KOREA INSTITUTE OF ENERGY RESEARCH

CONCEPT PAPER

for KIER International Cooperation project

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Title

SiC/C 2-in-1 Insulation Plates for Thermoelectric Module Efficiency Improvement

Description

1. Introduction – Thermoelectric (TE) module

2. Purpose - Alumina/Graphite sheet structure

(1) Low thermal conductivity - reduce the thermoelectric efficiency
(2) Heat loss minimization (between TE module and hot side)
(3) Manufacturing process step simplification

3. Strategy – SiC/C

(1) SiC - high thermal conductivity, electrically insulator, high strength, thermal stability at high temperature, low cost, simple manufacturing process

(2) SiC/C 2-in-1 structure

A. Diffusion annealing process
B. Powder metallurgy process

4. Benefit

(1) Overcoming technological barriers of the conversion-efficiency limit for the existing mid temperature range TE modules
(2) Maximize the commercialization potentials of TE-generation technology utilizing efficiency improvement
(3) Accessibility to the global TE generator market (~ 547.7 million USD by the end of 2020)

Outcomes*

- Heat transfer improvement,

: Thermal conductivity: over 5 times improvement as current (with Alumina: ~25 W/mK)

- Expected indirect outcomes

: Thermoelectric module conversion efficiency (Single type): 9 % (current: 8 %)

- Publications and/or Patents

: 2-4 SCI journal papers and 1 patent application

1. Introduction

Currently, a large amount of thermal energy is being rejected from many industrial processes or similar sources as waste heat at both low and high temperatures. Thermoelectric (TE) power generation has become a promising technology to recover waste heat by converting the excess heat directly into electricity via the Seebeck effect [1].

The basic TE module, which consists of p- and n-type TE materials connected electrically in series and thermally in parallel [2]. Figure 1 shows a typical TE module [3]. The TE materials in a module are linked together by thin electrically conducting strips, such as copper. The connecting links are held in good thermal/mechanical contact with electrically insulating plates that should be made from a material that conducts heat well. Alumina plates are often used but these are not particularly a good thermal conductor. Graphite layers, which are a compressible material with high thermal conductivity, fill most of the gaps between the TE module and the heat source.

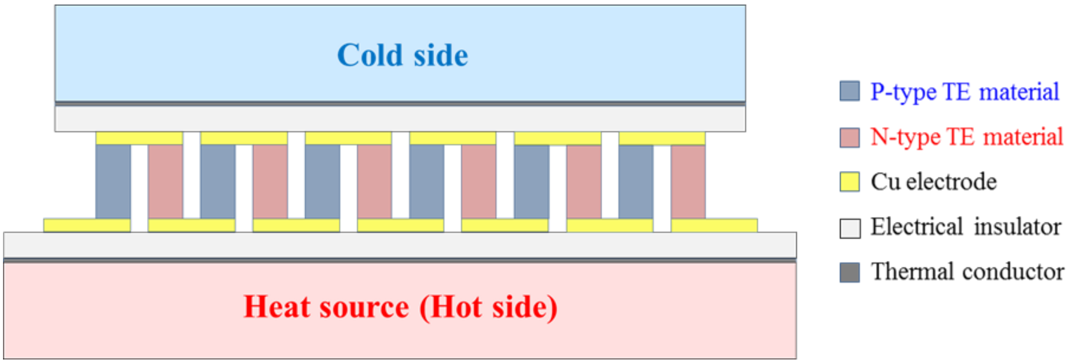

Figure 1. Schematic of a thermoelectric module.

2. Purpose

(1) **Thermal-conductive electrical-insulating plates**: the electrically insulating plates need to have (i) a good adhesion with copper electrodes to ensure thermal/mechanical robustness and (ii) high thermal conductivity to reduce heat loss from heat source to thermoelectric modules. Although the commonly used insulating plates made of alumina (Al_2O_3) can make a good contact with copper electrodes, their thermal conductivity (20-30W/mK) is not sufficiently high [4]. Since the TE efficiency is strongly determined by temperature difference, the heat transfer from heat source to TE materials without any loss is significant in TE module system and its efficiency.

(2) **Filling layer for improved heat transfer**: even the surface of TE module and the contact surface of heat source may look flat and smooth, but they consist of "peaks", and "valleys" [5] shown in Figure 2. When these two surfaces make contact with one another, the peaks from one material make contact with the peaks of the second material. The valleys create voids through which heat energy has difficulty passing through, in effect creating a thermally insulated area. This issue can be even more serious in a vacuum jacket that is strategically used to prevent oxidation problems of mid temperature TE systems.

Graphite layers have been used to fill the voids between TE modules and heat source and help improve heat transfer at the contact surface. However, although the graphite layer fills the majority of voids, thin and small air (or vacuum) gaps could still remain between the filler (graphite layer) and TE modules. These small gaps can significantly interrupt heat flow.

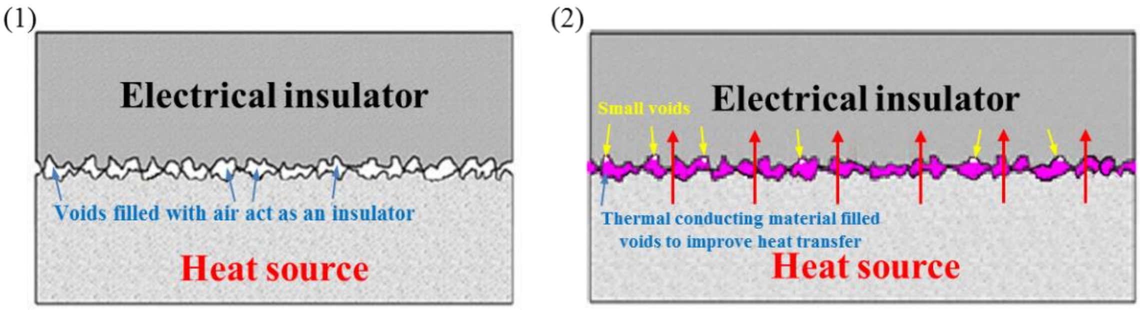

Figure 2. Magnified surfaces of thermoelectric module and heat source [5].

(3) **Cost-effective and simple fabrication process**: a typical TE module, as shown in Figure 1, is consist of a graphite layer (thermally conducting filler), alumina plates (electrically insulating plates), copper electrodes, and p-type/n-type TE materials. Therefore, appropriate assembly processes are needed in order to get all components together to make completed TE modules. If the assembly process can be simplified and made less costly, the overall manufacturing cost will decrease.

3. Strategy

(1) **SiC**: when looking for TE materials that offer both high thermal conductivity and electrical insulation, ceramics are reasonable choices. Silicon carbide (SiC) is one of the alternative materials for TE insulation plates.

- Higher thermal conductivity than alumina (SiC: 150 W/mK, Al_2O_3: 20-30 W/mK) [6]
- High levels of hardness, outstanding heat resistance, as well as durability
- Resistant to chemical corrosion, such as oxidation, than other non-oxide ceramics
- Cost effective and potential materials for structure engineering due to a simple manufacturing process.

PHYSICAL PROPERTY	AlN	SiC	BeO	Al_2O_3
Thermal conductivity(W/m-K) at 25°C	170-220	150	250-300	20-30
Thermal expansion coefficient ($x10^{-6}$/°C) from 25-400 °C (TCE of Si: 3.5-4$x10^{-6}$/ °C)	4.3-4.6	3.7	7.5-8.0	6.7-7.3
Dielectric constant at 25 °C and 1 MHz	8.8-8.9	40-42	6.5-6.7	8.5-8.9
Dielectric loss ($x10^{-4}$) at 1 MHz	1-5	500	1-5	2-3
Dielectric strength (kV/cm) at 25 °C	140-170	0.7	100	100
Electrical resistivity (Ω.cm) at 25 °C	$>10^{14}$	$>10^{14}$	$>10^{14}$	$>10^{14}$
Density (g/cm³)	3.26	3.21	3.01	3.97
Flexural strength (kg/cm²)	4000-5000	4500	2500	3000
Young's modulus (GPa)	343	460	378	378

Table 1. Physical properties of candidates materials (AlN, SiC and BeO) compared to Al_2O_3, reprinted from Ref. [6].

(2) **SiC/C 2-in-1 structure**: The proposed 2-in-1 structure is a combination of the thermal-conductive electrical-insulating layer and the filler explained previously. The resultant structure will be able to prevent the formation of voids that retard the heat transfer between insulating plates and heat source. We suggest **SiC/C 2-in-1 structure** with two different manufacturing processes; (i) diffusion annealing process (DA) and (ii) powder metallurgy process (PM). The two processes are displayed in Figure 3 and the details are described as follows.

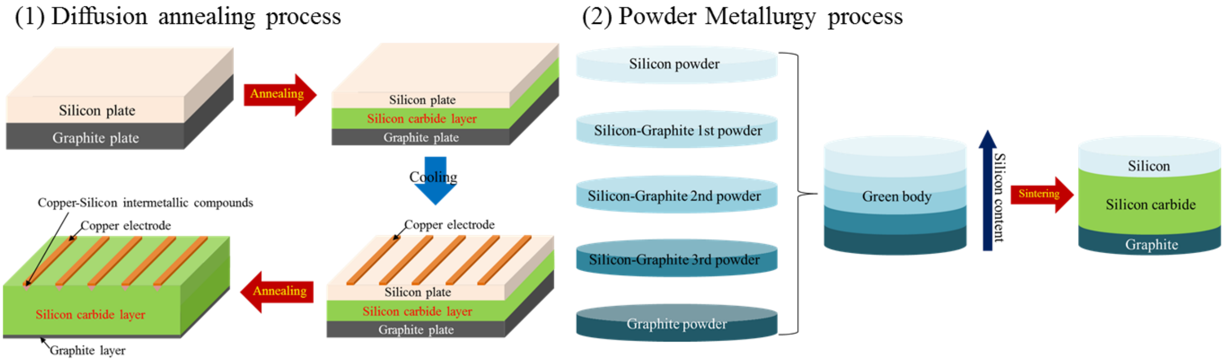

Figure 3. SiC/C 2-in-1 manufacturing process

A. Diffusion annealing process (DA)

SiC can be homogenously formed by carbon (C) diffusion into silicon (Si) driven by annealing. The precise control of heat-treatment process will allow us to fabricate well-designed Si/SiC/C layer. We will optimize the process to obtain SiC/C two layered plates from one process. The detailed procedure is as follows: the copper electrode array will be printed on the Si layer prior to the SiC formation process due to the good adhesion property between Si and Cu. Then, the Si layer is converted to SiC through additional diffusion annealing. Eventually, SiC/C 2-in-1 structure with the copper electrode can be produced.

B. Powder metallurgy process (PM)

With using powder metallurgy, the functionally graded material (FGM) concept can be introduced to make SiC/C 2-in-1 structure. FGM is a mixture of two different distinct materials fabricated in such a way that a volume fractions of the constituents are varied gradually in a predetermined composition profile [7]. The profile of the composition starts with 100 % graphite at the surface of the plate and varied gradually with intermediate composition through the thickness of the plate, ending with 100 % of Si at the other surface. The desired Si/SiC/C layered structure will be formed by optimizing the sintering condition. The copper electrode array is made on the Si layer. The remaining Si layer is converted to SiC through additional diffusion annealing. Finally, SiC/C 2-in-1 structure with copper electrode can be produced with the different process.

4. Benefit

- **SiC's high thermal conductivity** (**150 W/mK**, cf. Alumina: 20~30 W/mK) can improve the heat transfer, resulting in enhancing TE module conversion efficiency.

- The proposed **2-in-1 structure** has the possibilities to simplify the manufacturing procedure and to reduce overall manufacturing costs.
- Overcoming technological barriers of the conversion-efficiency limit for the existing mid temperature range TE modules – the conversion efficiency target in mid temperature TE modules is **20% within 5-6 years**, but ZT improvement by engineering p-/n-type thermoelectric materials may not be sufficient to achieve the challenging goal. The new 2-in-1 structure and its manufacturing process proposed in this concept paper will be able to reduce thermal losses from the heat source across the TE material. It will have a significant contribution on improving conversion efficiency and, ultimately, meeting the goal.
- Accessibility to the global market of TE; the global TE generator market is projected to reach **547.7 million USD by the end of 2020** (North America and Asia-Pacific hold the largest shares of the global TE generator market) [8]
- Maximize the commercialization potentials of mid temperature range TE-generation technology utilizing efficiency improvement
- High applicability to improve existing high-temperature energy technologies, such as the fields of fuel cells, solar cells, etc.

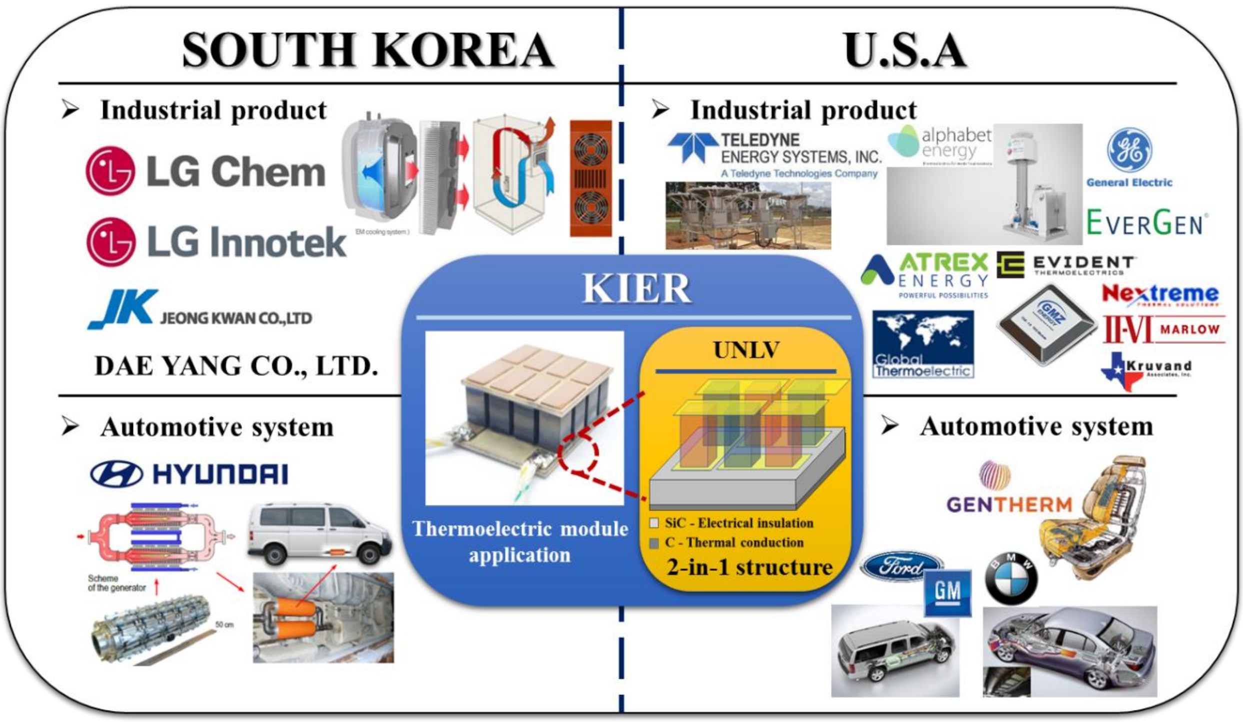

Figure 4. Potential market & demand of thermoelectric (TE) application for SiC/C 2-in-1 structure TE module

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