Profi ling Nanowire Thermal Resistance with a Spatial Resolution of Nanometers

Dan Liu,†‡§ Rongguo Xie,†‡§ Nuo Yang,‖ Baowen Li,*†‡§‖ and John T. L. Thong*†‡§

†Department of Physics and Centre for Computational Science and Engineering, National University of Singapore, Singapore 117546, Republic of Singapore
‡Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117583, Republic of Singapore
§NUS Graduate School for Integrative Sciences and Engineering, National University of Singapore, Singapore 117456, Republic of Singapore
‖Center for Phononics and Thermal Energy Science, School of Physics Science and Engineering, Tongji University, 200092 Shanghai, People’s Republic of China

Supporting Information

ABSTRACT: We report a new technique to profile the thermal resistance along a nanowire with a spatial resolution of better than 20 nm. Using this technique, we mapped the thermal conductivity along a Si0.7Ge0.3/NiSi0.7Ge0.3 heterostructured nanowire. We also measured the interfacial thermal resistance (ITR) across the Si/NiSi2 interface embedded in Si/NiSi2 heterostructured nanowires. The ITR does not change even for adjacent interfaces as close as ~50 atomic layers.

KEYWORDS: Thermal conductance, nanowires, nanostructures, thermal measurement, electron beam heating, nanoscale thermal transport

Thermal transport in nanowires differs significantly from that in bulk materials as phonon boundary scattering can play a significant or even dominant role when nanowire diameters approach the phonon mean free path. At even smaller diameters approaching the phonon wavelength, phonon confinement effects come into play.1 The prospect of enhancing the thermoelectric performance of semiconductors in the form of nanowires has triggered a spate of theoretical and experimental works.2−12

Because of the microscopic sample dimensions and the small heat flows involved, measuring thermal conductivity of nanowires is technically challenging. Currently the most popular technique is the thermal bridge method, which utilizes two thermally isolated microfabricated islands with resistance loops, one of which acts as a heater and the other as a passive temperature sensor, to which the ends of a nanowire are attached.13 The nanowire’s thermal conductance is calculated from the heat flow through the nanowire and the temperature difference between its ends. Since its invention, experimental studies using this technique have generated many exciting results and inspired further theoretical work. However, by its very nature, the thermal bridge method only yields the total thermal resistance of the nanowire connection between the two islands. This leads to two major limitations. First, the measured thermal resistance includes the parasitic contact resistance between the nanowire and the heat source/sink which could present a significant source of systematic error, particularly in cases where the conductance of the nanowire is large. For example, the thermal contact resistance can account for as much as 50% of the measured thermal resistance of a multiwalled carbon nanotube.14 Previous approaches to account for the contact resistance include extrapolating the length-dependent measurements of thermal resistance14 or by using the thermoelectric voltage drop across the contacts.15 Second, the measurement does not discriminate inhomogeneities along the nanowire. For example, in heterostructured nanowires, not only would the thermal conductivity vary with material composition along the wire, but each interface would also give rise to interfacial thermal resistance (ITR). The lack of an experimental technique to probe heat flow at the nanoscale limits our ability to examine and understand thermal transport in nanowire systems.

Here we present a new approach using a focused electron beam as a noncontact localized heat source to carry out spatially resolved thermal resistance and ITR measurements. We had previously introduced the technique to measure the thermal contact resistance between the sample and the heater/sensor islands in a thermal-bridge setup.7,13 In this paper, we present the electron beam heating technique in detail, address issues and limitations associated with the technique, and show

Received: November 8, 2013
Revised: December 20, 2013
Published: January 1, 2014

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that with the improvements made we are able to spatially resolve the thermal resistance of a heterostructured nanowire, including the ITR of each vertical interface embedded in the nanowire. Two nanoscale material systems of technological importance are studied. First, we use a silicon–germanium (Si0.7Ge0.3) nanowire embedded with nickel germanosilicide segments to show how the thermal conductance of both Si0.7Ge0.3 and germanosilicide segments are measured and how this technique circumvents the issue of thermal contact resistance inherent in the thermal bridge approach. Second, we demonstrate how the ITR across each silicon/nickel—silicide interface can be directly measured in epitaxial Si/NiSi2 heterostructured nanowires. This nanowire material system presents nearly abrupt interfaces at the atomic scale and represents a semiconductor—metal contact system that is widely used in modern CMOS electronic devices. Making use of the sharp heterointerface, we show that the spatial resolution of our technique can reach better than 20 nm. The technique allows us to probe the ITR of multiple interfaces along the nanowire. Measurements on adjacent interfaces at progressively smaller separations down to ∼50 atomic layers show the same results as those with larger separations.

The technique is described in the following few paragraphs. In a configuration that is similar to that used for thermal bridge measurements, the nanowire to be measured is suspended between two silicon nitride platforms with integral platinum (Pt) resistance loops. These islands are part of a microelectrothermal system (METS) device fabricated using standard silicon MEMS processes and are each suspended from the silicon substrate (thermal reservoir) via six long suspension beams. The islands are part of a micro-electro-thermal system device, showing the left and right platinum resistance sensor islands. A focused electron beam (purple cone) is used as a heat source. (b) Equivalent thermal circuit, showing the cumulative thermal resistance from the left island to the heating spot, and the temperature rise of left and right islands (ΔT_L and ΔT_R). (c) Electrical circuit showing the offset compensation arrangement, where the nominal resistance of the Pt loop is compensated by the variable resistors (R_b), so as to increase the sensitivity of the thermometry.

Figure 1. Experimental setup for electron beam heating technique. (a) Schematic of the microelectro-thermal system device, showing the left and right platinum resistance sensor islands. A focused electron beam (purple cone) is used as a heat source. (b) Equivalent thermal resistance circuit, showing R_b, the cumulative thermal resistance from the left island to the heating spot, and the temperature rise of left and right sensors (ΔT_L and ΔT_R). (c) Electrical circuit showing the offset compensation arrangement, where the nominal resistance of the Pt loop is compensated by the variable resistors (R_b), so as to increase the sensitivity of the thermometry.

Substrate (T_a)

Figure 1.

island has to be equal to the heat flux from the island to the substrate through the six beams, hence:

\[ \frac{\Delta T_i(x) - \Delta T_{ti}}{R_i(x)} = \frac{\Delta T_{tL}}{R_b} \]

where \( R_i(x) \) is the cumulative thermal resistance from the left island to the heating spot, and \( R_b \) is the equivalent thermal resistance of the six suspension beams connecting the left (or the right) island to the environment; \( R_b \) is measured by the thermal bridge method. \(^{7,13}\)

Likewise, if we consider the heat flux from the heating spot to the right island, we have:

\[ \frac{\Delta T_i(x) - \Delta T_{tr}}{R_i - R_i(x)} = \frac{\Delta T_{tR}}{R_b} \]

\( R_{tr} \), the total resistance of the nanowire plus the two contacts \( (R_{CL} \text{ and } R_{CR}) \), is measured by the traditional thermal bridge method, that is, by electrically heating the left island to raise its temperature by \( \Delta T_{tL} \) and measuring the temperature rise of
the right island \( \Delta T_{\text{R}} \). From eqs 1 and 2, \( R_i(x) \) can be written as:

\[
R_i(x) = R_0 \left\{ \frac{\alpha_0 - \alpha_i(x)}{1 - \alpha_0} \right\}
\]

where \( \alpha_i = \Delta T_i / \Delta T_0 \) and \( \alpha_0 = \Delta T_{1,0} / \Delta T_{\text{R}} \).

Underlying eqs 1 and 2 is the assumption that the thermal transport along the nanowire obeys Fourier’s law. The thermal resistance of the entire nanowire can then be considered as that of the left and right nanowire segments in series and is constant irrespective of the heat source position. Since \( R_i \) is a function of position \( x \), by scanning the electron beam along the nanowire from the left to the right island and recording the corresponding temperature rises \( \Delta T_L \) and \( \Delta T_R \), we obtain a spatially resolved thermal resistance profile of the nanowire.

The spatial resolution is limited by the heating volume within the nanowire, rather than by the electron beam spot size. Although the latter can be as small as 1 nm, the extent of the heating volume is typically much larger, with the lower bound set by the electron beam–specimen interaction volume. The latter is primarily determined by the energy of the electron beam, the diameter of the nanowire, and the local atomic composition. In general, thin wires and low atomic number composition favor a small interaction volume. However, for a given sample, the parameter to consider is the electron beam energy. In the case of a nanowire, the electron beam is mainly transmitted, and hence the forward-scattering profile defines the shape of the electron beam–specimen interaction volume. Here, a higher energy beam is desirable to reduce the extent of forward scattering within the nanowire, but the trade-off is that less of the incident electron energy is absorbed at very high beam energies. The choice of beam energy is then a balance between energy absorption, which depends on the nanowire diameter and its composition, and the spatial resolution.

Additionally, in the case of a semiconductor, the electron beam creates electron–hole pairs (EHPs) which diffuse along the nanowire and recombine, with part of the energy being released as heat. In a nanowire, surface recombination is likely to dominate and the carrier diffusion length would then be much smaller compared to that of the bulk material.16 Nevertheless, this phenomenon will enlarge the heating volume. Indeed, it is difficult to define the spatial resolution, which depends on how long a distance it takes before thermal equilibrium conditions are established in the material after it is locally perturbed by the high energy electron beam. Besides the EHP diffusion, the relaxation rate of hot carriers (which depends on the electron–phonon coupling strength) should also be considered. Hence the spatial resolution of this technique depends on the material properties, with a lower bound set by the electron-beam specimen interaction volume.

We carried out the experiment in a scanning electron microscope (SEM) chamber at high vacuum where heat loss through convection may be neglected. The focused electron beam is rapidly and repetitively scanned across the diameter of the nanowire, effectively creating a line heating source that is perpendicular to the wire axis. This heating source is then moved from the left to the right along the nanowire at a corresponding time constant that is much longer than the thermal time constant of the METS device (<10 ms) such that the thermal system is at steady state at every data collection point. Doubling of the scanning time gave rise to no observable differences within the bounds of noise. A Faraday cup beneath the device prevents backscattered and secondary electrons from striking the SiN\(_x\) islands, which would otherwise induce both unwanted heating and parallel conduction paths among the Pt loops as a result of electron-beam induced conductivity. The sensitivity of the resistance thermometry measurement set up is enhanced by adopting a differential circuit configuration to offset the nominal resistance of the Pt loop, as shown in Figure 1c, which allows us to use a more sensitive range of the lock-in amplifier. In conjunction with other techniques (see Supporting

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**Figure 2.** Spatially resolved measurement of thermal resistance. (a) TEM image of a Si\(_{0.7}\)Ge\(_{0.3}\)/NiSi\(_{0.7}\)Ge\(_{0.3}\) interface. Scale bar: 50 nm. (b) High-resolution transmission electron microscope (HRTEM) image of the Si\(_{0.7}\)Ge\(_{0.3}\)/NiSi\(_{0.7}\)Ge\(_{0.3}\) interface. The dark portion is NiSi\(_{0.7}\)Ge\(_{0.3}\), and the bright portion is Si\(_{0.7}\)Ge\(_{0.3}\). Scale bar: 5 nm. (c) SEM image of a heterostructured nanowire. Scale bar: 500 nm. (d) Upper: Temperature rise of left and right sensors (\( \Delta T_L \) and \( \Delta T_R \)) as a function of heating spot position (\( x \)). Lower: Cumulative thermal resistance \( R_i \) as function of distance from the left sensor. Thermal resistivity \( 1/\kappa = (dR/dx)A \), where \( A \) is the cross sectional area of the nanowire. \( \kappa(\text{Si}\(_{0.7}\)\text{Ge}\(_{0.3}\)) = 1.9 \pm 0.3 \text{ W/m-K} \) and \( \kappa(\text{NiSi}\(_{0.7}\)\text{Ge}\(_{0.3}\)) = 13.4 \pm 1.3 \text{ W/m-K} \).
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Figure 3. NiSi$_2$ fillet embedded in Si nanowire. (a) TEM image showing the Si/NiSi$_2$ interface is perpendicular to the Si nanowire axis. Dark portion: NiSi$_2$; bright portion: Si. Scale bar: 20 nm. Upper right inset: selected area electron diffraction (SAED) pattern of the Si portion. Lower left inset: SAED pattern with the electron spot enclosing the NiSi$_2$ fillet. Both Si and NiSi$_2$ SAED patterns can be seen here, and the pattern for NiSi$_2$ is highlighted by the yellow line. The growth direction of NiSi$_2$ is $[111]$, which is the same as that for Si. The zone axis for both Si and NiSi$_2$ is $[110]$. (b) HRTEM image of the Si/NiSi$_2$ interface, showing that it is nearly abrupt but with minor lattice disorder. Scale bar: 5 nm.

Information S1), we achieved a measurement sensitivity of better than 0.4 mK, which is necessary for this technique.

To highlight pertinent features of the spatially resolved thermal conductivity measurement, we carried out a measurement on heterostructured Si$_{0.7}$Ge$_{0.3}$/NiSi$_{0.7}$Ge$_{0.3}$ nanowires. The two material systems stand in contrast in terms of their electron energy absorption and thermal conductivity, the nickel germanosilicide being larger in both aspects compared to the silicon–germanium.

Such nanowires were synthesized by first depositing a thin nickel film on Si$_{0.7}$Ge$_{0.3}$ nanowires. Upon annealing, the nickel film agglomerates and reacts with the underlying Si$_{0.7}$Ge$_{0.3}$ nanowire to form NiSi$_{0.7}$Ge$_{0.3}$ segments. These segments alternate with Si$_{0.7}$Ge$_{0.3}$ segments with a typical pitch of 0.3–0.4 $\mu$m, as shown in Figure 2c. Figure 2b shows a lattice resolved transmission electron microscope (TEM) image: the bright portion is Si$_{0.7}$Ge$_{0.3}$, and the dark portion is NiSi$_{0.7}$Ge$_{0.3}$, interpreted from the lattice spacings (see Supporting Information S2.1). The interface is not exactly perpendicular to the heat flow direction, as seen from Figure 2c, and it also undulates over a range of ~15 nm (Figure 2a). One such nanowire was picked up by a nanomanipulator and fixed on the METS device by electron-beam-induced deposition of Pt (the configuration is illustrated in the Supporting Information S2.1). An 18 keV electron beam was scanned along the nanowire from left to right.

The upper part of Figure 2d shows the measured temperature rise of the left and right islands ($\Delta T_L$ and $\Delta T_R$). Since the power has to flow through both islands, the absorbed power is $P = (\Delta T_L + \Delta T_R)/R_p$, $\Delta T_L$ and $\Delta T_R$ are higher when the electron beam scans along a NiSi$_{0.7}$Ge$_{0.3}$ segment because compared to Si$_{0.7}$Ge$_{0.3}$ the denser NiSi$_{0.7}$Ge$_{0.3}$ absorbs more power from the electron beam.

The red line in Figure 2d is the cumulative thermal resistance $R_i$, calculated from eq 3. Note that in spite of the irregular shape of the NiSi$_2$ fillet, we could still extract $\Delta T_L$ and $\Delta T_R$ curves arising from variable heat absorption, $R_i$ increases monotonically from left to right, since $R_i$ is derived from the ratio of the power flows toward the left and the right, $(\Delta T_L/\Delta T_R)$, irrespective of the absorbed power. The linear increase in $R_i$ within the same material segment is expected as the segment is uniform both in terms of its structure and thermal conductivity. If we compare the two materials, $R_i$ increases at a lower rate in NiSi$_{0.7}$Ge$_{0.3}$ segments (of brighter appearance in the SEM image) compared to the Si$_{0.7}$Ge$_{0.3}$ segments. The thermal conductivity of Si$_{0.7}$Ge$_{0.3}$ and NiSi$_{0.7}$Ge$_{0.3}$ is calculated from the slope of $R_i(x)$ of the respective material segments, from which

$$\kappa = \frac{1}{(dR_i/dx)\cdot A}$$

where $A = \pi d^2/4$, $d$ representing the diameter of the nanowire.

From the measured data we obtain $\kappa$ (Si$_{0.7}$Ge$_{0.3}$) = 1.9 W/m·K, which is comparable to values reported in the literature, and $\kappa$ (NiSi$_{0.7}$Ge$_{0.3}$) = 13.4 W/m·K, which is much higher than that of the Si$_{0.7}$Ge$_{0.3}$ portion. Apart from being able to resolve heterogeneous nanowires, since $\kappa$ is calculated from $dR_i/dx$, this approach to measuring nanowire thermal conductivity avoids the uncertainty due to unknown thermal contact resistance ($R_{CL}$ and $R_{CR}$) in a conventional thermal bridge measurement.

As the Si$_{0.7}$Ge$_{0.3}$/NiSi$_{0.7}$Ge$_{0.3}$ interface is neither straight nor perfectly perpendicular to the 1D heat flow direction along the nanowire, the interfacial thermal resistance (ITR) could not be extracted unambiguously. In comparison, Si/NiSi$_2$ heterostructured nanowires provide nearly abrupt epitaxial interfaces, which allows us to evaluate the spatial resolution of the technique as well as study the ITR.

These nanowires were prepared by placing silicon nanowires in partial contact with nickel islands on a substrate. Upon high temperature annealing at 730 °C, Ni diffuses through the
nanowire, and at locations where there is a change in the surface energy (e.g., where there is a nanoparticle attached on the surface), NiSi$_2$ starts to nucleate and grow, forming a single-crystal fillet within the Si nanowire. The NiSi$_2$ fillet is perpendicular to the Si nanowire growth direction, as shown by Figure 3a. The selected area electron diffraction (SAED) pattern in the inset of Figure 3a shows that the fillet grows in the [111] direction, which is the same as that of the Si nanowire. In the particular case shown, the zone axis for Si and NiSi$_2$ are both in the [1 1 0] direction. The detail of the Si/NiSi$_2$ interface is shown in the lattice-resolved TEM image (Figure 3b). The interface is perpendicular to the nanowire growth direction, and nearly abrupt but with minor lattice disorders, for example, dislocations, lattice misfits, within a span of ∼5 nm at the interface (more details provided in the Supporting Information S2.2).

Such nanowire samples were fixed onto the METS device using the same procedure as that for the previous Si$_x$Ge$_{2-x}$/NiSi$_2$ heterostructured nanowire. A 29 keV electron beam was used to scan along the nanowire (Figure 4). Figure 4c shows the profile of the power absorbed by the nanowire from the electron beam in the vicinity of an interface. Since NiSi$_2$ is denser and better in stopping the electron beam than Si, a larger fraction of the incident beam power is absorbed in the NiSi$_2$ portion. As a result, the absorbed power $P$ increases rapidly as the electron beam traverses the interface. Based on the full-width-at-half-maximum (fwhm) of the differential absorbed power ($dP/dx$), the spatial extent of the energy absorption volume is determined to be ∼1.17 nm, with the portion in silicon (∼4.5 nm) being smaller than that in NiSi$_2$ (∼7.2 nm). This is in agreement with the Monte Carlo simulation results of absorbed energy volume in Si and NiSi$_2$ (insets of Figure 4c).

$R_s$ was calculated using eq 3 and is plotted as a red solid line in Figure 5a. The through-hole in our METS device allows us to carry out TEM imaging of the same sample, so that we can obtain the sample dimensions with nanometer precision, as shown superimposed in the background of Figure 5. We obtained $dR_s/dx$ by carrying out a linear fitting of $R_s$ for Si and NiSi$_2$ portions individually and extracted the nanowire diameter from the corresponding TEM image, from which the thermal conductivity of both portions is calculated as $\kappa(Si) = 33$ W/m·K and $\kappa(NiSi_2) = 33$ W/m·K, respectively, for the sample shown in Figure 4a. Measurements on different samples yielded very similar thermal conductivities because the nanowires are of nearly the same diameter (150 nm) and are all grown in the [111] direction. The electron contribution to the thermal conductivity of metallic NiSi$_2$ phase at room temperature (300 K) is calculated by Wiedemann–Franz law: $\kappa_e = \sigma L T$, where $L$ is the Lorenz number ($2.44 \times 10^{-8}$ W·Ω·K$^{-2}$), and $\sigma$ is the electrical conductivity of NiSi$_2$. The electrical resistivity has been reported as $\sim 35 \times 10^{-8}$ Ω·m for polycrystalline NiSi$_2$ films$^{19-21}$ and $\sim 3.0 \times 10^{-8}$ Ω·m for NiSi$_2$ nanowires synthesized by chemical vapor deposition,$^{22}$ the latter being lower because the NiSi$_2$ nanowire is single crystalline and defect-free. From this, $\kappa_e \sim 21-24.4$ W/m·K, and the rest (~10 W/m·K) could be attributed to the lattice contribution.

There is a step change in $R_s$ at the Si/NiSi$_2$ interface, which represents intuitively the ITR. As the electron beam traverses the interface between two materials with different energy absorption properties, $dP(x)/dx$ peaks (Figure 4c). The position of the material interface is close to but not exactly at this peak, but the offset is small, typically less than 1 nm, as shown in the Monte Carlo simulation in Supporting Information S3. We observe that the span where $R_s$ increases rapidly is mainly on the Si side. The reason for this could be due to the EHPs generated in the Si portion, which diffuse and recombine, especially at the interface, thereby altering the shape of heating volume. This is further discussed in Supporting Information S4. On the other hand, in the metallic NiSi$_2$ portion, the $R_s$ profile is seen to correspond to the energy absorption profile shown in Figure 4, with the transition in $P(x)$ taking place over a distance of <20 nm, showing the inherent spatial resolution of the technique.

To determine the ITR, we carried out a linear fitting of $R_s$ in both Si and NiSi$_2$ portions using data sufficiently far away from the interface (see Supporting Information S4) and extrapolated the two fitted lines to intersect with the interface. The difference between the values at the two intersects is taken as the ITR (denoted as $R_{INT}$). The interfacial thermal conductance (denoted as $h_{INT}$) is then calculated as $h_{INT} = 1/(R_{INT}A)$, which is a geometrically independent parameter. $h_{INT}$ was determined for several interfaces and plotted in Figure 6, as data points inside the red dotted circle. The average value is higher than that of the metal–semiconductor interface measured by Hopkins and Duda et al.$^{23,24}$ employing the time-domain thermoreflectance (TDTR) technique, for a number of reasons. First, compared to metals, a metal silicide has a better acoustic match with Si. Second, the interface for their TDTR measurement was formed by thermal evaporating metal on a

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**Figure 4.** Energy absorption at the interface between Si and NiSi$_2$. (a) SEM image of a Si/NiSi$_2$ heterostructured nanowire bridging the left and right sensor islands. Dark portion: NiSi$_2$; bright portion: Si. The gap between left and right islands is 5 μm. (b) Enlarged SEM image showing the embedded NiSi$_2$. Scale bar: 100 nm. (c) The absorbed power $P(x)$ measured as the electron beam is scanned across the interface in the region enclosed by the orange dashed rectangle in b. The actual interface is close to the peak of $dP(x)/dx$. Monte Carlo simulation of absorbed energy volume in both Si (left inset) and NiSi$_2$ (right inset).
silicon surface, whereas in our material system, the bonding between Si and NiSi$_2$ is covalent in nature. Better acoustic match and stronger bonds result in higher interfacial thermal conductance.

To understand the underlying physics, we numerically calculate the interfacial thermal conductance ($h_{\text{INT}}$) from the diffuse mismatch model (DMM)\(^\text{26}\) (more details of calculation can be found in Supporting Information S5) which gives rise to the value of $h_{\text{INT}}$ of 325 MW/m$^2$K$^{-1}$. Our experimental value ($\sim$500 MW/m$^2$K$^{-1}$) is larger than the value from DMM. The discrepancy may be qualitatively explained by considering the following. On the one hand, in our DMM calculations, the DOS of the bulk material is used instead of the DOS of nanowire as this is not available. This may give rise to error in the DMM calculations. On the other hand, the larger experimental conductance values might be caused by the so-called phonon bridging effect induced by a diffused interface. Recently, Zhou et al.\(^\text{26}\) have studied the effect of interface structure on the interfacial thermal conductance. They found that when the interface is changed from a very sharp one to a diffused one (in which the atoms of two materials interpenetrate around the interface), the temperature drop at the interface is reduced when the same heat flux is applied, which leads to the enhancement of interfacial thermal conductance in the diffused case as we observed in our experiment. Indeed, if we examine Figure 3b, we can see this kind of diffused interface. The $\sim$5 nm layer with disorder and dislocations at the interface serves as a buffer layer that bridges phonon transmission from Si to NiSi$_2$. The overlapping density of states (DOS) between the buffer layer/Si and buffer layer/NiSi$_2$ is larger than that between Si and NiSi$_2$ without an intervening layer, thereby providing more elastic scattering channels for phonons to transport across the interface. This phonon bridging effect has been fully investigated via nonequilibrium molecular dynamics.\(^\text{27,28}\) However, more detailed numerical calculations and experimental work need to be done to get a quantitative comparison.

As the electron beam heating technique makes it possible to directly measure the thermal resistance of individual interfaces, this opens up the possibility of investigating what happens when two interfaces are very close to each other, at separations that are comparable to the phonon mean free path. We conducted a series of experiments with progressively thinner NiSi$_2$ fillets, which brings the two Si/NiSi$_2$ interfaces into close proximity to each other, as shown in Figure 5. The thinnest fillet we could find is 16 nm (inset of Figure 5c). This thickness is comparable to the electron beam-specimen interaction volume, so the two steps in $R_i$ arising from the two interfaces could not be individually resolved, making it impossible to calculate the $R_{\text{INT}}$ of each interface. To manage this, we carried out linear fits to $R_i$ of the two Si portions away from the junction, as before. The two fitted lines are parallel to each other but separated by the jump in $R_i$ across the NiSi$_2$ fillet (denoted as $R_{\text{step}}$). $R_{\text{step}}$ comprises the resistance of the NiSi$_2$ fillet (denoted as $R_{\text{film}}$), and $2R_{\text{INT}}$ represents the two Si/NiSi$_2$ interfaces. The ITR of a single interface is then:

$$h_{\text{INT}} = \frac{1}{2R_{\text{INT}}A}.$$
\[ R_{\text{INT}} = \frac{R_{\text{step}} - R_{\text{fillet}}}{2} \]

where \( R_{\text{fillet}} = L/\kappa(\text{NiSi}_2)A, \) \( L = 16 \) nm, and \( A \) is the cross-sectional area. We assume \( \kappa(\text{NiSi}_2) = 30 \) W/m-K, based on the measured values for the samples shown in Figure 5a and b. However, the exact value of \( \kappa (\text{NiSi}_2) \) has a marginal effect on the value of \( R_{\text{INT}} \) obtained because of the small \( L \). \( h_{\text{INT}} \) is calculated in the same way as for previous samples, and its value is indicated by the red diamond in Figure 6. From this figure we can see that the \( h_{\text{INT}} \) of an interface separated by 16 nm distance (which is equivalent to \( \sim 50 \) NiSi\(_2\) (111) atomic layers) from another is the same as that of an isolated interface.

In this paper, we reported a new thermal measurement technique that is capable of profiling the thermal resistance of an individual nanowire with a spatial resolution better than 20 nm. In this technique, a focused electron beam is employed as a localized heat source to establish a temperature gradient along the nanowire. The heat fluxes from the two ends of the nanowire are measured using platinum resistor loops on two suspended thermally isolated islands. With improvements to the electrical measurement setup, a sensitivity of 0.4 mK, limited by quantization noise of lock-in amplifier could be achieved.

This electron beam heating technique was demonstrated on two material systems: Si\(_{0.8}\)Ge\(_{0.2}\)/NiSi\(_{0.5}\)Ge\(_{0.5}\) and Si/NiSi\(_2\) heterostructured nanowires. We show that, by scanning the electron beam along a heterostructured nanowire, we are able to measure the local thermal conductivities that varied with the material composition of the nanowire. Moreover, with the high spatial resolution and high sensitivity, we are also able to measure the interfacial thermal resistance (ITR) of a single Si/NiSi\(_2\) interface. Last but not least, we measured the ITR of two adjacent Si/NiSi\(_2\) interfaces with separations as small as 16 nm. We found that the ITR does not change even when there are only \( \sim 50 \) atomic NiSi\(_2\) layers in between two interfaces.

In summary, the electron beam heating technique is able to spatially resolve the thermal conductivity of an individual nanowire and also addresses the long-standing problem of ill-defined thermal contact resistance between the nanowire and the two islands, which is a serious drawback in the conventional thermal bridge method. Moreover, its capability of directly and separately measuring the ITR of multiple interfaces renders it a powerful tool to study how heat flows across interfaces at the nanometer scale. This technique is also extendable to low temperature measurement and probing how heat flows in complex networks.

**ACKNOWLEDGMENTS**

We thank Yee-Kan Koh, Xiangfan Xu and Sha Liu for helpful discussions and Hao Gong and Chunhua Tang for assistance in characterization of the nanowires. This work is funded by grant MOE2011-T2-1-052 from the Ministry of Education, Singapore, and grants R-144-000-284-646and R-263-000-626-646 from NUS. N.Y. and B.L. are also supported from NSF China through Grant 11334007.

**REFERENCES**


**ASSOCIATED CONTENT**

**Supporting Information**

Improvement on measurement sensitivity, sample preparation and characterization, Monte Carlo simulation showing the position of interface, obtaining the ITR, and numerical calculation of ITR between Si/NiSi\(_2\) interface. This material is available free of charge via the Internet at http://pubs.acs.org.

**AUTHOR INFORMATION**

**Author Contributions**

D.L. and R.X. contributed equally to this work.

**Notes**

The authors declare no competing financial interest.