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A low-cost MEMS tester for measuring single nanostructure's thermal conductivity

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ABSTRACT

A microelectro-mechanical (MEMS) tester that can be used to measure the thermal conductivity of nanowires and nanostrips has been developed. Error analysis showed our measurements were accurate within 21%. This device has a low fabrication requirement so that it can be made in most MEMS laboratories. To verify the function of this device, the thermal conductivity of a carbon nanofiber with a diameter of 225 nm was measured to be $14.7 \pm 3.1\,\mathrm{W m^{-1} K^{-1}}$, which is close to the value previously reported. This result was within the predicted measurement error and it proves that this device can be an effective tool for the research of nanostructures' heat transfer, especially for nano-thermoelectrics.

1. Introduction

Thermoelectric effects, including Seebeck and Peltier effects, are the most straightforward methods for converting between electrical energy and thermal energy. Under global pressure for sustainable energy supplies, and the constant demand for inexpensive integrated circuit (IC)-compatible micro-sensors and micro-actuators, a considerable amount of research regarding these effects has been carried out over the past two decades [1–7]. However, compared with the traditional refrigeration and power systems, the major disadvantage of today's thermoelectric materials is their low conversion efficiency. The effectiveness of a thermoelectric material is usually expressed by the dimensionless thermoelectric figure of merit, *ZT* as shown below:

$$ZT = \frac{S^2\sigma}{\kappa}T \tag{1}$$

where T is the temperature, S is the Seebeck coefficient, σ is the electrical conductivity and κ is the thermal conductivity [8].

Before the 1990s the maximum value of *ZT* had remained around "1". This is not high enough to compete with the efficiency of current refrigeration systems. In the early 1990s, Dresselhaus proposed her milestone theory [9,10], which predicted that a material's *ZT* could be enhanced by reducing its size down to nanoscale. This is because when the material's size is comparable with or smaller than phonon's mean free paths, the enhanced phonons' boundary scattering will cause a decrease of thermal conductivity κ. However, at the same time, these materials' electrical conductivities σ are less affected by their decreased size, because thermoelectric materials' electrons' mean free paths are usually much shorter than that of phonons'. From Eq. (1), we can find that *ZT* can be enhanced with a decreased κ and unchanged S and σ. Since then, this prediction has been confirmed by experimental results reported by different groups [11–17].

Currently, quantitative prediction of the possible enhancement of materials' *ZT* in nanoscale is an attractive topic. A lot of groups have developed models of nanoscale thermal transfer depending on different methods like phonon's mean free path (MFP) [18,19], Monte Carlo simulation [20], molecular dynamics simulation (MDS) [21,22] and so on. However, some reported experimental data cannot be well explained by these models. For example, Boukai et al. and Hochbaum et al. reported that the *ZT* of silicon nanowires is approximately 100 times higher than the *ZT* of Si bulk form when the diameters were several tens of nanometer [14–16], but current models expected a much smaller improvement.

These measurements have received wide spread attention because by researching them we may unveil unknown physical rules behind them. However, until now the reported measurement data was far from enough because of difficulties associated

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with measuring a nanostructure's thermal conductivity. So far, only a few methods have been reported. One method was reported by Borca-Tasciuc et al. [23]. In their work, they measured the thermal conductance of Bi_2Te_3 nanowires/alumina nanocomposite, and then compared this data with unfilled alumina templates to get Bi_2Te_3 nanowires' thermal conductivity. In this method, the dimensions of Bi_2Te_3 nanowires' were dependent on estimation. Compared with Borca-Tasciuc's method, a more straightforward way was to directly measure single nanostructures' thermal conductivity. Some groups employed laser heating and Raman thermography to measure single cantilevered Si nanowire's thermal conductivity [24,25]. Since this is a no-contact method, the process can be rapid and free of contact problems. However the difficulty of this kind of method was how to precisely estimate the fraction of laser power absorption for different kinds of samples. Some groups examined the '3ω' method, which is widely used to measure the thermal conductivity of thin films, and improved it to measure the thermal conductivity of carbon nanofibers [26–28]. Some groups used DC heating method to measure the thermal conductivity of nanofilm [29,30]. However, this method requires that the electrical resistances of test samples should be sensitive to temperature change.

Beside the Raman method and the '3ω' method, several attempts were made to develop a micro-scale instrument which was small enough to measure the thermal conductivity of these single nanostructures [31–33]. Such instruments usually have two suspended thermal isolation structures. Heaters and temperature sensors were integrated onto these structures. Nanostructure test samples were bridged between the two thermal isolation structures for measuring. By heating one isolation structure and detecting the temperature change on both isolation structures, the thermal conductivity of the test sample can be derived. These instruments must be small enough to hold a single nanostructure sample. They also need to be suitable for batch fabrication because loading the nanostructures is typically a destructive process with a low success rate. Recently, some work has been reported in this area. Sultan et al. developed a device which could precisely measure the thermal conductivity of nanofilm, but it is too big to work on nanowires [31]. Ono et al. developed an easy-to-fabricate device, but its measurement precision for nanowires' thermal conductivity, as they reported, was low [32]. Until now, one of the most popularly used such devices was developed by Hochbaum et al. [11,15,16,33,34]. In their devices, Silicon Nitride thin film islands were suspended to work as thermal isolation structures. On these islands, they used 200 nm wide Pt lines as heaters and thermometers. However, it is difficult for their device to be used widely because the 200 nm wide Pt lines were so fine. In order to batch fabricate these devices, projection lithography was used, which is unavailable in most MEMS laboratories.

Therefore, in order to promote the research on nanostructures' heat transfer performance, a tester with an acceptable measurement precision and an easy fabrication process needs to be developed. In this paper, we report on a MEMS tester that can be used to measure the thermal conductivity of single nanostructures. This device can be mass fabricated, so it can sustain a high loss rate during the test sample preparation process. Only average level facilities were utilized during the fabrication process. Finally, the thermal conductivity of a carbon nanofiber was measured to verify the tester. The measurement result is within 18% difference of the previously reported data [34]. Error analysis showed that the potential measurement error of this tester was within 21% and it can be obviously reduced by using a better probe station and choosing a tester which is suitable for the sample thermal resistance. In this paper, Section 2 describes the design and simulation of the tester. Section 3 illustrates the fabrication process. Section 4 details the device calibration. Section 5 covers the measurement of carbon nanofiber's thermal conductivity and discussion. Section 6 contains an error analysis, and Section 7 is the conclusion.

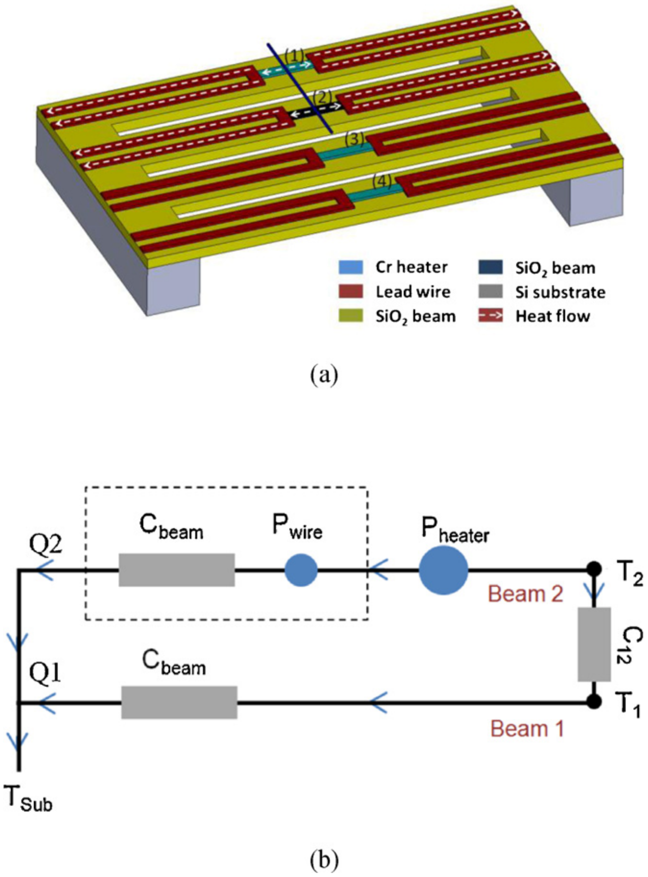

Fig. 1. (a) Schematic view of the designed MEMS device; (b) thermal flow of the device when measuring nanowire's thermal conductivity.

2. Tester design

2.1. Overview of the design

Fig. 1(a) shows a schematic three-dimensional view of the designed MEMS tester. It is composed of four suspended SiO_2 beams placed in parallel. The length of each beam is 400 μm and the width is 10 μm. The gap between each beam is 4 μm. On the beams, there are 2 μm wide heaters and lead wires. The heaters are placed in the center of each beam. The lead wires are on each side of the heater. The testing sample, which can be nanostructures like nanowires or nanostrips, is placed in the middle and spans at least two of the beams, as shown. One method to place these samples is to drop a solution containing the nanostructures onto a chip with devices in an array and then use a microscope to find the devices having nanostructures in position [33]. In our design we arranged each set of 4 beams as a group, to increase the chances for nanostructures to deposit in place. This arrangement also increases the yield of the device. As the chance for a nanostructure to deposit in position is still very low (1–2% according to our tests), the devices need to be mass fabricated for low cost.

To avoid the effect of convection and more precisely measure the thermal conductivity of the nanostructures, the whole test process will be run in a vacuum chamber. The effect of radiation is believed to be a minor factor [31,33]. The follow-up experiment also confirmed that these two factors did not cause detectable interference during the testing.