ULTRACOMPLIANT, PASSIVELY DECOUPLED THERMAL PROBE ARRAYS: LARGE AREA MAPPING OF NON-PLANAR SURFACES WITHOUT FORCE FEEDBACK

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ABSTRACT

This paper describes an 8-probe system for scanning thermal microscopy. The design of the probe array, along with the choice of polyimide as the structural material provides very large compliance that virtually eliminates the need for z-axis mechanical feedback both at the chip and probe level in contact mode scans. The high compliance accommodates significant variations in the sample surface, and also prevents damage to soft samples. In addition, since integrated actuators and accompanying circuitry are no longer required, the prospect of scaling to large numbers of probes for high speed, high resolution thermal mapping of large areas with simple detection circuitry is enhanced. Based on single probes fabricated in the same process, the estimated spatial resolution, thermal conductance resolution, and temperature resolution are 50 nm, 11 pW/K, and 1.2 mK respectively. Scalability and performance of the 8-probe prototype are evaluated, addressing issues of speed vs. resolution, thermal and mechanical decoupling. Results demonstrate that contact mode scans can provide better than 2 μm spatial resolution at speeds greater than 200 μm/sec with each probe.

I. INTRODUCTION

First introduced in 1986 [1], scanning thermal microscopy (SThM) has found a unique place among the several techniques of high resolution scanning microscopy. It permits mapping of topography, temperature, thermal conductivity, thermal capacitance, and performing micro-calorimetry with sub-100 nm spatial resolution [2]. The scanning probe has a thermal sensor (typically a bolometer) at a sharp tip located at the end of a cantilever. Scanning is best performed with the probe in contact with the sample to eliminate the high thermal resistance of an air gap, but this conventionally requires a mechanical feedback loop to prevent the probe from scratching the sample. As in atomic force microscopes, the contact force is sensed by measuring probe deflection with a reflected laser. The desire to increase throughput in scanning microscopy (both SThM and AFM) has prompted the design of arrays in which multiple probe tips scan in parallel [3-8]. With arrays, however, the problem of feedback becomes a difficult issue because parallel scanning requires each cantilever to have its own addressable feedback loop. Individual actuation of cantilevers has been explored, including piezoelectric films [3, 6], and thermal bimorphs [8]. While these approaches are effective for limited variations in topography, they do not easily accommodate samples with micron level topographical variation, such as integrated circuits or biological cells.

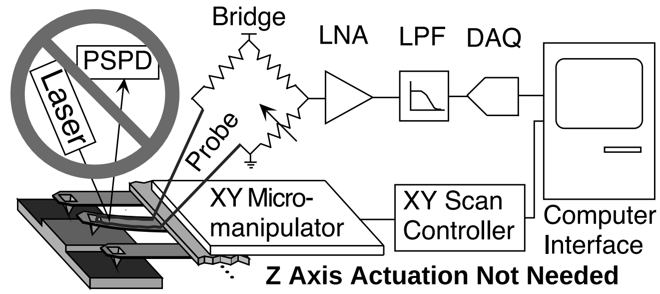

Fig. 1: Z-axis feedback and integrated actuators are not required in the ultracompliant microprobe array presented here. A simple open loop interface circuit is sufficient to bias the probe tip temperature and read the temperature via changes in probe resistance.

Furthermore, all types of integrated actuators require additional fabrication steps, control circuitry, and electrical interconnect, thereby increasing manufacturing and calibration complexity.

In this work we present an ultracompliant probe array that can be scanned across a sample with minimum force without mechanical feedback. The use of polyimide as the cantilever structural material, previously reported by our group, offers not only a high thermal isolation, but a very high compliance [9], resulting in a 10-100x reduction in contact force over conventional materials like silicon and its dielectrics. Consequently, the contact force for each cantilever in the array remains low over a wide range of deflections, eliminating the need for probe level feedback typically required to prevent damage to the sample and the tip. In addition, the structure can be designed in a manner such that the cantilevers are decoupled both thermally and mechanically, enabling high-speed parallel thermal mapping of samples with large topographical variation using simple detection circuitry and no integrated actuators (Fig. 1).

II. DEVICE STRUCTURE AND OPERATION

The structure of the probe array is shown in Fig. 2. Eight cantilevers extend off a single shank overhanging from the edge of the die. To scan a sample, the die is inverted and mounted on a motorized XY scanning stage (Fig. 1). Each probe in the array operates as a typical microbolometer. A thin film metal resistor on the probe tip is used to both heat the tip and detect temperature variations during the scan. The probe is connected to a Wheatstone bridge that provides bias current and senses changes in resistance. A low noise amplifier and low pass filter are used to minimize noise. A PC interface is used for data acquisition and to control the position of the XY scanning stage. As mentioned previously,

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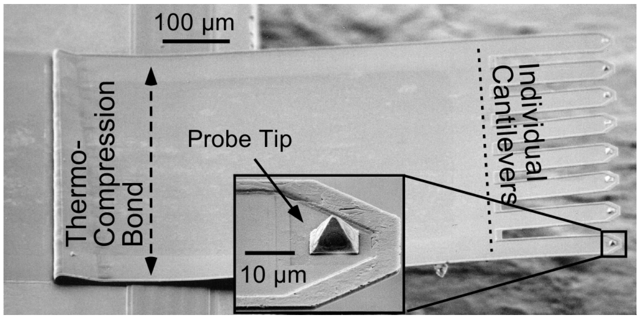


Fig. 2: SEM of the thermal probe array after assembly. Individual cantilevers protrude from a single shank. The entire array is flipped over and held in place in one step.

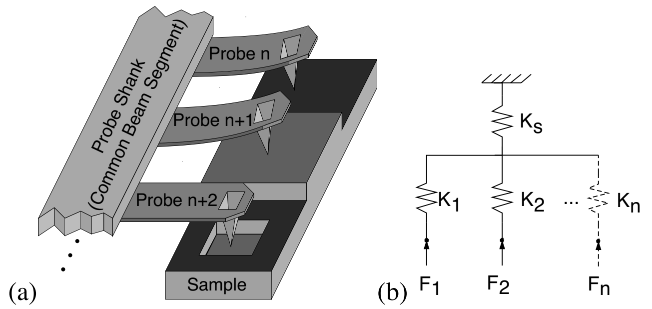


Fig. 3: (a) Schematic showing the conceptual operation of the probe array over a sample with large topographic variation. Each probe deflects vertically without affecting the other probes. (b) First order mechanical model of the array structure. For effective mechanical decoupling, the spring constant of the shank K_S should be large compared to the cantilever spring constants K_1, K_2, etc.

the low spring constant of the polyimide probes, typically 10-100x lower than conventionally used, enables scanning most samples in non-feedback contact mode without damage.

Mechanical operation of the array is depicted in Fig 3a. Ideally, each probe deflects without affecting others. During fabrication however, since all the probes are simultaneously flipped using a common segment of the beam for handling, some degree of coupling is inevitable. Intuitively, the system can be thought of as a simple mechanical network shown in Fig. 3b, with an array of springs representing individual cantilevers coupled to a single spring representing the common beam segment. The precise value of mechanical cross-talk between beams depends on a number of factors, including the design of the beams (i.e. the length and width of the separated segments and the common segments), the pre-deflection of the beams in contact, and the magnitude of attractive surface forces that exist between each tip and the sample. From the viewpoint of the designer, however, it is best to increase the lengths of the separated segments and minimize that of the common segment.

Thermal coupling between adjacent probes can be defined as $\Delta t_{P1}/\Delta t_{P2}$, i.e. the temperature shift in a probe caused by a shift in the adjacent probe. Finite element analysis was conducted in ANSYS, ignoring convection and assuming that the array is held 15 μm above a thermally conductive substrate. The primary path of heat exchange

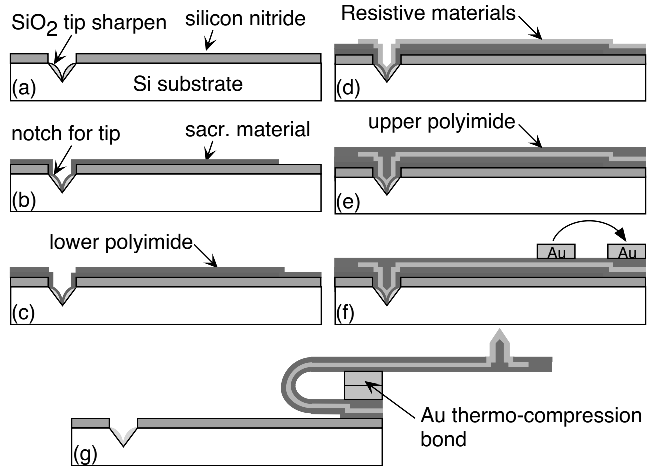


Fig. 4: Process flow for fabricating the polyimide based thermal probe array, suitable for post-IC processing. A tip notch is created, followed by a sacrificial layer, a resistor sandwiched between two layers of polyimide, and a gold layer for thermo-compression bonding. After etching the sacrificial layer, the probe is flipped, resulting in a probe overhanging the edge of the die.

between adjacent probe tips was found to be lateral conduction through air, and the coupling ratio is –24 dB. The factor improves by 10x if the distance between probe tips is doubled to 170 μm.

III. FABRICATION

The ultracompliant probe array is fabricated in a low temperature 7-mask process suitable for post CMOS fabrication. Shown in Fig. 4, the process consists primarily of surface micromachining with an additional thermocompression bonding step.

A mold for the tip structure is first created by anisotropic etching of silicon followed by an oxidation step for tip sharpening (Fig. 4a). Sacrificial titanium deposited below the cantilever structures facilitates release of the cantilevers

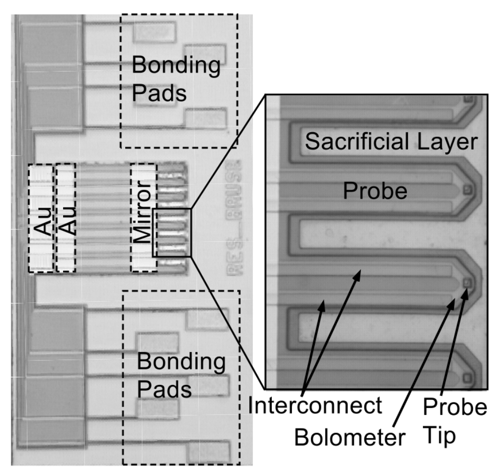
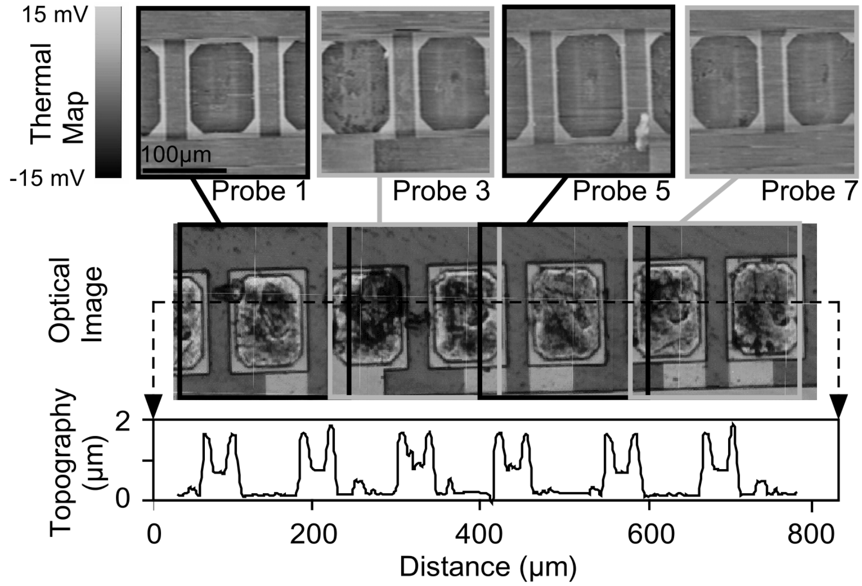


Fig. 5: Photograph of the thermal probe array before the flip-over step. The interconnect is a thick metal line to reduce the series resistance to the thin-film bolometer. The two gold regions mate when performing the thermo-compression bond.

Fig. 6: Reconstruction of a thermal image by combining overlapping scan regions. Shown here is a 750 μm x 200 μm area on a commercial IC containing 60 μm x 85 μm bonding pads with 120 μm pitch. (Top) Thermal images obtained from four probes spaced 170 μm apart scanning at 25 μm/sec. (Middle) Optical image. (Bottom) Horizontal line scan taken with a surface profilometer showing 2 μm topographical features between bond pads. In this scan, the thermal image conveys primarily topographical information, with sensitivity of 12 mV/μm, dynamic range greater than 2 μm, and a noise limited minimum detectable topography of 80 nm.



(Fig. 4b). The cantilever itself is formed by two polyimide layers (HD Microsystems P2613) with two metal layers embedded within. The first layer of polyimide is etched from the tip region to permit the metal tip (to be formed next) to contact the sample (Fig. 4c). A thin metal layer is then deposited in the mold to form both the metal tip and the resistor. A second, thicker metal layer forms electrical interconnection to the probe tip (Fig. 4d). The top layer of polyimide is used to insulate the metal and provide strength to the probe tip (Fig. 4e). Thick gold patterns are deposited after the second polyimide layer for thermocompression bonding (Fig. 4f). After release of the cantilevers in HF, the probe shank is flipped over and bonded at 200° C (Fig. 4g), resulting in a probe shank overhanging the edge of the wafer die (Fig. 2).

IV. EXPERIMENTAL RESULTS AND DISCUSSION

To validate the functionality of the probe array, a 750 μm x 200 μm area was scanned on a commercial IC containing bond pads. Four of the eight probes in the array were used, each generating a 200 μm x 200 μm image consisting of 100 lines scanned at 25 μm/sec. Raw data was subject to standard signal processing to remove scan artifacts such as linear trends, and filter out high frequency noise. Scan results (Fig. 6) illustrate how a thermal image may be reconstructed by merging overlapping scan regions. All measurements made over the 2 μm of topographical variation were obtained without force feedback.

With throughput being the main motivation behind arrayed probes, it is of interest to gauge the scan speed at which features can be resolved. Two 7 μm deep anisotropically etched silicon trenches coated with polyimide and gold were scanned at increasing speeds. Line scans in Fig. 8 reveal an observable feature of about 2 μm can be resolved at speeds up to 200 μm/sec. (In fact, 10 μm features can be resolved even at 2 mm/sec). The effective scan speed, which scales with the number of probe tips, is 1600 μm/sec for the 8 probe prototype. This suggests that a 1.5mm x 1.5mm IC with 2 μm minimum features can be imaged in approximately 12 minutes. However, to put this in perspective, it is also necessary to consider dynamic range, because most high throughput micro-probe systems [4,6] are not intended for mapping samples with wide surface variations.

Dynamic range and topographical resolution is demonstrated from the line scans in Fig. 7. Because this structure is coated with a thin gold layer of uniform thickness, it is expected that the thermal signal obtained will convey primarily topographical characteristics. The signal obtained is approximately linear with respect to topography. Using a 12 mA bias current, a 90 mV contrast is obtained over a 7 μm topographical variation, indicating a sensitivity of 12 mV/μm. Observed noise voltage is 1 mV, translating to a minimum detectable signal (MDS) of approximately 80

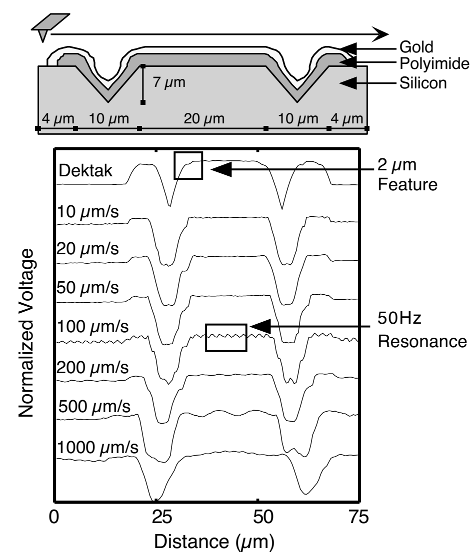


Fig. 7: Speed scaling study. Two 7 μm pits coated with polyimide and gold were scanned at increasing speeds. A 2 μm feature (labeled) is observed at speeds up to 200 μm/sec. Mechanical resonance at 50 Hz was observed at speeds above 100 μm/sec.

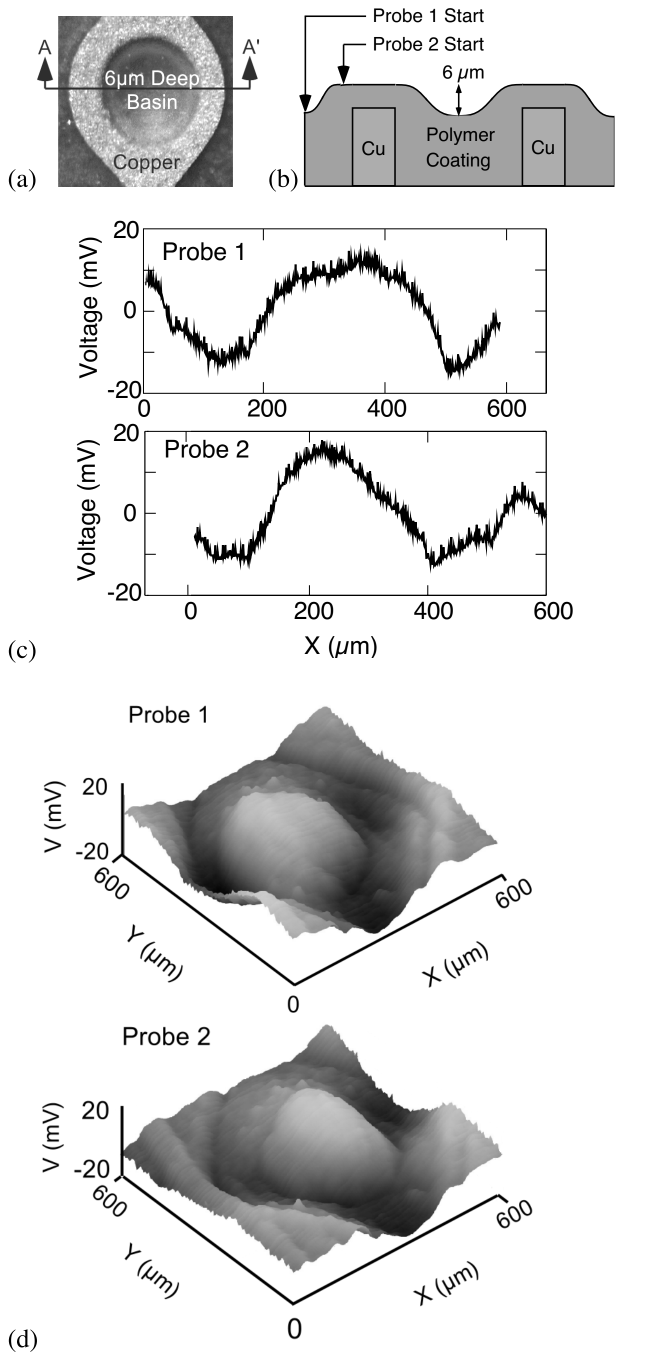


Fig. 8: Mechanical decoupling. (a) Optical image and (b) A-A' cross section of a via with 6 μm topography. (c) Line scans taken simultaneously from two thermal probes spaced 85 μm apart. (d) Two dimensional thermal images obtained from the two probes simultaneously.

nm. The probe, therefore, permits scanning with 6.5-bit resolution over a 7 μm dynamic range. This range is 10-100x higher than typical thermal probe arrays aimed at data storage applications.

Mechanical decoupling between adjacent probes was verified by imaging a via on a printed circuit board with a 6 μm depression simultaneously with two probes spaced 85 μm apart. Figure 9 shows that both probes obtain a thermal image independent of one another. Although the images are not identical (variation in tip resistance and tip wear can cause difference in the obtained signal), it is clear that the movement of probe 2 into the basin does not affect the signal of probe 1. The line scan as well as the 2-dimensional maps support a strong degree of mechanical decoupling over a 6 μm topography.

V. CONCLUSIONS

This effort has demonstrated that a mechanically decoupled 8-probe array can be used for parallel, high-resolution thermal mapping of features with large topographical variation without force feedback. Elimination of feedback is enabled by using ultracompliant probes that minimize contact force, preventing damage to both the tip and fragile samples. In non-feedback mode, 2 μm lateral features were resolved at speeds up to 200 μm/sec per probe, and 10 μm features can be resolved even at 2 mm/sec. Noise limited minimum detectable signal (MDS) for topographical variations was found to be 80 nm, and the dynamic range is > 7 μm. If feedback is used, single probe versions developed previously by the same technology [9] obtain an MDS of 1 nm.

ACKNOWLEDGEMENTS

The facilities used for this research include the Solid-State Electronics Laboratory at the University of Michigan.

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