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Experimental evidence of the working principle of thermal diodes based on thermal stress and thermal contact conductance – Thermal semiconductors

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ABSTRACT

This article gives an experimental evidence of the working principle of thermal semiconductor (TSC) devices proposed by dos Santos Bernardes (2009) [1]. For that, TSC working principle is introduced and the experimental procedures adopted for thermal conductivity measurements of a prototype are described. The prototype positioned appropriately between hot and cold plates of the test apparatus revealed heat flux asymmetry with reverse positioning, achieving a diodicity of 0.068 ± 0.0025. The disclosure of this behavior supports experimentally the functionality of the TSC mechanism as a thermal diode.

1. Introduction

Thermal diodes are devices which promote heat flow with a preferential direction, i.e. a device exhibiting an asymmetry in the heat flux when the temperature difference between two interacting thermal reservoirs is reversed [2]. Also known as thermal rectification, this phenomenon finds broad application in many modern fields such as heat distribution in spacecraft [3–6], cryogenics [7], solar energy dependent systems [8,9], energy savings through passive heating and cooling in buildings [10,11] or phononic computing [12,13]. In this fashion, rectifiers can also be relevant to mitigate global warming, to improve thermal features of clothes and shoes, to uplift heat storage capacity of systems, etc. As a result, efforts have been made recently to improve on the understanding of the thermal rectification phenomenon.

Current techniques for thermal rectification comprise rectifiers based on carbon and boron nitride nanotubes [14], semiconductor quantum dots [15], bulk cobalt oxides [16], theoretical models based on nonlinear lattices [17–20], graphene nano-ribbons [21,22], near-field radiative heat transfer [23] and other mechanisms [24]. Particular studies suggest theoretical models of thermal logical gates [12] and thermal transistors [25]. A theoretical study and an experimental suggestion of a radiative thermal rectifier based on non-linear solid state quantum circuits operating at cryogenic temperatures have been introduced returning a rectification up to 10%[1] [26]. Besides, two theoretical schemes of radiative thermal rectification based on near-field thermal radiation control have lately been proposed envisaging theoretically rectification of 25% and 41%[1] [27,28]. Recently, a thermal rectifier made of selective emitters based on spectrally tunable selective emitters was developed for thermo-photovoltaic applications [29]. Some authors also classify [30] thermal diode mechanisms considering surface roughness/flatness at material contacts, thermal potential barrier between material contacts, difference in temperature dependence of thermal conductivity between dissimilar materials at a contact, nanostructured asymmetry (i.e. mass-loaded nanotubes, asymmetric geometries in nanostructures, nanostructured interfaces), anharmonic lattices (typically 1D) and quantum thermal systems.

Outperforming the previously proposed devices schemes, a simple, scalable and almost universally implementable thermal diode, namely thermal semiconductors – TSC, was introduced by dos Santos Bernardes [1,31]. This mechanism consists in a compound of at least two materials with different thermal conductivities making use of the thermal stress effect to self-regulate the heat flux. The mode of operation of the proposed device consists of two parallel plates of a good conductor with internal fins, as shown in Fig. 1.

In this proposed configuration, the two fins of the right hand side wall are confined by two fins of the left hand side wall. The remaining space is filled with a good insulator and a gap filled with

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[1] Values based on Eq. (1).

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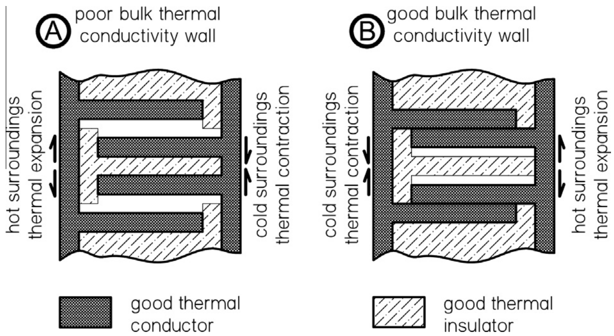

Fig. 1. Schematic mode of operation of TSC's.

a compressible low thermal conductivity fluid is left between fins with corresponding apparent surfaces. Thereby, higher temperatures at the left hand side of the wall promote its thermal expansion. On the other hand, lower temperatures at the right hand side of the wall promote its thermal contraction. These conjugated effects keep the corresponding fin surfaces with good heat conductivity apart from each other enhancing, by this means, the thermal insulation between the left and the right regions, as depicted in Fig. 1(A).

On the contrary, when higher temperatures occur at the left hand side and lower temperatures occur at the right hand side, thermal contraction and expansion take place, respectively. Because of these conjugated effects, the contact between the corresponding fin surfaces with good heat conductivity takes place establishing a thermal bridge. Through that, the capability of the system to conduct thermal energy increases, as shown in Fig. 1(B). This system is regulated exclusively by defined temperature gradients and no external drive is necessary to operate it. Thus, this system switches automatically between good or poor thermal conductivity by corresponding favorable or unfavorable temperature gradients respectively.

Based on a simple but smart solution, i.e. thermal stress and thermal contact conductance, TSC's hold remarkable characteristics and advantages, as such broad manufacturability – essentially, any material can be used to manufacture a TSC; universal implementability – subsequently, TSC's can operate under any conventional condition, i.e. from cryogenic to high temperatures ranges; scalability – TSC modus operandi is intrinsic to matter allowing its manufacturing in any size, e.g. macro-, meso-, micro- and nano-fields; and thermal contact conductance – there are some methods (thermal paste, thermally conductive compounds, conductive elastomers, adhesive tapes and phase change materials) to deal with this peculiar heat transfer issue enabling enhanced heat flux between surface to surface contacts. Summarizing, TSC thermal stress and thermal contact conductance mechanisms are liable to many tangible current thermal engineering developments.

1.1. Objective of this work

The object of the work reported here is to demonstrate experimentally the functionality of the TSC mechanism as a thermal diode. For that, a prototype was built following its work principle and experimental measurements were made as stated by GB/T10295-2008 standard. These measurements were lead taking into account two arrangements aiming the evaluating of the effective thermal conductivities in both forward and reverse operating modes regardless its level of rectification. Following the main goal of this work, the measured values of thermal conductivities are to be considered for comparative purposes mainly. In spite of that, these values represent actual thermal conductivity magnitudes.

1.2. Thermal rectification

Thermal rectification can be broadly defined as a material or structure which heat is transferred asymmetrically [30]. As mentioned before, different mechanisms can promote thermal rectification in solid systems. The work of reference [30] reviews exhaustively the literature looking for supporting or rejecting evidences which validate the thermal rectification hypothesis/mechanisms. They assert that the current mechanisms found in scientific literature have revealed lower levels of rectification and are not robust.

The rectification coefficient or diodicity η^* of a thermal diode used to represent its effectiveness is widely given by

$$\eta^* = \frac{k_f - k_r}{k_r} \tag{1}$$

where k_f and k_r are the effective thermal conductivities in the forward and reverse operating modes, respectively [32]. Similarly to some other researchers [14,30], Ref. [30] defines level of rectification η as

$$\eta = \frac{k_f - k_r}{k_f + k_r} \tag{2}$$

In both Eqs. (1) and (2), if k_f and k_r are the same, the level of rectification is zero ($\eta = 0$). These definitions return an ideal thermal rectifier when $k_f \gg k_r$. In this case however, Eq. (2) leads the level of rectification to a value of unity ($\eta = 1$). Eq. (2) is refereed as the formula to calculate the diodicity in this work. Refs. [27,28] calculated the diodicity making use of Eq. (1) returning obviously higher values.

2. Experimental analysis

2.1. Sample characteristics and positioning

A sample was built in accordance with the TSC's mode of operation, as shown in Fig. 2. It consists of three cylindrical parts, e.g. the confined element (01) and the confining element (03) made of a good conductor, and the insulating ring (02) made of a good insulator. They are assembled together as depicted in Fig. 3, where the insulating ring is positioned between the confined and the confining element. After assembly, the sample is guarded within a ring of insulation material with ~15 mm wall thickness and approximately the same sample height.

With the purpose to calculate the diodicity of the proposed sample, the thermal conductivities in the forward and reverse operating modes were measured for two sample positions respectively, high and low thermal conductivity conditions. Fig. 4 shows the sample positioning for high thermal conductivity condition, where thermal expansion of the confined part and thermal contraction of the confining part allow correspondingly the exposed surfaces to get in touch allowing thermal bridge. On the other hand, Fig. 5 represents the sample positioning for low thermal conductivity condition, where the reverse effect takes place.

2.2. Thermal conductivity measurement

The thermal conductivity of the sample was measured in accordance with GB/T10295-2008, standard test method for steady state thermal transmission properties by means of a calibrated heat flow meter apparatus. Experiments were conducted on the sample where the apparent thermal conductivity was measured under steady state one-dimensional test conditions with heat flow downwards. The test equipment used constant temperature plates (resolution 0.1 °C) with heat copper bases and 36 V safe voltage. The