Microelectronic Engineering 111 (2013) 126–129

Contents lists available at SciVerse ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Thermoelectric characteristics of Si nanowires transferred onto plastics in air

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ARTICLE INFO

Article history:
Available online 7 March 2013

Keywords:
p-Type Si nanowires
Thermoelectric
Infrared image
Plastic
Heat transfer

ABSTRACT

We propose a simple route to examine the thermoelectric characteristics of Si nanowires (NWs) with infrared (IR) images in air. A device platform is designed to investigate the reliability of the thermoelectric characteristics. The Seebeck coefficients of the Si NWs obtained from all the electrode-couples in the platform are nearly identical at about 140 μV/K, revealing the validity of the simple route. The directly measured Seebeck voltages are carefully compared with the sum of the individual Seebeck voltages, and the comparison is discussed in detail.

1. Introduction

Recently, thermoelectric technology has emerged as a promising green energy technology. Thermoelectric energy is renewable energy produced from naturally occurring or man-made temperature differences [1–6]. Until now, most research in the thermoelectric field has focused on the development of new thermoelectric materials, such as nanomaterials with high Seebeck coefficients [1,2]. However, in order to expand the use of thermoelectric technology, it is essential to find easy ways to examine the thermoelectric characteristics of nanomaterials. Up to now, in order to investigate the thermoelectric characteristics of nanomaterials, the temperatures of nanomaterials have been indirectly measured by converting from the resistance of the metal electrodes to the corresponding temperature in vacuum. The resistance of the metal varies with the variation in the dimension of the electrode (such as thickness, width, and length) and the entire electrodes do not have the same dimension due to unavoidable errors involved in the fabrication process. Thus, it takes a lot of time and effort to obtain the temperature of nanomaterials with the conventional method. Herein, we propose a simple route to directly examine the thermoelectric characteristics in air with the use of infrared (IR) images that show the heat radiated by the electrodes. Because the Seebeck effect describes the conversion of temperature differences directly into electricity, a facile way to examine the thermoelectric characteristics is to obtain the real-time IR images and the real-time experimental data of the electrical properties simultaneously. In this study, we design a platform to see if our proposed route is a suitable way to examine the thermoelectric characteristics. Fig. 1 shows a schematic of the device platform, which consists of two meander heaters and four electrodes with an interval of 40 μm on a heat-insulating plastic substrate. The thermoelectric material utilized in this study is Si nanowires (NWs) transferred onto the plastic substrate. These Si NWs are long enough to reach from the first electrode to the fourth electrode.

2. Experimental procedure

P-type [1 0 0]-oriented Si NWs with a resistivity of ~5 mΩ cm (2×10^{19} cm^{-3}) were fabricated from an *p*-type silicon wafer by the conventional top–down method including photolithography and an anisotropic etching process as follows. An anisotropic wet etching process flow using an aqueous solution of 25 wt.% tetramethyl ammonium hydroxide (TMAH, $(CH_3)_4NOH$) at 30 °C provided Si NWs with inverted-triangular cross sections. The etch rate of the (1 1 1) lattice planes was much lower than that of the other lattice planes so that a triangular shaped cross section surrounded by the (1 1 1) lattice planes remained. The inverted triangular Si NWs were transferred onto a plastic substrate as described previously [7,8]. In study, we chose polyethersulfone (PES) as the substrate because its thermal conductivity (0.18 W/m K) is lower than those of inorganic substrates such as SiO_2 (1.4 W/m K) [9,10]. Additionally, the softness of PES allows the successful transfer of the Si NWs onto the plastic substrate. Of course, other plastic materials such as polyamide (PA), polymethyl metacrylate (PMMA) and polyether ether ketone (PEEK) can be applied as substrates owing to their softness but, in view of thermal conductivity, PES is a more suitable substrate because its thermal conductivity is the lowest among those of PA (0.2 W/m K), PMMA (0.2 W/m K), and PEEK (0.25 W/m K) [11,12]. The plastic substrate with the transferred Si NWs was dipped into a buffered HF solution for 3 s to remove the native oxide formed on the Si NWs surfaces. The platform shown in Fig. 1 was then constructed by photolithography and

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0167-9317/$ - see front matter
http://dx.doi.org/10.1016/j.mee.2013.02.073

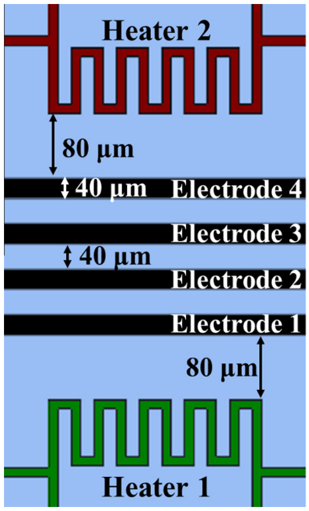

Fig. 1. Schematic diagram of the device platform.

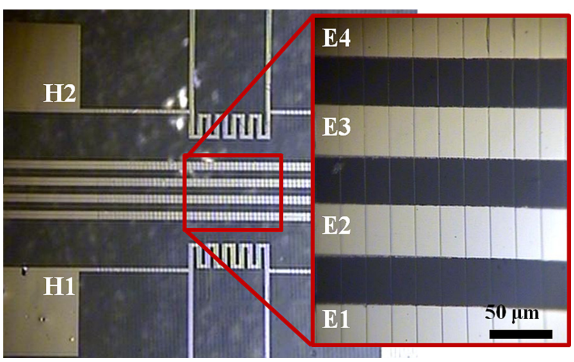

Fig. 2. Optical images of the thermoelectric device consisting Si NWs transferred onto a plastic substrate.

sputtering. The four electrodes (E1, E2, E3, and E4) were spaced with an interval of 40 µm, and two heaters (H1 and H2) were made of 300-nm-thick Pt. In order to obtain the temperature profiles of the thermoelectric devices, IR images were taken using an FLIR P660 infrared camera with a macro lens in air. The FLIR P660 has the sensitivity of 30 mK at room temperature and the uncertainty of 1%, which indicates that the temperature distribution of the IR image is accurate and reliable. The thermoelectric voltages of the Si NWs bridged between the electrodes were measured with an HP 4155C semiconductor parameter analyzer in air.

3. Result and discussion

Fig. 2 shows the optical images of our thermoelectric device constructed on a plastic substrate. Si NWs are bridged between the electrodes. Two heaters are used to examine the validity of our platform through the careful comparison between the thermoelectric voltages resulting from the temperature differences generated by each of the heaters. The magnitude of the thermoelectric voltage obtained by turning on the heater H1 is the same as that obtained by turning on the heater H2 with the opposite sign (see Supporting information, Fig. S1).

The IR images taken after 10 s, and the graphs of the temperature difference plotted as a function of time, are demonstrated in Fig. 3. The temperature distributions were obtained under the heating powers of (a) 6, (b) 11.5, and (c) 19.4 mW. The temperature difference (ΔT) corresponds to the temperature change from the final to initial values measured at the electrodes. The smallest ΔT (0.7 K) of E4 in Fig. 3(a) is clearly distinguishable from the IR image owing to the sensitivity and the uncertainty of infrared camera used in this study. After 5 s, H1 is turned on, and concurrently, ΔT is rapidly increased and keeps an equilibrium state until the heater is turned off. Heat conduction, also called diffusion, is shown by the elliptical isothermal line in the images. The temperature distribution of the device is more clearly expressed with a color scale as the heater power increases. The ΔT in the thermal equilibrium becomes lower toward the fourth electrode (E4) located on the far H1, which is attributed to the distance between H1 and each electrode.

Fig. 4 exhibits Seebeck voltages for the six electrode pairs in our platform, indicating an increase of the Seebeck voltage with the power of H1. E_{ab} refers to the two electrodes (E_a and E_b) used to examine the electrical characteristics of the Si NWs. The Seebeck voltage measured between E1 and E4 (or, E14) is the largest value, and that of E34 is the smallest value, which results from temperature gradients depending on the distance between the electrodes. If the same material with an identical Seebeck coefficient (S) is used as a thermoelectric material, the Seebeck voltage is directly proportional to the temperature difference according to the equation $\Delta V = S{\cdot}\Delta T$ [13,14]. In other words, the Seebeck coefficient should be identical for all electrode pairs used in this study. The Seebeck coefficient is determined to be 140 µV/K for six electrode pairs (see Supporting information, Fig. S2), and is comparable to those of Si-based thermoelectric devices [15–18].

The validity of our method is proven through careful comparison between directly measured Seebeck voltages and summed Seebeck voltages (as shown in Table 1). For thermoelectric devices with three electrodes, for example, E13, the Seebeck voltages can be obtained by summing the Seebeck voltages of E12 and E23. The difference between the directly measured and summed Seebeck voltages, for all cases, is less than 2%, which means that our method is appropriate to examine thermoelectric characteristics. In addition, the Seebeck voltage increases as the distance between electrodes increases, which indicates a tightened correlation between the Seebeck voltage and the length of the Si NWs.

4. Conclusion

We have proposed a simple route with the use of IR images to evaluate the characteristics of thermoelectric devices with Si NWs in air. The identical Seebeck coefficient obtained from the various electrode pairs of the thermoelectric devices indicates the reliability of our platform. The difference between the directly

Table 1
Comparison between the directly measured Seebeck voltages and the sum of individual Seebeck voltages.

Two electrodes		Three electrodes			Four electrodes		
Measured value (µV)		Measured value (µV)		Summation value (µV)	Measured value (µV)		Summation value (µV)
E_{12}	1.21	E_{13}	1.72	$E_{12} + E_{23} = 1.69$	E_{14}	1.87	$E_{12} + E_{23} + E_{34} = 1.85$
E_{23}	0.48	E_{24}	0.63	$E_{23} + E_{34} = 0.64$			$E_{12} + E_{24} = 1.84$
E_{34}	0.16						$E_{13} + E_{34} = 1.88$