USING NANOMATERIALS FOR LOCAL TEMPERATURE ENHANCEMENT FOR THERMOELECTRIC MICROGENERATORS

Y. Tseng,[1] Y. He,[1] S. Vasiraju,[1] Z. Gong,[1] W. Cheng,[1] W. Chen[2] and L. Que[1]
[1]Institute for Micromanufacturing, Louisiana Tech University
[2]Department of Physics, University of Texas at Arlington

Abstract: This paper reports a new type of thermoelectric microgenerators enabled by carbon nanotube-copper sulfide nanoparticles (CNT-CuS NPs) hybrid nanomaterial. The unique feature of this microgenerator is that it does not require any cooling or heat sinking element to maintain the temperature difference or gradient in the device. Instead, the integrated nanomaterials in the device will enhance the local temperature and thus cause and maintain an intrinsic temperature difference or gradient across the microgenerator, thereby converting light or heat into electricity directly.

Keywords: carbon nanotube-copper sulfide hybrid (CNT-CuS NPs) nanomaterials, local temperature enhancement, thermoelectric microgenerator

INTRODUCTION

Thermoelectric generators (TEGs) are based on Seebeck effect to convert heat, specifically the temperature difference, into electricity [1]. This technology has been widely and successfully used for scavenging many types of thermal radiation energies including the wasted heat from different sources [2]. In order to scale down TEGs and thus make them easily be integrated with microdevices and microsystems, for the past years different types of MEMS TEGs have been developed [3-6]. Even though the structural materials of the microdevices play very important role in the heat-to-electricity conversion efficiency [2], another very important issue is how to efficiently dissipate the heat and thus cause and maintain the temperature difference or gradient across the TEGs. To this end, usually cooling or heat sinking elements are required and thus integrated for improving the conversion efficiency of TEGs [3-6], indicating the possible extra power consumption to maintain the temperature difference or gradient between the "hot" and the "cold" parts in the thermocouples. Evidently the ideal case is that the temperature difference or gradient can be intrinsically generated and maintained by the TEGs themselves.

As a nanomaterial with unique optical and thermal properties, it has been found that carbon nanotube and its nanohybrids can absorb the light and thermal radiation significantly and thus can efficiently convert them into heat [7-10]. Hence, by integrating this type of nanomaterials, the local temperature of a microdevice can be modified.

Herein, we report a new type of thermoelectric micro generator enabled by nanomaterials and thus the temperature difference or gradient in the microdevice can be maintained intrinsically for electricity generation

DEVICE DESCRIPTION & FABRICATION

Device and its Operation Principle

Schematic of a thermoelectric microgenerator is shown in **Fig. 1**. It is a layered-structure and consists of a layer of Au deposited on p-type silicon substrate, a layer of silicon nitride, and a layer of Au deposited on silicon nitride. One region is coated with CNT-CuS nanohybrid thin film, which is covered by SU8.

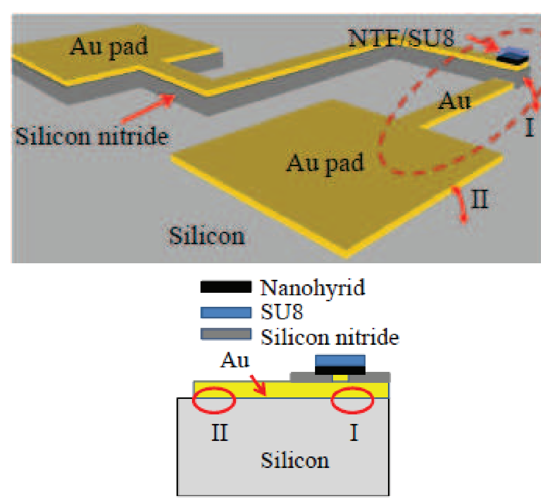

Fig. 1: Sketch of a thermoelectric microgenerator with integrated NTF:(left) angled topside view; (right) cross-section showing the junction I and II formed between silicon substrate and Au layer

The bottom Au layer forms the junctions between the p-type silicon. Specifically, the junction I and junction II are labeled in the cross-sectional sketch of the thermoelectric microgenerator. The top Au layer is electrically isolated from the silicon substrate by the silicon nitride layer underneath, serving as a metal wire connection to Junction I. The Seebeck coefficient (S_{si}) of the p-type Si doped with boron at a concentration in the range of 3×10^{18} to 2×10^{19} cm^{-3} is ~300 μV/K, while the Seebeck coefficient (S_{Au}) of Au is 1.94 μV/K [11]. If the temperature difference (ΔT_{I-II}) between Junction I and II exists, a thermoelectric voltage between them will be generated, which is roughly given by:

$$V = (S_{si} - S_{Au}) \times \Delta T_{I-II}$$

Fabrication Process

The fabrication process has two main steps: (i) synthesis of hybrid nanomaterials; (ii) integration of the nanomaterials with the micrcodevices.

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Synthesis procedure of hybrid nanomaterial: The CNT-CuS NPs hybrid nanomaterial is obtained by using a simple non-covalent binding synthesis technique. Specifically, the hybrid nanomaterial is prepared by using the oleylamine as the linker molecules between CNT and CuS NPs [12]. A certain amount (10 mg) of the SWNTs within 100 mL toluene solution containing 0.1% (v/v) oleylamine was sonicated in a nitrogen atmosphere and consequently stirred overnight. Then the oleylamine-functionalized SWNTs were isolated by centrifugation and rinsed with ethanol. The functionalized SWNTs were dispersed in 100 mL toluene followed by adding 100 μL solution of CuS nanoparticles. The mixture was sonicated for 1.5 h at room temperature. Then the SWNT-CuS NPs hybrid nanomaterials were precipitated by adding a small amount of methanol.

Thin films of both SWNT-CuS NPs hybrid nanomaterials and SWNT are prepared on a mixed cellulose ester (MCE) membrane using the vacuum filtration method [9]. Briefly, the nanohybrid and SWNT suspension are vacuum-filtered through a mixed cellulose ester (MCE) filter, separately. The resulting thin film on the filter is rinsed twice with isopropyl alcohol and deionized water and then dried at 80 °C for 2 hours to remove any remaining organic residues in the film. After drying, the film sheet can be either peeled off the filter or transferred onto a solid substrate.

Microdevice fabrication and integration: The fabrication process flow is illustrated in **Fig. 2**. Specifically, start from p-type silicon wafer, using a lift-off process, the bottom 250 nm thick Au layer is patterned on silicon substrate with 200 nm Ti as the adhesion layer. Then a layer of 400 nm thick silicon nitride is deposited and patterned. Using a lift-off process, the top Au layer of 250 nm is deposited and patterned. Then the thin film of the hybrid nanomaterial is transferred on the top Au layer. SU8 is spin-coated and patterned as a mask, following by the etching of the thin film of the hybrid nanomaterial. As a result, the hybrid nanomaterial is integrated in the Junction I region as shown in Fig. 2(f).

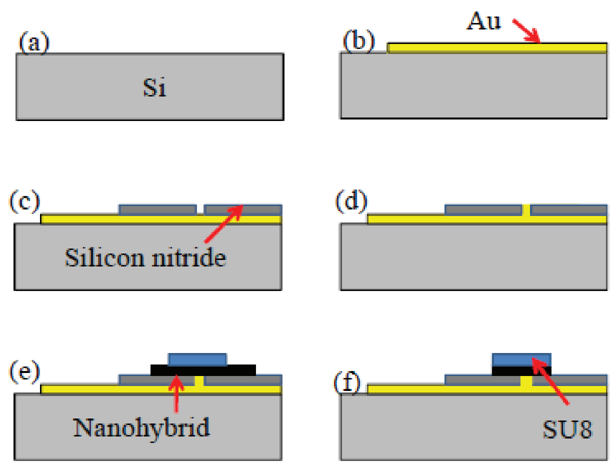

Fig. 2: Fabrication process flow: (a) Start with p-type silicon wafer; (b) Au pattern is formed on the silicon substrate; (c) Silicon nitride is deposited and then patterned; (d) top Au pattern is formed; (e) CNT-CuS nanohybrid thin film is transferred on the substrate and SU8 layer is patterned; (f)the hybrid nanomaterial thin film is patterned using SU8 as a mask

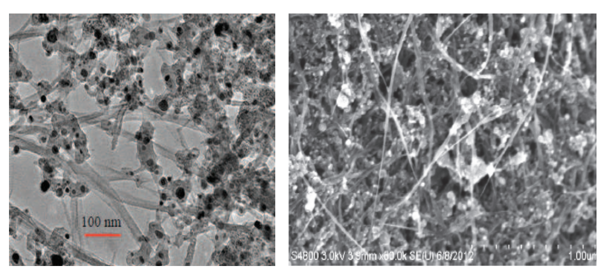

Fig. 3: (left) the TEM image of CNT-CuS NPs hybrid nanomaterial; (right) the SEM image of the CNT CuS NPs thin film

RESULTS AND DISCUSSION

A TEM image of CNT-CuS NPs hybrid nanomaterial is given in **Fig. 3(a)**. The CNTs decorated with CuS NPs is clearly visible. A SEM image of the thin film of hybrid nanomaterial is shown in **Fig. 3(b)**. Again it is clear that the CNTs are decorated with CuS NPs. A photo of a microdevice with integrated nanohybrid thin film (NTF) in the Junction I region is shown in **Fig. 4**.

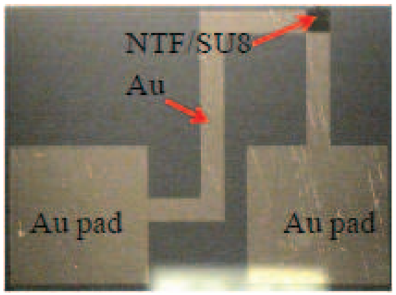

Fig. 4: Photo of a fabricated thermoelectric micro generator. The NTF is integrated in the Junction I region

The experimental setup is shown in **Fig. 5**. An Olympus TL-2 incandescent lamp is used to provide the light and thermal radiation source, while the measured voltages are recorded and stored in real time by a laptop computer.

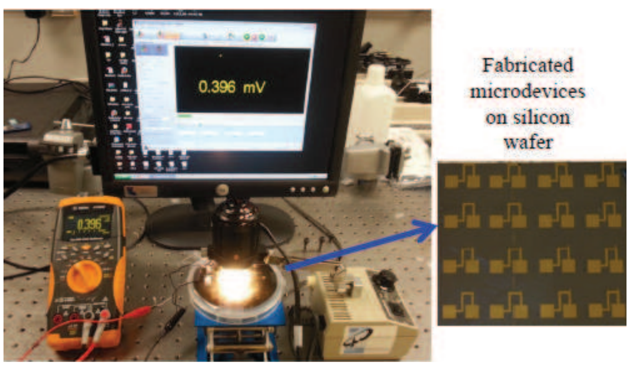

Fig. 5: The experimental setup for the measurements of voltages and currents by the thermoelectric microgenerators

As a comparison, for a microdevice *without* the integrated *NTF*, the measured open circuit voltage is ~0.01 mV as shown in **Fig. 6** under *uniform illumination* of the lamp. The uniform illumination means that all regions/parts of each microdevice are supposed to be exposed by the lamp with uniform light intensity and heat radiation. Under the same experimental conditions, **Fig. 6** also gives the measured open circuit voltage of the microdevice with the integrated *NTF*, its open circuit voltage is ~0.08 mV, which is 8 × the voltage generated by the microdevice without NTF. As a reference, without turning on the lamp, the voltage is essentially zero. Evidently, the NTF enhances the local temperature in Junction I region by absorbing the light and thermal radiation, hence the temperature difference between Junction I and Junction II increases. As a result, the generated voltage increases as expected.

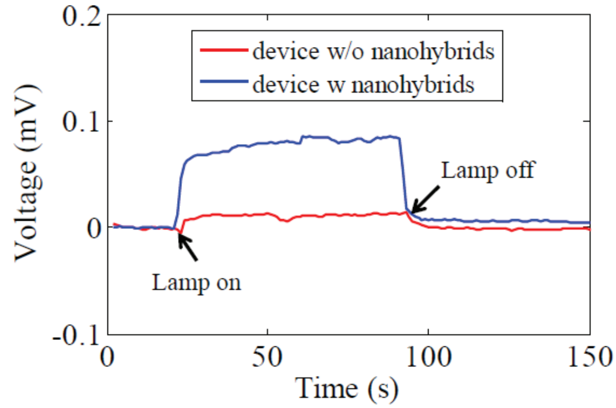

Fig. 6: Measured open circuit voltage (OCV) of a thermoelectric microgenerator with and without Nanohybrids (NTF) under uniform lamp illumination

Fig. 7 shows the measured open circuit voltages of these two types of devices when the lamp moves toward to and illuminates the *NTF* region. As can be seen, the devices with the integrated *NTF* can generate larger voltages. This again confirms the NTF enhances the local temperature of Junction I region, thus the measured voltage is higher than that of the microdevices without the integrated NTF.

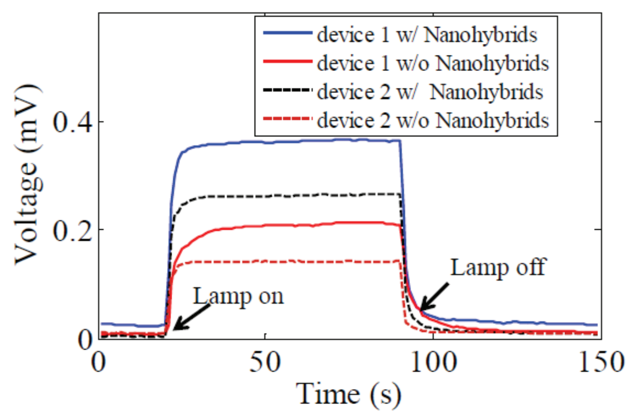

Fig. 7: Measured open circuit voltage (OCV) when the lamp illumination is only on the Nanohybrids(NTF) region compared to a device without the integrated Nanohybrids (NTF)

Finally, the output power by the microdevice has been measured. In this case, the light intensity and heat radiation is varied by changing the distance between the lamp and the microdevice. The lamp illuminates the Junction I region. **Fig. 8** gives the measured peak power by a microdevice under different light intensity and heat radiation. The output power is in the range of several or tens of nanowatts.

All above measurements suggest that the NTF plays an important role in the enhanced local temperature and thus the power generation. Especially, as evidenced in the measured results in **Fig. 6**, the intrinsic temperature difference or gradient between Junction I and Junction II is generated and maintained in the microdevice with the integrated NTF even though the microdevice is illuminated uniformly by the lamp, which offers us a new route to design thermoelectric generators. It is anticipated that by optimizing the optical and thermal properties of the NTF the generated voltage and power can be improved for each single device. Furthermore, the output voltage and output power can be further improved by fabricating hundreds of this type of microdevices and electrically connecting them properly.

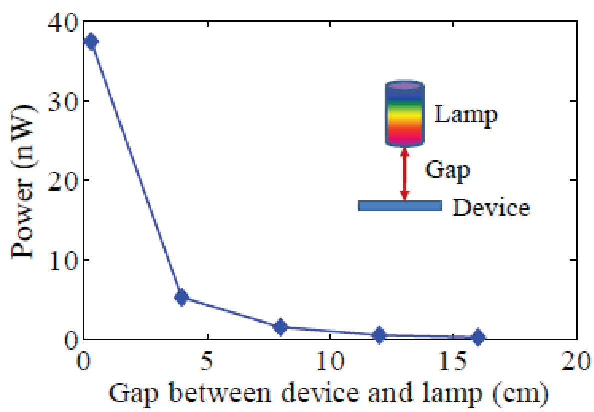

Fig. 8: Measured peak power by the thermoelectric microgenerator under different light intensity and temperature of the lamp by changing the gap between the device and the lamp

CONCLUSION

A new type of thermoelectric microgenerators has been fabricated and tested. The new feature of this type of microdevices is that the nanohybrid thin film (NTF) is integrated with the microdevices, serving as a local temperature enhancer. As a result, when these microdevices are exposed to light and thermal radiation, an intrinsic temperature difference or gradient across the thermoelectric microgenerators can be formed and maintained, resulting in continuous power generation even without integrating some specific heat sinking or cooling elements with the microdevices, which offers a new route to design thermoelectric power generation devices.

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