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High temperature imaging using a thermally compensated cantilever resistive probe for scanning thermal microscopy

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The authors have designed and fabricated AFM probes with an integrated resistive temperature sensor and a grooved cantilever structure. The grooved structure compensates for the bilayer thermal bending that normally occurs during scanning thermal microscopy of hot samples. These new probes show reduced bending at high temperatures when compared to commercial, conventional cantilever probes with a similar stiffness. This indicates that the mechanical balance introduced by the grooved structure plays a major role in reducing thermal bending. Successful temperature mapping is demonstrated on an active heater device reaching 108 °C, a sample that would be beyond the imaging capability of conventional probes. © *2012 American Vacuum Society*. [DOI: 10.1116/1.3664328]

I. INTRODUCTION

As semiconductor devices are continuously scaled, high power density coupled with the use of structures having poor thermal conductivity makes temperature control an increasingly important problem. Local thermal properties of the device structures are therefore of great interest and sub-100 nm resolution is required for the current generation of devices. Among the techniques available for thermal analysis, scanning thermal microscopy[1–3] (SThM) was developed to probe thermal properties with high spatial resolution. SThM employs a sharp temperature sensing tip that is brought into contact with a sample surface. If employing an active temperature sensor, the heated atomic force microscopy (AFM) tip is scanned across the sample surface producing a spatial map of sample thermal properties. These different properties are detected by monitoring the varying tip temperature resulting from changes in the localized heat transfer between the tip and sample surface. These changes can be the result of variations in topography, local temperature, or sample thermal conductivity. High spatial resolution has been achieved with nanofabricated SThM probes thanks to their small tip radius.[4,5]

However, nanofabricated SThM probes can suffer from thermally induced cantilever bending. This is due to the differential thermal expansion exhibited by the materials used to make the cantilever (typically silicon nitride) and the electrical connections to the sensor (typically gold). Since the gold leads are present on one side of the cantilever only, an increase or decrease in temperature will cause the cantilever to bend either away from or towards the sample, mimicking changes in applied force. In AFM the force between tip and sample is measured by detecting the change in bending of the cantilever away from its equilibrium position. A constant force may be applied between tip and sample by moving the sample towards or away from the tip to maintain a constant bending of the cantilever. In the case of the thermal probe; however, the equilibrium bend of the cantilever is a strong function of temperature. Thus if the temperature decreases the cantilever naturally bends towards the sample. The AFM feedback system interprets this as a decrease in the applied contact force between tip and sample, and moves the sample towards the tip to compensate. A decrease in temperature will cause the feedback loop to increase the force applied to the tip which can cause damage to the tip or sample or induce scan artifacts. A worse problem arises if the cantilever is heated. In this case the cantilever will bend away from the sample. The feedback loop will interpret this as being due to excessive force being applied and will move the tip away from the sample to reduce the applied force. At a certain temperature the thermal bend of the cantilever will correspond to a greater force than that commanded by the feedback loop and the sample will be withdrawn from the tip completely, breaking contact between tip and sample. Thermal bending of SThM cantilevers is therefore seen to be an important problem for the practical application of the technique. In this study, we demonstrate that this type of thermal bending can be significantly reduced by modifying the mechanical structure of the cantilever.

II. DESIGN AND FABRICATION

Initially, for the reduction of cantilever thermal bending we might consider a structure consisting of three layers; for example, gold films on both sides of a silicon nitride cantilever. This cantilever will not become thermally bent simply because the stress induced in the gold film on one side is balanced by that induced in the gold film on the other side. The simple addition of a compensating metal film on the other side of the cantilever is unfortunately impractical. To achieve the smallest possible sensor size the SThM sensor is defined in a self-aligned fashion. A sharp tip is defined in the

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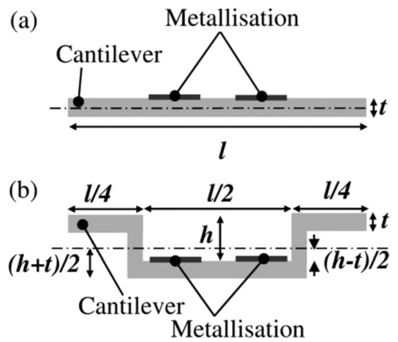

FIG. 1. Schematic diagrams of (a) flat and (b) grooved cantilever cross sections. The dashed lines indicate the neutral planes.

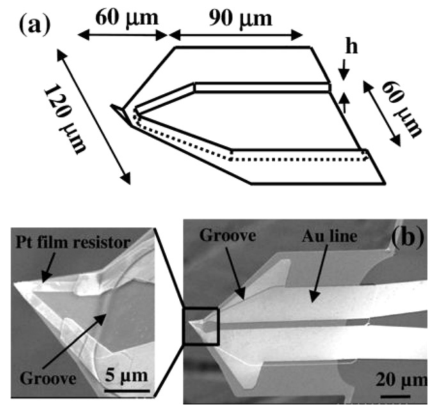

FIG. 2. (a) Schematic layout for the grooved cantilever. (b) SEM images of a fabricated grooved cantilever probe.

silicon nitride cantilever by electron-beam lithography and reactive-ion etching. The thermal sensor material (Pd or Pt film) is then deposited by evaporation over the end of the tip using a lift-off process. As a consequence the end of the tip is covered in metal regardless of any error in alignment between the tip definition and sensor definition lithography levels. Misalignment will make the sensor wider or narrower, changing its resistance, but the essential location of the sensor at the very end of the tip will be preserved. A necessary consequence of this process is that the sensor metal overhangs the silicon nitride tip at an angle of about 20° due to the use of evaporation to deposit Pd or Pt film. As the film builds up in thickness its lateral extent gradually increases as a natural consequence of the mechanism of film growth. Were one simply to evaporate a thermally compensating metal film on the back of the released wafer of probes then the compensating film would make electrical contact to the sensor and short it out. Lithographic constraint of the extent of the compensating film is, of course, impractical on released probes.

However, the reduction of cantilever thermal bending can be realized while still maintaining single-sided metallization using the concept of structural compensation. In this work, a cantilever structure with metallization within a central groove is used as a replacement for a conventional flat cantilever. Figure 1 shows schematic diagrams of the flat and grooved cantilever cross sections, in which the neutral planes of both types of cantilever are shown by dashed lines. For a flat cantilever, the concentrated bending moment is given by $M = \sigma \cdot t/2$, where t is the thickness of cantilever, and σ is the surface stress caused by the metallization. For a grooved cantilever, the distance between neutral plane and the plane of metallization is $(h - t)/2$, where h is the depth of the groove, and the t is the thickness of cantilever. In this case the concentrated bending moment is given by $M' = \sigma \cdot (h - t)/2$. As long as $t > h/2$, $M' < M$, the concentrated bending moment is reduced for the grooved cantilever. In the ideal case when $t = h$, the concentrated bending moment is reduced to zero, and there will be no longitudinal cantilever bending induced by the surface stress.

Based on this concept, the new type of cantilever probe with a central groove was designed and fabricated. Figures 2(a) and 2(b) show the schematic layout of the new cantilever structure, and SEM images of a real fabricated probe, respectively. Apart from the central groove, the width and length of new cantilever are the same as those of commercial SThM cantilever probes. Batch fabrication was carried out on a 380 μm thick 3 in. ⟨100⟩ oriented n type silicon wafer. After micromachining on both sides [Fig. 3(a)] grooves with a depth of 500 nm were produced by photolithography and subsequent CF_4 reactive ion etch [Fig. 3 (b)]. 350 nm of low stress silicon nitride was conformally deposited by plasma enhanced chemical vapor deposition (PECVD) to eventually form the cantilever [Fig. 3(c)]. This thickness is slightly less than that used in commercial flat cantilever probes (400 nm) compensating for the increased stiffness caused by the change in cantilever form. The rest of fabrication process was the same as that used for conventional flat cantilever probes.[4,6] One change, which had no impact on the mechanical performance of the probe, was the use of Pt thin film resistors as a thermometer instead of the Pd used for commercial probes. Pt has a higher melting point than Pd and is expected to withstand the higher temperatures that the new probe is designed for, while exhibiting a similar variation in

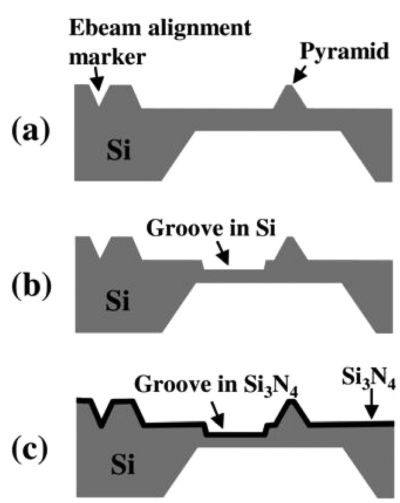

FIG. 3. Schematic diagrams showing the process used to fabricate the central grooves in cantilevers. (a) Top and bottom sides of a micromachined silicon wafer, (b) 500 nm deep grooves produced in silicon by dry etch, and (c) 350 nm PECVD silicon nitride film deposited.

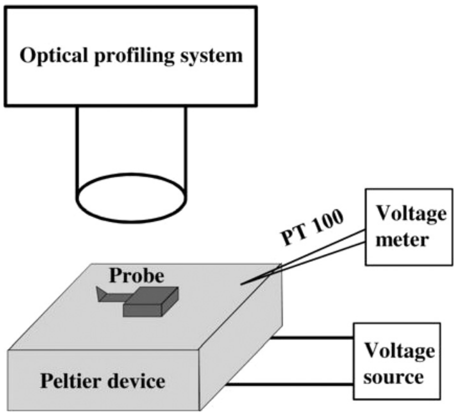

FIG. 4. Schematic diagram of experimental setup for thermal bending measurement.

resistance with temperature. In Fig. 2(b) Pt film resistors, Au connection lines and the groove are all indicated on a real probe.

III. RESULTS AND DISCUSSIONS

A. Thermal bending

The thermal bending of both grooved and commercial probes was measured using an optical profiling system (WYKO NT1100). The experimental setup is shown in Fig. 4. A platform consisting of a Peltier thermoelectric module and an associated PT100 temperature sensing element was constructed for heating the probes to a known temperature. The probe was mounted on top of platform with its tip facing up, as indicated in Fig. 4. Optical profiling images of cantilever probes were taken at various temperatures. Each was taken after the temperature of platform was stabilized. Figure 5 shows the three-dimentional profile image of a commercial probe at 64.7 °C. As the figure shown, cantilever bowing always took the form of the middle bending up and the free ends bending down. In Fig. 5, ΔZ represents the displacement of the free end relative to the highest point in the middle of cantilever, and ΔL is the length between these two points. The normalized displacement $\Delta Z/\Delta L$ at various temperature for both types of probes are summarized in Table I. The bending of the grooved cantilever at 115.6 °C is even less than that of the flat commercial probe at 64.7 °C, indicating that the thermal bending is indeed greatly reduced by the new design.

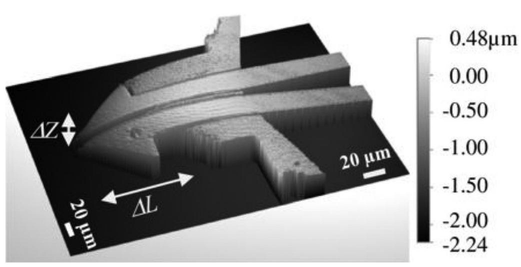

FIG. 5. Three-dimentional profile image of a commercial probe at 64.7 °C.

TABLE I. Normalized displacement ($\Delta Z/\Delta L$) of cantilever free end at various temperatures.

Types of probes	Temperature (°C)	$\Delta Z/\Delta L$
Flat	47.6	9.6×10^{-3}
	64.7	2.1×10^{-2}
	81.4	2.2×10^{-2}
Grooved	47.7	4.1×10^{-3}
	64.1	4.3×10^{-3}
	81.2	1.2×10^{-2}
	115.6	1.6×10^{-2}

B. Spring constant

The decrease in thermal bending for the grooved cantilever is due to mechanical balance of the designed structure rather than an increase in cantilever stiffness. The grooved cantilever would be expected to exhibit a greater stiffness due to its larger second moment of area if its dimensions were identical to those of flat cantilever apart from the central groove. However, in the present case the increase in shape stiffness has been compensated by reducing the cantilever thickness from 400 to 350 nm and by using PECVD silicon nitride instead of denser LPCVD silicon nitride. The spring constants of the two types of probe were measured using the method described by Gates *et al.*[7] They were 0.40 ± 0.02 N/m for the grooved cantilever and 0.35 ± 0.01 N/m for the commercial cantilever, respectively. This result, confirmed by finite element modeling, indicates that the probes are of similar stiffness, showing that mechanical balance plays the major role in reducing thermal bending for the grooved cantilevers.

C. High temperature imaging

To demonstrate high temperature scanning with a grooved cantilever probe, a Digital Instruments Dimension 3000 AFM system was employed to perform a contact mode scan. The setup for thermal scanning is shown schematically in Fig. 6(a), same setup as described by Dobson *et al.*[8] The probe was mounted on a small PCB which replaced the normal tip holder PCB on the microscope [Fig. 6(b)]. The probe was connected as a two-terminal resistance in a Wheatstone bridge with three other fixed resistors. The fixed resistors were precision 0.1% size 0805 resistors selected to have the nearest value to the measured resistance of the probe. The Wheatstone bridge was isolated from the sample by means of two surface mount transformers (Mini-Circuits TC9-1) which are 2.5 mm^2 in extent. Input to and output from the bridge were made via ultraminiature surface mount connectors Hirose type U-FL. The probe, fixed resistors, transformers and connectors were all soldered to the same small PCB which was then mounted in the AFM in the usual way. As a consequence no dc current was able to flow from the sample to the probe during operation. The stray capacitance coupling the probe and associated components to the rest of the experiment was estimated to be a few picofarads only. A particular advantage of this biasing scheme is that the probe tends to float to the same potential as the sample. Thus, the

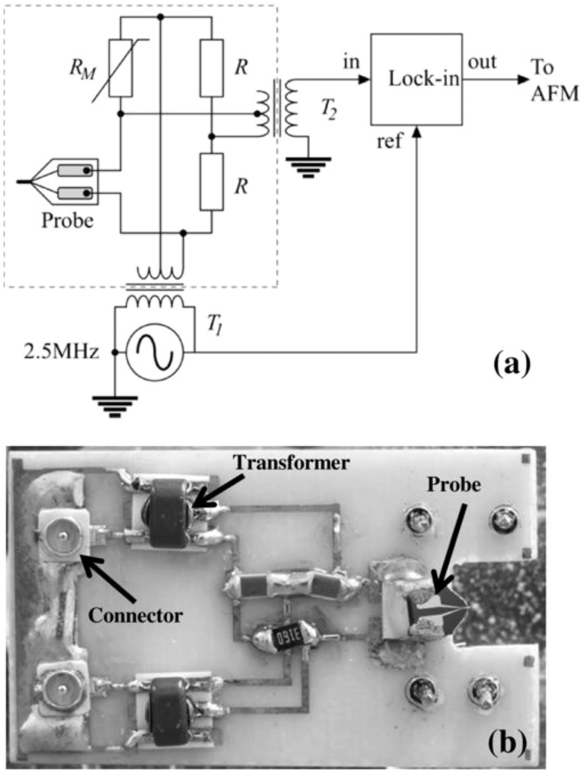

FIG. 6. (a) Schematic diagram showing the electrical arrangement used to bias the probe. The bridge is approximately balanced by selection of fixed resistor R_M. The bridge is matched to the 2.5 MHz oscillator and RF lock-in connections by means of two transformers, T_1 and T_2, which also serve to isolate the bridge from system ground. The probe and the rest of the bridge (the region within the dashed box) are therefore free to float to the dc potential of the sample without affecting the measurement of probe resistance. (b) Photograph of the PCB which replaced the normal tip holder PCB on the microscope.

electrostatic force between probe and sample has been found to be extremely small, independent of the potential of the sample. This is important when scanning over samples biased at high voltages: If an attempt is made to use an insulated coating on the probe, instead of transformer-isolation, it is found that the resulting electrostatic forces have been observed to be large enough to cause significant damage to the sample. Finally the signal from the bridge was demodulated using a home-made RF phase sensitive detector (lock-in amplifier) operating at 2.5 MHz.

In order to obtain accurate temperature mapping, the probe was calibrated using a microfabricated temperature standard based on a measurement of Johnson noise.[9] A sample of sapphire coated with layers of SiO_2, α-Si and 370 nm of nanocrystalline diamond was selected as the substrate. A heater device consisting of a 33 nm thick NiCr resistor with 100 nm thick gold connecting pads was fabricated on top of the sample. The resistance of the NiCr resistor was 166 ohms. A dc bias of 3.9 V s was applied across the NiCr resistor while the probe was scanned over the device. The topographic image and temperature map were obtained simultaneously, and are shown in Figs. 7(a) and 7(b), respectively. It can be seen that the hottest region of the resistor reached 108 °C, as shown in Fig. 7(c). This successful scan demonstrates that even at this temperature the thermal

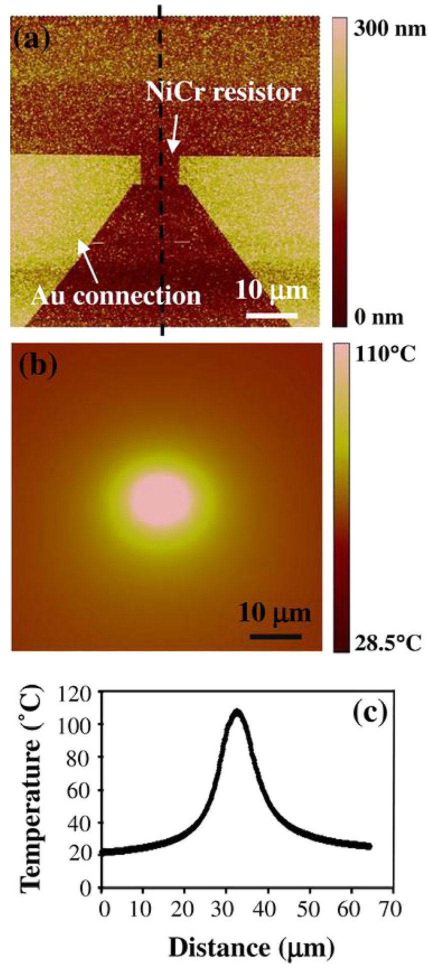

FIG. 7. (Color online) (a) Topographic and (b) temperature map of a heater device. (c) Temperature profile along the center of the device, which is indicated by the dashed line in (a).

bending of the cantilever was within the tolerable range of the AFM. Otherwise, the mechanical contact between tip and sample would be lost and the scan interrupted. This is the case for commercial cantilever probes, making them almost impossible to scan at temperatures higher than 60 °C.

IV. CONCLUSIONS

In conclusion, thermal compensation of the cantilever region of a SThM probe has been shown to allow temperature measurement on high temperature devices with good force control. With a further iteration of the cantilever design it should be possible completely to eliminate this most important limitation on the operating temperature of the SThM technique, allowing its use at very high and also very low temperatures.

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