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Thermo-electric finite element analysis and characteristic of thermoelectric generator with intermetallic compound

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ABSTRACT

Energy recycling is an important research topic worldwide. Thermoelectric generators (TEGs) are used to recycle energy. TEGs are suitable for small and medium-sized applications and industrial waste heat harvesting in medium to high temperatures. Traditional lead-free soldering cannot be applied at temperatures above 200 °C. The joint may melt and fail at exceedingly high temperatures. Therefore, determining the suitable bonding material to apply during TEG assembly is necessary. Ni/Sn/Ag was adopted as the joint material for TEG packaging in this study. The joints were bonded and transformed into a full intermetallic compound (IMC) through solid–liquid interdiffusion bonding (SLID) and solid–solid interdiffusion reaction. The IMC has a high melting point and can be utilized at temperatures above 200 °C. The mechanical strength of the joints was examined through shear test at different thermal treatment times. Shear strength declined with the increase in thermal treatment time. The TEG was assembled with 12 pairs of thermoelectric (TE) pillars, and its performance was measured through the slope method. The TE characteristics do not significantly vary before and after thermal treatment. With the established finite element (FE) model, temperature and output power were estimated at specific temperature loading through thermo-electrical FE analysis.

1. Introduction

Energy recycling is an important research topic worldwide. Thermoelectric generators (TEGs) are utilized to recycle energy. The advantages of TEGs include convenience, high reliability, and environmental friendliness. Given its flexibility in structural design and size, the TEG is suitable for small and medium-sized applications as well as industrial waste heat harvesting in medium to high temperatures. The TEG has a solid-state heat engine fabricated with semiconductor materials. The working principle of the TEG is based on the Seebeck effect. Both sides of the thermoelectric (TE) pillar are maintained by the different junction temperatures, which result in an open-circuit electromotive force as shown in Fig. 1. The equation of the Seebeck effect is as follows [1]:

$$\alpha = \frac{V}{T_h - T_c} \quad (1)$$

where α is the Seebeck coefficient, V is the voltage produced, and T_h and T_c are the temperatures on the hot and cold sides, respectively.

The characteristic of the TE materials is determined by the figure of merit (ZT). The equation of ZT is as follows [1]:

$$Z = \frac{\alpha\sigma}{\kappa} \quad (2)$$

where Z is the figure of merit, σ is the electrical conductivity, and κ is the thermal conductivity.

The TEG consists of an array of p- and n-type TE materials bonded between two substrates as shown in Fig. 2 [2]. These materials are connected electrically in a series to form a chain of p–n junctions but are thermally connected in a parallel arrangement. The TE materials are attached to the substrates by soldering. Many studies investigated the interfacial behavior of TE materials and bonding joints. Lead-free Sn-based solders are widely utilized as the bonding material in TEGs. However, the solder may creep, crack, and even melt when the operating temperature is at or above 150 °C [3–5]. Nickel is commonly used as a diffusion barrier to prevent extensive interdiffusion and interfacial reactions. Nickel diffuses readily in bismuth telluride compounds at elevated temperatures during soldering or annealing [6,7]. The joint materials and diffusion barrier should be selected with caution because both should be able to sustain high temperatures. A thermal–electrical–mechanical analysis was conducted in the simulation phase to investigate the output voltage, output power, and thermal stress

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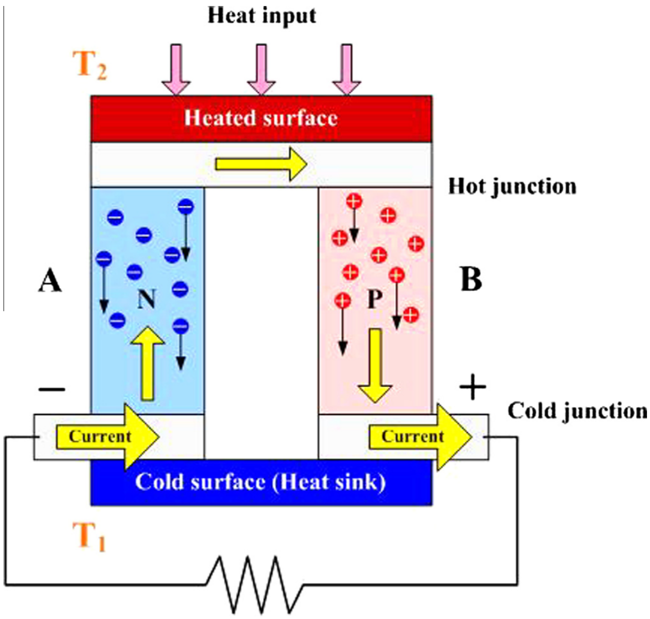

Fig. 1. Schematic diagram of the Seebeck effect.

of the TEG induced through a difference in temperature. The electrical and thermal simulation results were compared with the experimental results at different temperature conditions [8].

This research aims to investigate the use of intermetallic compounds (IMC) as a replacement for traditional solder materials in the interconnection joints. Ni/Sn/Ag was adopted as the joint material to assemble and form the TEG. After the bonding and thermal treatment processes, tin reacted with nickel and silver was entirely consumed to transform into a full IMC. The TEG with full IMC joints can be applied at temperatures above 200 °C because of the high melting point of the IMCs.

The composition and growth thickness of the IMCs were analyzed and examined through scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). The mechanical strength of the IMCs was measured at different thermal treatment times through a shear test. An increase in thermal treatment time

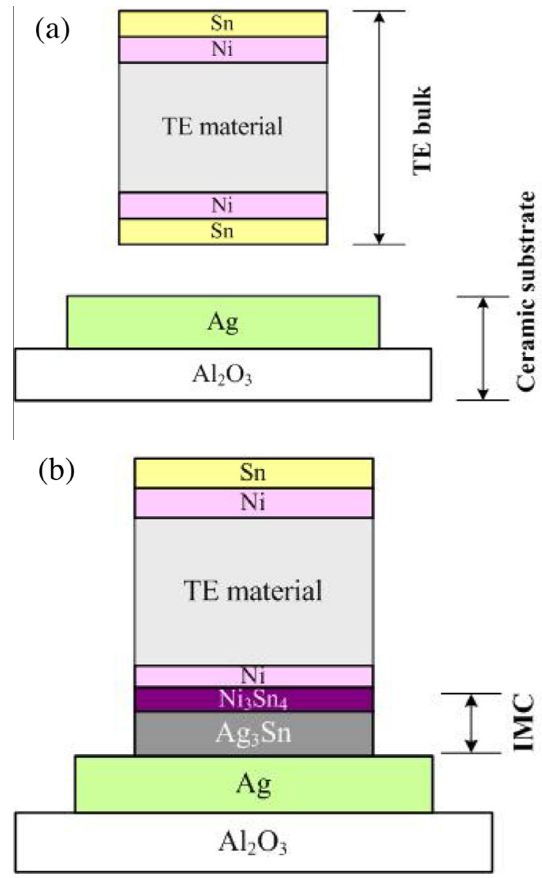

Fig. 3. (a) Schematic of the test sample and (b) tin was entirely consumed after reacting with nickel/silver to transform into a full IMC after bonding and thermal treatment process.

caused a decrease in shear strength. The fractured surface of the joints was observed and examined to understand structural strength after the shear test.

After TEG assembly, the TE characteristic of the TEG was measured through the slope method to obtain the Seebeck coefficient,

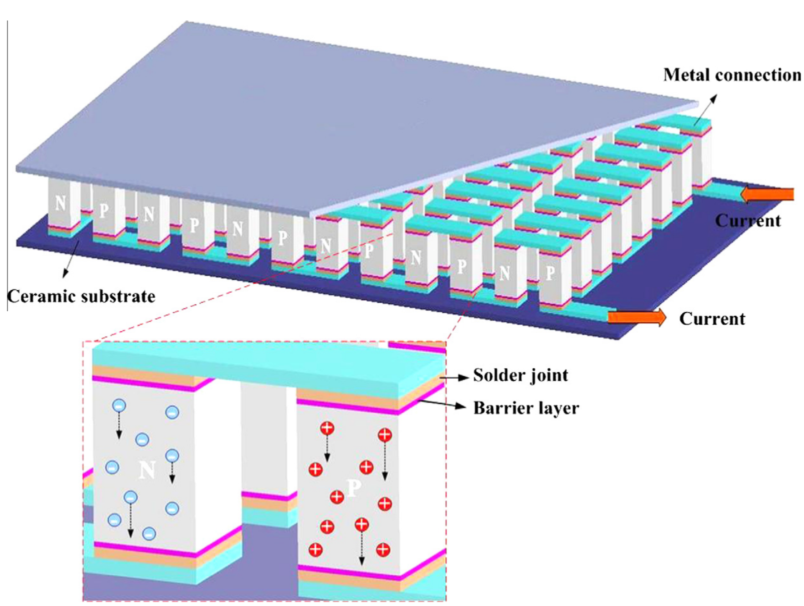

Fig. 2. Schematic diagram of the thermoelectric module.