Non rectification of heat in graded Si-Ge alloys

Sandra Carillo[*], M.G. Naso[**], E. Vuk[**] and F. Zullo[**]
[*]*Dipartimento di "Scienze di Base e Applicate per l'Ingegneria",*
LA SAPIENZA - *Università di Roma, Rome, Italy*
&
I.N.F.N. - Sezione Roma1, Gr. IV - M.M.N.L.P., Rome, Italy
[**] *DICATAM, Università degli Studi di Brescia, Via Valotti 9, Brescia, Italy*

Abstract. The possibility to obtain a thermal diode with functionally graded Si-Ge alloys is investigated. A wire with variable section is considered. After the introduction of a formula giving the thermal conductivity of the wire as a function of the species content and of the diameter of the wire, numerical and analytical results are presented supporting the impracticability to get a thermal diode with the characteristics here considered. However, the present study opens the way to further generalisations amenable to give applicative promising results.

Introduction

The thermal phenomenon that allows heat transfer in a suitable direction in a given material, while the heat flow is inhibited in the opposite direction, is called thermal rectification [1, 2]. This is the analogue of the current rectification of the electronic diodes and for this reason any device showing some thermal rectifying feature is called thermal diode. An homogeneous material characterized by a constant thermal conductivity is known to not possess any rectifying property [3]: the heat flows, under the same thermal gradient applied, equally in all the directions. It follows that, if a material possesses a rectifying effect, then the thermal conductivity λ is a non-homogeneous function of the temperature.

By non-homogeneous thermal conductivity we mean it depends also on the space variable $\mathbf{x}$. Despite to be necessary, this condition is however far from being sufficient: indeed, it has been shown [3] that, if the thermal conductivity is a separable function, i.e. if there exist two functions f and g such that $\lambda(T, \mathbf{x}) = f(T)g(\mathbf{x})$, then no rectifying effect can be observed in the material. A practicable process to obtain non-homogeneous values of macroscopic properties, such as the thermal conductivity, is the manufacturing of functionally graded materials, i.e. materials with a specific gradation in the composition in order to achieve particular performances or functions [5, 6]. One of the most common example of graded materials are materials made of binary alloys A_cB_{1-c}, where A and B are two different atomic species and c is the content of the specie A (so that $c \in (0, 1)$). In this work we present a detailed analysis of the possibility to get a thermal diode with graded Si-Ge alloys. The investigation is mainly based on the results given in [1], where a systematic approach has been introduced to find the optimal gradation of the species in order to maximize the efficiency of the fin. In the case of *graded materials*, the thermal conductivity may be also a function of the gradation in composition: for example, for binary alloys A_cB_{1-c}, λ is a function of T and of the species content c (see e.g. [4]). If the species content c is variable inside the material, i.e. $c = c(\mathbf{x})$, then the thermal conductivity becomes dependent on T and $\mathbf{x}$, $\lambda = \lambda(T, c(\mathbf{x}))$. The model presented is physical consistent and accurate: it represents a first approximation to construct further ones, for instance on introduction of new variables or different heat transfer laws, aiming to improve the model to achieve the rectification goal.

References

[1] M.G. Naso, E. Vuk, F. Zullo: On the optimization of heat rectification in graded materials, International Journal of Heat and Mass Transfer, 143, 2019.
[2] M. Peyrard: The design of a thermal rectifier, EPL, 76, 49, 2006.
[3] D. S. Go, M. Sen: On the Condition for Thermal Rectification Using Bulk Materials, J. Heat Transfer, 132, 2010.
[4] Schaffler F.: in Properties of Advanced Semiconductor Materials GaN, AlN, InN, BN, SiC, SiGe . Eds. Levinshtein M.E., Rumyantsev S.L., Shur M.S., John Wiley & Sons, Inc., New York, 149-188, 2001.
[5] E. Müller, Č. Drašar J. Schilz, W. A. Kaysser, Functionally graded materials for sensor and energy applications, Mater. Sci. Eng. A 362 (1) (2003) 1739.
[6] M. Naebe, K. Shirvanimoghaddam: Functionally graded materials: A review of fabrication and properties, Applied Materials Today 5, 223245, 2016.