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Anomalous Thermoelectric Characteristic of Silicon Nanowire Between Heavily Doped Silicon Pads

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Abstract

We have found experimentally an anomalous thermoelectric (TE) characteristic of n-type Si nanowire (NW) connected to heavily doped n^+-Si pads. We observed an opposite direction TE current of what is expected from the Seebeck coefficient of n-Si. The result is understandable by considering a ununiformity in the dopant concentration in the Si-NW TE device (TED). Dopant segregation at the SiO_2/Si interface leads to the formation of a potential barrier in the NW channel region, which impedes the diffusion of thermally activated electrons into the NW channel region, and it rather stimulates the injection of thermally generated minority carrier. The present result suggests important roles of the potential distribution and the behavior of minority carriers in nanoscale TEDs.

1. Introduction

Miniaturized energy harvesting device is anticipated as a key technology for realizing a trillion sensor network. Thermoelectric device (TED) is a promising energy harvesters which generates an electric power from any heat source. Recently silicon nanowires (Si-NWs) are emerging as a superior thermoelectric (TE) material [1,2] thanks to its low thermal conductivity [3-5]. The finding opens up a silicon-based TED which can be fabricated by the CMOS-compatible process.

In this work, we have characterized the thermoelectric property of Si-NWs fabricated by the top-down process. Unexpected TE current was observed, suggesting the effect of ununiformity of dopant distribution in the TEDs.

2. Experimental

Fig. 1 shows a schematic illustration of the TED fabricated in the present work. It has a Si-NW channel surrounded by thermally grown SiO_2 film, both ends of which are connected to heavily doped Si pads. TiN electrode film is deposited on the pads, and one of the pads is covered with an Al thermode film which conducts the heat supplied by a thermostated probe. The NW width W_{NW} is varied from 40 nm to 50 nm.

Fig. 2 shows fabrication process flow of the Si-NW TED. It was fabricated on lightly p-type doped (100) SOI wafer with 45nm thick Si, 145nm thick buried oxide (BOX) and 750μm thick Si substrate. <110>-oriented 50 Si-NWs and pads are fabricated by electron beam lithography and dry etching. After the patterning, thermal oxidation is performed in dry O_2 at 850℃ for 1h. And then, P ions are implanted at 25keV with a dose of $1.0\times10^{15}cm^{-2}$. An activation annealing is performed at 950℃ for 10min. The oxide layer of the pad regions is removed by HF solution. Finally, 165nm thick TiN and 300nm thick Al is deposited on the pad regions as electrode and thermode, respectively. Figs.3(a) and 3(b) show the SEM images of the TED.

Upon the evaluation of the TE characteristic of the TED, an AlN ceramics heat probe kept at a temperature T_{HOT}=338K is applied to the Al thermode, and the bottom of the SOI substrate is kept at T_{COLD}=273K. Thus a temperature difference ΔT=45K is provided across the TED. We measured TE current applying loading voltage V_{load} between two TiN electrode pads.

3. Results and Discussions

Fig. 4 shows an *I-V* characteristic of the TED with no temperature gradient, showing a normal ohmic resistance property. Figs. 5(a) and 5(b) show I_{TE}-V_{load} and TE power P_{TE} curves of the TED, respectively. Open circuit voltage V_{OC}, short circuit current I_{SC}, and maximum TE power P_{max} are 150μV, -3.48nA and 0.127pW, respectively. However, the direction of the TE current is opposite of what is expected from the Seebeck coefficient of n-Si. The result suggests that the TE current was curried by holes.

This is explained by assuming the ununiform potential distribution in the Si-NW TED, as shown in Fig. 6. Because of the dopant segregation effect at the SiO_2/Si interface [6], the potential may raise in the NW channel. Excess electrons and holes generated by the thermal agitation in the hot side pad will diffuse into the NW channel, but the potential barrier in the NW impedes the electron diffusion. On the other hand, hole injection is rather stimulated, leading to the opposite TE current.

This scenario is validated with a 2D TCAD simulation [7]. Fig. 7 shows the simulation model of $n^+/n^-/n^+$ structure, and the device parameters are summarized in Table I. Fig.8 shows the simulated relation between I_{SC} and the temperature of HOT source T_{HOT}. The direction of the TE current changes depending on the temperature gradient, and there is a case that the opposite TE direction current flows as well as the present experimental result. The normal direction of the TE current of n-Si appears at higher T_{HOT}. The result shows that the importance of the behavior of minority carrier in nanoscale TEDs with ununiform potential distribution.

4. Conclusions

We have found experimentally an anomalous characteristic of Si-NW TEDs, in which the TE current flows in an opposite direction of what is expected from the Seebeck coefficient of n-Si. This is considered to be induced by an ununiformity in the dopant concentration occurred by a dopant segregation effect at the SiO_2/Si interface in the NWs. The ununiform dopant distribution forms a potential barrier in the NW region, which impedes the diffusion of thermally activated majority carriers and but stimulates the injection of minority carrier. The present result suggests important roles of the potential distribution and the behavior of minority carriers in nanoscale TEDs.

Acknowledgements

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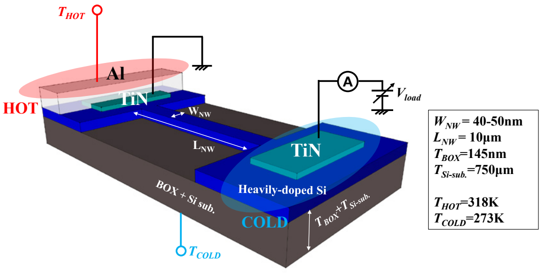

Fig. 1 Schematic of Si-NW thermoelectric device (TED).

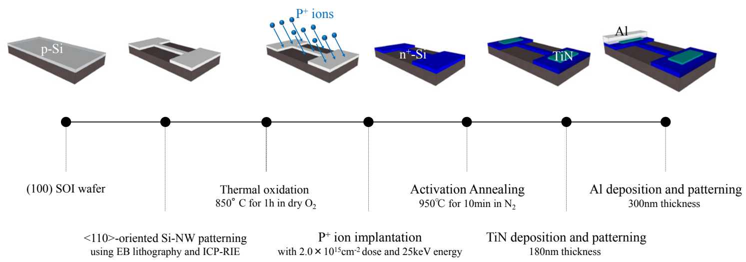

Fig. 2 Fabrication procedure of Si-NW TEDs with TiN/Al pads.

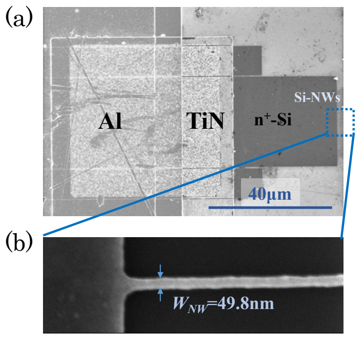

Fig. 3 SEM image of Si-NW TEDSs (a) TiN electrode and Al thermode (b) Si-NW channel.

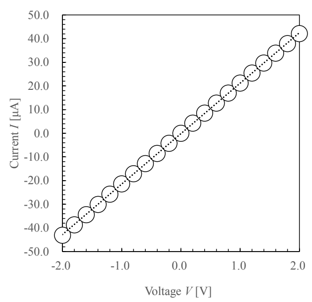

Fig. 4 *I-V* characteristics of the Si-NW devices.

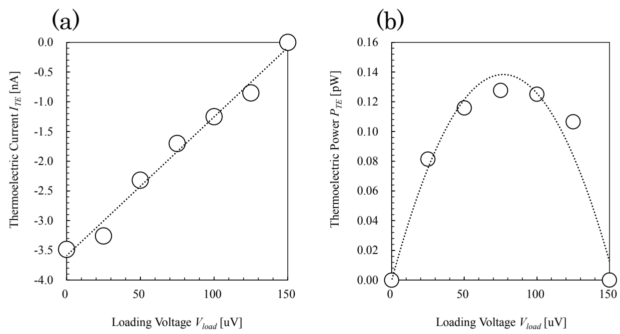

Fig. 5 TE characteristics of the TED (a) I_{TE}-V_{load} characteristic of the TED (b) P_{TE} curves of the TED.

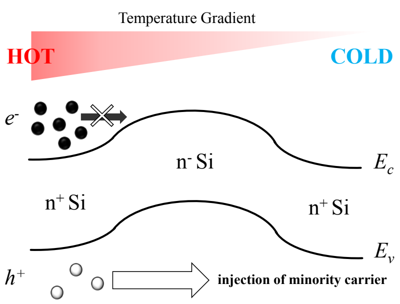

Fig. 6 Schematic of injection of thermally generated minority carrier.

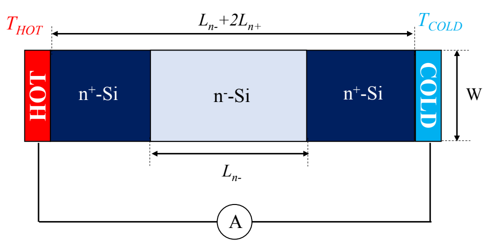

Fig. 7 Schematic of device structure for 2D TCAD simulation.

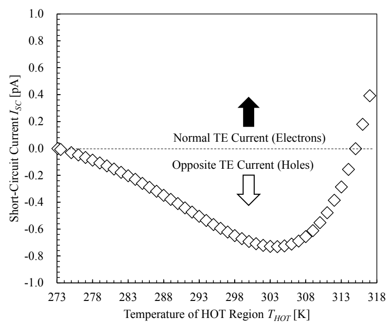

Fig. 8 Simulated relation between I_{SC} and T_{HOT}.

Table I Device parameters used in 2D TCAD TCAD simulation.

Temperature of HOT region T_{HOT} [K]	Temperature of COLD region T_{COLD} [K]	Doping density of n^+ Si region $N_{D(n+)}$ [cm^{-3}]	Doping density of n^- Si region $N_{D(n-)}$ [cm^{-3}]	Length of n^+ Si region L_{n+} [μm]	Length of n^- Si region L_{n-} [μm]	Width of structure W [nm]
273-318	273	1.0×10^{20}	1.0×10^{15}	5.0	0.5	20