Thermal Diodes and Advanced Thermal Circuits for Energy Harvesting and Conservation

by

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Technical Summary

The manipulation of thermal energy has a wide variety of important applications including thermal computation, thermal energy harvesting, and heat management. This thesis focuses on the development and application of three types of advanced thermal circuit elements: thermal diodes, thermal insulators, and high thermal effusivity materials.

Materials designed to undergo a phase transition at a prescribed temperature have been advanced as elements for controlling thermal flux. Such phase change materials can be used as components of reversible thermal diodes, or materials that favor heat flux in a preferred direction. It is shown mathematically that the interface of a phase change material with a phase invariant one can function as a simple thermal diode. Criteria are derived analytically for the ideal choice of the system's thermophysical parameters and temperature operating range, and the model is applied to several experimental systems in the literature. Motivated by this model, a micro and nanoporous polystyrene foam that houses a paraffin-based phase change material, fused to PMMA, is designed to produce mechanically robust, solid-state thermal diodes capable of ambient operation. Thermal rectifications ratios up to 1.34 are measured, and it is shown that such devices perform reliably enough to operate in dynamic thermal circuits capable of transforming oscillating temperature inputs into single polarity temperature differences. As a follow-up to this work, thermal diode performance is drastically enhanced through the introduction and analysis of the concept of a Dual Phase Change Thermal Diode (DPCTD) as the junction of two phase change materials with similar phase boundary temperatures but opposite temperature coefficients of thermal conductivity. An ambient DPCTD enabled by the junction of an octadecane-impregnated polystyrene foam polymerized using a high internal phase emulsion template and a poly(N-isopropylacrylamide) aqueous solution is designed and fabricated, and it shows an enhanced thermal rectification ratio both experimentally (2.6) and theoretically (2.6).

There is a pressing need for durable energy harvesting techniques that are not limited by intermittency, and capable of persistent and continuous operation over extended periods of time in a variety of environments. Ambient thermal fluctuations of various frequencies are identified as abundant, ubiquitous sources of such energy. In this work, a theory is presented for the operation and design of a thermoelectric energy harvester interfaced with thermal diodes, which I term a thermal resonator, that is capable of efficiently capturing the energy in such fluctuations. It is concluded that current thermal diodes could produce approximately a factor of two improvement in current thermal energy harvesting performance. Further enhancements in thermal diode performance, specifically the temperature bias necessary for the activation of thermal rectification, are necessary to reach the upper bound (factor of five) of improvement relative to current harvesters. A more easily realized thermal resonator can be constructed through the incorporation of high thermal effusivity materials with a thermoelectric heat engine. Herein, materials are designed that maximize the thermal effusivity by impregnating copper and nickel foams with conformal, chemical-vapor-deposited graphene and octadecane as a phase change material. These materials are ideal for ambient energy harvesting to generate persistent dual polarity electrical power from thermal fluctuations over large ranges of frequencies. Theory and experiment demonstrate that the harvestable power for these devices is proportional to the thermal effusivity of the dominant thermal mass. To illustrate, persistent energy harvesting from diurnal frequencies is measured, extracting as high as 350 mV and 1.3 mW from approximately 10 ^{o}C diurnal temperature differences. A thermal resonance device also has particular advantages for the desert environment, where sand and sandstorms often obscure solar devices, and extreme temperature and high solar fluence confound conventional energy harvesting and storage. A device is designed, fabricated, and tested for the conversion of temperature fluctuations to power in the harsh desert environment using a high thermal effusivity material specifically tuned to the environment of Thuwal, Saudi Arabia. The composite consists of a highly porous and thermally conductive nickel foam impregnated with eicosane as a phase change material for enhanced thermal capacity. The device is tested for a period of two weeks in Saudi Arabia, extracting as high as 2 mW from approximately 10 ^{o}C diurnal temperature fluctuations.

Closed-cell foams are widely applied as insulation and essential for the thermal management of protective garments in extreme environments. This work develops and demonstrates a strategy for drastically reducing the thermal conductivity of a flexible, closed-cell polychloroprene foam to 0.031 W m^{-1} K^{-1}, approaching values of an air gap (0.027 W m^{-1} K^{-1}) for an extended period of time (>10 hours). Ultra-insulating neoprene materials are synthesized using high-pressure processing at 243 kPa in a high-molecular-weight gas environment (e.g., Ar, Kr, or Xe). A Fickian diffusion model describes both the mass infusion and thermal conductivity reduction of the foam. A wetsuit made of ultra-insulating neoprene is demonstrated to be capable of extending dive times to 2-3 hours in water below 10 ^{o}C, compared with <1 hour for the state-of-the-art.

These results further the engineering of devices intended for the manipulation of thermal energy with applications ranging from thermal conservation, to thermal energy harvesting, to thermal computation.

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