Enhancement of power factor in a Ag-Bi-Ag planar thin film thermoelectric device

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1. Abstract

The electrical resistivity, ρ, and the Seebeck coefficient, S, of an Ag-Bi-Ag planar thin film thermoelectric device are measured, at room temperature, as a function of the length ratio $x=L_{Bi}/L_{tot}$, where L_{Bi} is the length of Bi layer and L_{tot} is the total length of the device. The interface effect in the Ag-Bi contact and its contribution to the resistivity and Seebeck coefficient is investigated. From the above measurements the resultant thermoelectric power factor is calculated. The experimental results are compared with the appropriate theoretical values calculated by treating these devices as an electrical and thermal circuit. The thermoelectric power factor of the device P(x) exhibits larger values than the power factor of pure Bi. This power factor enhancement is observed in the range $0.3<x<0.5$, depending on the Ag-Bi contact area. A similar enhancement has been observed for bulk composite thermoelectric devices with sandwich-structure. However to our knowledge, this is the first time that the same phenomenon is reported for planar thin film thermoelectric devices

2. Introduction

In recent years, there is a great interest in finding materials and structures for use in highly efficient cooling and energy conversion systems [2, 3]. Especially nanowire, quantum well and superlattice structures [4-6] are materials with high power factor $P=S^2/\rho$, where S is the Seebeck coefficient, and ρ is the electrical resistivity. P depends on the transport properties of the material, and enters the dimensionless thermoelectric figure of merit $ZT=PT/\kappa$, where κ is the thermal conductivity of the material and T is the material's temperature. In other words, P provides a measure of the quality of the material for cooling purpose.

Several years ago, the power factor of a two-component device with lamellar structure, was has beencalculated by Bergman [7]. In this theoretical work, it was predicted that the power factor of such device can sometimes be greater than the power factor values of both materials consisting this device. But this result strongly depends on the Seebeck coefficient sign of those materials. In another experimental work by Odahara[8], a power factor enhancement was obtained in a macroscopic cylindrical sandwich-structured Cu-Bi-Cu device. Although, the experimental evidence comes close to the theoretical results, the model proposed in the latter case is different and simpler than the theoretical work of Bergman. On the other hand, in both cases a resultant power factor enhancement is obtained by sandwich-structured devices.

To the best of our knowledge, there is no published report on thermoelectric properties of a planar thin film device, where a thermoelectric material is placed between two metallic contacts, laying on a substrate. Although this structure looks like the sandwich structure proposed by Odahara [8], it is completely different due to the presence of the substrate. Additionally in the former case, the contact surface between the thermoelectric material and the metal is of the order of a few mm^2, while in the latter case there is an overlap between the materials the width of which might affect the thermoelectric properties of the device.

In order to study the differences mentioned above, the electrical resistivity and the Seebeck coefficient of an Ag-Bi-Ag planar thin film thermoelectric device are investigated, as a function of the length ratio $x=L_{Bi}/L_{tot}$, where L_{Bi} is the length of Bi layer and L_{tot} is the total length of the device. The effect of the overlap width is also investigated.

3. Experimental details.

Ag-Bi-Ag planar devices were made on glass substrates, by thermal evaporation. Initially, a thin Al foil shadow mask was placed in the middle of the substrate, and an Ag thin film ~150nm-thick was evaporated. Then the shadow mask was removed and another negative shadow mask was placed on the metal, leaving the centre of the substrate uncovered. Then the Bi film, of the same thickness as the Ag, was evaporated. Attention was paid, so that the overlap between the two materials, in the two contact areas, to be uniform in all film width, and its length to be as similar as possible. All evaporations were done using a conventional thermal evaporator with a quartz crystal thickness monitor. The base pressure of the thermal evaporator was ~5x10-6Torr. Two planar devices were made: one with narrow overlap (~80μm) and another with broad overlap (~160μm), in order to investigate the overlap dependence of the transport properties in this kind of devices. Besides an Ag thin film as well as a Bi thin film were made, for studying the purity of the materials deposited, by XRD experiments. Scanning Electron Microscopy pictures were taken in order for the overlap width to be measured, while the profile of the device was made, by AFM experiments, to confirm the anaglyph of the device.

Resistivity $\rho_d(x)$ and Seebeck coefficient $S_d(x)$ measurements are performed as a function of x, at room temperature. For resistivity measurements the 4-probe technique is employed, while steady state technique is used for Seebeck coefficient measurements. In order to vary the ratio x, the distance between the voltage leads was changed. The same case is for the Seebeck measurements as well, where the relative distance of the thermocouples and the thermal voltage leads was changed simultaneously. Except for measuring the ρ_d and the S_d, the initial resistivity and Seebeck values for Ag (ρ_{Ag}, S_{Ag}) and for Bi (ρ_{Bi}, S_{Bi}) were measured on the same planar device. These values (table 1) are used as initial parameters for calculations, using the model proposed by Odahara [8] for Cu-Bi-Cu sandwich structures.

4. Results and Discussion

Resistivity measurements as a function of x are presented on Figure 1, for both devices.

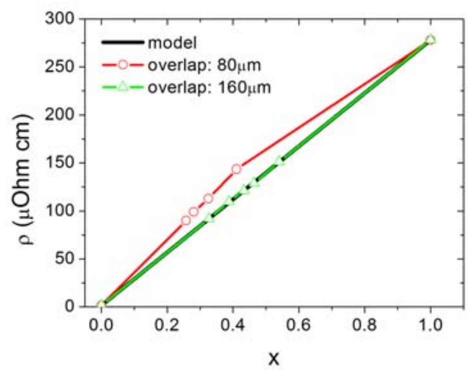

Figure 1: Resistivity as a function of x, for the two devices with different overlap. The lines among the experimental data are guide for the eyes

It is obviously seen that, ρ is linearly dependant on x, as predicted by the applied theoretical model. However, resistivity increases with decreasing the contact overlap. This phenomenon can be attributed to the contact resistance. The total resistance of such a device can be described by the following equation:

$$R_{tot} = 2R_{Ag} + R_{Bi} + 2R_C \quad (1)$$

where R_{Ag} is the Ag resistance, R_{Bi} is the Bi resistance and R_C is the contact resistance. This contact resistance depends on the overlap existed between the two layers. As this overlap decreases, the contact resistance increases, increasing also the total resistance and the resulting resistivity of the device.

Seebeck coefficient as a function of x is demonstrated in Figure 2. In both cases the experimental values are smaller than the theoretical values. This deviation of the experimental data from the theoretical model has also been observed in Ag/Bi-Te/Ag macroscopic devices [9] and in our case can be attributed to the substrate.

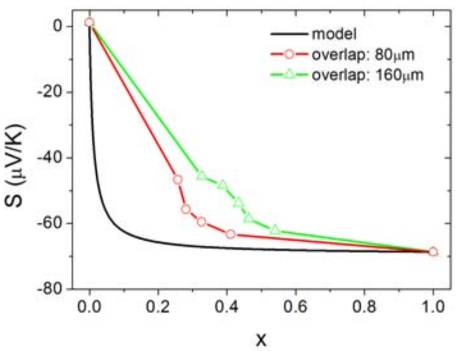

Figure 2: Seebeck coefficient as a function of x, for the two devices with different overlap. The lines among the experimental data are eye guides.

As it has been already mentioned both devices were grown on glass substrate. Establishing a constant heat flux, in order to measure the themoelectric voltage, a portion of the heat is dissipated through the substrate. This portion of the heat depends on the thickness of the substrate (the thicker the substrate, the more heat is dissipated) as well as the thickness of the device (the thicker the device is the less heat passes to the substrate). It is also depends on the thermal conductivity of the substrate. In both devices, the thickness of the substrate and the device are kept constant, so that the heat

	Ag		Bi	
	bulk	Thin film	bulk	Thin film
ρ(μOhm cm)	1.58	1.57	125	278
S (μV/K)	1.51	1.27	-70	-68.9
κ(W/ cm K)	4.29	4.60*	0.079	0.050*
P(μW/cm K^2)	1.44	1.03	39.2	17.1
ZT	10^{-4}	$6.65x10^{-5}$	0.147	0.102

* These values are calculated using the Wiedemann-Franz law

Table 1: Resistivity and Seebeck coefficient for starting materials. Bulk values are reported on ref. [8] and ref. [9], while thin film values are measured on the device.

dissipation due to the substrate to be the same. Moreover the glass has lower thermal conductivity than the Bi and Ag and thus the heat prefers to pass through the device instead of glass. But there is still a heat loss that cannot be prevented.

Although there is this deviation between the theoretical and experimental values, regarding the Seebeck coefficient of the devices, in both cases the experimental data behave like the theoretical model. Moreover, as the overlap decreases, the Seebeck coefficient values come closer to the model results. This feature may be explained as follows: The contact between the Ag and the Bi is a metal-semimetal contact. It is known that in such kind of contacts an energy barrier may exist. Charge carriers moving from the metal to the semimetal, must have energy equal or greater than the energy barrier in order to overcome it. In any other cases they will be reflected by the barrier. This charge carrier reflection affects the thermoelectric power of the device [10]. The barrier height depends on the overlap between the two materials. The broader the overlap the lower the barrier height is and more charge carriers can pass through the contact.

In figure 3 the resultant power factor is demonstrated as a function of x, for both devices. It is seen that there is a local maximum at x~0.3 for the device with the narrow overlap. This local maximum seem to be shifted to x~0.5 as the overlap

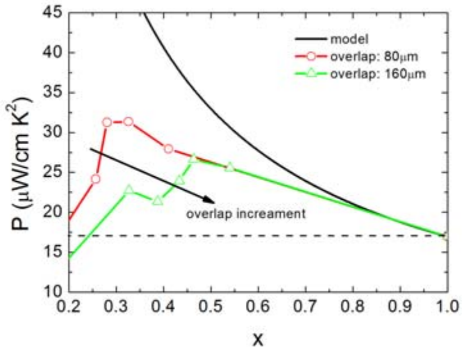

Figure 3: Power factor vs x for the two different devices. The dashed line corresponds to the power factor of pure Bi.

broadens. The maximum power factor achieved in the narrow and the broad overlap case is 31.4μW/cm K^2 and 26.6μW/cm K^2 respectively.

These values are 85% and 57% greater than the power factor of the pure Bi, which is found to be 17 μW/cm K^2. Moreover these power factor values are comparable to power factor values of high-performance bismuth-telluride compounds [11, 12], but they are one order of magnitude lower than those obtained in Cu-Bi-Cu cylindrical devices [8].

5. Summary

The electrical resistivity, ρ, and the Seebeck coefficient, S, of an Ag-Bi-Ag planar thin film thermoelectric device are measured, at room temperature, as a function of the length ratio $x=L_{Bi}/L_{tot}$, where L_{Bi} is the length of Bi layer and L_{tot} is the total length of the device. The effect of the overlap width in the above properties is also investigated. The electrical resistivity was found to be a linear combination of the resistivity of the pure materials. An additional resistance occurred as the overlap became narrow, coming from the contact resistance increasing. The measured Seebeck coefficient does not reach the calculated values in any case, but it has similar behaviour as the theoretical model. Moreover, the broadening of the overlap causes the decreasing of the absolute values of Seebeck coefficient. Finally, the power factor is found to have a local maximum at x~0.3 which shifts to higher x values and lower P values, as the overlap broadens. The maximum P values obtained can be compared to power factors of high efficiency thermoelectric materials such as bismuth-telluride compounds, but they are considerably lower than P values obtained from macroscopic sandwich-structured Cu-Bi-Cu devices.

6. References

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