Low temperature characterization of heated microcantilevers
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I. INTRODUCTION

The atomic force microscope (AFM) has evolved to become the most widely used scientific instrument for nanometer-scale sensing and manipulation, and heated AFM cantilevers have offered unique opportunities for AFM-related applications. Heated cantilevers were originally developed for data storage but also have been used in other applications such as thermophysical property measurement, thermal dip-pen nanolithography, thermal force measurement, and microscale explosive vapor detection. However, nearly all of the published reports of heated cantilever applications are for room temperature. While one paper places the cantilever in a cryostat, no paper has reported detailed cryogenic operation.

Cryogenic atomic force microscopy, or cryo-AFM, provides promising opportunities for AFM-based applications at low temperatures, perhaps most notable is high resolution imaging of biomolecules. By operating AFM at 77 K, difficulties in achieving high resolution at room temperature can be overcome, such as sample softness or thermal motion of macromolecules. Radenovic et al. showed that a cryo-AFM in ultrahigh vacuum can accurately measure DNA plasmid height, while the room temperature measurement provides only half of the true value. The probe mechanical properties such as resonance frequency, spring constant, and quality factor depend upon temperature. Few if any cryo-AFM studies have focused on thermal applications. If heated AFM cantilevers were used as a thermal source in cryo-AFM, new AFM measurements would be possible such as thermal property measurement of frozen cells, low temperature calorimetry, study of local heating effect on freezing processes, and thermal management in cryopreservation. The low-temperature electrical and thermal behavior of heated cantilevers must be understood in order to realize these applications.

This article describes electrical and thermal behaviors of heated AFM cantilevers at low temperatures. While varying the stage temperature in a cryostat, steady-state characterization was performed by monitoring the temperature-dependent cantilever electrical resistance. For periodic heating analysis, electrical and thermal transfer functions were derived and used to determine frequency-dependent cantilever thermal behaviors as well as the thermophysical properties of the cantilever at low temperatures. The periodic cantilever temperature was calculated from the measured properties and thermal diffusion time. The results obtained in this work aim to expand the use of the heated microcantilevers to cryogenic conditions.

II. EXPERIMENT

Figure 1(a) shows a scanning electron microscope (SEM) image of a cantilever having an integrated heater. The fabrication processes of the cantilevers has been discussed previously. The cantilever is made from single crystal silicon with regions of phosphorus doping. The heater, of size 8 μm × 16 μm, is highly resistive with a phosphorus...
doping of around $10^{17}$ cm$^{-3}$. The heater region is the most resistive part of the cantilever and thus dissipates most of the electrical power when the current flows through the cantilever. The cantilever legs are phosphorus doped at around $10^{20}$ cm$^{-3}$. The presence of the thermal constriction between the heater and leg regions improves the cantilever heating and cooling efficiency. Since the cantilever thickness can vary depending on the etching condition, it was measured with SEM to be 590 nm with 10% uncertainty.

The experiment was performed with a heated microcantilever mounted in a Janis He-3-SSU-He3 refrigerator. Figure 1(b) shows the stage of the cryostat containing a resistive heater and a thermometer so that the stage temperature can be controlled by a proportional-integral-derivative (PID) temperature controller. A 100 Ω platinum resistance thermometer measured temperature from 77 K to room temperature. The cantilever resistance was monitored simultaneously to verify thermal equilibrium between the stage and the cantilever. The measurements were performed at various stage temperatures starting from 77 K. Vacuum condition better than $10^{-7}$ bar was maintained during the experiment. In this vacuum condition, thermal conduction along the length of the cantilever dominates thermal radiation.

The cantilever was characterized in under both steady (dc) and periodic (ac) heating excitation. In dc operation, the cantilever was characterized by obtaining its temperature-dependent electrical resistance. In periodic-heating operation, or ac operation, harmonic voltage signals across the cantilever was measured with a lock-in amplifier under a differential scheme. While increasing the driving frequency at a fixed input voltage, the ac experiment was performed by measuring the harmonic cantilever voltage and the current, which can be obtained by $I=V_s/R_s$, where $V_s$ is the voltage drop across the sense resistor and $R_s$ is the sense resistance. The sense resistor was a noninductive 10 kΩ resistor with 1% tolerance. This resistor response is purely resistive at frequencies up to 100 MHz.

III. STEADY-HEATING OPERATION

The cantilever resistance is temperature dependent and can be used to estimate the temperature of the heater region. Figure 2 shows temperature calibration of the cantilever resistance, when the stage was in thermal equilibrium with the cantilever. The cantilever power dissipation during the measurement was 0.2 μW, yielding a heater temperature increase $\sim 0.02$ K. Figure 2 shows that the cantilever resistance increases dramatically as temperature decreases. This behavior is much different from the cantilever resistance change above room temperature. At low temperature, the cantilever temperature coefficient of resistance (TCR), defined as $b(T)=1/(R)dR/dT$, is negative and large. At 100 K the estimated cantilever TCR is $-0.023$ K$^{-1}$, which is about twice that of platinum, 0.013 K$^{-1}$. This large TCR suggests that the heated cantilever can sensitively measure cryogenic temperature.

The temperature dependence of the cantilever resistance may be understood using a model for the temperature-dependent resistivity of phosphorus-doped silicon. Assuming that the minority carrier density is negligibly small, the resistivity can be calculated as $\rho=1/(q\mu_n)$, where $q$, $n$, and $\mu_n$ are, respectively, the electron charge, density, and mobility. Even though silicon electron density and mobility have been extensively studied and general knowledge is available in textbooks, there are not many resistivity models that accurately predict the resistivity change for wide range of temperatures from 50 to 400 K and doping levels from...
10^{10} \text{ to } 10^{21} \text{ cm}^{-3}. Furthermore, available models from the literature are not consistent with each other because the models still have many restrictions.\textsuperscript{18,24,25} Here we develop a model for the cantilever resistance by modifying available models for bulk silicon.

Recently, Mnatsakanov \textit{et al.}\textsuperscript{26} suggested a simple analytical carrier mobility model that is applicable to various semiconductors for a wide range of temperatures and dopant densities, with accuracy within 7\% on average.\textsuperscript{26} The modeling of the electron density for n-doped silicon starts from the charge neutral condition, which equates the electron density and the ionized donor density \( n = N_D^i \) if the minor carrier numbers are negligible. Assuming Fermi-Dirac statistics, parabolic energy bands, and a single-energy impurity level, Blakemore\textsuperscript{27} developed a model for calculating the electron density, in which the electron density and the ionized donor density are

\[ n = N_C F_{1/2}(\eta) \]  

and

\[ N_D^i = N_D^0 \left[ 1 - \frac{1}{1 + 0.5 \exp ( (E_D - E_F)/k_B T )} \right]. \]  

\( F_{1/2}(\eta) \) is a Fermi-Dirac integral of order 1/2 as a function of \( \eta = (E_F - E_F^*)/k_B T \), based on zero energy level of the valence band, i.e., \( E_F = 0 \), \( E_F \) is the Fermi energy; \( E_F \) is the band gap energy given by \( E_F = 1.165 - 0.000473 T^2/(T+673) \); \( k_B \) is the Boltzmann constant; \( N_D \) is the dopant density; and \( E_D \) is the donor energy level. The donor energy level \( E_D^0 \), or the donor ionization energy \( \Delta E_D = E_F^* - E_D \), is dependent upon the dopant density according to the \( N_D^{1/3} \) law\textsuperscript{18,30}

\[ \Delta E_D = \Delta E_D(0) - \beta N_D^{1/3} \]  

where \( \Delta E_D(0) = 0.045 \text{ eV} \) is the ionization energy of the phosphorus donor, and \( \beta \) is a coefficient to be used as a fitting parameter. The electron density model given by Eqs. (1)–(3) was verified by comparing computed electron densities with the measured values\textsuperscript{31,32} over the temperature range from 50 to 300 K for several dopant densities lower than \( 1 \times 10^{18} \text{ cm}^{-3} \): they are in good agreement within 8\%. For dopant concentrations higher than approximately \( 1 \times 10^{19} \text{ cm}^{-3} \), however, this model generates a considerable error because a high donor energy band is broadened and begins to merge with the conduction band, generating more free carriers than Eq. (2). The calculation\textsuperscript{30} and measurement\textsuperscript{28} suggested that when the doping concentration is higher than \( 1 \times 10^{19} \text{ cm}^{-3} \), the dopant density is fully ionized and thus becomes independent of temperature: that is, the electron density is the same as the dopant density.

Based on the electron mobility and density models, the cantilever resistance was calculated with two fitting parameters. The first fitting parameter was \( \beta \) determined to be \( 1.7 \times 10^{-8} \text{ eV cm} \), which is in the same order of those obtained in previous research\textsuperscript{18,30}. Another fitting parameter was the effective dopant density of the heater and estimated to be \( 5.9 \times 10^{17} \text{ cm}^{-3} \). However, since the leg region is heavily doped over \( 10^{20} \text{ cm}^{-3} \), the electron density of the leg region was simply obtained from the impurity diffusion analysis for given ion-implantation parameters. The calculated electron density of the leg is \( 4.3 \times 10^{20} \text{ cm}^{-3} \). Figure 2 shows the calculated cantilever resistance together with the measurement. The cantilever resistance measurements were very accurate within 0.1\% uncertainty, and the agreement between the measurement and calculation is within 3\% relative error on average. The inset in Fig. 2 shows the modeled resistance of the heater region and that of the leg region including the thermal constriction and the anchor. From the inset, it is clear that most of the cantilever resistance is attributed to the heater region: the heater resistance takes more than 97\% of the cantilever resistance at 100 K and 93\% at room temperature. This result confirms that power is predominantly dissipated in the heater region. Under steady heating, Fig. 2 can be used to directly estimate the heater temperature from the cantilever resistance.

The drastic increase of the cantilever resistance at low temperatures can be attributed to electron freezing and large impurity scattering at the heater region. Compared to the heater region, the heavy dopant concentration of the leg region is completely ionized, and thus the leg resistance experiences little change with temperature. Note that the scattering rate is inversely proportional to the mobility \( \mu = q/m^*_e \gamma \), where \( m^*_e \) is the electron effective mass and \( \gamma \) is the scattering rate. At around room temperature, the cantilever resistance becomes almost constant because the slightly increasing electron density competes with the slightly decreasing electron mobility. The decreasing mobility at room temperature is because increasing lattice scattering due to the increasing phonon density of states exceeds the decreasing impurity scattering. If temperature further increases over room temperature, the lattice scattering rate will continuously rise while the electron density becomes saturated, resulting in the increase of the cantilever resistance. However, the boundary scattering effect is negligibly small because the electron mean free path of is the order of 10 nm,\textsuperscript{33} much smaller than the cantilever thickness.

Figures 3(a) and 3(b) show the dc characteristics of the cantilever measured at different stage temperatures. The cantilever resistance decreases as the cantilever voltage increases, which is consistent with Fig. 2. The cantilever resistance at \( T_0 = 77.8 \text{ K} \) is reduced to the room temperature resistance when the cantilever voltage is around 1 V, indicating that the cantilever heater temperature is near 300 K. For higher stage temperatures, the cantilever resistance goes through the minimum values around 1.3 k\Omega and then increases. When compared with cantilever response at room temperature shown in the insets, this increasing resistance is because of the temperature rise above room temperature. In fact, the cantilever can be heated much higher than room temperature as long as the electrical current through the cantilever does not exceed the maximum current density the cantilever can hold: if the current exceeds the limit, current congestion at the thermal constriction will cause a local temperature rise above silicon melting temperature. Because the cantilever heater temperature can be controlled from 77 to 300 K when the cantilever base resides at 77 K, the heated cantilever could be used as a local thermal management tool in various cryogenic applications.
IV. PERIODIC-HEATING OPERATION

A. Electrical and thermal transfer functions

In order to correctly interpret the ac experimental results and extract meaningful thermophysical properties from data, several analytical and numerical approaches have been suggested for various thermal systems. Recently, Dames and Chen suggested a general framework of thermal and electrical transfer functions of a sample containing a line heater, such that the electrical and thermal responses of the sample can be clarified when it is under a periodic joule heating with or without a dc offset. However, their transfer functions are not applicable when power is not uniformly dissipated over the sample, which is the characteristic feature of the heated cantilever. Previous reports provide an insufficient framework to analyze the heated cantilever, and so this article establishes transfer functions that overcome these limitations and can be applied to more general cases.

When the cantilever is heated by a sinusoidal current at angular frequency $\omega$, $I(t) = I_1 \sin(\omega t)$, the cantilever resistance can be approximated to

$$R_c(t) = R_0 \left[ 1 + \sum_i \xi_i b_i \theta_i(t) \right]$$

under the condition that the cantilever consists of four electrically active parts, i.e., heater, thermal constrictions, leg, and anchor. Here, $R_0$ is the dc cantilever resistance at a specific temperature, $b_i$ and $\theta_i(t)$ are, respectively, the TCR and averaged temperature oscillation at each part. $\xi_i = R_i/R_0$ denotes the ratio of the individual resistance to the dc cantilever resistance, satisfying $\Sigma \xi_i = 1$. The index $i$ is taken as $h$, $c$, $l$, and $a$, each of which denotes heater, thermal constriction, leg, and anchor region. Equation (4) is valid for both linear and nonlinear resistance systems as long as the temperature oscillation amplitude is small: The nonlinearity is involved in the temperature-dependent dc resistance and TCR. Since $\Sigma \xi_i b_i \theta_i(t) \ll 1$ in Eq. (4), the power dissipation at the cantilever can be approximated to $\dot{Q}(t) = I(t)^2 R_0$, and the temperature oscillation $\theta_i(t)$ can be written as

$$\theta_i(t) = \dot{Q}_i(t) \otimes Z_c, i,$$

where $\dot{Q}_i = \xi_i \dot{Q}(t)$ is the power dissipation of each part, $\otimes$ denotes convolution, and $Z_c, i$ is the inverse Fourier transform of the thermal transfer function $Z_{0, i}$. By combining Eqs. (4) and (5) and employing Ohm’s law, the voltage drop across the cantilever can be expressed as

$$V(t) = I(t) R_0 \left[ 1 + R_0 \sum \xi_i^2 b_i Z_{c, i} \otimes \hat{I}^2(t) \right].$$

If the thermal transfer function of the cantilever is defined as

$$Z_c = \frac{1}{b_0} \sum \xi_i^2 b_i Z_{c, i},$$

where $b_0$ is the cantilever TCR obtained from the measurement, electrical transfer functions over the harmonics $n$ can be expressed as

$$\frac{V_{\text{rms}, n}}{2 b_0 R_0^2 \text{rms}} = X_{n, \text{rms}}(\omega) + j Y_{n, \text{rms}}(\omega),$$

where $j = \sqrt{-1}$. Here, $X_{n, \text{rms}}$ and $Y_{n, \text{rms}}$ are in-phase and out-of-phase electrical transfer functions and can be related with thermal transfer functions, as suggested by Dames and Chen.

The thermal transfer function of the cantilever can be obtained by modeling heat transfer in each region of the cantilever. Since the thermal resistance across the thickness and the width of the cantilever is very small compared to the thermal resistance along or from the cantilever, one-dimensional transient heat conduction equation is appropriate for the thermal modeling of the cantilever

$$C_i \frac{\partial \theta_i(x, t)}{\partial t} = k_i \frac{\partial^2 \theta_i(x, t)}{\partial x^2} + \frac{\dot{Q}_i(t)}{V_i},$$

where $\theta_i(x, t)$, $C_i$, $k_i$, and $\dot{Q}_i(t)$ are the temperature oscillation, the volumetric heat capacity, the thermal conductivity, and the power dissipation of each region of volume $V_i$. The equation is set on the local coordinate of the control volume: $x$ ranges from 0 to $l_i$, the length of the $i$th region. Since the cantilever is symmetric, only half of the cantilever is mod-
eled with the adiabatic boundary condition at the free end. The opposite end at the anchor can be assumed to be maintained with the stage temperature as the silicon base can be taken as a heat sink. Good vacuum condition during the experiment prevents the convection heat loss from the cantilever to the environment. Radiation heat loss can also be neglected during the periodic-heating operation of the cantilever. According to Lu et al.,37 radiation heat loss can be neglected if $8 \sigma T_0^4 / \pi^2 k d < 1$ for a suspended blackbody sample, where $\sigma = 5.67 \times 10^{-8}$ W/m$^2$ K$^4$ is the Stefan-Boltzmann constant, $T_0$ is the base temperature, $l$ is the sample length, $k$ is the thermal conductivity, and $d$ is the thickness. The estimated criterion value for the heated cantilever is $3.72 \times 10^{-3}$, which is small enough to neglect radiation heat loss.

If $\dot{Q}(t)$ is expressed as $\dot{Q}(t) = Q_\omega \cos(\omega_H t)$, $\text{Re}[Q_\omega e^{j \omega_H t}]$, Eq. (9) can be Fourier transformed as

$$j \omega_C \theta_{ai} = k_i^2 \frac{\partial \theta_{ai}}{\partial x^2} + \frac{Q_{ai}}{V_i},$$

(10)

where $\theta(x, t) = \text{Re}[\theta_{ai} e^{j \omega_H t}]$ and $\omega_H$ is the heating frequency. Equation (10) can be solved with a modified matrix formulation.39 After considerable manipulation, $\theta_{ai}$ can be obtained with the following equation:

$$\theta_{ai}(x, \omega_H) = Q_\omega \left\{ W_i(0, \omega_H) \cosh[\beta_i (1 + j)] + \frac{f_i(0, \omega_H)}{k_i A_i \beta_i (1 + j)} \sinh[\beta_i (1 + j)] \right\},$$

(11)

where $\beta_i = \sqrt{\omega_H/2 \alpha_i}$ is the thermal wave vector, $\alpha_i = k_i / C_i$ is the thermal diffusivity, $W_i(x, \omega_H) = \theta_{ai} / Q_\omega = (\xi(\omega_H) / \omega_H CV_i)$ is an equivalent temperature oscillation, and $f_i(x, w) = -k_i A_i W_i(x, w) / \alpha_i x$ is the nondimensional heat transfer rate at each region. The thermal transfer function of each region can be calculated from Eq. (11), yielding

$$Z_{ai}(\omega_H) = \frac{W_i(0, \omega_H)}{\xi_i \beta_i l (1 + j)} \sinh[\beta_i l (1 + j)] + \frac{f_i(0, \omega_H)}{\xi_i k_i V_i \beta_i^2 (1 + j)^2 (1 - \cosh[\beta_i l (1 + j)])} + \frac{1}{j \omega_C V_i},$$

(12)

Thus, the thermal transfer function of the cantilever can be obtained from Eqs. (7) and (12). It should be emphasized that the thermal transfer function can be interpreted as the thermal impedance, representing the amount of temperature rise for a given unit ac power.

In order to compromise the deviation of the thermal transfer function caused by using a voltage source, not an ideal current source, in the experiment, thermal transfer function is modified to

$$Z_{ai} = Z_r \left(1 - \frac{R_i}{R_{total}}\right)^{-1},$$

(13)

where $Z_r$ is calculated from Eq. (12), and $R_{total}$ is total resistance including the cantilever resistance, the wire resistance, and the output impedance of the voltage source. Equation (12) is now combined with Eq. (13) to characterize electrical and thermal cantilever response under periodic heating. In addition, cantilever thermophysical properties such as the thermal conductivity and specific heat can be obtained from the measurement.

**B. Results and discussion**

As in the dc characterization, the ac experiment was performed for different stage temperatures from 77 to 200 K. $1 \omega$ and $3 \omega$ cantilever voltage signals were measured while a small input voltage (i.e., $V_{rms} = 0.3$ V-rms) was applied to the circuit. Figures 4(a) and 4(b) show in-phase and out-of-phase $1 \omega$ cantilever voltages for three stage temperatures. The in-phase signals in Fig. 4(a) maintain their values until around 10 kHz and drastically decrease. On the other hand, the out-of-phase signals have valleys in the range from 30 to 100.
kHz, depending on the stage temperature. These cantilever responses are due to changing electrical impedance of the cantilever, rather than changing thermal characteristics. The equivalent circuit illustrated in the inset of Fig. 4(a) represents the cantilever as a parallel connection of a resistor $R_c$ and a capacitor $C_c$, yielding the cantilever voltage as

$$V_{1\omega} = \frac{R_c V_{IN}}{(R_s + R_c) + j\omega R_c C_c}. \quad (14)$$

The 1$\omega$ cantilever voltages calculated from the above equation are plotted together in Fig. 4 with solid curves. Calculated values agree very well with the measurement except around valleys of out-of-phase signals at higher stage temperatures. The cantilever capacitance $C_c$ is estimated in the order of 100 pF. This parasitic capacitance depends on cantilever geometries and its operation environments. In fact, the presence of the cantilever capacitance and/or inductance significantly changes the cantilever electrical behavior at frequencies higher than 10 kHz. Combined with the cantilever capacitance, the decreasing cantilever resistance with temperature reduces the signal magnitudes and shifts the valley position of the out-of-phase signal to the higher frequency. Since the electrical impedance effect on the 1$\omega$ signal is significant, the thermal information of the 1$\omega$ signal is hardly recognizable: after all, the harmonic cantilever voltage change due to the thermal effect is on the order of 100 $\mu$V rms for the setup input voltage, much smaller than that due to the electrical impedance effect.

Figures 5(a) and 5(b) show the in-phase and out-of-phase electrical transfer functions obtained from the 3$\omega$ cantilever voltage signals. In Fig. 5(a), the in-phase 3$\omega$ transfer function $X_{3\omega}$ maintains its magnitude up to around 100 Hz before approaching zero, because a driving frequency less than 100 Hz provides enough time for the cantilever to reach a thermal equilibrium with the environment. Since $X_{3\omega} = -\text{Re}[Z_3(2\omega)]/4$ and $Y_{3\omega} = -\text{Im}[Z_3(2\omega)]/4$, the decrease of $X_{3\omega}$ and $Y_{3\omega}$ magnitudes with increasing temperature indicates that the cantilever thermal impedance decreases with temperature. The peak location of $Y_{3\omega}$ moves to a smaller frequency as temperature increases, which implies that the propagation speed of the thermal information along the cantilever becomes slower at high temperatures due to increasing phonon scattering rate.

The calculated electrical transfer functions are plotted together as solid curves in Fig. 5. The calculation and the measurement are in excellent agreement at low frequencies, but deviate at high frequencies. The deviation could be explained by two reasons. First, $X_{3\omega}$ and $Y_{3\omega}$ can be modulated by the electrical impedance at high frequencies. The deviation frequency of $X_{3\omega}$ at 77.8 K is approximately 1 kHz, coincident with 2 kHz at which the out-of-phase 1$\omega$ voltage in Fig. 4(b) starts to change: the 3$\omega$ signal reflects the thermal response at 2$\omega$. Moreover, the calculation and the measurement agree much better at higher stage temperature, being an additional evidence of the signal modulation because the impedance effect is pushed to higher frequencies as temperatures increase. Another possible reason of the deviation is that the modeling did not consider a depletion region between the heater and the thermal constrictions, which may affect the high frequency thermal response of the cantilever.

A huge difference of the carrier concentration at the heater boundary can enhance the scattering rate in a small depletion region, forming a “hot spot” whose thermal response spectrum is located at high frequencies. A shoulder observed in measured $Y_{3\omega}$ at around 10 kHz, but not in calculated $Y_{3\omega}$, might be due to the presence of this depletion region. The depletion region effects should be investigated as future research and will not be further discussed here.

Despite the deviation between the calculation and the measurement at high frequencies, good overall agreement enables the extraction of cantilever thermophysical properties. Particularly, the properties of the heavily doped leg region can be obtained through the fitting process to the measurements. Even though the electrical resistance is dominated by the heater region, the thermal resistance of the cantilever mostly depends on the heat conduction through the leg. Thus, thermal conductivity of the leg region and the specific heat (or thermal diffusivity) will determine the cantilever thermal transfer function, especially at low frequencies. Due to the small size of the heater and relatively large thermal conductivity of lightly doped silicon, the thermal behavior of the cantilever is not sensitive to the thermal conductivity of the heater region. The thermal conductivity at

![Fig. 5. The electrical transfer functions converted from the 3$\omega$ cantilever voltage for different stage temperatures. (a) The in-phase electrical transfer functions and (b) out-of-phase transfer functions are plotted and compared with the calculation, which are plotted with solid curves.](image-url)
the heater is not adequate as a fitting parameter. Instead, thermal conductivity of the heater was taken from literature\textsuperscript{41} considering the cantilever thickness.\textsuperscript{42} Specific heat of the heater region was assumed to be the same as that of the leg region. Figures 6(a) and 6(b) respectively show the thermal conductivity and the specific heat of the leg region. Compared to the thermal conductivity shown in the inset as a reference,\textsuperscript{43} the leg thermal conductivity is around half the reference value, and its peak position is shifted to higher temperature. These differences are mainly due to the heavy doping concentration (4.3 × 10\textsuperscript{20} cm\textsuperscript{-3}) and thin cantilever thickness (0.59 μm): Phonon-carrier and phonon-impurity scattering increase with doping level\textsuperscript{14} while phonon-boundary scattering increases as the layer thickness decreases.\textsuperscript{42} the estimated phonon mean free path at temperature range being considered is comparable to the cantilever thickness, reducing the thermal conductivity by nearly 50%. As shown in Fig. 6(b), the specific heat of the cantilever leg is very close to that of pure and bulk silicon.\textsuperscript{45} A small increase of the specific heat from that of pure silicon is expected because the Debye temperature of silicon slightly decreases with the doping level.\textsuperscript{46} The decrease of the Debye temperature $\theta_D$ enhances the specific heat by $C \propto (T/\theta_D)^3$ when temperature is low (i.e., $T/\theta_D < 50$).\textsuperscript{47} The successful extraction of thermophysical properties of the cantilever indicates that the heated cantilever structure could be used more broadly for thermophysical property measurements. The cantilever structure could have an advantage over other approaches, since uncertainties associated with the finite thermal conductance of conventional metal-deposited apparatus\textsuperscript{37,42} can be eliminated. Thermal conductance measurements have been previously reported for suspended, doubly clamped polysilicon beams,\textsuperscript{48} but the present article extends the technique to periodic measurements at low temperature, and combines modeling with measurements.

The uncertainties in the property extraction, which are estimated to be ±5.4% for the thermal conductivity and ±5.2% for the specific heat on average, are combinations of the uncertainties of the TCR, the thickness of the cantilever, and the measurement of harmonic cantilever voltage and other electrical properties. The relatively large uncertainties at low temperatures are mostly due to the uncertainty of the TCR. The cantilever resistance at low temperature varies dramatically with temperature, changing the TCR significantly even with a small uncertainty of 0.1% in the resistance measurement. Another source of uncertainty may come from the extraction procedure of the thermophysical properties, because the calculated transfer functions deviate from the measurements: see Fig. 5.

From the obtained thermophysical properties, the thermal diffusion time can be determined from $\tau = 4l^2/\alpha$, where $2l$ is the whole cantilever length: Since the anchor region experiences little temperature rise during heating, only heater, thermal constriction, and leg regions are considered as the cantilever. Figure 7 shows the diffusion time for different temperatures. The increase of the diffusion time with increasing temperature is attributed to the decreasing thermal diffusivity, shown in the inset. Considering the physical meaning of the diffusion time, which is the time taken for the
V. CONCLUSIONS

This article investigates the electrical and thermal responses of a heated AFM cantilever at low temperatures to extend its use in a cryogenic environment. The cantilever resistance increases with decreasing cantilever temperature, due to carrier freezing and the decrease of the mobility. The steady-heating cantilever characterization reveals that the cantilever heater temperature can increase above 300 K when the environment is at liquid nitrogen temperature. Under periodic-heating operation, the electrical impedance of the cantilever significantly distorts the in-phase cantilever voltage at high frequencies and complicates the thermal analysis. To ease the thermal analysis, this article developed electrical and thermal transfer functions of the cantilever. The thermal conductivity and specific heat of the leg region were obtained by comparing the transfer functions with the measurements. The estimated thermal diffusion time is in the order of 1 ms. The cantilever response at high frequencies becomes out of phase and is restricted within the heater and thermal constriction regions. The results obtained here clearly depict the cantilever electrical and thermal behavior at low temperature, which is critical for a safe and efficient cantilever operation in cryogenic environments.
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