thereby modifying local polarization and carrier distribution. When PANI coats or adsorbs onto the CNT surface, temperature-induced modulation is further enhanced via π – π interactions and localized de/protonation processes, significantly influencing interfacial energy barriers. CNTs form a continuous percolation network in which charge transport is governed primarily by tunneling; temperature-dependent expansion and chain mobility in the PVA matrix alters the intertube spacing, enabling quasi-exponential modulation of the tunneling barrier and thereby enhancing temperature sensitivity.

In addition, soft interfacial structures composed of hydrogen bonds and interfacial dipoles among PVA, PANI, and CNTs introduce temperature- and humidity-responsive ion and proton conduction pathways. Some hydrogen bonds may reversibly break and re-form as temperature rises, further adjusting interfacial barriers and carrier mobility. The combined effect of these mechanisms ensures that the effective conduction pathways of the network remain highly sensitive to thermal perturbations. The inherent mechanical flexibility of the composite network also preserves stable isothermal-line configurations under bending or minor positional displacement, as shown in Figure 5d, consistent with the macroscopic thermal-distribution characteristics observed in Figures 5a and 5b.

Figure 6 presents the performance evaluation of the PVA/PANI/CNT composite flexible temperature sensor. In Figure 6a, the relative resistance as a function of temperature (R/R_0) exhibits a pronounced negative temperature coefficient (NTC) behavior, with a maximum temperature coefficient (TCR) of approximately $-3\%/^\circ\text{C}$, indicating high sensitivity to

thermal perturbations. The decrease in resistance with increasing temperature can be attributed to the underlying conduction mechanisms of the composite. PVA, serving as the polymer matrix, provides mechanical flexibility and hydrophilicity but is intrinsically insulating; PANI provides π -conjugated conduction pathways, while CNTs form a three-dimensional electrically percolating network. As temperature rises, enhanced thermal motion in the PVA chains reduces tunneling distances and improved contact among the conductive constituents (CNTs and PANI), thus lowering resistance. Meanwhile, the thermally stabilized doped state of PANI (e.g., EB-to-ES transition) increases carrier concentration, further improving conductivity. The extended π - π interactions and high aspect ratio of CNTs ensure continuity of conduction paths, enabling significant resistance variation even in the lower-temperature regime, thereby producing a pronounced TCR response.

The magnified region enclosed by the red dashed box highlights the low-temperature resistance variation. A peak TCR value of approximately $-3\%/^{\circ}\text{C}$ is observed at around 25°C , indicating maximal sensitivity in this temperature range. This pronounced TCR behavior arises from multiple synergistic microscopic processes: slight thermal expansion of the PVA matrix increases chain mobility, modulating nanoscale gaps between CNTs and enhancing tunneling conduction; simultaneously, the protonation state of PANI becomes highly responsive in this temperature regime, with molecular chains transitioning from a rigid to a more flexible configuration, significantly improving local carrier mobility. Additionally, the van der Waals interactions between CNTs become comparable to thermal vibration energies, leading to dynamic reorganization of the conduction pathways. The superposition of these effects results in a thermally activated reconfiguration of the composite network, producing reversible, high-sensitivity macroscopic electrical responses.

Figure 6b shows the real-time resistance variation before and after finger contact. The moment of contact induces an immediate drop in R/R_0 , followed by a rapid recovery once contact is removed. Both the response and recovery times are within a few seconds, demonstrating exceptional sensitivity to small thermal disturbances (e.g., localized heating from skin contact, typically 30 – 35°C). Upon touching, slight softening of the PVA matrix compresses the CNT network, improving conductive connectivity, while thermal activation of PANI increases local carrier transport, jointly reducing resistance. After removal, the system returns to thermal equilibrium, the PVA matrix contracts, and the conductive pathways revert to their initial state. This fast and reversible response confirms the sensor's suitability for epidermal and human-machine interface sensing.

Figure 6c illustrates the resistance response under periodic heating and cooling. The relative resistance follows a repeatable oscillatory pattern synchronized with the imposed temperature cycles. The amplitude remains stable throughout repeated thermal cycling, indicating excellent thermal durability and reliability.

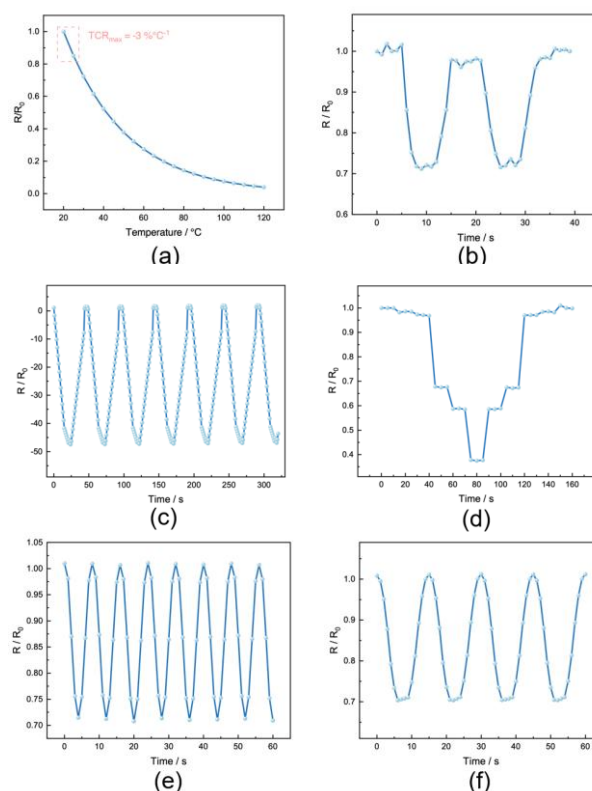


Figure 6: Performance characterization of PVA/PANI/CNT composite flexible temperature sensor: (a) Temperature coefficient (TCR) curve; (b) Finger-touch response; (c) Continuous temperature-rise and fall response; (d) Symmetric step-like temperature-change test; (e, f) Real-time respiratory detection signals under different breathing rates

The consistent waveform suggests strong interfacial adhesion between the PVA matrix and the PANI/CNT conductive network, without delamination or fatigue-induced degradation – an essential requirement for implantable or long-term physiological sensing environments.

In Figure 6d, stepwise temperature changes are applied to the sensor. The relative resistance exhibits well-defined plateau-like regions at each temperature stage: upon heating, R/R_0 decreases; during isothermal intervals, the resistance stabilizes; upon cooling, the resistance gradually returns to its initial value. This step-like behavior reflects the reversible structural adjustments of the composite—thermal expansion of PVA reduces CNT/PANI spacing during heating, enhancing tunneling conduction, whereas contraction during cooling restores the original network geometry. The absence of hysteresis and the stability of each plateau confirm the sensor's strong repeatability and its reliable thermo-electrical coupling mechanism, supporting its use in multi-zone temperature mapping and precise thermal regulation applications.

Figures 6e and 6f display real-time respiratory monitoring signals under different breathing rates. In both datasets, periodic oscillations in resistance correspond closely to the breathing cycle: resistance

increases during inhalation (lower-temperature air flow) and decreases during exhalation (warmer, more humid breath), producing clear and continuous waveforms. The frequency and amplitude of the oscillations accurately track changes in breathing pattern, demonstrating the sensor's capability to detect subtle thermal fluctuations (as small as 2–4 °C). This sensitivity originates from variations in CNT tunneling barriers induced by microthermal disturbances and from temperature-dependent carrier mobility changes in PANI. Additionally, PVA's hydrophilicity enhances interaction with moisture during exhalation, further amplifying the signal. The combined thermal and humidity responsiveness provides multidimensional sensing capability, making the sensor particularly suitable for human health monitoring, sleep assessment, and wearable diagnostic systems.

The sensor's ability to resolve distinct breathing rates with high fidelity further confirms the stability of its thermoresistive network. For rapid breathing, the oscillation frequency increases, while for slow breathing, the waveform becomes more extended; in both cases, waveform morphology remains stable, with no drift or distortion. This robustness highlights the potential of the composite material system for long-term physiological monitoring.

3.3. Integration validation and real-time thermal monitoring of GaN devices

Figure 7 illustrates the conceptual layout of the interdigitated electrode array. The flexible temperature-sensing units are arranged in a circular active region, where each red structure represents an individual interdigitated electrode pair forming part of a high-resolution two-dimensional temperature-sensing matrix.

The overall array is designed such that multiple independent sensing cells are periodically distributed across the substrate, with each cell comprising a pair of interdigitated metal fingers. The array includes electrode pairs with various feature sizes, all fabricated on a single wafer. The interdigitated configuration significantly enhances temperature-measurement sensitivity and spatial resolution. Compared with conventional planar electrodes, the interdigitated geometry increases the effective electrode area and reduces the carrier transport distance, enabling more efficient detection of thermally induced resistance variations. This advantage is particularly important for the PVA/PANI/CNT composite, whose temperature response arises primarily from reconstruction of the percolation network and modulation of tunneling barriers; the intensified local electric-field distribution produced by interdigitated electrodes improves detection fidelity for such rapid and subtle conduction changes.

The array architecture also provides superior mechanical compliance and electrical stability. Each sensing cell behaves independently, allowing the array to accommodate local strain and mechanical deformation – such as bending or curvature matching – without compromising overall circuit integrity. Furthermore, the

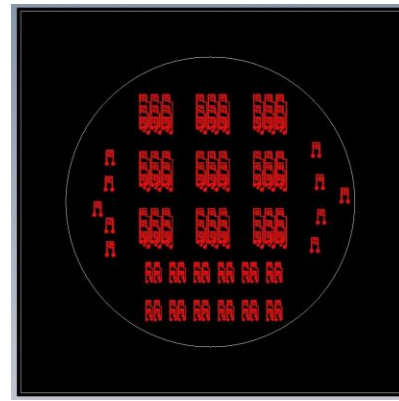


Figure 7: Schematic layout of an interdigitated electrode array. The figure shows the array-like arrangement of flexible temperature sensing units within a circular working area. Each red structure represents an independent interdigitated electrode, which is used to form a high-resolution two-dimensional temperature-sensing matrix

multi-point sampling strategy mitigates the influence of local material defects or contact variations, improving reliability. In implantable or curved-surface integration scenarios, the inherent adaptability of the array provides a critical advantage over traditional continuous electrodes.

Figure 8 displays the array measurements under three operational conditions: (a) before device activation, (b) during active operation, and (c) after the device reaches steady-state thermal equilibrium.

The array test encompasses three functional modules within the same device platform: a commercial external NTC temperature sensor (platinum-based) on the left, and GaN-based SBD and MOSFET modules with built-in temperature sensors in the middle and on the right, respectively. In *Figure 8a*, before power is applied, all three modules exhibit uniform temperatures very close to ambient (approximately 24–25 °C), demonstrating consistent initial conditions and indicating that no significant self-heating or local dissipation occurs prior to operation.

In *Figure 8b*, once the device is powered, the overall temperature rises significantly, and a distinct spatial gradient emerges. Multiple locations within the SBD and MOSFET modules reach high-temperature regions of approximately 80–86 °C, while edge regions or areas closer to dominant heat-spreading paths remain at lower temperatures (slightly above 70 °C). These results indicate that the source/junction regions within the power devices heat up first and that heat then spreads outward along the package and copper conductors. In contrast, the external NTC sensor consistently reports lower temperatures, reflecting its sensitivity predominantly to case- or PCB-level temperatures rather than the rapidly increasing internal junction temperatures. The discrepancy highlights the limited sensitivity of external sensors to localized hot-spot development, which is strongly shaped by thermal interfaces and large time constants.

In *Figure 8c*, after prolonged operation, the device reaches steady state. The central and sub-central regions of the SBD and MOSFET modules exhibit temperatures of approximately 107–110 °C, while peripheral nodes remain considerably lower (approximately 100 °C or less). These results confirm the presence of persistent 8–15 °C spatial temperature variations even under steady-state conditions. At this stage, external NTC readings still significantly underestimate actual junction temperatures. When combined with the dynamic observations in *Figure 8b*, the overall underestimation of junction temperature by external sensors can be inferred to be approximately 10–20 °C, accompanied by response delays ranging from several tens of seconds to several minutes.

The sequential evolution of the dataset – from the initial uniform temperature distribution, through the transient rise, to the final steady-state equilibrium – reveals several intrinsic thermal characteristics of power semiconductor devices. At the beginning of operation, the uniform temperature across all sensing nodes reflects stable calibration and consistent baseline conditions. As the device enters the transient heating stage, internal self-heating progresses far more rapidly than thermal diffusion through the surrounding packaging and structural layers, leading to the early emergence of localized junction hot spots. Once the system reaches steady state, a persistent and substantial temperature difference remains between the junction and the case, accompanied by pronounced in-plane thermal gradients. These observations collectively illustrate the characteristic disparity between internal junction heating dynamics and the slower, interface-limited thermal response of external temperature-sensing structures.

These characteristics reflect established thermal mechanisms of power semiconductor devices: built-in sensors located near or within active regions capture the true dynamics of junction heating, whereas external NTC sensors—limited by packaging materials, interface resistance, and PCB thermal pathways—measure delayed and substantially lower temperatures.

Consequently, relying exclusively on external NTC readings in applications requiring over-temperature protection, power derating, or lifetime modeling (e.g., based on junction-temperature cycling and peak-value tracking) introduces considerable risk. Delayed thermal protection triggering, masked junction-temperature peaks, and inaccurate inputs for reliability models may occur. In contrast, built-in temperature sensing within the SBD and MOSFET modules provides accurate observation of both fast transients and steady-state conditions, enabling more stringent safety-threshold settings and improved closed-loop thermal control.

The experimental results thus confirm that internal flexible temperature sensors are not merely an enhancement but a functional necessity for accurate junction-temperature monitoring and protection in GaN power-electronic systems.

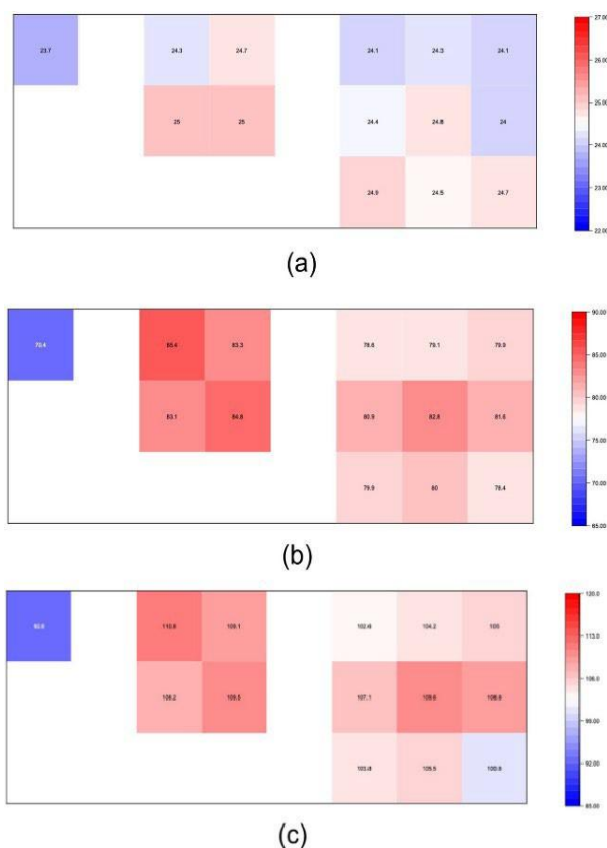


Figure 8: Array testing results of the sensor: (a) Array temperature distribution when the device is not powered on; (b) Temperature distribution during the device's operation; (c) Array temperature distribution after the device reaches steady state

4. Conclusion

This study presents a flexible temperature sensor based on a PVA/PANI/CNT ternary composite and, through systematic material characterization, device fabrication, thermal-field simulation, and multi-scenario experimental validation, demonstrates its broad potential for thermal monitoring in implantable GaN devices as well as in wearable health-monitoring applications. By constructing a multiscale conductive framework composed of a CNT percolation network, a protonation-regulated conductive structure in PANI, and a hydrogen-bonded flexible PVA matrix, the sensor exhibits temperature-dependent dynamic modulation of electronic tunneling pathways at the microscopic level, enabling an exceptionally high temperature coefficients ($\text{TCR} \approx -3\%/^{\circ}\text{C}$) within the low-temperature regime. This characteristic allows the device to accurately reflect local thermal-field variations of GaN power chips under weak-convection implantable conditions and provides a reliable foundation for high-resolution environmental and physiological sensing.

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