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ABSTRACT

Quantifying the temperature of microdevices is critical for probing nanoscale energy transport. Such quantification is often accomplished by integrating resistance thermometers into microdevices. However, such thermometers frequently become structurally unstable and fail due to thermal stresses at elevated temperatures. Here, we show that custom-fabricated scanning thermal probes (STPs) with a sharp tip and an integrated heater/thermometer can accurately measure the temperature of microdevices held at elevated temperatures. This measurement is accomplished by introducing a modulated heat input to the STP after contacting the microdevice with the STP's tip and characterizing the DC and AC components of the STP's temperature. From these measured temperature components, the tip-to-sample thermal resistance and the microdevice surface temperature are deduced simultaneously via a simple lumped-capacitance model. The advances presented here can greatly facilitate temperature measurements of a variety of heated microdevices.

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Quantifying the temperature of heated microscale devices is critical for successfully employing them in probing nanoscale transport via conduction and radiation. Such quantification becomes challenging for small devices at high temperatures due to the difficulties in integrating reliable temperature sensors. Previous work for quantifying high temperatures at the micro/nanoscale has relied on employing approaches such as the phase change of nanoparticles,¹ Raman spectroscopy,² complicated approaches involving integration of fine thermocouples,³ which lead to destruction of the microdevice rendering them useless for intended studies, and other optical approaches.⁴ Typical examples requiring the characterization of the temperature of microdevices are related to the exploration of near-field thermal transport^{5,6} and near-field based thermophotovoltaic energy conversion^{3,7} where heated microdevices are routinely employed. In this work, we show that scanning thermal probes (STPs), which have been recently employed for probing a number of interesting thermal phenomena,^{8–18} can be used to quantitatively measure the temperature of heated microdevices [also referred to as the device under test (DUT)] in a nondestructive manner.

The main challenge for quantitative temperature sensing using STPs is the determination of tip-sample thermal contact resistance (R_{TS}), which dominates heat transfer between the sample and the probe in the contact mode. Previous studies have employed techniques such as the null-point measurement,^{19–21} which nullifies the probe-

sample heat flow, and a two-step approach,⁸ which employs two independent measurements at each point/pixel corresponding to the sample to account for R_{TS} . While these techniques represent an important step forward, they may not fully capture changes in R_{TS} , arising during scanning due to complex sample topology or probe tip abrasion. Therefore, accurate measurements of surface temperature require simultaneous determination of R_{TS} . One such technique has been recently developed⁹ for sensing modulated sample temperatures. However, it cannot be directly applied for measuring temperatures of heated DUTs, such as those considered in this work, because modulation of the temperature may lead to thermal stresses, which damage the sample or may cause measurement artifacts due to thermal expansion and contraction of the sample.

Our approach to quantify the temperature of heated DUTs relies on custom-fabricated STPs [see Fig. 1(a)] with “T-shaped” beams that enable both a relatively large mechanical stiffness and a low thermal conductance (see the [supplementary material](#)). These probes also feature an integrated Pt resistance thermometer, which allows both temperature sensing and heating of the STP (see the [supplementary material](#)). In our method, we measure the thermal response of the STP to heat inputs in two *scenarios*: (i) when the STP is in contact with the DUT [see Fig. 1(c)] and (ii) when it is far away from the DUT. As explained below, the measured thermal responses in these two

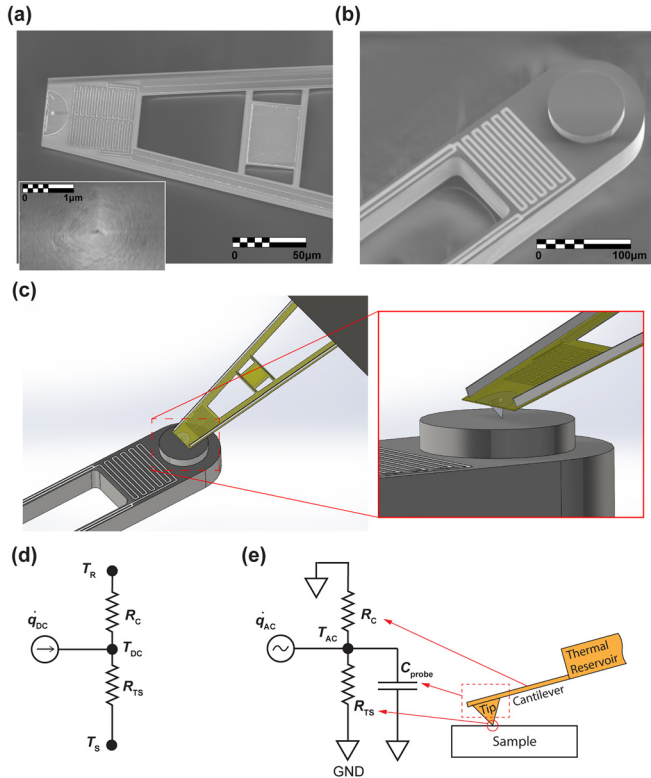


FIG. 1. (a) Scanning electron micrograph (SEM) of the STP probe with an integrated Pt heater/thermometer, and T-shaped beams. The inset shows the STP tip. (b) SEM of the suspended microdevice (DUT) with an embedded Pt heater/thermometer. (c) Schematic illustrating the geometry of the STP in contact with heated DUT. Note that, to obtain a clear view, the tip height is exaggerated. (d) DC- and (e) AC-equivalent thermal resistance network corresponding to the geometry shown in (the temperatures T_R and T_S are set to zero for the AC network) (c). T_{DC} and T_{AC} represent the STP tip DC temperature and AC temperature amplitude, respectively. T_S , R_C , and R_{TS} represent the DUT temperature, thermal resistance corresponding to the beams of the STP, and tip-sample thermal contact resistance, respectively. While C_{probe} , $\dot{q}_{DC}$, and $\dot{q}_{AC}$ represent the lumped thermal capacitance of the STP, and the DC and AC components of the heat input to the STP, respectively.

conditions enable us to quantify the temperature of the heated DUT. All the measurements reported here were performed under ultra-high vacuum conditions ($\sim 10^{-9}$ mbar) and in contact mode with a constant contact force of 50 nN.

The thermal behavior of the STP under unmodulated (DC) and modulated (AC) heat inputs can be described by a dynamic lumped-capacitance thermal model,^{21,22} as represented by the thermal networks illustrated in Figs. 1(d) and 1(e), respectively. In these figures, T_S represents the surface temperature of the DUT that needs to be quantified, while T_R and T_{DC} represent the thermal reservoir and probe tip DC temperatures. The thermal capacitance of the probe, C_{probe} , is lumped in the probe tip node. In addition, R_C and R_{TS} represent the thermal resistances of the probe cantilever and tip-sample contact. The parameters C_{probe} and R_C depend on temperature-dependent material properties and are obtained from a set of calibrations. Key to quantitative measurement of T_S is a direct measurement of R_{TS} , which depends on the detailed geometry, tip-sample force, and

the local thermal and mechanical properties of the tip at the point of contact and can vary spatially and temporally as the tip-sample geometry and mechanics change. Below, we explain how R_{TS} is characterized via a modulated heat input to the probe.

We first note that the STP can be heated by supplying an AC at frequency f_1 to the probe heater, which results in an AC heat input at frequency $2f_1$ as well as a DC heat input via Joule heating. Further, the laser employed to detect the deflections of the STP introduces additional DC heating. Hence, the total heat input to the STP has a DC component ($\dot{q}_{DC}$) and AC component ($\dot{q}_{AC}$), resulting in DC and AC temperature changes of the probe (see the [supplementary material](#) for details).

To quantify the values of R_C and C_{probe} , we characterized the thermal frequency response of our STP. These experiments were performed at various DC temperatures (T_{DC}) achieved by varying the incident laser power on an STP not in contact with the DUT. At each T_{DC} , a modulated heat input $\dot{q}_{AC} = 6.1 \mu\text{W}$ at various frequencies was applied to the STP heater. The resulting temperature oscillation amplitudes of the STP (T_{AC}) are shown in Fig. 2(a) as distinct curves at each DC temperature. Using the low frequency (0.5 Hz) data, the thermal conductance of the probe ($G_C = 1/R_C$) was estimated for various values of T_{DC} as shown in Fig. 2(b). It can be seen that the probe conductance increases as a function of temperature, which can be attributed partly to an increase in thermal conductivity²³ of SiN_x from which

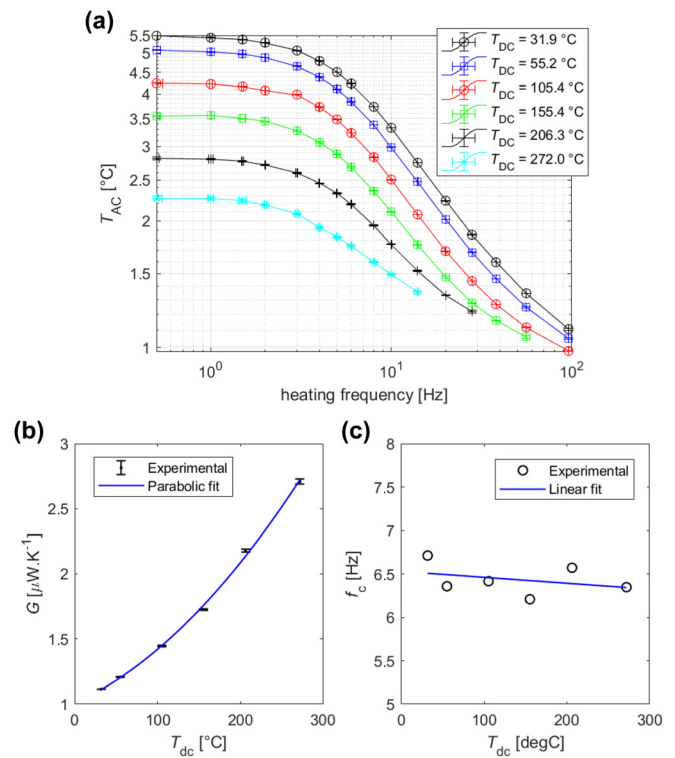


FIG. 2. (a) Frequency response of an STP probe that is located away ($10 \mu\text{m}$) from the sample surface measured at various STP tip DC temperatures established by varying the laser power incident on the STP. All data points are obtained at a constant heating amplitude of $\dot{q}_{AC} = 6.1 \mu\text{W}$. (b) Thermal conductance of the probe at the low-frequency limit (0.5 Hz) as a function of probe temperature. (c) Thermal cutoff frequency of the STP probe based on the -3dB point as a function of probe temperature.

our STPs are made, and partly to the radiative conductance of the membranes (which feature large absorption cross sections^{24–26}) of the STP that increases with temperature. Finally, Fig. 2(c) shows the thermal cutoff frequency (-3 dB point) that is weakly dependent on temperature, from which one can estimate the thermal capacitance of the probe ($C_{\text{probe}} = G_C/2\pi f_C$).

In order to quantify R_{TS} , we performed an experiment where the STP cyclically comes into contact with the surface of the DUT and moves up to a height of $\sim 2 \mu\text{m}$ above the surface. At these gap sizes, contributions from radiative heat transfer (especially near-field radiative heat transfer) are expected to be negligibly small^{11,27} (i.e., $R_{\text{TS}} \gg R_C$). As the STP comes into contact with the sample and separates from it, T_{DC} and T_{AC} values were continuously recorded. In order to

distinguish the two cases, we label the DC and AC temperatures of the STP as $T_{\text{DC-o}}$ and $T_{\text{AC-o}}$ (when the STP tip is separated from the sample) and $T_{\text{DC-c}}$ and $T_{\text{AC-c}}$ (when the STP is in contact with the sample). We note that the contact of the STP with the DUT results in a change in the AC and DC components of the STP temperature. We quantify the change in AC temperature by defining the ratio $r = (T_{\text{AC-o}}/\dot{q}_{\text{AC-o}})/(T_{\text{AC-c}}/\dot{q}_{\text{AC-c}})$, where $(\dot{q}_{\text{AC-o}})$ and $(\dot{q}_{\text{AC-c}})$ are the AC heat inputs before and after the contact, respectively. These two heat inputs are slightly different due to a change in the electrical resistance of the heater upon contact. One can calculate R_{tot} (defined as $R_{\text{tot}}^{-1} = R_C^{-1} + R_{\text{TS}}^{-1}$) using the measured r and the relation below where $\omega = 4\pi f_1$ is the angular frequency of AC heat input to the STP (see the SI for full derivation),

$$R_{\text{tot}} = \sqrt{\frac{R_C(T_{\text{DC-o}})^2}{r^2(1 + R_C(T_{\text{DC-o}})^2 C_{\text{probe}}(T_{\text{DC-o}})^2 \omega^2) - R_C(T_{\text{DC-o}})^2 C_{\text{probe}}(T_{\text{DC-c}})^2 \omega^2}}. \quad (1)$$

Subsequently, the tip sample contact resistance can be obtained from $R_{\text{TS}}^{-1} = R_{\text{tot}}^{-1} - R_C(T_{\text{DC-c}})^{-1}$. Note that R_C is temperature dependent, whose value at any given probe temperature ($T_{\text{DC-c}}$) can be obtained from the data in Fig. 2(b), and is utilized in evaluating R_{TS} . Once R_{TS} is determined, the sample temperature can be obtained from (see the supplementary material),

$$T_s = \frac{R_{\text{TS}}}{R_C}(T_{\text{DC-c}} - T_{\text{DC-o}}) + T_{\text{DC-c}} + R_{\text{TS}}(\dot{q}_{\text{DC-o}} - \dot{q}_{\text{DC-c}}). \quad (2)$$

In order to confirm the validity and accuracy of the proposed measurement technique, we employed a suspended microdevice as a DUT whose temperature (T_s) can be increased and simultaneously measured using an integrated Pt resistance thermometer/heater (PRT) [Fig. 1(b), see supplementary material for measurement details]. In these studies, the STP was placed close to the center of the microdevice mesa as shown in Fig. 1(c). At each value of heating power applied to the microdevice, a sequence of approach and retract cycles was performed and T_{DC} , T_{AC} values were recorded. Figures 3(a) and 3(b) show the time series of this measurement (bandwidth of ~ 1 Hz) at two heating powers of the microdevice (0 and 56 mW) corresponding to surface temperatures of $T_s = 25.1$ and 330.6°C , respectively, each showing two repeats of approach and retract cycle.

As can be seen in Fig. 3(a), $T_{\text{DC-o}} \approx 45^\circ\text{C}$, which is due to $\dot{q}_{\text{DC}}$ provided by the AFM laser as well as the DC component of heat input by the probe heater. When the probe is placed in contact with an unheated microdevice, $T_{\text{DC-c}}$ drops to $\sim 35^\circ\text{C}$ as a result of the contact to a colder surface. In the subsequent retract and contact phases, the probe establishes a significantly different contact and reaches $\sim 40^\circ\text{C}$, which indicates the stochastic behavior of R_{TS} . This variation in R_{TS} is also reflected in the independently measured T_{AC} , which is correspondingly lower. In Fig. 3(b), we present data from an experiment where the DUT is heated. It can be seen that $T_{\text{DC-o}} \approx 50^\circ\text{C}$ when the probe is retracted, which is higher than the previous case of Fig. 3(a) due to additional far-field radiative heating of the probe by the DUT surface. During the first approach, the $T_{\text{DC-c}}$ value reaches $\sim 149^\circ\text{C}$,

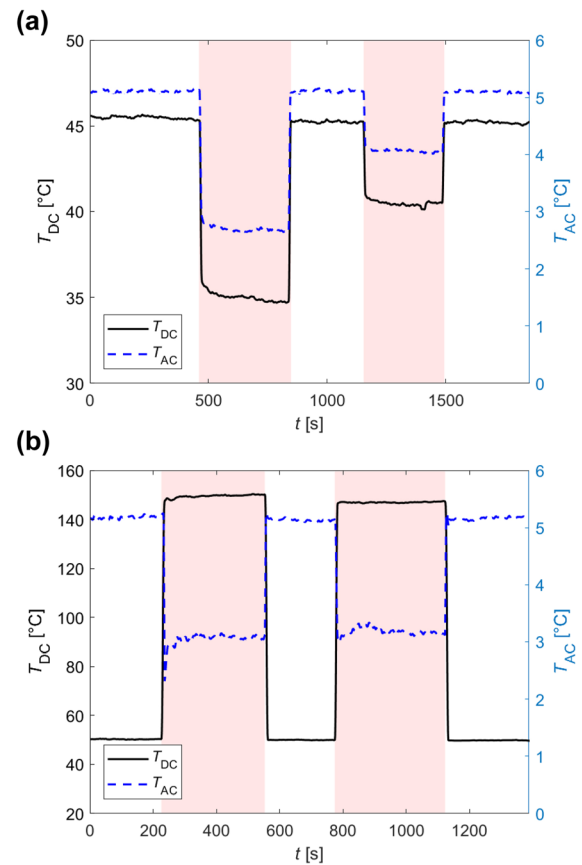


FIG. 3. Time series of DC and AC temperatures of the STP tip (T_{tip}) during two successive contact (pink shaded regions) and retraction cycles (unshaded) on the silicon mesa of the heated microdevice. The surface temperatures are chosen to be $T_s = 25.1^\circ\text{C}$ for the experiment shown in (a) and $T_s = 330.6^\circ\text{C}$ for the experiment shown in (b).

while during the second approach, it reaches $\sim 147^\circ\text{C}$, which indicates that in this experiment, the two approaches lead to similar contacts. This is also reflected in the T_{AC} signal, which shows a very small difference between the two contacts.

In order to quantify the surface temperature, we use Eqs. (1) and (2), where each data point corresponding to the probe contact (shaded regions in Fig. 3) is used separately to obtain various estimates of T_{DC-o} and an average of data points when the probe is retracted (unshaded regions in Fig. 3) is used to estimate T_{DC-o} . This procedure leads to evaluation of R_{TS} and T_S for each data point during contact. The results from this analysis are shown in Figs. 4(a) and 4(c), from which it can be seen that the R_{TS} values for the first and second approach demonstrate different mean values of $0.87 \times 10^6 \text{ K}\cdot\text{W}^{-1}$ and $3.00 \times 10^6 \text{ K}\cdot\text{W}^{-1}$, indicating that different contact geometries were established during these two approaches. On the other hand, the mean values of R_{TS} for the second experiment, shown in Fig. 4(b), are similar, i.e., $1.08 \times 10^6 \text{ K}\cdot\text{W}^{-1}$ and $1.21 \times 10^6 \text{ K}\cdot\text{W}^{-1}$ for the first and second approach, respectively. Overall, these measured values of R_{TS} were found to be in good agreement with expectations (see the supplementary material) based on models from previous work.²⁸

Histograms corresponding to the measured temperature T_S from the data in Figs. 4(a) and 4(c) are shown in Figs. 4(b) and 4(d),

respectively. From Gaussian fits to each histogram, the mean values of T_S in each of the experiments are estimated to be 24.5°C and 327.0°C with standard deviations of 0.7°C and 9.0°C (standard deviations corresponding to raw data are 1.2°C and 13.3°C), respectively. These estimates are to be compared with independent temperature measurements using the thermometer embedded into the DUT, which indicates 25.1°C and 330.6°C . As can be seen, the agreement between the two measurements is good; however, at higher temperatures, the uncertainty is found to increase possibly due to fluctuations in R_{TS} at high temperatures.

Finally, in Fig. 5, we present experimental data from validation measurements at various surface temperatures that were achieved by varying the power dissipated in the instrumented DUT. As can be seen, the measured data from the STP are in very good agreement with DUT PRT measurements up to 330°C . Above $\sim 370^\circ\text{C}$, the PRT resistance of the heated DUT starts to drift, making the measurements unreliable. However, the measurements performed using the STP continue to correlate well with the increasing power up to 417°C (as estimated from the STP measurements) at which point the Pt heater on the DUT failed, making it impossible to evaluate the response at even higher temperatures. It is not entirely surprising that the STP is capable of measurements at high surface temperatures as the net

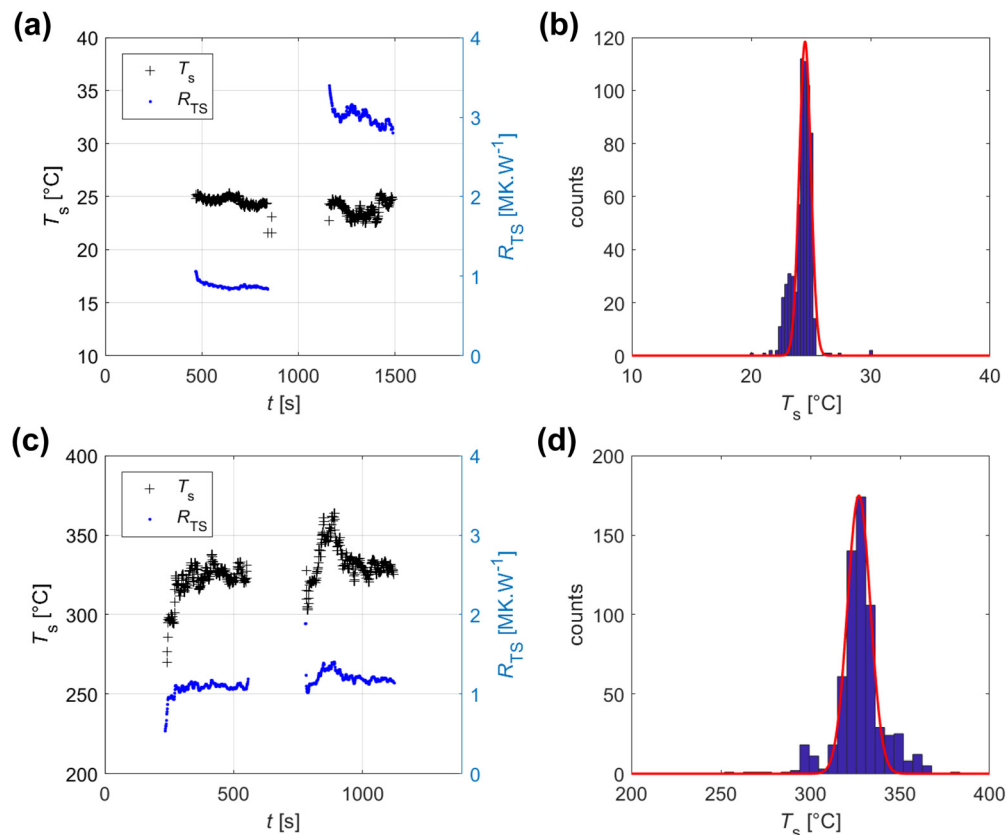


FIG. 4. Values of surface temperature (T_S) and tip-sample thermal contact resistance (R_{TS}) estimated from the data shown in Fig. 3. For the data shown in (a), the surface temperature of the microdevice (T_S) was set to be 25.1°C , whereas for the data shown in (c), it was chosen to be 330.6°C . (b) Histogram constructed from the T_S data shown in (a). (d) The same as (b), but for data shown in (c). Gaussian fits to the data in (b) and (d) are shown in red.

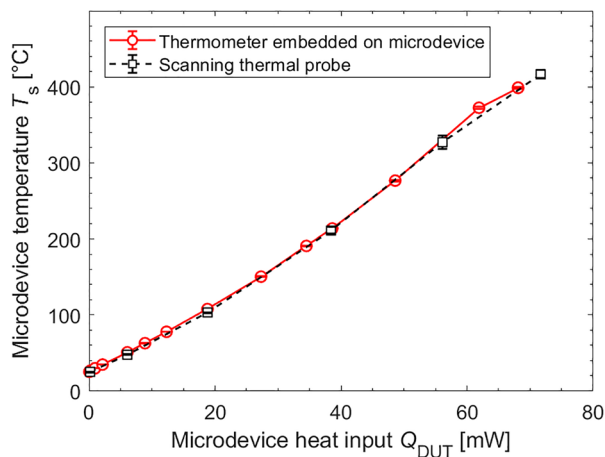


FIG. 5. Measured temperature (T_s) of the heated microdevice (DUT) using the STP (black) and a Pt resistance thermometer (red) integrated into the heated microdevice as a function of power dissipated in the microdevice (Q_{DUT}). Note that T_s is not a linear function of Q_{DUT} because the thermal conductance of the heated microdevice decreases from $238 \mu\text{W}\cdot\text{K}^{-1}$ to $178 \mu\text{W}\cdot\text{K}^{-1}$ as the temperature is increased from 25°C to 372°C . The error bars correspond to ± 1 standard deviation as estimated as estimated from the Gaussian fits to the histograms shown in Fig. 4.

temperature rise of the STP is much smaller than that of the DUT due to the large tip-sample thermal resistance (R_{TS}). In general, a higher R_{TS} value is expected to result in an increased operating temperature range of the STP at the expense of reduced temperature sensitivity. In future studies, the R_{TS} value can, in principle, be tuned for each experiment; for instance, one can increase R_{TS} by depositing a thin layer of low conductivity material on the sample or the probe (such as Al_2O_3). However, a detailed analysis of the temperature distribution across the deposited thin film may be required for achieving quantitative measurements of the true sample temperature.

In summary, the temperature measurement approach described here represents a direct method for measuring the temperature of microdevices that is particularly well suited for small devices operated at high temperatures. This approach leverages the large thermal resistance of a nanoscale contact, which serves to both minimize the perturbation of the microdevice temperature and limits the temperature rise of the probe, enhancing the range of temperatures that can be measured. The agreement between the temperatures measured with the STP and those with the Pt thermometer integrated into the microdevice supports the robustness of the approach reported in this paper. We expect that the developed method can greatly help in characterizing microscale devices employed in a range of nanoscale energy transport experiments.

See the [supplementary material](#) for details of probe fabrication, finite element analysis of probe stiffness, and thermal analysis of probes.

AUTHORS' CONTRIBUTIONS

A.R., S.Y., and Y.L. contributed equally to this work.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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