International Journal of Thermal Sciences 50 (2011) 648–662

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Review

A review of thermal rectification observations and models in solid materials

N.A. Roberts, D.G. Walker*

Department of Mechanical Engineering, Vanderbilt University, Nashville, TN 37325, USA

ARTICLE INFO

Article history:
Received 8 September 2010
Received in revised form
22 November 2010
Accepted 1 December 2010
Available online 15 January 2011

Keywords:
Thermal rectification
Non-equilibrium transport
Nanostructured materials

ABSTRACT

Thermal rectification is a phenomenon in which thermal transport along a specific axis is dependent upon the sign of the temperature gradient or heat current. This phenomenon offers improved thermal management of electronics as size scales continue to decrease and new technologies emerge by having directions of preferred thermal transport. For most applications where thermally rectifying materials could be of use they would need to exhibit one direction with high thermal conductivity to allow for efficient transport of heat from heat generating components to a sink and one direction with low conductivity to insulate the temperature and heat flux sensitive components. In the process of understanding and developing these materials multiple mechanisms have been found which produce thermally rectifying behavior and much work has been and is being done to improve our understanding of the mechanisms and how these mechanisms can be used with our improved ability to fabricate at the nanoscale to produce efficient materials which have high levels of thermal rectification.

1. Introduction

Thermal rectification is a phenomenon in which thermal transport along a specific axis is dependent upon the sign of the temperature gradient or heat current. Thermal rectification has been a topic of interest dating back to its initial experimental observation in 1936 by Starr [1]. Since then, there have been several experimental and theoretical studies performed in an attempt to understand what mechanisms cause thermal rectification. With an improved understanding of how thermal rectification is achieved, devices like thermal transistors, thermal logic circuits and thermal diodes could be developed and utilized in micro/nanoelectronic cooling as well as thermal memory and computations. In a recent meeting of the thermal management community it was mentioned that devices like thermal switches will be necessary for our ability to cool electronics effectively in the future as device sizes become smaller and as we move toward stacked chip designs and more complicated thermal management problems [2]. Currently several mechanisms for thermal rectification have been proposed including 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 (ie. mass-loaded nanotubes, asymmetric geometries in nanostructures, nanostructured interfaces), anharmonic lattices (typically 1D) and quantum thermal systems. Each of these mechanisms will be examined in detail.

Since the first known observation of thermal rectification activity in the area has been sporadic with a very large increase in interest in the last decade. Fig. 1 shows the number of publications related to thermal rectification since the original observation in 1936. In the 1960s and 1970s interest in this area was advanced because of the studies of composite materials that were of great interest in the aerospace industry [3]. In the 2000s we see an explosion of interest mostly due to the 1D non-linear lattices initially presented by Terraneo et al. [4] and the experiments of non-uniformly mass-loaded nanotubes by Chang et al. [5]. These works along with our improved ability to model, synthesis and characterize systems at the nanoscale have led to an increasing trend in thermal rectification research in the latter part of the 2000s and into the current decade which is shown in the inset of Fig. 1.

At first look, thermal rectification may appear to violate the 2nd Law of Thermodynamics, but we can provide common simple examples where rectification is indisputable. A difference in the Nusselt number is observed in natural convection when two parallel plates are oriented horizontally relative to gravity and separated by a gas as shown in Fig. 2. When the lower plate is heated, the heat transfer is driven by buoyancy induced flows and is governed by Rayleigh–Bernard convection in addition to conduction if the Rayleigh number is greater than the critical value of $Ra_{cr} = 1708$ which is given by [6]

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* Corresponding author.
E-mail address: greg.walker@vanderbilt.edu (D.G. Walker).

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doi:10.1016/j.ijthermalsci.2010.12.004