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Enhancement of Thermoelectric Performance of p-type Short Silicon Nanowires

Y. Himeda[1], S. Hashimoto[1], S. Oba[1], R. Yamato[1], T. Matsukawa [2], and T. Watanabe [1]
[1] Waseda Univ.
3-4-1, Ohkubo, Shinjuku-ku, Tokyo 169-8555, Japan
Phone: +81-3-5286-1621 E-mail: y.sky@fuji.waseda.jp
[2] AIST
1-1-1, Umezono, Tsukuba-shi, Ibaraki 305-8568, Japan

Abstract

We experimentally demonstrate that the thermoelectric (TE) power of p-type Si nanowire (SiNW) is enhanced by shortening their length. We fabricated planar SiNW micro thermoelectric generator (μTEG) patterned on SOI substrate by EB lithography and reactive ion etching. The effective Seebeck coefficient, which is determined by the open circuit voltage and the temperature difference across the SiNW, increases as the length of SiNW shortens, which leads to the enhancement of the TE power density. Similar trend was also observed in n-type SiNWs in our previous work. These results indicate that TE power density can be improved by miniaturizing and integrating both n-type and p-type SiNWs within the proposed μTEG architecture.

1. Introduction

For the realization of internet of things (IoT) society, miniaturized energy harvesters, which generate electrical power from environmental energies, is urgently required as a power source of self-powered sensor nodes. Recently, a silicon nanowire (SiNW) is found to be a superior thermoelectric (TE) material thanks to its suppressed thermal conductivity[1,2]. Moreover, the possibility is coming up to fabricate the low-cost Si-based thermoelectric generator (μTEG) by CMOS-compatible process.

In conventional SiNW-μTEG structures, SiNW TE leg was designed as long as possible to minimize the parasitic thermal resistance effect. Whereas, we recently proposed a planar μTEG structure whose TE power density is scalable by shortening the TE legs[3]. We have demonstrated that the TE power of an n-type SiNW-μTEG is enhanced by shortening the SiNW length[4]. However, not only the n-type leg but also the p-type one is required to obtain the high output voltage from the TEG. In this paper, we investigate the length dependency of the TE power for p-type SiNW-μTEGs.

2. Experimental

Figure 1(a) shows a schematic of the fabricated μTEG. We fabricated three types of μTEGs with varied TE leg length L_{NW} = 8μm, 46μm and 90μm. Figure 1(b) shows optical microscope images of the μTEGs.

Figure 2 shows fabrication process flow of the μ-TEGs. First, 400 SiNWs and NiSi pad are patterned on a SOI wafer with a 55 nm thick SOI, a 145 nm thick BOX and 750 μm thick Si substrate. The SiNWs were patterned by EB lithography and dry etching. Both ends of SiNWs are connected to NiSi pads. Second, the SiNWs are oxidized in dry O_2 to form a 20 nm thick SiO_2 film. Then, B^+ ions were implanted at the dose of 5.0 x 10^{14} cm^{-2}. Next, thermal oxide film of pad is partially removed, followed by Ni deposition and silicidation annealing to form NiSi pad.

TE characteristics is measured with electrical probe system equipped with micro IR thermography camera. The heat source is provided by a micro thermostat consists of AlN ceramic plate and micro heater. The thermostat is attached onto one of the NiSi pads. The temperature of the micro heater T_{HOT} varied from 30 °C to 90 °C. Bottom of the substrate is maintained at constant temperature of T_{COLD} = 17 °C. Upon the measurements, temperature distribution in SiNW was measured by the micro IR camera. TE current is measured applying load voltage V_{load}.

3. Results and Discussion

Figure 3 shows I_{TE}-V_{load} characteristics of the p-type μTEG (L_{NW} = 8μm) for varied T_{HOT}. Figure 4 shows P_{TE}-V_{load} characteristics of the μTEG for varied T_{HOT}. Both of TE current and TE power increases as T_{HOT} increases. The maximum power is given by $P_{TE} = (S\varDelta T)^2/4R$, where S, $\varDelta T$ and R are the Seebeck coefficient, the temperature difference across the SiNW, and the internal resistance respectively. The maximum power observed in this work increases in proportion to $(T_{HOT} - T_{COLD})^2$, indicating that the parasitic thermal resistance is kept constant during the measurement of the same μTEG.

Figure 5 shows $P_{TE(max)}$ -L_{NW} and R-L_{NW} characteristics of the p-type μTEG. $P_{TE(max)}$ increases as the NW length decreases. In Fig. 5, the calculated thermoelectric power P_{calc} is plotted only assuming the change in R due to L_{NW} change, i.e., the open-circuit voltage $V_{oc}=S\varDelta T$ is assumed to be unchanged from the value of the longest leg device. The experimental $P_{TE(max)}$ is smaller than the P_{calc}, suggesting that a parasitic electric resistance is remained in the μTEG. The non-linear dependence of R on L_{NW} also reveals the presence of the parasitic electric resistance. The possible origin of the parasitic resistance is the NiSi/Si contact, which may be minimized by optimizing the dopant concentration in the SiNW.

Figure 6(a) and 6(b) show a temperature distribution in the μTEG captured by the micro IR camera, and the temperature difference $\varDelta T$ across the SiNW leg. $\varDelta T$ decreases as the SiNW length decreases. Figure 7 shows the effective Seebeck coefficient for varied L_{NW}, which is given by the open circuit voltage divided by the temperature difference across the SiNW. The effective Seebeck coefficient is enhanced by shortening the SiNW length. Similar result was also observed in n-type μTEGs in our previous works[3,4]. The enhancement is attributed the non-uniform temperature distribution in the SiNW legs[3]. A large temperature gradient is localized in the vicinity the hot side electrode, so that the thermoelectric power is generated in very limited part of the SiNW.

4. Conclusions

Nanowire length dependency of the TE performance of p-type SiNW μTEG is investigated. The thermoelectric power density and effective Seebeck coefficient increase as the length of SiNW shortens, as well as our previous work on n-type SiNW μTEG. The proposed μTEG architecture is advantageous to realize high TE power density by miniaturizing and integrating both n-type and p-type devices.

Acknowledgements

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References

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(a) (b)

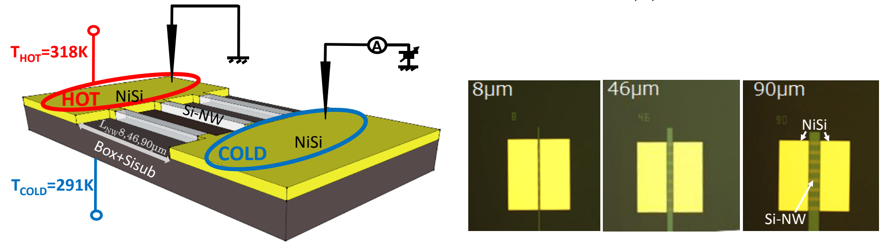

Fig.1 Fabricated device structure (a) Schematic of Si-NW thermoelectric device (b) Optical microscope images of Si-NW thermoelectric device

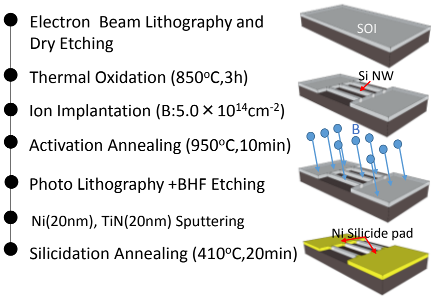

Fig. 2 Fabrication procedure of Si-NW μ-TEG

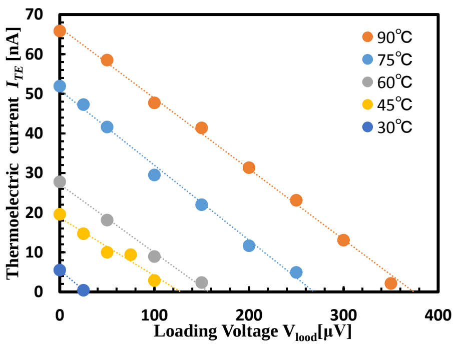

Fig.3 I_{TE}- V_{load} characteristics in p-type Si-NW with varying T_{hot}

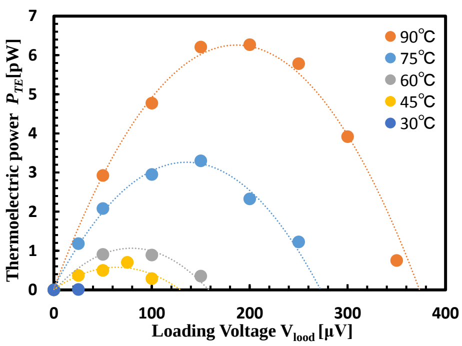

Fig.4 P_{TE}- V_{load} characteristics in p-type Si-NW with varying T_{hot}

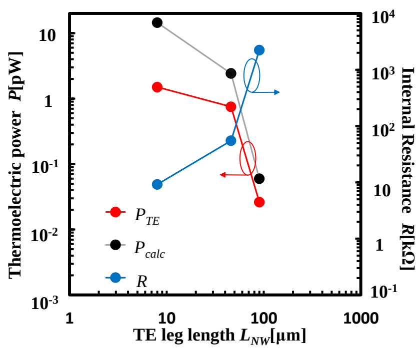

Fig.5 P_{TE}, P_{calc}, and R-L_{NW} characteristics of the p-type μTEG

(a) (b)

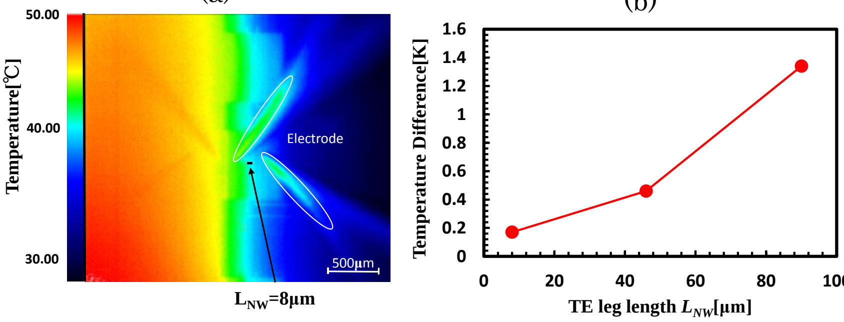

Fig.6 (a) Temperature distribution of the μTEG including a thermography (b) Temperature difference ΔT across the SiNW leg

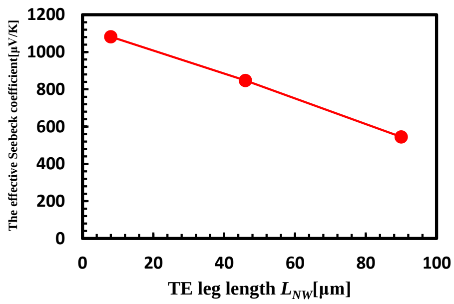

Fig.7 The effective Seebeck coefficient -L_{NW} characteristics