A Self-Powered Temperature Sensor Based on Silver Telluride Nanowires

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Thermoelectric devices are effective in harvesting energy from waste heat with a temperature difference relative to the environment, which can be applied in vehicles, aircrafts, and power plants. In our research, we developed a thin, lightweight, and flexible thermoelectric nanogenerator based on the nanocomposite of silver telluride (Ag2Te) nanowires and poly(3,4-ethylendioxythiophene):poly(styrenesulfonate) (PEDOT:PSS). The Seebeck coefficient of the nanocomposite was determined to be 100 μV/K. A linear relationship between the output voltage and the temperature difference across the thermoelectric nanogenerator was observed. Not only for the purpose of energy harvesting, the thermoelectric nanogenerator can also function as a self-powered sensor for water temperature measurement.

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Increasing research efforts have been devoted to renewable energy owing to the large energy consumption in recent years. Comparing to fossil fuel, renewable energy with the advantages of reduced carbon emission and secure long-term energy supply is more mandatory for the sustainable development of the world. Nanogenerators, which are emerging new energy technologies that can harvest renewable energy from the environment, have attracted global attention.1–4 Thermoelectric nanogenerator, which works based on thermoelectric effect,5–7 is capable of converting waste heat into electricity with a temperature difference relative to environmental temperature. Many studies have demonstrated that nanomaterials can enhance their ZT values by suppressing the thermal conductivity compared to their bulk counterparts. The reduction of thermal conductivity in nanomaterials is because phonon scattering and energy-dependent scattering of electrical carriers occur in the presence of nanoscale interfaces.12 These properties result in nanomaterials are good candidates to fabricate thermoelectric nanogenerator to harvest tiny-scale thermal energy13,14 and show the potential to be applied in the collection of heat energy from vehicles, aircrafts, and power plants. In addition, thermoelectric nanogenerator can be used as alternative to photovoltaic cells to convert solar energy into electrical power.15–18

In this paper, we developed a thin, lightweight, and flexible thermoelectric nanogenerator (Figure 1a) based on the nanocomposite Ag2Te nanowires and poly(3,4-ethylendioxythiophene):poly(styrenesulfonate) (PEDOT:PSS). The Ag2Te nanowires were synthesized at ambient temperature, which means that the energy-saving concept can be completely utilized, starting from the nanomaterial preparation. The as-prepared thermoelectric nanogenerator showed a Seebeck coefficient of 100 μV/K and a linear relationship between the output voltage and the temperature difference across the device. Under a temperature difference of 25°C, the thermoelectric nanogenerator provided an output voltage of 2.6 mV. And we have demonstrated that the thermoelectric nanogenerator can be applied as a self-powered sensor for water temperature measurement within a response time of 10 seconds.

Experimental

We used a two-step chemical method to prepare the Ag2Te nanowires. First, Te nanowires were synthesized through a chemical reduction approach at ambient temperature. 0.016 g tellurium dioxide powder (TeO2, 99.9%, Showa Chemical) was directly put into an 8 M hydrazine solution (N2H4, 80%, Showa Chemical) containing sodium dodecyl sulfate (SDS, ≥ 98.5%, Sigma–Aldrich). Ultrapure water from a Milli-Q ultrapure system (18.2 MΩ cm) was used in this study. After a reaction time of 2 hours, Te nanowires with the average diameter and length we used in this paper were formed. The size of Te nanowires can be controlled by merely adjusting the reaction time.19 Then the solution containing the as-synthesized Te nanowires were centrifuged to remove excess chemicals and byproducts. Then the Te nanowires were re-dispersed in a 10 mM SDS solution (9 mL) to prepare Ag2Te nanowires. Silver nitrate (AgNO3, ≥ 99%, Sigma–Aldrich) with a final concentration of 1 mM was added to the SDS solution containing Te nanowires. Through a redox reaction between Ag+ ions and Te atoms, Te nanowires finally converted to Ag2Te nanowires. The reaction time was set up for 1 hour and then the formed Ag2Te nanowires were subjected to two centrifugation/wash cycles to remove most of the matrices. The Ag2Te nanowires were re-dispersed in ultrapure water (10 mL).

Figure 1. (a) Photograph of the fabricated Ag2Te nanowire-based thermoelectric nanogenerator. (b) TEM images of the as-synthesized Te nanowires. (c) EDX analysis of the prepared Ag2Te nanowires. (d) TEM image of the prepared Ag2Te nanowires.
To fabricate the thermoelectric device, a polyethylene terephthalate (PET) sheet was selected as the substrate. Then, aluminum was deposited on the PET substrate as the bottom conductive electrode. The dimensions of the PET substrate were 3 cm × 1.5 cm. The nanocomposite of Ag2Te nanowires and PEDOT:PSS was dropped slowly to the Al deposited PET substrate and dried at ambient temperature for 12 hours. Ag paste was applied as the top conductive electrode of the thermoelectric device. Two copper wires were connected to the Al and Ag conductive electrodes as leads for electric measurements. A UV/Vis spectrophotometer (V730, Jasco) was used to measure the absorption spectra of Te and Ag2Te nanowires. JEOL JEM-1200 EX II transmission electron microscopes (TEM) and JSM-7600F field emission scanning electron microscope (FESEM) were used to measure the size and shape of the prepared Te and Ag2Te nanowires. An energy dispersive X-ray system (Inca Energy X-Max, Oxford, UK) was used to determine the composition of the prepared Ag2Te nanowires. For the measurement of the electric performance of the thermoelectric device, a low-noise voltage preamplifier (Stanford Research System Model SR560) and a low-noise current preamplifier (Stanford Research System Model SR570) were used.

Results and Discussion

The preparation of Ag2Te nanowires is starting from the synthesis of Te nanowires. The synthesis of Te nanowires is accomplished by solution-phase approach, which is through a chemical reduction method conducted at ambient temperature. This indicates that the energy-saving concept can be completely utilized, starting from the nanomaterial preparation. First, a bottle of solution with DI water and reduction agent (N2H4, 8 M) was prepared. Second, TeO2 powder (0.016 g) was added to the solution. The mixture was kept at ambient temperature for 2 hours to make sure the reduction of TeO2 to form Te colloids (amorphous and trigonal nanoparticles). The growth of Te nanowires was through the deposition of Te atoms (either reduced from residual TeO2 or dissolves from amorphous Te nanoparticles) onto trigonal nanoparticles. The aspect ratio of Te nanowires can be controlled by varying the reaction time.19 Figure 1b shows the TEM image of synthesized Te nanowires. The average diameter and length of the as-synthesized Te nanowires are 18 nm and 820 nm, respectively. To prepare Ag2Te nanowires, Te nanowires were reacting with silver ions for 1 hour at ambient temperature for the conversion of Te into Ag2Te.20 A typical energy dispersive X-ray (EDX) analysis of the Ag2Te nanowires is displayed in Figure 1c, revealing that the atomic ratios of Ag/Te are 2/1 in the Au-Ag2Te nanowires. Then the Ag2Te nanowires were mixed with PEDOT:PSS and then dropped on a PET substrate in order to enable the device with flexibility (Figure 1a). From the TEM images shown in Figures 1c and 1d, we can observe that the Te nanowires and Ag2Te nanowires have difference in their morphology, which Te nanowires are firmly straight and Ag2Te nanowires are little curved in contrary with Te nanowires. The average diameter of Ag2Te nanowires is around 21 nm. Finally, after drying nanowires are little curved in contrary with Te nanowires. The average diameter of Ag2Te nanowires. For the measurement of the electric performance of the thermoelectric device, a low-noise voltage preamplifier (Stanford Research System Model SR560) and a low-noise current preamplifier (Stanford Research System Model SR570) were used.

the flexible thermoelectric nanogenerator with a mug and called it as a smart mug. Figure 3a shows the photograph of the smart mug attached with the Ag2Te nanowire-based thermoelectric nanogenerator on the surface. We then applied the smart mug to measure the water temperature. The output voltage generated from the thermoelectric nanogenerator reached −0.21, −0.1, 0.25, 0.6, 0.8 and 1.0 mV at the ΔT of −12, −5, 15, 28, 37 and 50 °C between water temperature and ambient temperature, respectively (Figures 3b and 3c). The output voltage increased as the temperature difference became larger. To further study the linearity between temperature difference and output voltage, we calculate the correlation coefficient, which turns out to be 99%. Figure 3d shows the linear relationship between the output voltage and the different water temperature in the smart mug.

Summary

In summary, a thermoelectric nanowire-based nanogenerator has been developed and measured the electric output. The as-developed thermoelectric nanogenerator shows the characteristics of thin, lightweight, and flexible. With the dimensions of 3 cm × 1.5 cm, the thermoelectric nanogenerator can provide an output voltage of 2.6 mV at a temperature difference of 25 °C. In addition, we have also demonstrated that the thermoelectric nanogenerator can be easily
attached on a container and function as a self-powered sensor to measure the solution temperature.

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