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Fabrication and characterization of ultrathin thermoelectric device for energy conversion

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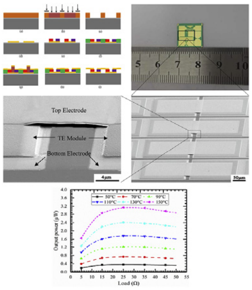
HIGHLIGHTS

- Novel hybrid fabrication method was developed for the first time.
- Non-contact lithography and photoresist melting were applied concurrently.
- The method was suitable for batch processing in the micro/nanoscale range.
- The peak output power density is 0.29 W/m^2 and 2.9 × 105 W/m^3.

GRAPHICAL ABSTRACT



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ABSTRACT

The fabrication of a micro/nano-scale thermoelectric module is very challenging. In this paper, a reliable and efficient hybrid fabrication method for ultrathin thermoelectric devices based on the non-contact exposing, photoresist melting and microfabrication technology is presented. The total thickness of the thermoelectric module is about 1 μm. Twenty-one devices are fabricated successfully, of which each is composed of 127 pairs of thermoelectric legs connected in series with an average resistance of 25 Ω. Experimental results indicate that ultrathin thermoelectric device work stable and reliable, and demonstrate that the method presented is suitable for fabrication of thinner and higher integrality devices beyond TE devices in the micro-nanoscale range. Without a load and at the temperature of 150 °C, the output voltage and output current are 18.5 mV and 671.9 μA, respectively; summarily, at the temperature of 50 °C the output voltage and current are 6.1 mV and 240.1 μA, respectively. The peak output power density is 0.29 W/m^2 and 2.9 × 10^5 W/m^3. In addition, a one-dimensional heat transfer model is established to obtain a quantitative characterization for further numerical modeling. The present research can provide a useful guide for the design of a micro/nano-scale thermoelectric device in the near future.

1. Introduction

The thermoelectric devices harvest the electric power from the heat converting the heat directly to the electric energy by the Seebeck effect [1,2], which makes them the promising environmental-friendly means for energy conversion. Due to the inherent advantages such as absence of the noise, pollution, and mechanical vibration and so on [3–7], thermoelectric devices have been already widely used in vehicles

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Nomenclature

A_p	contact area of the pipe (mm^2)
$\boldsymbol{d}$	distance between the chromium mask and the photoresist (μm)
d_i	inner diameter of the pipe (mm)
d_o	outer diameter of the pipe (mm)
h	equivalent convection heat transfer coefficient (W/(m·K))
I	output current (A)
l	pipe length (mm)
L_T	distance of the photoresist thermal reflowing (μm)
n	number of thermoelectric couples
Nu	Nussle number
P	power output of the TE device (W)
Pr	Prandtl number
Q_c	removal heat flux (W)
Q_h	total incident heat flux (W)
Q_l	heat flux of the cooling side (W)
$Q_{\text{up-c}}$	heat flux of the cooling system (W)
r	internal resistance value of TE device (Ω)
R	load resistance (Ω)
R_{down}	interface resistance between heat source and TE device (K/W)
Re	Reynolds number
R_l	thermal resistance of cooling systems (W/K)
$R_{\text{up-c}}$	thermal resistance between the TE device and the cooling system (W/K)
S	Seebeck coefficient value (V/K)
t	time (min)
T_{c}	cold end temperatures of the thermoelectric device (K)
T_{h}	heating temperature (K)
T_{down}	temperatures at the hot junction (K)
T_{up}	temperatures at the cold junction (K)
T_∞	environment temperature (K)
T	absolute temperature (K)
U	open circuit output voltage of the TE device (V)
Z	thermoelectric coefficient (/K)

Greek symbols

η_{max}	thermoelectric conversion efficiency
κ	equivalent of the thermal conductivity of the TE module (W/(m·K))
κ_{water}	thermal conductivity of cooling water (W/m·k)
μ_T	fluid velocity (μm/min)
ρ	density of the photoresist (g/cm^3)
δ_p	wall thickness of the pipe (mm)
ΔT	temperature difference (K)

Abbreviations

TE	thermoelectric module
N	N-type semiconductor material
P	P-type semiconductor material
MEMS	Micro-electromechanical Systems
UV	ultraviolet
DC	direct current
ZT	thermoelectric figure of merit

[8–11], wearable devices [12–18], solar energy systems [9,19,20], and industrial waste-heat recovery systems [21–23] to convert the human body temperature or waste-heat into the electrical power improving the operating efficiency and reducing the costs [24]. Several decades years ago, many fabrication methods for TE devices were developed, such as printing [12,18,25,26], physical vapor deposition (PVD) [13,27–30], spark plasma sintering [7,31–35], hot-pressing [36,37], metal-organic chemical vapor deposition (MOCVD) [38], and so on. The thermoelectric materials applied to the TE devices are diversiform. However, the traditional thermoelectric material has a very low ZT value and cannot be commercialized [39]. In recent years, a large number of studies have suggested that low-dimensional thermoelectric materials have a significant enhancement in ZT value [40–43]. However, owing to the limitation of micro-nanoscale fabrication, it is a very challenging subject. Therefore, along with the development of microfabrication technology [44], the micro-electro-mechanical systems (MEMS) techniques such as mask lithography, PVD, chemical vapor deposition (CVD), reactive ion etching (RIE), and so on have attracted more attention recently. These microfabrication techniques have been successfully applied to fabricate various sensors, actuators, integrated circuit (IC), and other electronic devices [4,27,45–48].

Using the advantage of the microelectronics industry, more and more components, devices, and instruments have been miniaturized during the past few years. In addition, the thermoelectric materials have been evolved from bulk thermoelectric materials to the low-dimension thermoelectric materials, such as nanowire, super lattice and multiple-thin film of thermoelectric materials [49–55]. Moreover, miniaturization can improve the thermoelectric modules integration density, and consequently increase the electric power output. Therefore, realizing miniaturization of the thermoelectric devices has attracted more and more attention [56,57].

The miniaturized thermoelectric converters can output the microwatts or milliwatts power for some MEMS devices. Utilizing the MEMS technology, hundreds of P-N thermoelectric-material couples can be connected in series, and a series of thermoelectric material couples form the thermoelectric modules which can output higher DC voltage. However, it is very difficult to fabricate the microscale devices; therefore it is urgent to develop a simple but reliable method for fabrication of thermoelectric converter devices.

One of the critical processes in the fabrication of the microscale thermoelectric devices is construction of the air bridge. In fact, that is an extremely complex process consisted of spin coating, soft baking, mask aligning, UV exposure, and developing of the exposed area, magnetron sputtering electrode metal and thermoelectric material, and lifting off. There are two key issues for a photoresist sacrificial layer during the fabrication process [58]. The first issue is the thickness homogeneity of the Au top electrodes along the bridge profile after patterning the Au top electrodes. The thickness of the Au electrodes on the sidewall of the sacrificial layer is relatively thinner compared to the other areas because of the shadowing effect which results in a poor connection at the sharp edge of the sacrificial layer. This problem can lead to the Au electrode fracture in the subsequent fabrication steps and increase the device internal resistance significantly. The other issue is that untreated sacrificial layer may be removed during the following developing process. In order to solve these problems, an effective fabrication method was presented. This method exposes the sacrificial layer by precise controlling of UV exposure dose, removes the exposed part, then, treats it by a plasma asher to make the sacrificial layer be even with the TE legs, and deposits a very thin Au film to protect the sacrificial layer from exposing and removing in the developing solution but making it dissolved in the acetone [59]. Although this method is feasible, it is unreliable and complicated. Moreover, it is difficult to control the depth of the exposure part, and the surface underexposure part after developing and etching by a plasma asher is very rough which can increase the resistance of the thin metal electrode. Besides, the additional steps not only increase the fabrication time but also the cost.

In this paper, a novel, reliable hybrid fabrication method for air bridge construction is demonstrated. Besides, to cascade every two