Measurement of Figure of Merit for a Single β-Silicon Carbide Nanowire by the Four-Point Three-ω Method

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ABSTRACT

The thermoelectric figure of merit (*ZT*) of a single ϐ-Silicon Carbide (SiC) nanowire (NW) was measured using the four-point three-omega (3-ɤ) method for the first time. The electrical conductivity (σ), thermal conductivity (κ), and Seebeck coefficient (S) were measured on the same measurement platform consisting of four point probe. To this end, we developed a novel technique in which focused ion beam (FIB) lithography and nanomanipulation are employed for fabricating a measurement platform and placing a single NW.

Keywords: *β-SiC nanowire, 3ω method, thermal conductivity, Seebeck coefficient, figure of merit*

INTRODUCTION

Because of its physically and chemically durable and stable features under harsh environmental conditions, Silicon Carbide (SiC) is known as a material promising substitute candidate for silicon. And also it is expected to present some advantages in terms of dissipated power, stability and high voltage operation. For this reason, SiC NW may be used for a high performing thermoelectric device. Thus, it is essential to evaluate and hence measure *ZT,* the dimensionless thermoelectric figure of merit. ϐ-SiC NWs were used for the measurements.

In order to do this, we employed the 3-ɤ method in which the third harmonic amplitude as a response to an applied AC current at fundamental frequency, ɤ, can be expressed in terms of thermal conductivity. Electrical conductivity was evaluated by using the four-point probe method. To measure the Seebeck coefficient, a nanoscale heater (~100 nm) prepared by electron-beam deposition in a dual beam FIB chamber was used for generating a temperature gradient across the nanowire. The placement of a single ϐ-SiC NW was accomplished by the direct-pulling-out method, which was demonstrated in our previous publication [1]. FIB with a nanomanipulator was utilized to place a single ϐ-SiC NW on the platform.

EXPERIMENT

The measurement was made on a Silicon Nitride (SiN) membrane to prevent heat loss through the substrate from the nanowires. A microelectrode pattern on top of the membrane was made by sputtering Au/Cr and used for thermoelectric measurement. The 8-wired electrodes for electrical interface were patterned with the conventional photolithography technique. Potassium hydroxide (KOH) was used for selectively etching Si at the center of the substrate to create a thin (500nm) membrane structure which has the dimension of 300x300 um. The membrane structure also serves as a thermally insulating layer. A trench (a through hole) is created by FIB milling for this purpose as shown in Fig. 1. This trench minimizes heat flow through the membrane. FIB was finally used to tailor a

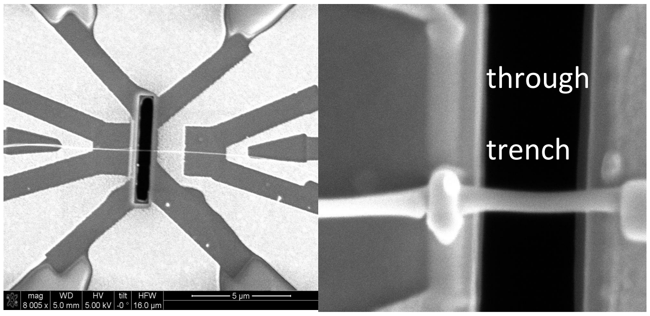

Figure 1. Placed a б-SiC NW on the 4-point probe

desired 4 point probe structure with an ion beam milling.

Single-crystalline б-SiC NWs were grown by using a horizontal conventional hot-wall chemical vapor deposition (CVD) furnace. Oxidized Si/SiO_2 wafers were used as substrates for SiC NW growth. Methyltrichlorosilane (MTS, CH_3SiCl_3) was used as a source precursor because it has the same ratio of Siï C and can easily decompose at a low temperature. H_2 was used as both the carrier gas that transfers the source precursor through a bubbler to the quartz reactor and as a diluent gas that regulates the concentration of the mixture containing MTS vapor and carrier gas. The diameter of fabricated SiC NWs varied from 60 up to 100 nm while they were a few tens of micrometers long. Its structural characterization was already reported in the previous paper [2] which shows cubic zinc blend structure with a <111> growth direction.

A single SiC NW was extracted from a bundle of SiC NWs with the aid of a nanomanipulator. Then it was placed on the pre-patterned 4 point probe structure. Detailed procedure for placing a single SiC NW can be found in the previous report [1]. A lock-in amplifier (Stanford Research System SR850) was used for obtaining 3-ɤ signals. An alternate current (AC) source (Keithley 6221) was used to provide a stable current supply. Figure 2 shows a schematic diagram of the experimental setup for measuring the thermal conductivity.

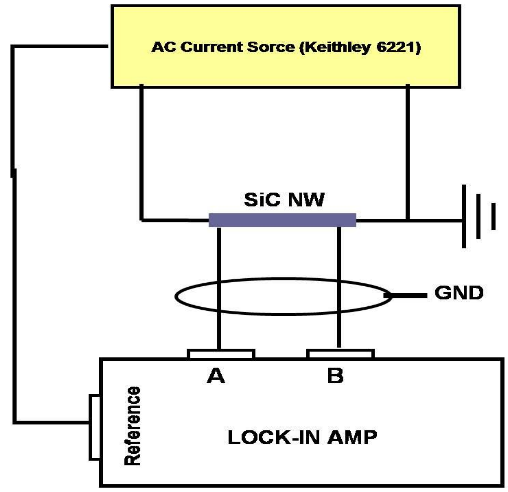

Figure 2. Schematic view of 3-ɤ measurement for the thermal conductivity of б-SiC NW

MEASUREMENTS AND RESULTS

The 3-ɤ signal correlates with thermal conductivity through the following equation.

$$V_{3\omega,rms,vac} \cong \frac{\sqrt{2} I_0^3 R R' L}{\pi^4 \kappa S}$$

Where, L, $R\left[= R_0 + R'(T - T_0)\right]$, and S are length, electrical resistance, and cross sectional area of the SiC nanowire, respectively. R' is the temperature gradient of the resistance at room temperature defined as $(dR/dT)_{T_0}$ and κ is the thermal conductivity of the SiC nanowire. In Fig. 3, the temperature gradient of the resistance and the 3-ɤ voltage are shown.

The electrical conductivity was measured to be a few tens of µA at 1V gate voltage and the thermal conductivity was shown to be 82 ± 6 W/mK. Boundary scattering attributed to the size confinement and phonon-defect scattering may contribute to reducing the thermal conductivity of SiC in a nanoscale as compared to a bulk SiC. The Seebeck coefficient was obtained to be 1.21mV/K by using the same measurement platform. We measured the

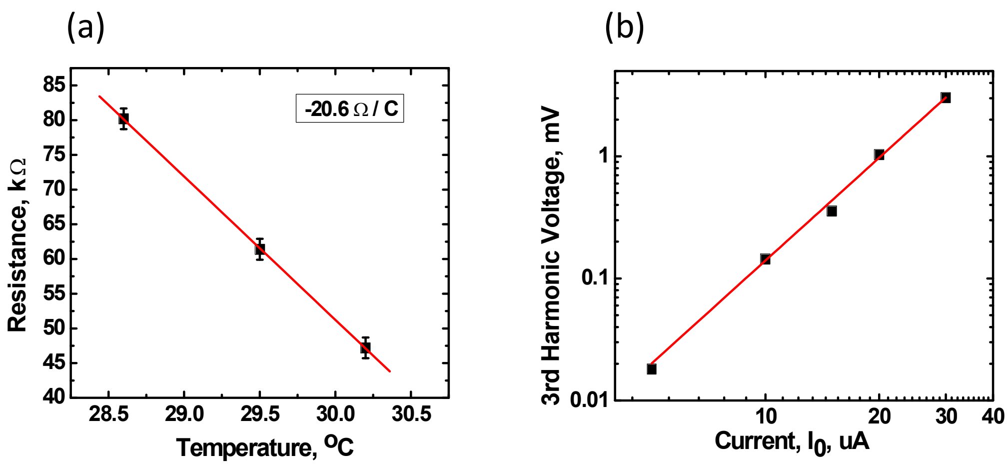

Figure 3. (a) Temperature gradient of the resistance and (b) 3ω voltage measurement for β-SiC NW

steady state temperature of the IB-Pt heating source from its calibrated temperature coefficient as the resistance of the heating source was measured. And then the voltage difference was measured across the nanowire before and after turning off the applied current to the heating source. Electrical resistivity was shown to be ~2.0×10^{-4} Ωm. Due to the reduction of the thermal conductivity, the dimensionless thermoelectric figure of merit, *ZT*, which was expressed as $ZT = S^2T/\rho\kappa$, where *S* is the Seebeck coefficient, *T* the absolute temperature, ρ the resistivity, and κ the thermal conductivity of a β-SiC NW, was measured to be 2.64×10^{-2}. This value is 20 times higher than the reported maximum *ZT* for a bulk SiC [4].

We used a FIB ion beam-induced Pt (IB-Pt) thin line (200x110x2240nm) as a heating source since its resistance could be easily controlled by geometrical configuration. The resistance of IB-Pt at room temperature was found to be 1.72 kΩ. And the temperature coefficient, α ($=(1/R_0)(\Delta R/\Delta T)$, where R_0 is the reference resistance of IB-Pt), was obtained to be 2.1×10^{-2}/°C. Figure 4 shows the result of the temperature coefficient measurement. The resistance change by the temperature change was ~36 Ω/°C, which corresponds to ~2% resistance variation per one degree change of the temperature. Relatively larger variation of the resistance might be used for a good nanoscale heating source.

CONCLUSION

The thermoelectric figure of merit (*ZT*) of a single β-Silicon Carbide (SiC) nanowire (NW) was measured using the four-point three-omega (3-ω) method for the first time. The electrical conductivity (σ), thermal conductivity (κ), and Seebeck coefficient (*S*) were measured sequentially on the four point probe. The measured *ZT* was 2.64×10^{-2} which was 20 times higher than the reported maximum value of a bulk β-SiC. The four-point probe for the three-omega (3-ω) method is a novel platform for the thermoelectric characterization, which easily provides the integrated formulation for electrical and thermal characterizations and even for an optical characterization, for example, photocurrent and optical transmission measurements.

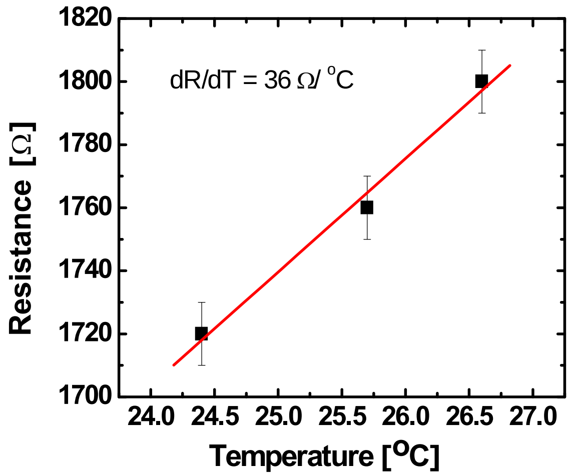

Figure 4. Temperature gradient of the resistance measurement of the IB-Pt as a heating source. dR/dT is ~36 ɋ/°C

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REFERENCES

[1] K. M. Lee, T. Y. Choi, S. K. Lee and D. Poulikakos, nanotech. **21,** 125301, 2010

[2] K. Rogdakis, S. Y. Lee, M. Bescond, S. K. Lee, E. Bano, and K. Zekentes *IEEE Trans. Elec. Dev.,* **55**, 1970-1976, 2008

[3] H. Seong, H. Choi, S. Lee, J. Lee, and D. Choi, Appl. Phys. Lett., **85,** 1256, 2004

[4] Fujisawa et al, Renewable Energy, **33**, 309ï 313, 2008