



Advanced Thermal Circuits for Complex Thermal Management

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Description

Many reports reveal that over 60% of primary energy consumption is lost as waste heat [1], posing significant challenges such as global warming, the energy crisis and complex thermal management problems. Traditional active thermal control techniques (e.g., fans, coolant pipes) and passive ones (e.g., phase change material, coating material) typically have fixed thermal properties. Some modern heat-manipulating technologies, such as those utilizing structural characteristics [2,3] or material properties [4,5], can enhance or suppress heat flow in specific directions or areas. However, they are limited to a single thermal property. Fixed-and-single thermal conductivity makes them insufficient to meet dynamic thermal management requirements or support thermal circuits in achieving selectable operations.

Thermal diodes, analogous to electrical diodes in their gating function, exhibit switchable and dual-directional heat transport ability, that is, they allow phonons carrying thermal current to flow in the forward direction and impede the flow in the reverse direction. Since Starr first demonstrated the thermal rectification effect in a copper/cuprous oxide interface in 1936 [6], many theoretical and experimental studies have been published to investigate various thermal rectification mechanisms. Conductive thermal diodes, distinct from convective and radial diodes, often rely on Phase-Change Materials (PCM-diodes), Two-Segment Structures (TSS-diodes) and Structural Functional Materials (SFM-diodes). PCM-diodes primarily undergo transitions under small thermal biases because of the narrow critical temperature range for crystalline structure transitions [7-9]. TSS-diodes typically operate at low temperatures due to the two segments requiring opposite temperature coefficients of thermal conductivity k , while most materials' $k(T)$ peaks occur below room temperature. SFM-diodes, with thermal conductivity determined by the ideal match between the elaborately designed-structures and adopted materials, have proven reliable functionality under ambient conditions across a large temperature bias.

As a result, thermal diodes a nonlinear toolkit of thermal engineers that goes beyond these linear elements (thermal resistors and capacitors) develop and demonstrate a strategy for some particular scenarios. For example, scenarios where conventional electronics

cannot be used (e.g., explosion-proof and flammable material storage) or where electronic signals are vulnerable to interference (e.g., electromagnetic interference and radiation). Herein, treat heat as an information carrier and manipulate it rather than electrical signals, then advanced thermal circuits would be formed by thermal diodes and resistors to execute desired thermal logic operations, such as AND, OR functions and more. When thermal circuits are designed, fabricated and tested under fluctuating ambient conditions, this combination will advance the engineering of thermal energy manipulation devices with applications like thermal communication, calculations and (anti-)detection.

Conclusion

Traditional active and passive thermal control techniques, along with some modern heat-manipulating technologies, have fixed-and-single thermal properties, making them inadequate for handling complex thermal management problems. Emerging thermal diodes, designed analogously to electric diodes, have switchable and dual-directional heat transport abilities, making them suitable to face various challenges. Specifically, conductive thermal diodes achieve asymmetric thermal conductance by utilizing phase change materials, two-segment structures and structural functional materials. By embracing these technologies and strategies, thermal diodes constitute thermal circuits and thermal energy is utilized as a versatile technology. Then, energy utilization efficiency will be promoted to meet the needs of biological and low-power/power-free scenarios and abundant thermal information will be processed to support communication, calculations and (anti-)detection when electronic signals fail.

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