Chapter 10
Anodized Aluminum as Effective and Cheap Alternative Substrate for Thermoelectric Generators

F. Assion, V. Geneiß, M. Schönhoff, C. Hedayat, and U. Hilleringmann

Abstract The wide usage of thermoelectric generators (TEG) is still blocked by very high product costs. This paper presents anodized aluminum (Al) as an effective and cheap alternative for ceramics like alumina (Al_2O_3) or aluminum nitride (AlN). Al has a significantly higher thermal conductivity as both named ceramics. In addition, the lower thermal stability of Al is still high enough to work with bismuth telluride based modules, which are most common. To show the advantages of the changed substrate, finite element method (FEM) simulations were performed. These simulations show that by changing the cold side substrate material the temperature drop across the substrate is reduced by 60 K. This correlates to a theoretical power gain of more than 20 %. Furthermore, Al can be shaped much easier than a ceramic material. The biggest advantage is obviously the price. Anodized Al is around twenty times cheaper than Al_2O_3. To demonstrate the easy fabrication of the proposed substrate, samples were prepared only with widely used processes like those used for conventional printed circuit boards.

Keywords Al_2O_3 • Substrate • Anodized Al • Costs • TEG

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Introduction

The wide usage of thermoelectric generators (TEG) is still blocked by very high product costs. Almost all commercially produced TEGs nowadays are mounted on ceramics like alumina (Al_2O_3) or aluminum nitride (AlN). On the one hand, these materials have a very high thermal stability and a rather good thermal conductivity, which makes them interesting for thermoelectric applications. On the other hand, they are very expensive and their thermal conductivity actually drops with rising temperatures. Furthermore, the maximal working temperature of thermoelectric (TE) materials used nowadays is rather low so the high thermal stability might not really be needed. This paper is not the first one calling the use of expansive ceramic substrates into question [1] by looking at requested cost–performance ratios of around one Euro per watt for TEGs.

Anodized aluminum (Al) could be an effective and cheap alternative for ceramics used nowadays. For good module efficiency, the thermal resistance of a TEG substrate must be as low as possible. Al has a significantly higher thermal conductivity as both named ceramics (see Fig. 10.1).

In addition, the lower thermal stability of Al is still high enough to work with bismuth telluride (Bi_2Te_3) based modules that are most widely spread. Bi_2Te_3 based modules have a maximum working temperature of around 300 °C.

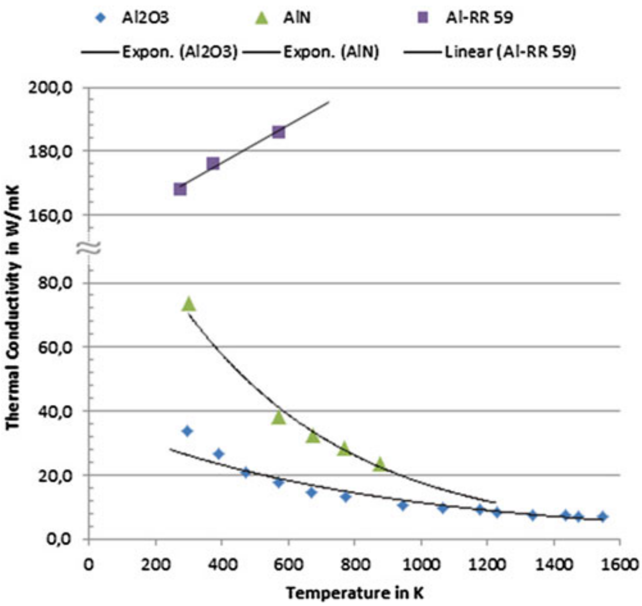

Fig. 10.1 Thermal conductivity of Al_2O_3, AlN, and Al vs. temperature [2–4]

Experiment and Results

To show the advantages of the substrate change finite element method (FEM), simulations were performed with the CST Studio Suite. All material properties are given in Table 10.1. In the simulation, a theoretical silicon/germanium (SiGe) TEG was analyzed. The TEG was placed between a 20 °C cold side and a 600 °C hot side. Caused by the rather high thermal conductivity ($\kappa = 4.0–5.9$ W/m K [5]) of the SiGe material, the thermocouples are short ($l = 1$ mm). Shorter thermocouples lead to a better cost–performance ratio and therefore reduce the overall costs of TEG systems [6]. The hot side substrate is a 0.5 mm thick Al_2O_3. The cold side mounting material has for mechanical reasons a thickness of 1.6 mm.

In Fig. 10.2, the simulation results of two different substrates are shown. The temperature distribution reveals the losses inside the particular mounting substrate. On the left picture the substrate is a commercially used <92 % pure Al_2O_3 ceramic with a thermal conductivity of $\kappa = 14–24$ W/mK [8, 9]. With this substrate, the thermocouple cold side temperature is 99 °C, which means nearly 80 K temperature difference, are lost. By using an anodized Al substrate (1.5 mm Al + 0.1 mm Al_2O_3), the thermocouple cold side temperature decreases to 39 °C (compare Fig. 10.2, right).

This means that by changing the cold side substrate material the effective temperature difference across the thermocouples increases by 60 K, which is a relative increase of more than 11 %. Moreover, since the temperature difference is squared to get the output power this equals a theoretical power gain of 23 %. Even by consideration that this is a theoretical example and that the output power gain also

Table 10.1 Material properties of the simulation model

Material	SiGe	Al	Al_2O_3	References
Density in g/cm^3	3.009	2.7	3.6	[5, 7, 8]
Therm. conductivity in W/mK	4.0–5.9	237	14–24	[5, 7–9]
Specific heat in J/kgC	770	900	850–1,050	[5, 7, 8]

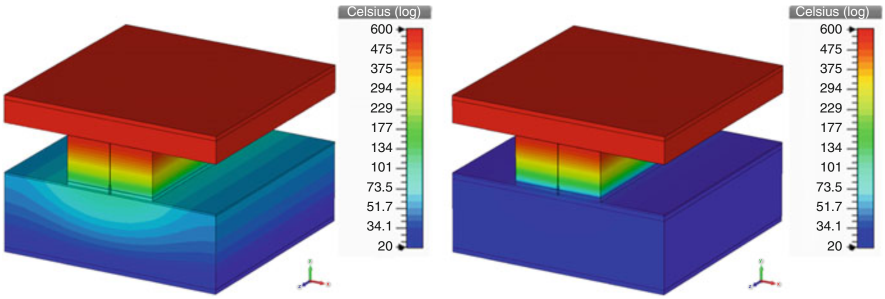

Fig. 10.2 FEM-simulations of thermocouples with Al_2O_3 (*left*) and anodized Al (*right*) substrate (*log scale*)

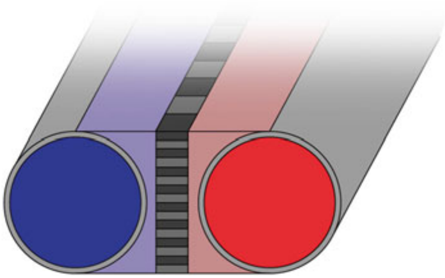

Fig. 10.3 A theoretical round shaped TEG between two pipes

Table 10.2 Prices for different materials

Material	Price	Reference
AlN	70 €/cm^3	[11]
Al_2O_3	1.3 €/cm^3	[12]
Al (anodized)	0.06 €/cm^3	[13]

causes a higher needed input power, the message is clear. High thermal conductive substrates lead to higher output powers. Earlier simulations have already shown this trend [10].

In addition, there are still two more things to be mentioned by comparing anodized Al vs. Al_2O_3 and AlN. Al can be shaped much easier than a ceramic material which could be used for a further reduction of the thermal resistance by more detailed substrate shapes. Even round shapes can easily be processed and, due to the high thermal conductivity of Al, the added thermal resistance is rather small (compare Fig. 10.3).

The biggest advantage is obviously the price. Anodized Al is around twenty times cheaper than Al_2O_3 and even a thousand times cheaper than AlN (see Table 10.2). Depending on the substrate's share of total costs, the cost reduction can be in the region of several single percentages.

To demonstrate the actual behavior of the proposed new TEG substrate, several samples have been prepared. Figure 10.4 shows two pictures of the same sample. The left one is taken with a light microscope at a 50-times magnification. For the other one a confocal laser scanning microscope (CLSM) was used. In the shown pictures the Al_2O_3-layer in the middle has a thickness of about 36 µm. It was grown in sulfuric acid at room temperature with a current density of 20 mA/cm^2. Tests have shown that layers with a minimum of 12 µm are thick enough to insulate the top cupper (Cu) layer from the lower Al-substrate. However, to ensure mechanical stability the Al_2O_3 has to be a little thicker. Even though for thermal reasons the Al_2O_3-layer should be as thin as possible.

On top of the Al_2O_3 is a 45 µm thick Cu-layer which shall be used to connect the single thermocouples to a complete TEG. It was grown by a simple galvanic step in Cu(II) sulfate with a current density of 28 mA/cm^2 onto a thin sputtered titanium start layer. The start layer was deposited by magnetron sputtering in argon at a pressure of 2.4 Pa and 2 kW DC power. The gap between the metal and the insulation

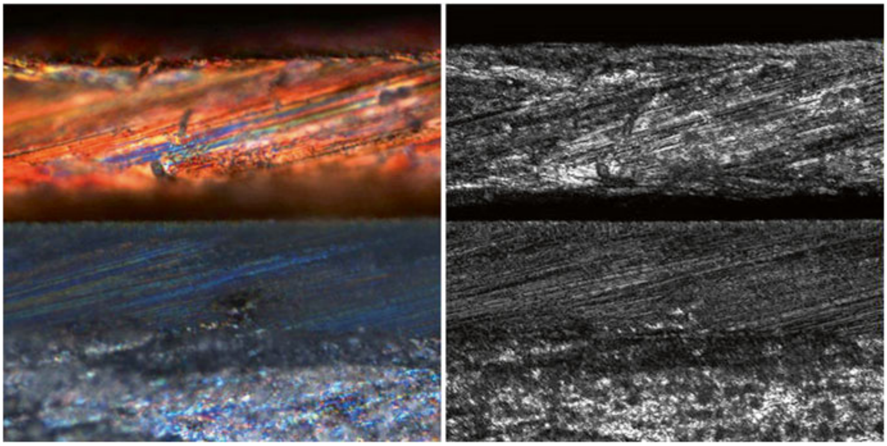

Fig. 10.4 Cross section view of anodized Al with Cu metallization—light microscope (*left*)/ CLSM (*right*)

accrued during the sample preparation. Exchanging the titanium with titanium nitride will enhance the adhesion and will thereby enhance the mechanical stability. To structure this layer conventional printed circuit board processes can be used.

Conclusions

It was shown that anodized aluminum is a cheap alternative for ceramics used nowadays. In special cases, anodized aluminum will actually enhance the output power of the device. In the simulated example, the exchange of the substrate revealed a power gain of over 20 %. Even though this is a constructed case, the consequences are distinct. It was also demonstrated that the substrate can be made very easily with widely used processes like those used for usual printed circuit board. In the end, anodized aluminum is at least one order of magnitude cheaper than usually used ceramics.

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