

UDC 621.315.592:536.2
EDN: ATYWXM

PACS: 66.70.-f, 81.05.-t, 85.35.-p

Conformal thermal metamaterials – new opportunities for managing heat flows in electronics

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Received 13.10.2025; revised 2.11.2025; accepted 11.12.2025

Overheating is a fundamental barrier to the development of electronics due to the rapid increase in heat flux density (up to 200 W/cm² in processors). The paper presents the results of the development and validation of a new class of materials – Conformal Thermal Metamaterials (CTM), possessing a unique triad of properties: pronounced thermal conductivity anisotropy ($\lambda_{xy}/\lambda_z \approx 20\text{--}30$, where $\lambda_{xy} = 60\text{--}80$ W/(m·K), $\lambda_z = 2\text{--}4$ W/(m·K)), enabling "heat flow turning"; conformality – the ability to precisely replicate surface topography and bend up to 180° for geometric flow control; auto-effect of thermal contact improvement due to micro-extrusion of internal thermal paste. CTMs occupy an intermediate position (level L1+ "flexible planar routing") between rigid anisotropic plates and heat pipes, combining their advantages at a lower cost. Validation experiments on LED strips, point LED sources, and power resistors showed a reduction in crystal temperature by 28–45 °C, equivalent to a 2–3 times increase in service life. The efficiency of CTMs, comparable to aluminum radiators, has been proven, with the potential to create completely flat, radiator-free devices.

Keywords: thermal metamaterials; thermal conductivity anisotropy; conformal materials; thermal routing; LEDs.

DOI: 10.51368/2949-561X-2025-6-17-20

Introduction

The issue of excess heat dissipation accompanies the development of any technology, but in electronics it is particularly critical. As the specific power increases (e.g., up to 10–15 W/mm² in LED systems and up to 200 W/cm² in processors), so does the heat generation, thus leading to overheating and reduced efficiency and reliability of components. Traditional solutions, such as bulky isotropic heat sinks and thermal interfaces, have exhausted their potential as a result of facing limitations including incomplete contact, rigid geometry, and isotropic thermal conductivity. Therefore, the search for alternative materials for heat dissipation has become a major industrial priority. One promising solution is the use of synthetic diamonds grown by chemical

vapor deposition from carbon plasma followed by polishing to an ideal crystalline structure. As a result, they fit to the chip surface as tightly as possible and ensure efficient heat dissipation from hotspots [1]. However, the cost of this solution remains high due to complex manufacturing processes. Hybrid solutions, such as diamond-copper heat sinks, are being developed simultaneously [2]. Considering that the leading global manufacturers adopt manufacturing of 2 nm chips and implement increasingly complex chip packages, the search for new solutions ensuring effective heat dissipation and thermal flow management has become a vital problem [3].

One of such fundamentally new approaches is the use of thermal metamaterials [4], whose properties are determined not by chemical

composition, but by a specially designed microarchitecture. Such materials feature unique properties that cannot be developed using natural substances [5] and consist of numerous elementary cells of a specific shape and size arranged in a periodic pattern [6].

This paper presents the results of the development and experimental validation of conformal thermal metamaterials (CTMM), a new class of materials that combine strong anisotropy of thermal conductivity with geometric flexibility and manufacturability.

Materials and methods

The basis of CTMM is a metal matrix frame [7, 8], which is an assembly of specially bonded micro-profiled and micro-perforated sheets of aluminum foil (see Fig. 1). This matrix is fully impregnated with a highly viscous thermal paste based on zinc oxides. The thickness of sheet samples is 1–1.5 mm.

CTMM shown in Fig. 1 feature a unique triad of characteristics that cannot be found in natural materials.

One such characteristic of CTMM thermal properties is thermal conductivity anisotropy. The developed architecture provides the anisotropy having a technical significance. The transverse thermal conductivity (λ_z) is 2–4 W/(m·K) (measurements were conducted in LG and Foxconn laboratories), while the longitudinal thermal conductivity (λ_{xy}) is 60–80 W/(m·K) (measurements were conducted in laboratories in Sweden and Germany). The anisotropy coefficient reaches 20–30, enabling the effective implementation of the heat flow “turn” effect and its transport within the material’s plane.

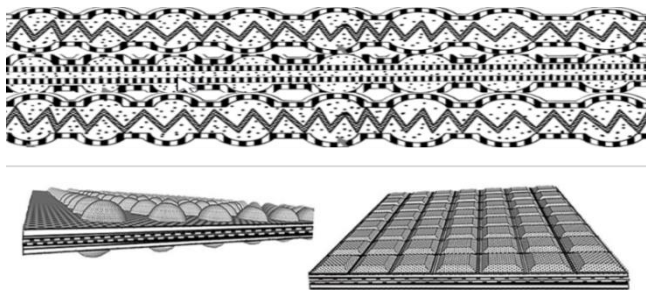


Fig. 1. Topology variants of conformal thermal metamaterials

Another key (mechanical) characteristic is the conformity and flexibility of presented CTMM. Due to the presence of numerous micro-cells and use of thin, ductile foil, CTMM is able to precisely replicate the shape of almost any contacting surface – from a rectangular chip on a printed circuit board to a cylindrical laser – even under minimum pressure. The material bends easily in any direction (up to 180°), thus offering fundamentally new prospects for the geometric management of heat flows. For example, obstacles can be bypassed by simply bending CTMM, which is infeasible for rigid graphene plates.

The third feature (technological) is automatic improving of thermal contact (autothermal contact). During mounting, the thermal paste is extruded through micro-perforations onto the surface (resulting in a “honeycomb effect”), which displaces air, the main enemy of heat transfer, and ensures practically ideal contact in combination with the matrix plasticity.

If CTMM are considered in terms of their ability to manipulate heat flows (heat collection in area A (collector), concentration, transportation, and unloading in area B (emitter), then the concept of thermal routing can be introduced to systematize the capabilities of CTMM, which allows classifying the existing solutions into the following levels:

- L0 (no routing) – isotropic materials (metals, plastics, ceramics), where the flow direction is dictated by external gradients;
- L1 (rigid planar 2D routing) – anisotropic materials (graphenes) that conduct heat in a straight line due to their rigidity;
- L2 (3D routing) – heat pipes, which effectively transfer the heat from point A to point B but are expensive and require additional bulky collectors and heat sinks.

In this classification, CTMM take an intermediate position marked as L1+ (flexible planar 2D+ routing). They not only collect and transport the heat like graphenes, but, due to their conformity and flexibility, can also easily change the trajectory and final destination of heat delivery, bypassing obstacles and adapting to the actual three-dimensional geometry of the device.

Experimental validation of CTMM thermal characteristics was conducted using LED strips, point LED modules, and high-power resistors. Temperature fields were recorded using Testo 873 thermal imager in Super Resolution mode.

Experimental section

To evaluate the effectiveness of CTMM for distributed heat sources, an experiment was conducted to cool an LED strip. The strip was mounted in a plastic profile: its one half was cooled passively, its other half – with an inserted piece of CTMM (see Fig. 2).

As can be seen from Fig. 2, the LED strip at 15 V reached the temperature of 126 °C with passive cooling and 86 °C when cooled using the inserted piece of CTMM. Thus, the temperature difference across lenses (chip temperature indicator) was approximately ~ 40 °C in favor of the section comprising CTM. Temperature reduction by 40 °C can extend the service life of LED several times or allow for a significant increase of light flux.

Steady-state junction temperatures (see Fig. 3) proved to be practically identical, thus confirming the feasibility of front-side cooling and heat flow redirection.

To compare the effectiveness of CTM with standard heat sinks, an experiment was conducted to cool high-power resistors. Several cooling schemes were applied (Fig. 4): a basic scheme using only thermal paste for cooling; a traditional scheme using a E-shaped heat sink for cooling; and a scheme using CTM, where two CTM plates formed a closed “cocoon”-like shell around the resistor.

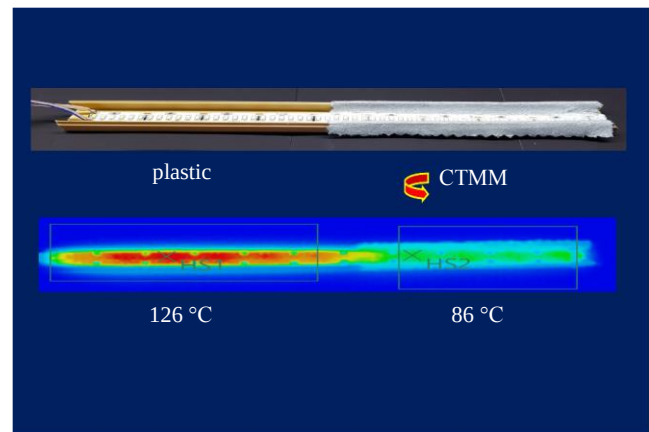


Fig. 2. Comparison of temperature fields of the LED strip in standard cooling conditions (plastic profile) and with the use of CTMM

To demonstrate the “thermal turn” effect, the ability to redirect the heat flow by 180° was shown using high-power point LEDs. One LED was cooled by a traditional E-shaped heat sink, while the other was cooled by tulip-shaped CTM that enveloped the sides and rear and redirected the heat forward (Fig. 3).

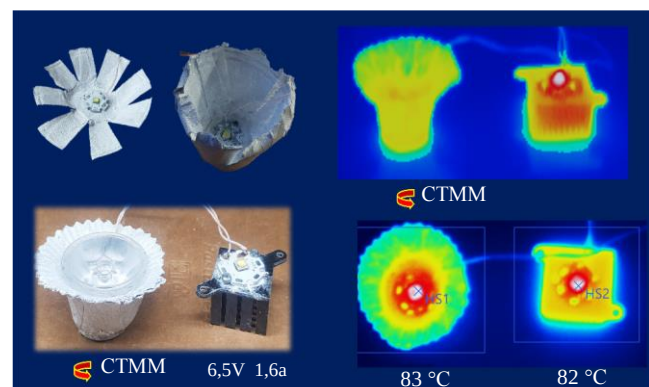


Fig. 3. Temperature comparison of high-power point LEDs under traditional (rear) cooling (U-shaped aluminum heat sink) and with the use of tulip-shaped CTMM (front cooling)

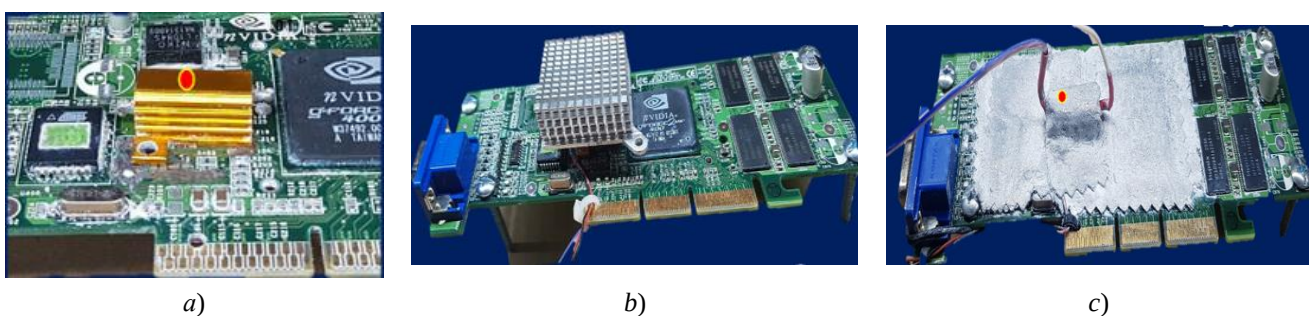


Fig. 4. Cooling schemes for the high-power resistor: a) – thermal paste only; b) – standard aluminum heat sink; c) – CTM cooling (“cocoon” configuration)

Temperature of high-power resistors vs. dissipated electrical power for all three cooling schemes is shown in Fig. 5.

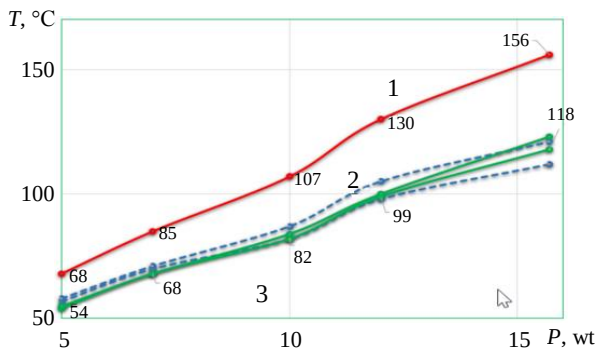


Fig. 5. Temperature of high-power resistors vs. dissipated electrical power for the cooling schemes: 1 – thermal paste only; 2 – standard aluminum heat sink; 3 – CTM (“cocoon” configuration)

As can be seen from the curve in Fig. 5, the use of CTM in the “cocoon” configuration (line 3) across the entire load range up to 16 W provided the efficiency equivalent to that of a standard aluminum heat sink (dashed line 2) and significantly outperformed the scheme with thermal paste only (line 1). Thus, the feasibility of turning a printed circuit board into an actual effective flat heat sink using CTM is confirmed.

Conclusion

The developed conformal thermal metamaterials represent a full-featured solution for controlling heat flows in modern electronics. CTM exhibit a unique triad of properties: anisotropy ($\lambda_{xy}/\lambda_z \approx 20\text{--}30$), conformability (bending up to 180°), and autothermal contact, which provides unprecedented flexibility in heat control. Temperature reduction of LED chips by $28\text{--}45^\circ\text{C}$ has been experimentally confirmed, which is equivalent to increase of service life by 2–3 times. In terms of cooling capacity, CTM are equivalent to traditional heat sinks in a number of cases, while they provide a significant reduction of device size and mass, opening the way for flat designs not comprising heat sinks. The concept of L1+ level thermal routing has been implemented to enable full manipulation of heat with CTM: heat collection, concentration, transportation, and directional dissipation, including its turn by 180° . Future applications of CTM include cooling of devices with pulsed heat generation (lasers, lidars) and using CTM for electromagnetic shielding elements of printed circuit boards.

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