Nanotopographical imaging using a heated atomic force microscope cantilever probe

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Abstract

This paper reports quantitative topographical measurements using a heated atomic force microscope (AFM) cantilever probe. The study compares topographies measured by the cantilever thermal signal to topographies measured by the laser-deflection signal of an AFM system. The experiment used 20 and 100 nm tall Si gratings as topographical test samples. The cantilever heater temperature ranged from 130 to 640 °C, and the cantilever power ranged from 1.5 to 6.6 mW. The measured topography sensitivity, which is the fractional change of the heated cantilever resistance, has a $|\Delta R_{\text{cant}}|/R_{\text{can}}$ of $4.5 \times 10^{-5}$ to $1.1 \times 10^{-3}$ per vertical nanometer, which is 10–100 times greater than that of similarly sized piezoresistive cantilevers. In a proof of concept demonstration, the heated cantilever measures the topography of a microfabricated platinum line of thickness 100 nm on a silicon dioxide substrate. © 2006 Elsevier B.V. All rights reserved.

Keywords: Thermal microscopy; Cantilever; Atomic force microscopy

1. Introduction

The atomic force microscope (AFM) has become one of the most widely used tools for sensing and actuating on the nanometer scale [1]. In typical AFM operation, a reflected laser is used to monitor the position of the AFM tip over a surface. Laser detection of the cantilever tip position is relatively easy in conventional AFM. However laser detection is very difficult or impossible to implement for very large arrays of AFM cantilevers [2]—it would be impractical to align and measure many thousand lasers reflected from many thousand cantilevers. Successful cantilever array technology requires each cantilever to have its own integrated sensor that can be individually addressed. Several strategies exist for integrated sensing of the tip position during AFM operation. The tip position can be sensed by measuring, for example, a tunneling current [1], a mechanical strain using embedded piezoresistors [3], or the flow of heat using a heat source and thermometer [4–6]. This paper explores quantitative nanoscale topographical sensing using a silicon AFM cantilever having an integrated heater-thermometer.

Nanotopographical measurements with a heat probe tip were first demonstrated 20 years ago [6], with a heater-thermometer attached to the end of a scanning probe tip. Thermal conduction between the probe and the sample was modulated by the probe interaction with the substrate, and so the probe temperature could provide vertical position feedback to the tip as it scanned over the surface. More recently, silicon cantilevers with integrated heater-thermometers were shown to operate in a similar manner, with heat flow from the cantilever to the substrate modulated by the height of the features on the substrate [4,5]. The sensitivity of the thermal probe was found to be very high compared to the sensitivity of piezoresistive cantilevers [7]. Because the read element is integrated directly into the probe, it is possible to perform metrology with large arrays of cantilevers having integrated heater-thermometers [2,8]. Thermally based topography metrology using a probe array has enabled data reading in a scanning probe data storage system [8].

Much research has focused on understanding heat transfer in silicon heater-cantilevers for data storage [9]. Because data reading with the thermal probe requires relative nanotopographical information and not absolute nanotopographical information, little effort has been made to understand the use of or optimize the thermal probe reading for quantitative measurements. One theoretical study reported a detailed analysis of the design of
silicon heater-cantilevers for nanotopographical measurements [10]. However there is no published report that makes quantitative measurements of cantilever sensitivity when used for nanotopographical measurements.

Silicon heater-cantilevers have been shown to be useful well beyond data storage, with applications in nanometer-scale manufacturing [11–13]. These manufacturing applications would be enhanced by performing in situ metrology with the same heatable probes. However, quantitative understanding of cantilever sensitivity would enhance their manufacturing capabilities.

This paper reports quantitative measurements of the sensitivity of heatable silicon AFM cantilevers used for nanotopographical measurements. The experiments measure the electrical resistance of the heatable silicon AFM cantilever scanning over silicon grating structures of height 20 and 100 nm. The measured cantilever electrical signals compare well with the reflected laser signal of the AFM system. Finally, the heated probe is used to measure the topography of a microfabricated thin platinum film on a silicon dioxide substrate.

2. Instrumentation and experimental method

The experiments used silicon heater-cantilevers fabricated in our group [14]. The cantilevers are similar to those developed for data storage [4,8,15]. The cantilevers were fabricated using a standard silicon-on-insulator (SOI) fabrication process that has been described elsewhere [14] and not reviewed here. Fig. 1(a) shows a scanning electron microscope (SEM) image of the heated cantilever. Fig. 1(b) and Table 1 show the cantilever geometries and properties. The area of the heater region was $8 \times 16 \mu m^2$. Leg width and leg length were 15 and 135 $\mu m$, respectively. The cantilever tip height and the cantilever thickness were close to 1 $\mu m$. The cantilever had an electrical resistance of 1.2 k$\Omega$ at room temperature. The cantilever legs were heavily doped to $1 \times 10^{20}$ cm$^{-3}$ for electrical leads while the heater region was lightly doped to $1 \times 10^{17}$ cm$^{-3}$. About 90% of the total cantilever electrical resistance is due to the low-doped highly resistive heater region [14]. When electrical current flows through the cantilever, heat generation occurs in the resistive heater region, while little heating occurs in the highly conductive legs.

Fig. 2 shows the fundamental concept for the thermal sensing of nanotopography [5,7,10]. Heat generated in the heater region flows across the air gap to the sample and also flows away through the cantilever leg. In Fig. 2, $q_{\text{air}}$ and $q_{\text{leg}}$ are the heat flow from the cantilever to the air gap and the heat flow through the leg, respectively. The very small cantilever surface area and the stable bulk air motion result in negligible convective heat transfer between the cantilever and the ambient air. The thermal conductance between the cantilever and the substrate beneath the cantilever tip is much greater than the conductance due to convection, radiation, or conduction between the cantilever and its environment [5,7,10]; even though the 1 $\mu m$ thickness of air between the cantilever and the substrate has a low thermal conductivity at 0.03 W/m-K. Thus much more heat flows across the air gap, $q_{\text{air}}$, than flows into the nearby environment. The silicon legs of the cantilever have a thermal conductivity of near thickness.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Heated cantilever</th>
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<tbody>
<tr>
<td>Leg length</td>
<td>135 $\mu m$</td>
</tr>
<tr>
<td>Leg width</td>
<td>15 $\mu m$</td>
</tr>
<tr>
<td>Thickness</td>
<td>1 $\mu m$</td>
</tr>
<tr>
<td>Heater size</td>
<td>$8 \times 16 \mu m$</td>
</tr>
<tr>
<td>Heater doping</td>
<td>$1 \times 10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Leg doping</td>
<td>$1 \times 10^{20}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Doping type</td>
<td>Phosphorous</td>
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Fig. 1. (a) The scanning electron microscope (SEM) image of a heated cantilever and (b) the schematic of a silicon microcantilever having an integrated solid-state heater. When electrical current flows through the cantilever, heat generation occurs mostly in the heater region located at the free end of the cantilever.

Fig. 2. The concept for the thermal sensing of nanotopography using a heated cantilever. The heat flow from the cantilever across the air gap to the substrate is $q_{\text{air}}$, and the heat flow from the heater region through the legs is $q_{\text{leg}}$. Most of the generated heat eventually flows across the air gap into the substrate.
148 W/m-K, and so between 20 and 40% of the heat generated initially flows down the cantilever legs, shown as \( q_{\text{leg}} \). However nearly all of this heat flow down the legs eventually flows away from the cantilever legs, across the air gap, and into the nearby substrate. The ratio \( q_{\text{air}}/q_{\text{leg}} \) depends upon the specific details of the cantilever design including cantilever thickness and cross-sectional area [9,10]. However for all practical cantilever designs, thermal conduction across the air gap into the nearby substrate governs thermal transport from the cantilever, as most of the heat generated in the cantilever heater region flows into the sample. Thus, the air gap thickness is a dominant parameter for the thermal characteristics of the heated cantilever when operated near a substrate.

As the heated cantilever scans over a substrate, the tip follows the contours of the substrate topography. As the cantilever tip follows a topographical feature that moves the cantilever away from the substrate, the thermal resistance between the cantilever and the substrate increases, and the cantilever temperature increases for constant heating power. The opposite happens as the tip scans into a feature that causes the cantilever to move closer to the surface: thermal conductance from the cantilever increases, and the temperature decreases at constant heating power. The electrical resistance of the doped silicon cantilever is a strong function of temperature, and so a temperature change in the cantilever results in a change in the cantilever electrical resistance [16]. By monitoring the variance of the electrical resistance as the cantilever scans over a textured surface, it is possible to measure topography.

Fig. 3 shows the experimental setup used to measure thermal topographic signals and the topographies of nanostructures. In Fig. 3, \( V_{\text{tot}} \), \( V_{\text{sense}} \), \( V_{\text{cant}} \), \( R_{\text{sense}} \), and \( R_{\text{cant}} \) are total input voltage for the system, voltage across a sense resistor, voltage across the cantilever, the resistance of a sense resistor, and the cantilever resistance, respectively. A dc voltage source applied a constant voltage across the cantilever and a serial sense bridge resistor of 1.5 k\( \Omega \). The sense resistor served to protect the cantilever by limiting current flow through the cantilever at high power operation. A commercial AFM system (Asylum Research MFP-3D-SA AFM) scanned the heated cantilever tip in contact with a sample. An analog to digital converter (ADC) in the AFM controller recorded the sense resistor voltage as a function of cantilever position on the sample. Simultaneously, the AFM system optically recorded the topography of the sample. A superluminescent diode (SLD) illuminated at 810 nm on the cantilever tilted downward to the horizontal plane with an angle of 11\(^\circ\), and a Position Sensitive Detector (PSD) in the AFM head monitored the deflection of the laser beams. The ADC converted voltages from the PSD into the vertical displacement. Post-processing generated the 3D images of both thermal topographic signals and laser-deflection based topographies.

The cantilever electrical resistance is a strong function of the cantilever temperature, and thus the thermal characterization of the cantilever is necessary to investigate the performance of the cantilever for the nanotopography measurement. A commercial Raman spectroscopy system [17] system, Renishaw In Via Raman Microscope with 180\(^\circ\) backscattering geometry was used to measure heater temperatures of the cantilevers that were suspended in the ambient for various power dissipations. We have previously published a description of the method used to calibrate the cantilever thermistor using Raman spectroscopy [14,18] and do not review the details here.

The calibration was conducted by following steps from (1) to (3):

1. When the cantilever was suspended in the ambient, cantilever resistances and cantilever heater temperatures were measured at various power dissipations.
2. The cantilever heater temperatures were characterized as a function of the cantilever electrical resistance at various power dissipations.
3. The cantilever heater temperatures were determined by substituting the measured resistance of the cantilever whose tip touched the sample surface into the characteristic function, generated in (2), of the cantilever electrical resistance. With this method, it is possible to calibrate the cantilever temperature to within 5\(^\circ\)C over the temperature range of interest [14,18].

The thermal characteristics of cantilever resistances were carefully explored at various voltages and power dissipations, and the results are plotted in Fig. 4(a) and (b). Fig. 4(a) shows the resistances of the heated cantilevers at various total voltage inputs when the cantilever is suspended in the ambient, and the cantilever tip touches the sample surface. The gradients of the cantilever resistance, \( R_{\text{cant}} \), with respect to the total input voltage, \( V_{\text{tot}} \), i.e., \( \Delta R_{\text{cant}}/\Delta V_{\text{tot}} \) change from the positive to negative due to the sign change of the temperature coefficient of the cantilever resistance [14]. The point at the sign change of \( \Delta R_{\text{cant}}/\Delta V_{\text{tot}} \) from positive to negative is the intrinsic carrier-based thermal runaway point [16]. At the thermal run away point, the cantilever heater temperature was found to be nearly 640\(^\circ\)C. Fig. 4(a) shows that a higher voltage is required to achieve a specific cantilever resistance or temperature as the tip touches the
sample surface, and the thermal runaway point increases from 5.2 to 6.6 V. This shift is due to the higher power that can be dissipated by the thermal conduction across the air gap into the nearby sample as the cantilever tip touches the sample surface.

Fig. 4(b) shows cantilever resistances and cantilever heater temperatures as a function of the cantilever power. The profiles of the resistances to the power dissipations show similar patterns to those of the resistances to the voltage inputs. The similarity between the profiles of the resistances to the power dissipations and the profiles of the resistances to the voltage inputs is mainly due to the fact that the cantilever power dissipation almost linearly depends on the total voltage input below the thermal runaway point. When the cantilever is operated at a temperature below thermal runaway, the sensor response is very well behaved. Fig. 4(b) shows the cantilever heater temperature ranges from 25 to 760 °C. The thermal run away point occurs at 4.1 mW when it is far from the substrate at 6.8 mW when the tip is in contact with the surface. As the cantilever approaches the silicon substrate from far away, the cantilever power dissipation at constant temperature increases by about 60%. From these figures, it is clear that there is a complex interplay between the cantilever electrical resistance, cantilever voltage, dissipated power, temperature, cantilever thermal properties, and driving electronics. A full analysis of this system and all of its implementations is not possible within a single manuscript. This investigation is therefore limited to a single cantilever type, two simple topographies and a simple driving circuit.

3. Experimental results

The experiments investigated the thermal and electrical signals from the heated cantilever as it scanned over Si calibration gratings of height 20 and 100 nm, and compared these signals to the cantilever displacement obtained by the laser-deflection based measurement. The experiments determined the sensitivity and the resolution of the topography mapping using a heated cantilever probe and then obtained the topographical image of a microfabricated platinum element.

3.1. Cantilever electrical and thermal characteristics

The analysis begins with comparison of the laser-deflection based topographies and the thermal topographic signals. Measured thermal topographic signals were of the voltages across the cantilever, $V_{\text{cant}}$, varying along the nanotopography as in Fig. 3. The change of $V_{\text{cant}}$ results from the changes in cantilever resistance as the cantilever temperature is modulated by surface topography.

Fig. 5(a.1) and (a.2) shows the 3D images of the laser-deflection based topography and the thermal topographic signal for 20 nm tall Si gratings, and Fig. 5(b.1) and (b.2) shows the topography and the thermal signal for 100 nm tall gratings. The power dissipation in the cantilever was near 4 mW for the measurements of Fig. 5. Qualitatively, the thermal topographic signals were very similar to the laser-deflection based topographies. As the cantilever tip moved to the top of the grating, the cantilever temperature increased, which resulted in the increase of the cantilever electrical resistance. As can be seen from Fig. 4, the cantilever resistance is linear with the applied voltage at this operation point, and so the cantilever voltage increased as well. Cantilever voltages varied by 2.8 mV for 20 nm tip displacement and by 14 mV for 100 nm tip displacement. A small amount of noise is apparent in the thermal signal for the measurement of the 20 nm gratings, to be discussed later. For this combination of electrical operating conditions and the topography tested, the cantilever remained in its linear operation regime, and so the change of the cantilever voltage was close to linearly proportional to the tip displacement. Operation at higher power or on a different topography could yield a different relationship between topography height and the cantilever sensor signal. A more detailed analysis follows.

In order to explore the interrelationship among electrical and thermal topographic signals and nanotopographies, line scans were extracted from the experiment and plotted in Fig. 6.
Fig. 5. 3D images of laser-deflection based topographies and thermal topographic signals of (a.1 and a.2) 20 nm and (b.1 and b.2) 100 nm tall silicon gratings. Thermal topographic signals were generated by the measured voltages across the heated cantilever. The thermal signal was obtained at the total applied voltage of 5 V, and the power dissipation in the cantilever was near 4 mW.

Fig. 6. The laser-deflection based topography and thermal and electrical signals associated with the thermal reading of topography for the 100 nm high Si gratings. The total voltage, $V_{\text{int}}$, was 5 V. (a) is the laser-deflection based topography of gratings. (b) shows the voltages across a sense resistor and a cantilever. (c) shows the electrical resistance of the cantilever and the thermal resistance from the cantilever. (d) shows the cantilever heater temperature and the power dissipation in the cantilever.
Fig. 6(a) shows the laser-deflection based topography, and Fig. 6(b)–(d) shows electrical and thermal signals for the 100 nm tall Si gratings for $V_{\text{tot}} = 5 \, \text{V}$. Fig. 6(b) shows $V_{\text{sense}}$ and $V_{\text{cant}}$ as the cantilever scans over the gratings. As the cantilever tip moves to the top of the grating, the thickness of the air gap between the cantilever and the substrate increases. The thicker air gap causes the higher thermal resistance between the cantilever and the gratings, and results in the increase of the cantilever temperature. The increased temperature induces the increase of the cantilever resistance and the cantilever voltage. The total circuit voltage is constant, and thus the sense voltage behaves oppositely to the cantilever voltage. The cantilever voltage shows a very similar profile to the optically measured topography, with $V_{\text{cant}}$ changing at 0.14 mV per nanometer of the cantilever tip displacement.

Fig. 6(c) shows the cantilever electrical resistance, $R_{\text{cant}}$, and the calculated thermal resistance, $R_{\text{th}}$, between the cantilever and its environment. The profile of the cantilever electrical resistance follows the topography very well, with about 1% change of the cantilever resistance for 100 nm of the vertical displacement. The value of $R_{\text{th}}$ was calculated as the temperature difference between the heater and its environment divided by the power dissipation in the cantilever. The evaluated change of the thermal resistance is about 2% per 100 nm change of the vertical displacement. Fig. 6(d) shows various cantilever heater temperatures and power dissipations in the cantilever as the cantilever scans over the grating topography. The increase of the thermal resistance, as the cantilever tip moves to the top of the grating, causes the increase of the cantilever heater temperature, nearly 7°C although the cantilever power dissipation decreases by 0.01 mW due to increased cooling of the cantilever. The thermal measurements provide quantitative evidence as to the physical mechanism of the thermal mapping of the topography.

### 3.2. Sensitivity of topography mapping

Having the thermal and electrical measurements described above, it is possible to determine cantilever sensitivity. The topography sensitivity of the cantilever probe can be defined as the fractional change of the cantilever resistance for the vertical displacement of the cantilever tip [4]:

$$\text{sensitivity} = \frac{|\Delta R_{\text{cant}}|}{R_{\text{cant}} \Delta z}$$

(1)

where $|\Delta R_{\text{cant}}|/R_{\text{cant}}$ is the fractional change of the cantilever resistance, and $\Delta z$ is the vertical displacement of the cantilever tip. Note that $\Delta R_{\text{cant}}$ is defined as the difference in cantilever resistance as it scans over the gratings, not the difference between contact and out of contact.

Fig. 7 shows the topography sensitivity of the heated cantilever as a function of $V_{\text{tot}}$ and grating height. The average resistance change for 20 and 100 nm of tip displacements were normalized by the resistance when the cantilever tip places on the bottom of the grating, and then the sensitivity was determined dividing it by the tip displacement. The cantilever sensitivity for scans over the 20 nm gratings varies from $4.5 \times 10^{-5}$ to $4.4 \times 10^{-4} \, \text{nm}^{-1}$ for total voltages varying from 3 to 6.6 V, which correspond to powers of 1.5–6.6 mW. The cantilever sensitivity for 100 nm gratings, ranges from $4.5 \times 10^{-5}$ to $1.1 \times 10^{-3} \, \text{nm}^{-1}$ for total voltages varying from 3 to 6.6 V which correspond to powers of 1.5–6.6 mW.

The determined sensitivities show considerable dependence on the applied voltage; the sensitivities vary by one to two orders of magnitude. The considerable sensitivity variance to the various applied voltage is mainly due to the significant variance of the cantilever resistance gradient with respect to the applied voltage, $\Delta R_{\text{cant}}/\Delta V_{\text{tot}}$. It should be noted that $\Delta R_{\text{cant}}/\Delta V_{\text{tot}}$ resulted from the temperature dependence of the cantilever resistance. Sensitivity profiles show steep increase from 6.5 to 6.6 V and the best sensitivity at $V_{\text{tot}} = 6.6 \, \text{V}$. The steep increase of the sensitivity with the voltage change is mainly due to the high temperature coefficient of electrical resistance at high temperature and near the thermal runaway point.

For comparison purposes, Fig. 7 shows the topography sensitivity of a piezoresistive cantilever having a similar size to the heated cantilever. The sensitivity of the piezoresistive cantilever was determined by a similar way reported in [7], and it is close to $1 \times 10^{-5} \, \text{nm}^{-1}$. Overall, measured sensitivities for the heated cantilever are one to two orders of magnitude greater than the sensitivity of the piezoresistive cantilever. The value of $1 \times 10^{-5} \, \text{nm}^{-1}$ is actually quite generous. The reported topography sensitivities of piezoresistive cantilevers have been reported as $5 \times 10^{-8} \, \text{nm}^{-1}$ [3], $2.1 \times 10^{-6} \, \text{nm}^{-1}$ [19], $2.5 \times 10^{-6} \, \text{nm}^{-1}$ [20], $3 \times 10^{-6} \, \text{nm}^{-1}$ [21], $3.5 \times 10^{-6} \, \text{nm}^{-1}$ [22], $4.1 \times 10^{-6} \, \text{nm}^{-1}$ [23] and $8 \times 10^{-6} \, \text{nm}^{-1}$ [24], which are all significantly less values than the measured topography sensitivity with the heated cantilever. It can be concluded that overall, the sensitivity of the heated cantilever is significantly higher than that available from previously reported piezoresistive cantilevers. The resolution, the minimum detectable size to the vertical direction, is found to be 1–3 nm, and is in this case limited by the resolution of the ADC. The resolution could be improved...
by the use of a higher resolution ADC. We plan future studies on noise-limited resolution in the heated AFM cantilevers.

The speed of the thermal imaging will be limited by the time required for heat to flow from the cantilever to the substrate, the cantilever thermal time constant, the cantilever mechanical resonance characteristics, and the noise in the cantilever. The heated AFM cantilever has a thermal time constant in the range 1–10 μs. The measurements described above were made for a tip scan speed of 42 μm/s. The mechanical resonant frequency for this cantilever was 75 kHz. A cantilever with a higher resonant frequency would be possible, although changes to the cantilever design that targeted increased cantilever mechanical time constant could change the cantilever thermal characteristics. The tradeoffs between thermal, electrical, and mechanical properties of the cantilever are described in [4,7,9,10]. The fundamental noise mechanisms in resistively heated AFM cantilevers have been briefly discussed elsewhere [7] but not reported in detail, and we suggest that this is an important future study. Regardless of how the thermal cantilever compares with a conventional laser-deflection based AFM in speed, it is important to note that the thermal cantilever can be parallelized into a large array much more readily than a conventional laser-deflection based AFM. Array operation would enable much higher system-level imaging speeds than the conventional AFM.

3.3. Topographical imaging of a microfabricated metal element

In order to show nanotopography measurements on an actual microstructure, the heated AFM cantilever was scanned over a platinum strip having 8 μm width and 100 nm thickness. The platinum strip was deposited on a silicon dioxide film of 1 μm thickness on a silicon substrate. Fig. 8(a)–(c) shows the images of the platinum strip that were taken with different metrologies: the optical microscope image in Fig. 8(a), the laser-deflection based topographic image in Fig. 8(b), and the thermally sensed topographic image in Fig. 8(c). When compared with Fig. 8(a), Fig. 8(b) provides better resolution, showing more spots whose sizes are smaller than the resolution which optical microscope can offer. Several spots in the figures are photoresist residues that were made with a cantilever for which the tip was covered with photoresist. The thermal topographic image in Fig. 8(c) depicts the spots most clearly among the three images, suggesting that the resistance change of the heated cantilever could provide a good image resolution as the photodiode signal change.

In order to accept thermal topographic images as true surface topographies of a sample consisting of different materials, it should be confirmed that the air gap between the cantilever and the substrate is the most dominant factor that modulates thermal conductance from the heated cantilever. The main heat transfer mechanisms between the cantilever and the substrate are tip-sample conduction and the air conduction across the gap. Previous research showed that the air conduction dominates over the tip-sample conduction when the heater size is on the order of a micrometer [25], allowing the air conduction as a predominant heat transfer mechanism in the thermal topographic imaging. A simple thermal network analysis of the air conduction from the cantilever heater to the substrate reveals that the thermal resistance of a 100 nm thick platinum layer is on the order of 10 K/W, approximately four orders of magnitude smaller than the thermal resistance of the air gap. The equivalent vertical displacement for 10 K/W thermal resistance change is estimated to be 0.06 nm; the thermal topographic image would not be dis-

Fig. 8. AFM scanning results of a platinum metal strip of 8 μm width and 100 nm thickness. (a) Optical image taken with an optical microscope. (b) The laser-deflection based topographic image. (c) Thermal image taken with the sense voltage change. For comparison in the image resolution, several spots were intentionally made on the strip with a cantilever whose tip was covered with photoresist.
torted by the platinum strip. When the layer thickness is fixed at 100 nm, the thermal conductivity equivalent to 1 nm vertical displacement is approximately 4.3 W/m-K, indicating that the error of the thermal topography method would be less than 1 nm for a wide range of the layer thermal conductivity.

4. Conclusion

This study employed a self-heated silicon cantilever probe to perform topographical measurements on Si calibration gratings of height 20 and 100 nm, and to demonstrate the thermal mapping of the nanotopography of a fabricated microstructure. Thermally sensed topographies were compared with the laser-deflection based topographies. The detailed experimental study suggests topography images with good accuracy. The cantilever sensitivity, which is the fractional change of the signal with respect to an increase in temperature, is approximately 4.5 × 10^-3 to 1.1 × 10^-3 nm K^-1. The measured sensitivity is significantly higher than the fraction of a piezoresistive cantilever. For the demonstration of the thermal measurement of the actual nanostructure, the heated cantilever measured the topography of a microfabricated metal line on a silicon dioxide substrate. The measurements reported here are for one specific cantilever type. A different cantilever geometry could have different electrical, thermal, or mechanical characteristics as described in Refs. [4,9,10]. However the measurement approach and results presented here are generally valid for all of the thermal cantilever studies referenced herein.

References


Biographies

Kyoung Joon Kim received the BS degree in mechanical design and production engineering from Chung-Ang University, Seoul, Korea in 1999, the MS degree in mechanical engineering from the University of Minnesota, Minneapolis, MN in 2002, and the PhD degree in mechanical engineering from the University of Maryland, College Park, MD, 2006. He is currently a postdoctoral fellow in mechanical engineering at the Georgia Institute of Technology. His main research interests include nanoscale thermal metrology and manufacturing, heat transfer in nano/micro systems, and NEMS/MEMS.

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William P. King received the BS degree in mechanical engineering from the University of Dayton in 1996 and the MS and PhD degrees in mechanical engineering from Stanford University, Stanford, CA, in 1998 and 2002, respectively. Between 1999 and 2001, he spent 16 months in the Micro/NanoMechanics Group of the IBM Zurich Research Laboratory. In July 2002, he joined the faculty of the Woodruff School of Mechanical Engineering at Georgia Tech, Atlanta, assistant Professor. His group works on thermal engineering of micro/nanomechanical devices, including thermomechanical data storage and nanoscale thermal processing. He is the winner of the NSF CAREER award (2003) and the DOE PECASE award (2005). In 2006 he was named to the TR35—one of the most innovative people under the age of 35 by Technology Review Magazine. He sits on the scientific advisory board at 5 companies.