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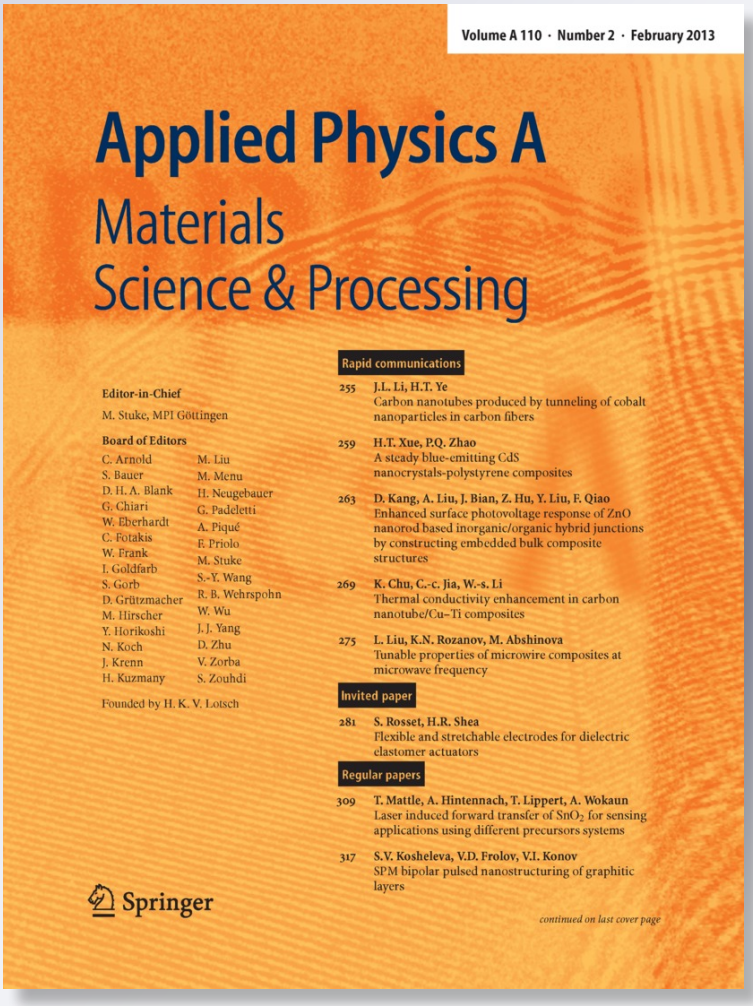

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Abstract A contact transient electrothermal technique (CTET) is developed to characterize the thermal transport between one-dimensional conductive and nonconductive microscale wires that are in point contact. This technique is a significant advance from the transient electrothermal method that is used to characterize the thermophysical properties of individual one-dimensional micro-wires. A steady-state analytical solution and a transient numerical solution are used to independently determine the value for the thermal contact resistance between the wires at the contact point. The CTET technique is applied to measurement of the thermal contact resistance between crossed Pt wires (25.4 μm diameter) and the thermal contact resistance between a glass fiber (8.9 μm diameter) in contact with a Pt wire (25.4 μm diameter). For Pt wire contact, the thermal contact resistance increases from 8.94×10^4 to 7.05×10^5 K/W when the heating current changes from 20 to 50 mA. For the Pt/glass fiber contact, the thermal contact resistance is much larger (2.83×10^6 K/W), mainly due to the smaller area at the contact point.

1 Introduction

There are several techniques available to characterize heat transfer in one-dimensional micro/nanoscale fibers and wires. These include the 3ω method [1–3], optical heating and electrical thermal sensing (OHETS) technique [4], a pulsed laser-assisted thermal relaxation (PLTR) method [5, 6], and a transient electrothermal (TET) technique [7]. These methods have all successfully been used to obtain thermophysical properties of micro/nanoscale wires, fibers and tubes.

In the 3ω method [1–3], an ac current of frequency ω is fed to the sample, which creates a temperature oscillation at frequency 2ω. If the sample has linear I–V behavior, this will cause a resistance oscillation at frequency 2ω. The product of this resistance oscillation and the oscillating heating current results in a voltage oscillation at frequency 3ω. The amplitude and phase shift of this third harmonic voltage variation can be measured and used to determine the thermophysical properties of the sample. The OHETS technique [4], developed by Hou et al., uses a periodically modulated laser beam to induce a periodic heating in the sample. At the same time, a small dc current is fed to the sample. The resistance change due to the heating of the sample can be measured by measuring the change in voltage across the sample, and used to obtain the thermophysical properties of the sample. A similar technique is the PLTR method [5, 6]. In this technique, a small dc current is fed through the sample to probe its temperature variation. The sample is irradiated by a pulsed nanosecond laser to quickly heat the sample. The temperature decay after this initial pulsed heating can be used to find the properties of the sample.

For the TET technique [7], the sample is fed a step dc current, which causes a transient temperature rise. This temperature evolution can be sensed by measuring the voltage increase across the sample. The thermophysical properties of the sample can be obtained from the measured temperature rise. The TET technique has several advantages over other techniques like the 3ω or OHETS methods. Unlike the 3ω technique, the TET can be applied to metallic, nonconductive, and semiconductive samples. In addition, the measurement time for these other techniques can be relatively

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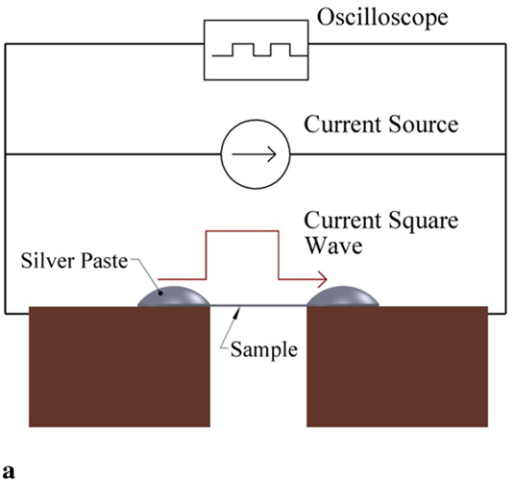
long, often several hours. For the TET technique, the measurement time is very short, often less than one second.

While heat transfer in one-dimensional micro/nanoscale wires has been well studied, the thermal transport between these wires in contact has not been largely addressed. There have been some experimental methods to study this problem. Yang et al. measured the thermal contact resistance (TCR) between individual crossed carbon nanotubes (CNTs) using a microfabricated device method [8]. Guo et al. investigated heat transfer in arrays of aligned TiO_2 nanotubes [9]. The thermal contact resistance between the TiO_2 nanotubes was measured in the process, however, in this case the contact resistance being measured was that in the cross tube direction between parallel nanotubes. The T-type probe is another method that has been developed in the past to measure the thermal properties of microscale wires and fibers [10, 11]. This technique involves a hot wire through which a heating current is fed. One end of the to-be-measured sample is attached to the center of the hot wire and the other end to a heat sink. The properties of the sample wire can be determined from the measured voltage change in the hot wire in a measurement similar to the 3ω method. If no interfacial material is used to enhance the thermal contact between the sample and the hot wire, then this technique can be applied to measure the thermal contact resistance between the wires. Wang et al. measured the thermal contact resistance between Pt wires [12]. They reported a dimensionless TCR that was related to the surface roughness of the samples and the amount of deflection caused by contact.

In this paper a contact transient electrothermal (CTET) technique is developed based on a modification of the TET technique and used to measure the TCR between crossed micro-wires and fibers. By characterizing the thermal transport across a single point, what is being characterized is essentially zero-dimensional heat transfer. This has not been well characterized before in the context of thermal contact resistance between micro/nanowires. The only comparable technique is the T-type probe method. However, the T-type probe can only give a dimensionless normalized TCR. To obtain an actual value for the TCR, information about the contact area, surface roughness, and mechanical properties of the sample must be known. The CTET technique is straightforward and directly determines the TCR in units of K/W. The CTET technique also has the same advantage of the T-type probe that the TET has over the 3ω method; namely, a much shorter measurement time and a superior signal to noise ratio. In Sect. 2, the experimental principle is presented. In Sect. 3, the physical model is developed. The experimental details and results are discussed in Sect. 4.

2 Experimental methods

In the TET technique, the sample whose properties are to be measured is suspended between two electrodes as shown in Fig. 1(a). A direct current is then fed through the wire. This current will induce electrical heating, causing a temperature change, and in turn a resistance change. This resistance



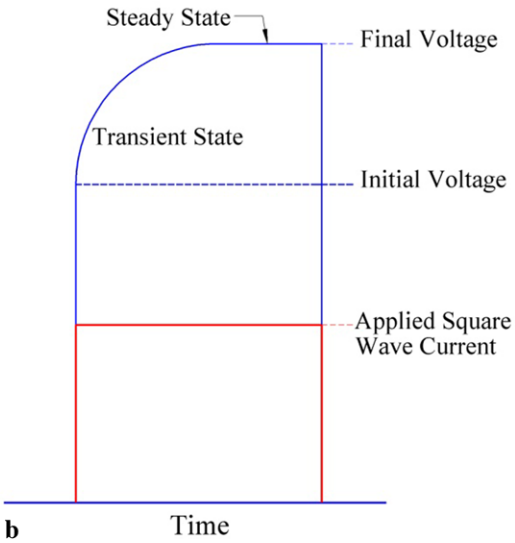


Fig. 1 (**a**) Schematic of the experimental principle and setup for the TET experiment. A step current is provided by a low noise current source and the voltage response is recorded with an oscilloscope. (**b**) Voltage response to a step heating current through the sample. The step current is shown in *red* and the voltage response in *blue*. The change in sample resistance due to electrical heating creates a transient voltage rise to a final state steady-state voltage. This transient voltage rise is used to determine the thermal properties of the sample

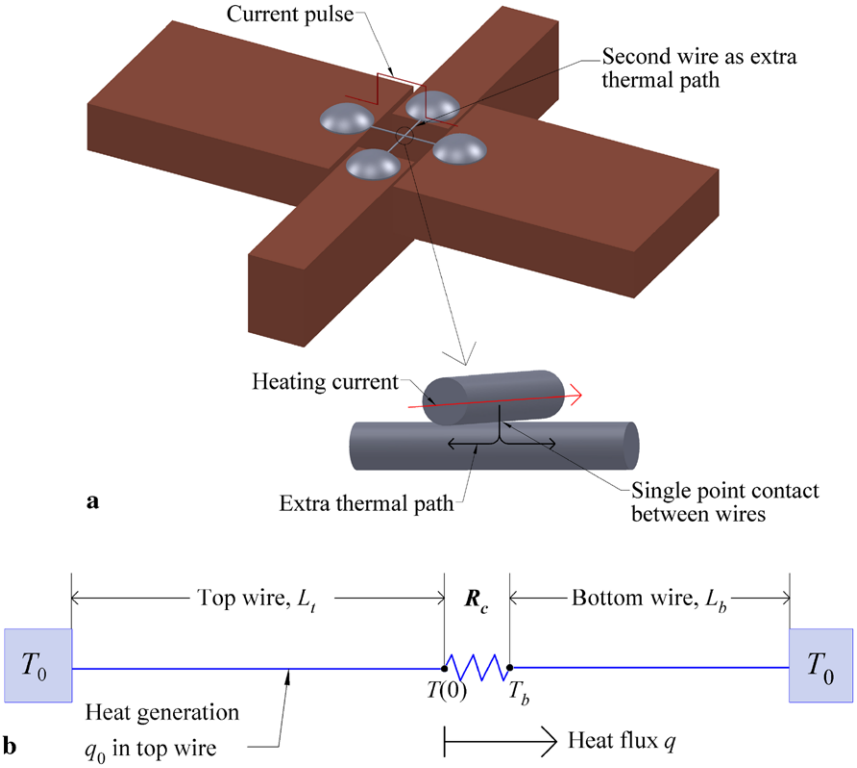


Fig. 2 (**a**) Principle of the CTET experiment. The single-point contact between the wires enables additional heat transfer to occur from the top wire to the bottom wire. (**b**) Heat transfer model used in analysis using symmetry condition. L_t and L_b are half the measured lengths of the *top* and *bottom* samples, respectively. Heat generated in the top wire is conducted into the bottom wire at the contact point, where there is a thermal contact resistance R_c

change can be sensed by measuring the change in the voltage across the wire, as shown in Fig. 1(b). In this way, the temperature evolution can be probed by measuring the voltage evolution. The thermal diffusivity can then be obtained by fitting the normalized measured temperature change to a theoretical curve.

The concept of thermal characterization is similar for the CTET technique. However, the quantity to be measured is not the thermal diffusivity of the sample, but rather the thermal contact resistance between two crossed micro/nanowires or fibers. A first wire is mounted in a similar manner to that in the TET technique, suspended between two electrodes. In addition, a second wire is mounted onto a second stage, also suspended between two electrodes. A schematic of the experimental principle is shown in Fig. 2(a). A step current is fed through the first sample to induce electrical heating, as in the TET technique. However, when there is another wire in contact with the first sample, some heat will be conducted into the second wire, lowering the average temperature of the first wire. This temperature evolution will be qualitatively different from that obtained from a single wire TET measurement given the same heating current in two ways. First, the final steady-state temperature will be lower than in a single wire. Second, the wire in contact will reach the steady state quicker than a single wire. The thermophysical properties of the samples such as thermal conductivity, density, and specific heat, must be known in order to measure the thermal contact resistance with this technique. These properties can be either found from the literature, or can be determined from a separate TET measurement of the single wire (top wire).

Figure 1(a) shows the experimental setup for the TET measurement. The experimental setup for the CTET is identical, with the exception of a second wire being in contact with the wire through which current is being fed. The current is supplied by a low noise Keithley 6221 current source. The low noise current source is crucial to providing a sharply rising step current to reduce uncertainty in the measured temperature evolution. A high speed digital oscilloscope TDS7054 is used to record the voltage evolution.

Each of the samples are suspended between two copper electrodes and secured with colloidal silver paste. The silver paste ensures both good electrical and thermal contact. The base on which the top sample is suspended is designed to allow room for the bottom sample. The bottom base is specially designed to allow for good contact between the fibers, but not interfere with the flow of current through the top fiber. In the experimental setup, the top base is fixed and the bottom base is attached to a three-dimensional microstage. The bottom sample can be positioned precisely so that the contact point is in the middle of both samples. The bottom sample is then raised slowly to ensure there is solid contact, but not raised far enough that the samples are bent. The experiment takes place in a vacuum chamber evacuated to a low pressure to minimize the influence of air convection.

In the TET and CTET techniques, if the sample of interest is not electrically conductive, it is coated with a thin layer

of Au for the purpose of making it conductive. The coating is applied in a Denton Desk V vacuum coating device, which deposits a coating in the range of tens of nanometers thick.

3 Physical model

3.1 TET technique

In the TET technique, if the diameter of the wire is much less than the length, the heat transfer can be considered one-dimensional in the axial direction. The governing equation is

$$\frac{\rho c_p \partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} + q_0 \tag{1}$$

for thermal conductivity k, density ρ, and specific heat c_p. q_0 is the electrical heating power from the supplied current and is assumed to be constant. The initial temperature over the entire length of the wire is T_0. The electrodes are much larger than the diameter of the wire, so the boundary conditions at each end of the wire are taken to be held at constant temperature T_0. The detailed solution to the governing equation is given in Guo's work [7]. The final solution is given here for the average temperature of the sample:

$$\begin{aligned} T(t) &= \frac{1}{L}\int_{x=0}^{L} T(x,t)\,dx \\ &= T_0 \frac{8q_0L^2}{k\pi^4} \\ &\quad \times \sum_{m=1}^{\infty} \frac{1-\exp[-(2m-1)^2\pi^2\alpha t/L^2]}{(2m-1)^4}. \end{aligned} \tag{2}$$

When the sample has reached steady state, the final average temperature becomes $T(t\to\infty) = q_0L^2/(12k)$. The electrical heating can be expressed as $q_0 = I^2R/(AL)$, with cross-sectional area A and sample length L. The temperature can be normalized as $T^* = [T(t) - T_0]/[T(t\to\infty) - T_0]$, which is found to be

$$T^* = \frac{96}{\pi^4}\sum_{m=1}^{\infty}\frac{1-\exp[-(2m-1)^2\pi^2\alpha t/L^2]}{(2m-1)^4}. \tag{3}$$

The voltage evolution recorded by the oscilloscope is directly related to the average temperature change in the sample as

$$\begin{aligned} U(t) &= IR_0 + I\eta\frac{8q_0L^2}{k\pi^4} \\ &\quad \times \sum_{m=1}^{\infty}\frac{1-\exp[-(2m-1)^2\pi^2\alpha t/L^2]}{(2m-1)^4}. \end{aligned} \tag{4}$$

Here $U(t)$ is the measured voltage, R_0 the initial resistance of the sample, and η the temperature coefficient of resistance of the sample. If η is not known, it can be obtained by performing a calibration experiment.

To determine the value of the thermal diffusivity, different trial values are used to calculate the normalized temperature increase. The trial value giving the best fit (least square) of the experimental data is taken as the sample's thermal diffusivity.

3.2 CTET technique

To calculate the thermal contact resistance (TCR) between the two wires, the problem is symmetrical about the contact point, so that half the length of both the top and bottom wires can be considered in the heat transfer analysis as shown in Fig. 2(b). Two methods have been developed to calculate the value of the thermal contact resistance from the measured voltage/temperature evolution. The first one is a steady-state analytical solution where the contact resistance is determined from the final average temperature rise of the top sample. The second one is based on a transient numerical solution by fitting the transient response of the top wire under step electrical heating. These two methods are described in the next sections.

3.2.1 Analytical solution

Taking the contact point as the origin, there is a temperature jump between the top and bottom wires at $x = 0$ due to the TCR. It is expected that the temperature of the top wire at the contact is higher than that of the bottom wire. The temperature of the top wire at $x = 0$ is designated as $T(0)$. The temperature of the bottom wire at $x = 0$ as T_b. For the bottom wire, the governing equation for one-dimensional heat transfer with no heat generation is $A_bk_b\,dT/dx = q$ for cross-sectional area A_b and thermal conductivity k_b of the bottom fiber and constant heat flux q. We set the boundary conditions for the bottom fiber to be $T(L_b) = 0$ and $T(0) = T_b$.

The governing equation for the top fiber considering one-dimensional heat transfer with constant heat generation $\dot{q}$ is $d^2T/dx^2 + \dot{q}/k_t = 0$ where k_t is the thermal conductivity of the top wire. The boundary conditions for this equation are $T(L_t) = 0$ and $dT/dx = q/A_tk_t$ at $x = 0$. The governing equation in each wire can be solved, and combined with the definition of the thermal contact resistance, $R_c = [T(0) - T_b]/qA_t$, where A_t is the cross-sectional area of the top fiber, an expression for the TCR is obtained as

$$R_c = \left[\frac{3\dot{q}L_t^2/4A_tk_t}{\dot{q}L_t - 3\bar{T}k_t/L_t} - \left(\frac{L_t}{A_tk_t} + \frac{L_b}{A_bk_b}\right)\right]. \tag{5}$$

In this analysis the temperature is normalized so that the initial temperature is zero. Therefore, in the above expression, the final average temperature of the top wire $\bar{T}$ is simply the final temperature increase measured in the experiment.

It should also be noted that the lengths L_t and L_b in the above expression are actually half the measured lengths of the wires due to the symmetric nature of the problem. Also because of the symmetric nature, only half the heat actually transported through the contact point is considered. The temperature drop at the interface is the same, but the heat flux through the point is double that calculated. Therefore, the reported value of the TCR is half of the value obtained by this equation. Heat transfer from convection and radiation is negligible in this analysis.

3.2.2 Numerical solution

There is no analytical solution for the transient thermal response of the top wire due to the presence of the TCR. Therefore, a finite difference method is used to numerically solve the heat transfer equation. When the temperature distribution over the length of each wire is known for each time step, an average temperature over the top wire is found in order to give its average temperature evolution. In the CTET measurement, the resistance of the top wire will increase due to heating, resulting in a slight increase in the heating power since the heating current is maintained constant. This small heating power increase is also considered in our numerical solution to fit the transient experimental data.

In the TET technique, the measured temperature evolution is normalized and fitted to a theoretical curve. For a single wire that is not in contact, the normalized curve is independent of the actual temperature of the sample. For the CTET technique, it is the actual temperature rise that is fitted to a theoretical curve. In order to do this fitting, the actual temperature rise must be known. The temperature change can be calculated from knowledge of how the electrical resistance changes with temperature. Different values of R_c can then be tried until the numerically calculated temperature evolution best fits the experimental data. A least square fitting algorithm is used to find the best fit value of the TCR. Again, because of the symmetric nature of the problem, only half the heat transferred through the contact point is considered. Thus the actual value of the thermal contact resistance is half of the value obtained by the data fitting and is reported as such.

4 Results and discussion

4.1 Thermal transport across microscale Pt wire contact

The TET technique was used to measure the thermal diffusivity of a Pt wire sample first. The values obtained by experiment can be compared to reference values for Pt to verify the accuracy of the technique. A separate 4.50 mm Pt wire sample of diameter 25.4 μm was prepared and measured with the TET technique using a heating current of 50 mA. The measured thermal diffusivity was 2.38×10^{-5} m^2/s. This is about a 5 % difference from the reference value of 2.51×10^{-5} m^2/s. The data fitting for this measurement is shown in the inset of Fig. 3. This demonstrates the effectiveness of the TET measurement for obtaining thermal properties of micro/nanoscale wires and fibers.

The CTET technique was used to measure the thermal contact resistance between two crossed Pt wires. In the CTET measurement, both a top sample and bottom sample are prepared. The bottom wire was made shorter than the top wire to ensure that the thermal resistance of the bottom

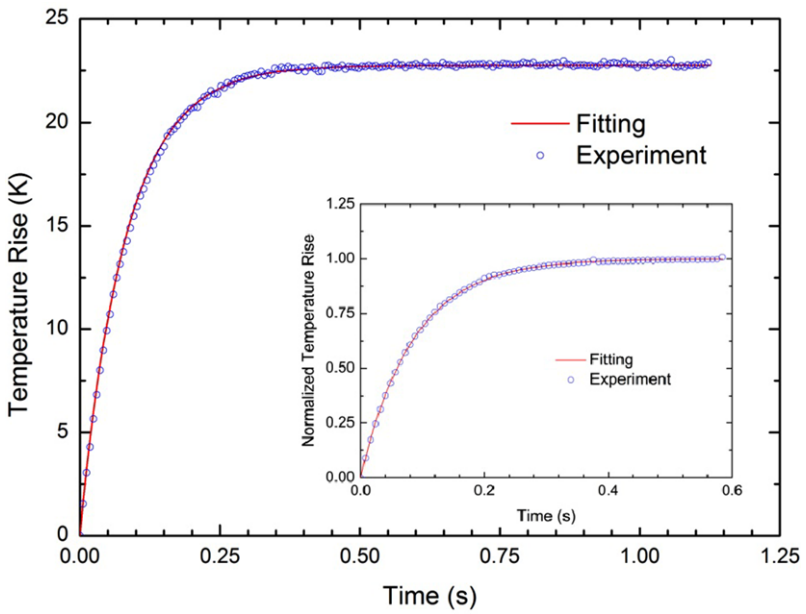


Fig. 3 Data fitting for CTET measurement of crossed Pt wires. The *top wire* had a length of 4.25 mm and *bottom fiber* is 0.96 mm long. The measurement was done at 50 mA. *Inset* shows data fitting for a TET measurement done at 50 mA on a separate 4.50 mm long Pt single wire sample

wire was small compared to the TCR. In order to do the data analysis, knowledge of how the electrical resistance of the top sample changes with temperature is needed. For Pt wire the resistance varies as $R(T) = (L/A)\rho_0(1 + \eta(T - T_0))$, where L and A are the sample length and cross-sectional area, respectively, η the temperature coefficient of resistance and ρ_0 the electrical resistivity at a reference temperature T_0. This equation was used to calculate the initial resistance of the sample, rather than measuring the initial resistance. This is because the Pt wire is highly conductive, and the resistance of the sample is on the same order as the total resistance of the electrodes and measurement leads, thus relying on measured resistances can introduce significant error into the measurement. Values of η and ρ_0 for a reference temperature of 20 °C, as well as other bulk properties used in the data processing are given in Table 1.

Two sets of samples were prepared and characterized with heating currents ranging from 20 mA to 50 mA. The measured values of the TCR between the crossed Pt wires range from about 8.94×10^4 K/W to 7.05×10^5 K/W. The measured TCR increases with increased heating current. The steady-state analytical model and the transient numerical model generally agree well with each other. The experimental conditions and results are listed in Table 2. Taking as an example the first sample set measured at 50 mA, the steady-state solution gives a resistance of 5.42×10^5 K/W and the numerical solution gives a resistance of 5.57×10^5 K/W. This is in agreement within 3 %. The fitting of the experimental data to the numerically calculated temperature rise in the top wire for this measurement is shown in Fig. 3. There is sound agreement between the fitting results and experimental data.

Table 1 Properties used in Pt wire CTET data processing

Thermal conductivity	71.6 W/m K
Specific heat	145 J/kg K
Density	21450 kg/m^3
Temperature coefficient of resistance	0.003927 K^{-1}
Resistivity at 20 °C	0.106×10^{-6} Ω m
Diameter	25.4 μm

Figure 4 shows the trend of generally increasing TCR with increasing heating current. In general, the thermal conductivity of metals decreases as temperature increases, due to increased electron–phonon scattering. It is possible that there is also an increased scattering at the contact point at higher temperatures, leading to increased TCR. More importantly, when a higher current is used in the measurement, the sample, especially the top wire, will have a larger temperature rise. This will lead to greater thermal expansion, especially at the center of the top wire. This thermal expansion could result in a weaker contact between the top and bottom wires, resulting in a higher TCR. Figure 4 also shows the generally good agreement between the two independent models, with the exception of the measurement at 40 mA. For the second set of samples, the 20 mA measurement was done first, and then the 30 mA and 40 mA measurements were done immediately after. It is possible that the measurements at 20 and 30 mA affected the sample, especially the contact point between silver paste and Pt wire. Such a factor could be responsible for the disagreement between the transient and steady-state fitting results. In the numerical transient state fitting of the TCR, a value for the specific heat of Pt which is about 9 % higher than the reference value was used to get the best fitting results. The reference value for Pt is 133 kJ/kg K, while the value used in the calculation was 145 kJ/kg K. This is considered to be within the uncertainty of the measurement. Considering the diameter of the Pt wire is 25.4 μm, if we assume their contact point has a characteristic size around 1 μm or larger, a reasonable estimate for the actual contact area would be 1–10 μm^2. This would correspond to a per-unit area TCR of about 10^{-7}–10^{-5} m^{2}K/W, close to the thermal contact resistance of typical mechanical contact points ($\sim 10^{-6}$ m^{2}K/W) [13].

5 Thermal transport across microscale glass fiber–Pt wire contact

The CTET technique was also used to measure the thermal contact resistance between a glass fiber in contact with a Pt wire. Just like the TET technique, the CTET technique can

Table 2 Experimental conditions and results for Pt wire CTET measurements

Sample pair	Top wire length (mm)	Bottom wire length (mm)	Heating current (mA)	Resistance of sample (Ohms)	Steady-state temperature rise (K)	Analytical R_c (K/W)	Numerical R_c (K/W)
1	4.25	0.96	50	0.896	22.9	5.42×10^5	5.57×10^5
1	4.25	0.96	50	0.896	22.6	4.12×10^5	4.21×10^5
2	4.22	1.00	20	0.890	2.9	8.99×10^4	8.94×10^4
2	4.22	1.00	30	0.890	6.9	1.30×10^5	1.04×10^5
2	4.22	1.00	40	0.890	14.1	7.05×10^5	4.42×10^5

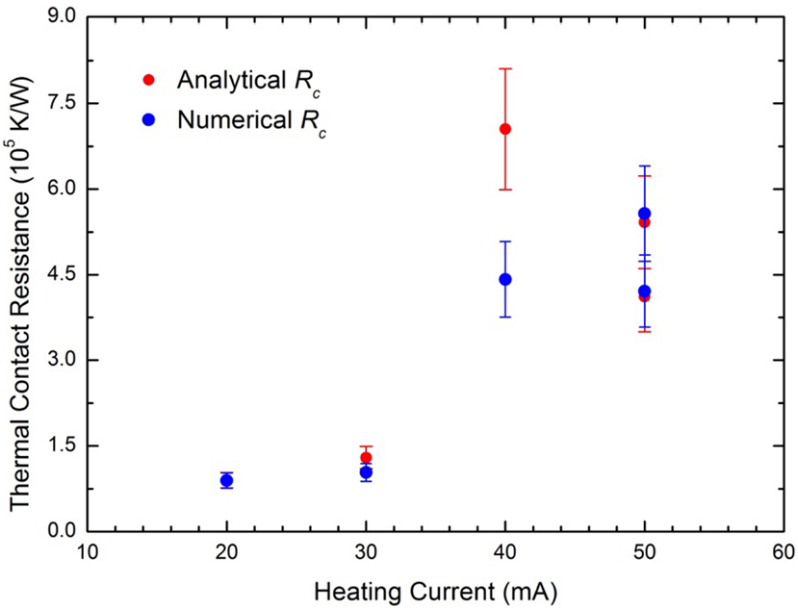


Fig. 4 Thermal contact resistance between crossed Pt wires at different heating currents. Error bars indicate 15 % uncertainty in the measurement. There is good agreement between the steady state and numerical solutions, with the exception of the 40 mA measurement

also be used to for measuring nonconductive wires/fibers. To do this, the glass fiber is coated with a thin Au film to enable electrical heating. A 0.84 mm glass fiber sample of diameter 8.9 μm was prepared and coated with a thin Au film. This glass fiber sample is shown in Fig. 5. A 1.00 mm long bottom Pt wire sample was also prepared. Due to its low thermal conductivity and high surface emissivity, radiation has a large effect on longer glass fiber samples. A shorter length of less than 1 mm minimizes the influence of radiation on the measurement.

Unlike the Pt wire, the properties of the glass fiber are not known, so they must be measured separately in a TET measurement. The density ρ of the fibers has been previously measured in our lab and found to be 2070 kg/m^3. The value of the specific heat c_p was obtained from the literature. An effective thermal diffusivity α_e is obtained from the TET measurement. This is an effective value because it includes the influence of the Au coating, but this is sufficient for the purpose of the CTET measurement. An effective thermal conductivity is calculated from the definition of the thermal diffusivity: $k_e = \alpha_e \cdot \rho c_p$. Here the Au coating is thin enough compared to the diameter of the fiber that it will not have an effect on the effective ρc_p. The average steady-state temperature rise for the fiber is found from the below equation:

$$\Delta T = \frac{I^2 R_f L}{12 k_e A} \tag{6}$$

This temperature rise is used along with the final measured change in resistance to determine how the resistance changes with temperature: $dR/dT = \Delta R/\Delta T$.

Both the TET and CTET measurements were done with a heating current of 120 μA through the coated glass fiber. The measured voltage evolution in the glass fiber is shown in Fig. 6 for both measurements. Two important effects can be seen in this figure. First, the final steady-state temperature is lower when the glass fiber is in contact with the Pt wire compared to the final temperature of the single fiber measurement. Based on the voltage rise, it is estimated the temperature rise in the CTET measurement is about 63 % of that for single glass fiber under the same electrical heating. This indicates that the bottom Pt wire helps reduces the total thermal resistance. Second, the time it takes to reach steady state is shorter for the fibers in contact than for a single fiber. In the TET measurement, it takes 0.179 second for the glass fiber to reach 90 % of the maximum temperature rise. When the glass fiber is in contact with the bottom Pt wire, this time is reduced to 0.112 second. Both of these effects are due to the additional heat transfer that occurs from the glass fiber into the Pt wire. In both the TET and CTET measurements, unique information can be extracted from the transient and steady-state portions of the temperature evolution. In the TET experiment, the transient portion yields the thermal diffusivity of the sample, while the steady-state portion yields information about the thermal conductivity. In the CTET experiment, the transient and steady-state portions allow for two independent methods of calculating the thermal contact resistance.

The least squares fitting of the TET and CTET measurements are shown in Fig. 7. From the TET measurement, the effective thermal diffusivity was measured to be 9.04×10^{-7} m^2/s, which gives an effective thermal conductivity of 1.39 W/m K. The glass fiber was then placed in contact with the Pt wire sample and a CTET measurement was conducted. A steady-state temperature increase of 10.6 K was recorded. The value for the TCR between

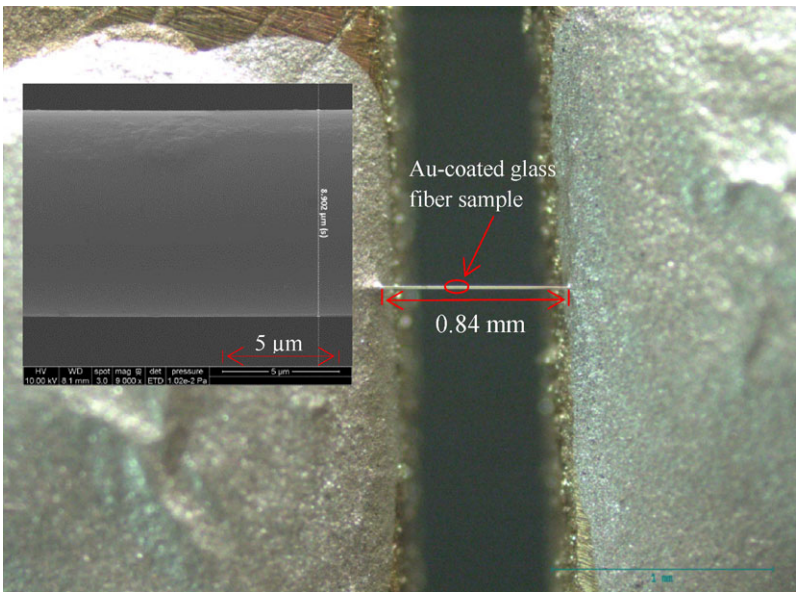


Fig. 5 Image of 0.84 mm long glass fiber sample coated with a thin layer of Au and mounted to the electrodes using silver paste. *Inset* shows a scanning electron microscope (SEM) image of the glass fiber. The diameter of the coated fiber was determined to be 8.9 µm

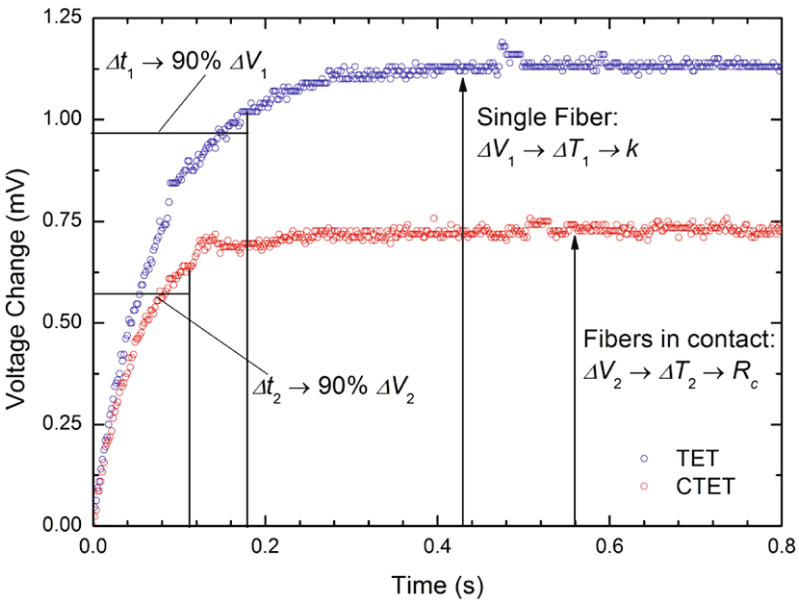


Fig. 6 Comparison of measured voltage rise between TET and CTET measurements on glass fiber and glass fiber crossed contact with Pt wire, respectively. When the fiber is in contact with the Pt wire, the final temperature rise is lower than for a single fiber. In addition, the fiber in contact reached steady state sooner. Information about thermal properties is extracted from the TET measurement. The thermal contact resistance is extracted from the CTET measurement

the fibers obtained from the steady-state solution is 2.83×10^6 K/W, while the numerical solution yielded a value of 2.74×10^6 K/W. Sound agreement is observed between the theoretical fitting and experimental results. The two independent methods for calculating the TCR are also in good agreement. The experimental conditions and results from the glass fiber TET and glass fiber/Pt wire CTET measurements are given in Table 3. The TCR between the glass fiber and the Pt wire is about an order of magnitude greater than the TCR between Pt wires. First of all, glass and Pt have very different density and acoustic properties, thereby there will be strong phonon scattering at their interface, leading to increased thermal contact resistance by phonons. Second, the structural difference between Pt wire and the gold coated on the glass fiber will induce more electron reflection at their interface, resulting in a larger thermal contact resistance. More importantly, the glass fiber has a much smaller diameter than the Pt-wire. Therefore the contact area in the glass fiber–Pt wire experiment will be much smaller than that in the Pt–Pt measurement, leading to a much larger local contact resistance.

Recent work has shown that even at very low pressures, heat conduction to the surrounding gas may have some effect on the measured thermal properties. This will not affect the accuracy of the measurement of the TCR, however, provided that the TET and CTET measurements are done at the same pressure. Both measurements were done at a pressure of 30 mTorr. Therefore, the rarefied gas conduction effect

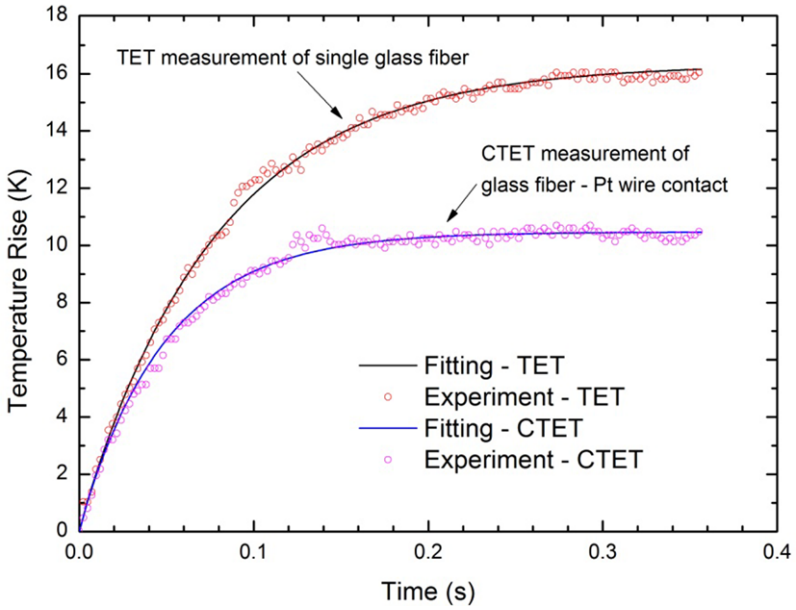


Fig. 7 Least square fitting for the TET measurement of single glass fiber and CTET measurement of glass fiber in contact with a Pt wire. Both measurements were done using a 120 μA heating current

Table 3 Experimental conditions and results for glass fiber TET and CTET

Glass fiber length	0.84 mm
Heating current	120 μA
Resistance	1400 Ω
Effective thermal diffusivity	9.04×10^{-7} m^2/s
Effective thermal conductivity	1.39 W/mK
Temp. coefficient of resistance	0.573 Ω/K
Pt wire length	1.00 mm
Steady-state temp. increase	10.6 K
Analytical R_c	2.83×10^6 K/W
Numerical R_c	2.74×10^6 K/W

will be the same for both measurements and included in the effective value of the thermal diffusivity.

In order to obtain a high accuracy from the CTET technique for measuring thermal contact resistance, great care must be exercised in choosing the sample length. The top wire (electrically heated wire) and the bottom wire have a thermal resistance (R_t) of $L_t/(2k_tA_t)$ and (R_b) $L_b/(2k_bA_b)$, respectively. A_t and A_b are the cross-sectional areas of the top and bottom wires. A general guideline in experimental design is that the thermal contact resistance (R_c) between the two wires should be on the same order of R_t or smaller. Also R_c should be larger than R_b in order to have a high measurement sensitivity. This will ensure R_c plays a dominant role in controlling the heat conduction when the two wires are in contact. Taking the glass fiber–Pt wire case as an example, R_t of the glass fiber is 2.43×10^6 K/W, and R_b of the Pt wire is 6.89×10^3 K/W. So the measured thermal contact resistance between them (2.74×10^6 K/W) is much larger than R_b, and ($R_b + R_c$) is the same order as R_t. This ensures sound accuracy in final evaluation of R_c.

6 Conclusion

In this work, a technique (CTET) was developed to characterize the thermal transport across a single point between crossed one-dimensional micro-wires. Two independent methods were developed for data analysis to obtain the thermal contact resistance between the crossed samples. The first method is a fitting of the transient temperature response to a step current. The second method is based on the steady-state temperature rise. Values obtained from each of these methods are in good agreement. Measurements were performed on crossed Pt wires (25.4 μm diameter), and thermal contact resistances on the order of 10^5 K/W were obtained. It was found the thermal contact resistance increased with the heating current used in the experiment. This is because larger electrical heating gives a higher temperature rise of the sample and more thermal expansion, resulting in weaker contact between the wires. The thermal contact resistance between a glass fiber (8.9 μm) and a Pt wire was measured to be 2.4×10^6 K/W, much larger than that across the Pt wire contact. This is largely due to the reduced area at the contact point since the glass fiber has a much smaller diameter than the Pt wire.

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References

1. L. Lu, W. Yi, D.L. Zhang, Rev. Sci. Instrum. **72**, 2996–3003 (2001)
2. T.-Y. Choi, D. Poulikakos, J. Tharian, U. Sennhauser, Nano Lett. **6**, 1589–1593 (2006)
3. J. Hou, X. Wang, P. Vellelacheruvu, J. Guo, C. Liu, H.-M. Cheng, J. Appl. Phys. **100**, 124314 (2006)
4. J. Hou, X. Wang, J. Guo, J. Phys. D, Appl. Phys. **39**, 3362–3370 (2006)
5. J. Guo, X. Wang, D.B. Geohegan, G. Eres, C. Vincent, J. Appl. Phys. **103**, 113505 (2008)
6. J. Guo, X. Wang, D.B. Geohegan, G. Eres, Funct. Mater. Lett. **1**, 71–76 (2008)
7. J. Guo, X. Wang, T. Wang, J. Appl. Phys. **101**, 063537 (2007)
8. J. Yang, S. Waltermire, Y. Chen, A.A. Zinn, T.T. Xu, D. Li, Appl. Phys. Lett. **96**, 023109 (2010)
9. L. Guo, J. Wang, Z. Lin, S. Gacek, X. Wang, J. Appl. Phys. **106**, 123526 (2009)
10. J.L. Wang, M. Gu, X. Zhang, Y. Song, J. Phys. D, Appl. Phys. **42**, 105502 (2009)
11. J. Wang, M. Gu, X. Zhang, G. Wu, Rev. Sci. Instrum. **80**, 076107 (2009)
12. J. Wang, B. Song, M. Gu, X. Zhang, Int. J. Heat Mass Transf. **53**, 5350–5354 (2010)
13. F.P. Incropera, D.P. Dewitt, T.L. Bergman, A.S. Lavine, *Fundamentals of Heat and Mass Transfer*, 6th edn. (Wiley, Hoboken, 2007)