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Piezoresistive Probe Array for High Throughput Applications

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Abstract

Microcantilevers are used in a number of applications including atomic-force microscopy (AFM). In this work, piezoresistive deflection-sensing elements are integrated onto micromachined cantilevers to increase sensitivity, and reduce complexity and cost. An array of probes with 5nm gold ultrathin film sensors on silicon substrates for high throughput scanning probe microscopy is developed. The gauge factor of the piezoresistive sensor is 3.16 ± 0.05 and the deflection sensitivity is 0.2 ppm/nm. Plots of the change in resistance of the sensing element with displacement are used to calibrate the probes and determine probe contact with the substrate. Topographical scans demonstrate high throughput and nanometer resolution.

Keywords: microcantilevers; atomic force microscope; scanning probe array; piezoresistive sensing; parallel imaging.

1. Introduction

Microcantilevers are used in a number of applications including atomic-force microscopy (AFM) [1]. Piezoresistive deflection-sensing elements are integrated onto micromachined cantilevers to increase sensitivity, and reduce complexity and cost. These sensing elements are made by selectively doping silicon [2], or by depositing metal or metal oxide films on cantilevers such as gold [3, 4]. Compared with doped-silicon sensing elements, deposited metal film elements have important advantages including simplified fabrication, a lower manufacturing cost, and the capability to scale down to smaller dimensions while maintaining sensitivities. Metallic sensing elements enable the use of alternative substrate materials (such as polymers), that tend to exhibit higher compliance properties and improved thermal isolation. Ultrathin metal film sensing elements with thickness less than 10nm have increased piezoresistive sensitivity [5]. Microcantilevers with metal film elements have been used as microheaters [6] and for scanning thermal microscopy [7]. Ultrathin metal films exhibit higher thermal coefficient of resistance [8]. Using metal sensors is relatively simple to expand to a one or two dimensional probe array for higher throughput multi-location measurements overcoming AFMs throughput limitations. Higher throughput is very important in many applications ranging from failure analysis and production applications (where entire wafers or large areas need to be examined in relatively short time) to biological applications.

The probe arrays described in this paper include a monolithic integration on each cantilever of a heating element (which can also be used for temperature sensing) and a deflection (or displacement) sensing element. Gold films of 5nm thickness were deposited on a silicon cantilever to form both sensing elements. The probes operate without the need of an optical lever required by AFM systems. In addition, the probes have a very large

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dynamic range of tens of micron. This paper is an expansion of prior work on single cantilevers with monolithically integrated displacement sensors and micro heaters/thermal sensors for melting point measurements and thermo-mechanical analysis [6], material characterization of mechanical properties [9], and scanning probe microscopy [9].

2. Device fabrication

The device is fabricated in a process described in Fig. 1. The process starts with a silicon-on-insulator (SOI) wafer. A thermal oxide masking layer is deposited and patterned for the probe tip. The tip is formed using timed KOH anisotropic etching. The oxide mask is then removed and the tip is sharpened with several oxide sharpening steps. A 100 nm-thick silicon oxide is thermally grown on the wafer to provide electrical insulation. The cantilever is patterned on the front side of the wafer with the Bosch deep reactive-ion etching (DRIE) process. Metal lines are evaporated and patterned on top of the cantilever structure with lift-off process to form the sensing elements. The thicknesses of the metal layers are measured during the evaporation and the variation is within ±10%. The chip is then shaped by a back side DRIE process with an etch rate of 3 µm/min. The buried oxide layer of the SOI wafer acts as an etch stop to prevent the back side DRIE from attacking the Si cantilever structures. Finally, the probes are released by removing the buried oxide layer using buffered HF etchant.

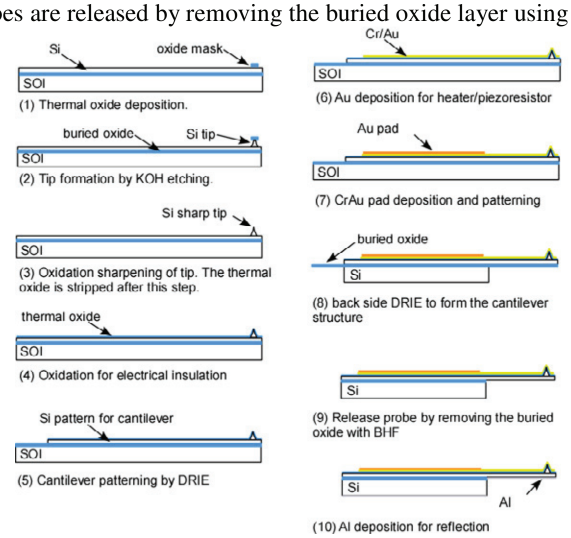

Fig. 1. Process flow for fabricating the probe array.

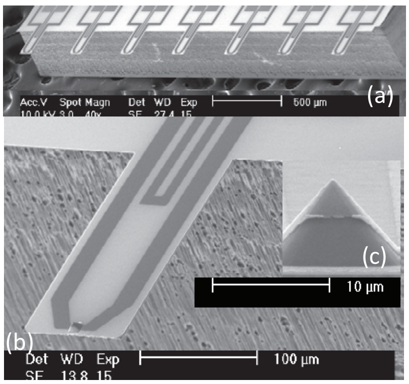

Fig. 2. (a) SEM of the probe array. (b) Individual cantilevers include two resistors, one over the tip serving as a localized heater/thermal sensor and a second closer to the base serving as a piezo-resistor for deflection measurements. Inset (c) SEM close-up of the tip.

Figure 2 shows the probe array developed. The design includes two sensing elements on one cantilever, each of which consists of a 5nm gold film located on a silicon cantilever. The resistor covering the tip area forms a micro-bolometer and the resistor near the base of the cantilever forms the deflection sensing element. The rectangular cantilever is 100 µm wide, 200 µm long, and 2 µm thick. The resulting cone shaped tip has a 100nm diameter and 7.5 µm high.

3. Experimental results and discussion

The resistances of the active elements used for these measurements are 433 Ω, 413 Ω, 409 Ω, and 406 Ω respectively. The noise spectrum of the sensors is measured with a built-in battery-based power source in a low-noise current preamplifier (Stanford Research Systems SR570). The output voltage of the current preamplifier is then fed into a spectrum analyzer (Agilent 4395A) for noise measurement. The noise spectrum of the sensors is found to be dominated by Johnson noise in the whole spectrum.

Figure 3 shows a method to determine contact by monitoring the probes optically through a high resolution microscope. As soon as the probes come in contact with the sample their reflection changes.

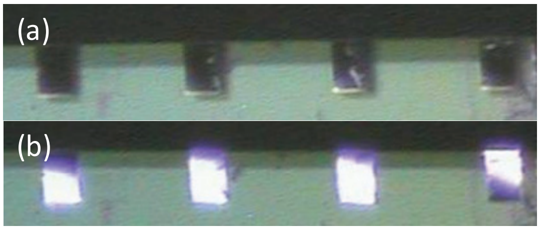

Fig. 3. Picture of four probes (a) before contact and (b) after contact.

The change in resistance of the sensing element with cantilever deflection is directly measured using a micro-Ohm meter (Agilent, HP-34420A), without the need of an interface amplifying circuit. The data is acquired with a LabView program. A piezoelectric XYZ stage with 100 μm range and nanometre resolution on each axis (PiezoJena, Tritor 100) is used to move the sample underneath the probe.

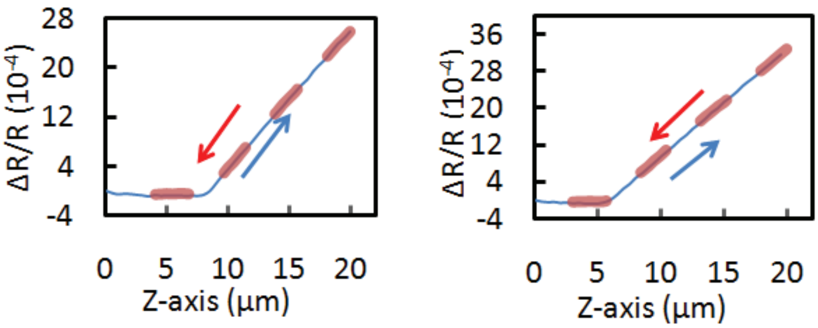

Fig. 4. Force-curves of probe 1 and probe 2 on a glass substrate.

Force-curves can be used to determine probe-sample contact and to calibrate the probes. In figure 4 the arrows indicate the direction of the movement. The blue line represents the trace (probe and sample moving toward each other) and the red dashed thick line represents the re-trace (probe and sample moving away from each other). The vertical axis is the change of the resistance of the resistor measured with a multimeter and the horizontal axis is the Z-axis movement toward and away from the sample measured with the piezoelectric stage. From the curves, the deflection sensitivity of both probes ((ΔR/R)/deflection) is calculated to be 0.2 ppm/nm. From [9, 10] and the experimental data, the average gauge factor is calculated to be 3.16 ± 0.05.

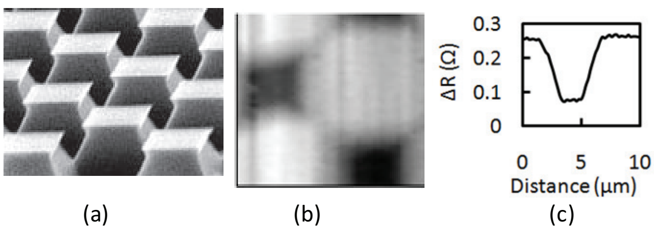

Fig. 5. *(a)* SEM of 10 μm pitch square grating with 1 μm height. (b) A high resolution 10μm x 10μm area scan. The probe moved in 0.2 μm steps in the X direction and 0.4 μm in the Y direction. (c) Line scan of (b).

Figures 5b and 5c show a 10µm x 10µm area scan and a 10µm line scan over the top surface of a 10 µm pitch square grating with 1 µm height. The curves in Fig. 5b and 5c are plot of the change in resistance, ΔR/R, vs. the in-plane (XY plane) movement, and show the scanned surface profile of the grating. In figure 5b the probe moved in 0.2 µm steps in the X direction and 0.4 µm in the Y direction. The change in resistance of the sensing element with cantilever deflection is directly measured using a micro-Ohm meter. Eliminating the need for an optical lever is particularly useful when an array of probes is used to increase throughput like in Fig. 6. In Fig.6 unprocessed data of 40µm x 40µm area scans acquired by 4 different probes scanned over the 10 µm pitch square grating are shown. The probes moved in 1 µm steps in the X direction and 1 µm in the Y direction. Indicative line scans for each probe are shown.

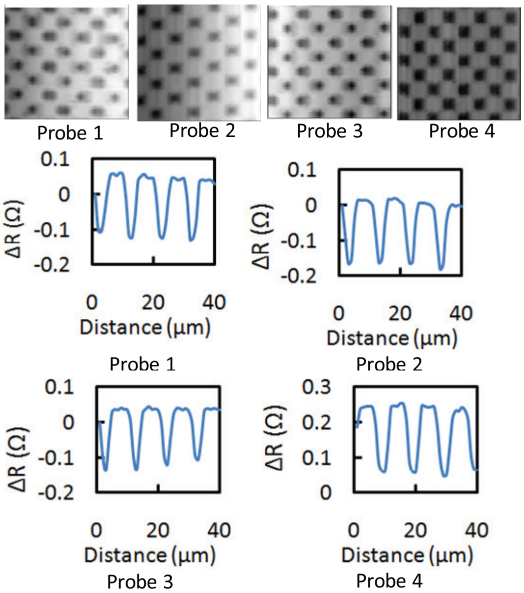

Fig 6. A 40µm x 40µm area scan acquired by 4 different probes scanned over the 10 µm pitch square grating.

4. Conclusions

In conclusion, an array of probes with 5nm gold ultrathin film sensors on silicon substrates for high throughput scanning probe microscopy are described. This is a continuation of our previous work [6, 9]. The gauge factor of the piezoresistive sensor is 3.16 ± 0.05 and the deflection sensitivity is 0.2 ppm/nm. Plots of the change in resistance with displacement are used to calibrate the probes. Topographical scans demonstrate high throughput and nanometre resolution.

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