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Power enhancement of silicon nanowire thermoelectric generator by using metal/dielectric thermally conductive layer

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Abstract

Silicon nanowire (SiNW) is a promising thermoelectric generator (TEG) due to its significantly reduced thermal conductivity and almost unaffected power factor compared to bulk Si. A cavity-free planar SiNW-TEG structure has been proposed in our previous study. A thermally conductive (TC) layer is necessary for the heat spreading from the heat source to the hot side of each thermoelectric module in TEGs. However, the use of TC layer will introduce an additional parasitic thermal resistance in TEGs, which decreases the thermoelectric power. Here, we show that the output power of SiNW-TEG can be enhanced by using metal/dielectric TC layers comparing with the use of AlN thin film. Furthermore, the output power of SiNW-TEG increases with the decreasing thermal resistance of TC layers.

1. Introduction

With fast advances of the IoT industry [1], it is forecast that there will be more than 64 billion IoT devices by 2025. Wireless power supply is urgently required for the data collection, processing, and transmission of the wireless sensor networks in the IoT society. Based on the Seebeck effect, TEG can convert directly heat energy into electrical energy when a temperature difference is present. With increasing efficiency of thermoelectric materials and decreasing power consumption of IoT sensor nodes, TEGs have attracted great attention to extend battery lifetime or even replace batteries for powering sensor nodes using heat energy from ambient temperature differences. Silicon nanowire (SiNW) is a promising thermoelectric generator (TEG) due to its significantly reduced ther-mal conductivity and almost unaffected power factor compared to bulk Si [2].

To generate a high thermoelectric voltage for applications, TEGs are composed of many thermoelectric modules connected electrically in 9series and thermally in parallel. A TC layer is necessary for the heat spreading from the heat source to the hot side of each thermoelectric module. However, the use of TC layer will introduce an additional parasitic thermal resistance in TEGs, which will decrease the efficient temperature difference across the thermoelectric module. Therefore, it is required to reduce the parasitic thermal resistance introduced by the TC layer. TC layer should be electrically insulative because it directly contacts with the electrodes of TEGs. Aluminum nitride (AlN) is a good candidate as TC layer due to its high thermal conductivity. However, the thermal conductivity of AlN nanometric thin films decreases dramatically compared with bulk AlN. By comparison, nanometric metal thin films such as Al and Cu have a comparable thermal conductivity to their bulk counterpart. Therefore, metal films are good candidates as TC layer if a dielectric layer is employed to electrically isolate the metal layer and the TEG. In this study, we show that the output power of SiNW-TEGs could be significantly enhanced by using metal/dielectric TC layers comparing with AlN thin film. Furthermore, the output power of SiNW-TEGs increases with the decreasing thermal resistance of TC layers.

2. Experimental

Figure 1(a)~(d) illustrates the main fabrication steps of the SiNW-TEGs. The details of the fabrication process can be found in our previous research.[3] However, in this new device, we fabricate two outstretched electrodes to keep way the electrical probes from the thermostat. The thermostat was heated to 40 °C as the heat source, while the substrate was maintained at 20 °C as the heat sink during the measurement of thermoelectric properties.

SiNW-TEGs with 6 different TC layers were prepared. Figure 2 (a) and (b) show the schematic of the Al/Ti/SiO_2 TC layer on SOI substrate and the TEM image with 150 nm-thick Au coating. The multilayered TC layer has a metal/adhesive/insulating structure. Al and Cu are used as the metal layer, Ti is used as the adhesive layer, SiO_2 and AlN are used as the insulating layer. The structures and thicknesses of the TC layers are shown in Table 1. The SiO_2 film was deposited by a non-reactive RF sputtering method using SiO_2 as the sputtering target. While the AlN film was deposited by a reactive RF sputtering using Al target while flowing Ar/N_2 mixture into the chamber. TC layers were also grown on a silicon on insulator (SOI) substrate for measuring their thermal resistance. The thermal resistance was measured using the frequency-domain thermoreflectance method (ω method). The details of the measurement are shown in the previous research.[5]

Table 1 Structures and thickness of TC layers.

Sample No.	Structure	Thickness (nm)
1	AlN	300
2	$Cu/Ti/SiO_2$	300/10/10
3	Cu/Ti/AlN/Ti	300/10/10/10
4	$Al/Ti/SiO_2$	300/10/30
5	$Al/Ti/SiO_2$	300/10/20
6	$Al/Ti/SiO_2$	300/10/10

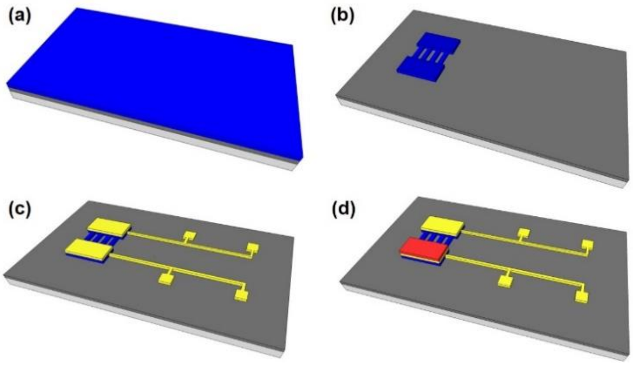

Fig. 1 Main fabrication steps of the SiNW-TEGs.

3. Results

Figure 3 shows the I–V and power curves of all the SiNW-TEGs with 6 different TC layers. it can be clearly seen that the highest open-circuit voltage (V_{oc}) and thermoelectric power is obtained when $Al/Ti/SiO_2$ structure with a 10 nm-thick SiO_2 layer is employed. Furthermore, the maximum thermoelectric power (P_{max}) decreases when the thickness of SiO_2 layer in $Al/Ti/SiO_2$ structure is increased. When AlN is used as the TC layer, P_{max} is the lowest. It is known that the total thermal resistance of the a TEG comprises the thermal resistance of the TEG legs and the parasitic thermal resistance. The two components of the thermal resistance act in series. A relative increase in the parasitic thermal resistance will result in a decrease in the temperature difference across the TEG legs, and therefore thermoelectric voltage. We plot V_{oc} and P_{max} as a function of thermal resistance of thermal conductive layers in Figure 4, which shows that both V_{oc} and P_{max} increase with the decreasing thermal resistance of thermal conductive layers. Therefore, the thermoelectric power could be further enhanced if the thermal resistance of TC layer is further reduced. This can be realized by thinning the insulating layer or lowering the thermal boundary resistance at metal/dielectric interface.

3. Conclusions

In this study, we have shown that the output power of SiNW-TEGs could be significantly enhanced by using metal/dielectric TC layers comparing with the use of AlN thin film. Furthermore, the output power of SiNW-TEGs increases with the decreasing thermal resistance of TC layers.

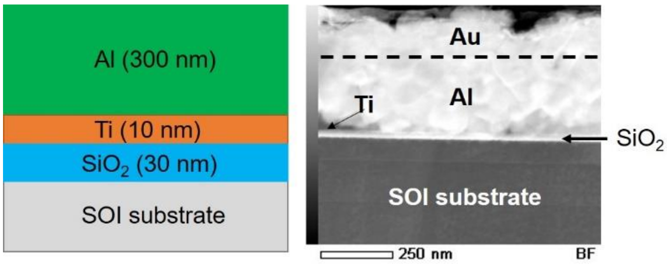

Fig. 2 Schematic of the $Al/Ti/SiO_2$ TC layers on SOI substrate and the TEM image with a 150 nm-thick Au coating.

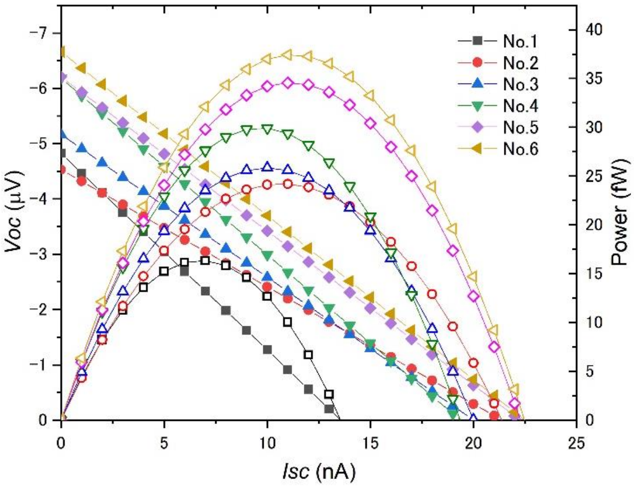

Fig. 3 I–V and power curves of SiNW-TEGs with 6 different TC layers.

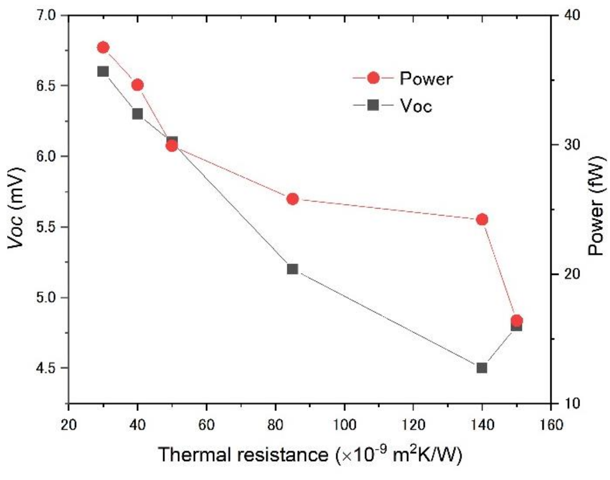

Fig. 4 *Voc* and *Pmax* as a function of the thermal resistance of TC layers.

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