THIN-FILM FLEXIBLE THERMOELECTRIC MODULE WITH NANOSTRUCTURED ZINC OXIDE ARRAY ON A POLYIMIDE SUBSTRATE

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Lightweight thin-film flexible thermoelectric (TE) modules can be used as wearable low-power power sources for small gadgets and biosensors. The human skin temperature varies from 28 °C to 37 °C with the change in environment temperature from 0 °C to 35 °C. In addition, the heat flux varies from 50 to 150 W/m^2 during regular body activities. Thus, theoretically a wearable TE module can generate a maximum of 180 μW/cm^2 from human skin (the skin temperature and heat flux are assumed to be 34 °C and 20 mW/cm^2, respectively) at an ambient temperature of 22 °C. Typically, the chest, head, and the warmest area of the wrist (near the radial artery) of a person in an office have a temperature of about 34 °C. Therefore, these body parts are useful for energy harvesting. However, the thorax is more sensitive to local cooling in cold weather, and for human comfort, the heat flux must be significantly limited. Therefore, in experiments at low ambient temperatures, the maximum power can be obtained for a TE module worn on the wrist. As calculations have shown, if a TE module has a TE element length of 3 cm, then in typical winter weather conditions at a temperature of -15 °C, a fairly large temperature gradient ΔT of 43-50 K can be obtained. In this work, a submicron-thick semiconductor nanostructured zinc oxide (ZnO) film was used to create a lightweight flexible wearable thermoelectric module, since ZnO is biocompatible, stable in the environment, and has a Seebeck coefficient of -100 μV/K. The nanostructured ZnO film was grown by the Successive Ionic Layer Adsorption and Reaction (SILAR) method to obtain the *n*-type *n*-ZnO/PI TE element for the TE module. Four n-ZnO/PI strips with an area of 0.5×3 cm^2 each were equipped with thin-film Al contacts and electrically connected in series by four thin chromel wires, which were used as low-power *p*-type TE elements because the Seebeck coefficient of chromel is +24 μV/K. For the electrical connection of Al/*n*-ZnO/PI with chromel and with the external circuit, an electrically conductive epoxy adhesive containing silver was used, and thus ohmic contacts were obtained, which was confirmed by the linear volt-ampere characteristic of the TE module. The thermoelectric parameters at ΔT = 50 K of the manufactured flexible TE module with four thermocouples made of four Al/n-ZnO/PI strips and four thin chromel wires were investigated by recording its load current-voltage characteristics. Under operating conditions, the TE module was attached to the jacket cuff (the warm contact was located near the wrist and the cold contact was on the outside of the cuff), the TE module's open-circuit voltage was 25 mV, the short-circuit current was 80 nA, and the output power was 0.48 nW without any human activity. Several such TE modules, combined into a lightweight, wearable TE generator, can power biosensors for monitoring the heart, pulse, or blood glucose levels.