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Measurement of Thermoelectric Properties of Single Semiconductor Nanowires

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We have measured the thermopower and the thermal conductivity of individual silicon and indium arsenide nanowires (NWs). In this study, we evaluate a self-heating method to determine the thermal conductivity λ. Experimental validation of this method was performed on highly n-doped Si NWs with diameters ranging from 20 nm to 80 nm. The Si NWs exhibited electrical resistivity of $\rho = (8 \pm 4)\,\mathrm{m}\Omega\,\mathrm{cm}$ at room temperature and Seebeck coefficient of $-(250 \pm 100)$ μV/K. The thermal conductivity of Si NWs measured using the proposed method is very similar to previously reported values; e.g., for Si NWs with 50 nm diameter, λ = 23 W/(m K) was obtained. Using the same method, we investigated InAs NWs with diameter of 100 nm and resistivities of $\rho = (25 \pm 5)\,\mathrm{m}\Omega\,\mathrm{cm}$ at room temperature. Thermal conductivity of λ = 1.8 W/(m K) was obtained, which is about 20 to 30 times smaller than in bulk InAs. We analyzed the accuracy of the self-heating method by means of analytical and numerical solution of the one-dimensional (1-D) heat diffusion equation taking various loss channels into account. For our NWs suspended from the substrate with low-impedance contacts the relative error can be estimated to be ≤25%.

Key words: Thermopower, thermal conductivity, Seebeck coefficient, self-heating method

INTRODUCTION

The suitability of a material for thermoelectric applications is governed by the conversion efficiency of heat into electrical power. This efficiency is a function of the thermoelectric figure of merit $ZT = T\sigma S^2/\lambda$, where T is the absolute temperature, σ is the electric conductivity, S is the Seebeck coefficient, and λ is the thermal conductivity. Semiconducting nanowires (NWs) are considered as promising candidates for thermoelectric power generation.[1–3] Compared with bulk semiconductors, NWs can have lower thermal conductivity and a potentially higher power factor σS^2.[4,5]

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The ZT value of NWs is typically derived from individual measurements of σ, S, and λ. The conductivity σ is usually determined using four-probe or transmission-line methods. The measurement of S requires applying a temperature gradient along the NW and measuring both the thermal voltage and the temperature difference between two contacts. This can be realized using NWs placed on nonconducting substrates with metallic heater structures, thermometers, and electrical contacts, all of which can be fabricated using electron-beam lithography-defined test structures.[6]

Direct measurement of the thermal conductivity λ of NWs is more complicated. Due to scaling and increasing surface-to-volume ratio, the thermal conductance of single NWs is comparable to or smaller than the thermal conductances of thermometers and test devices.[1,2,7] Therefore, dedicated