Investigating material and functional properties of static random access memories using cantilevered glass multiple-wire force-sensing thermal probes

Rimma Dekhter, Edward Khachatryan, Yuri Kokotov, and Aaron Lewis
Division of Applied Physics, The Hadassah Laser Center, Department of Ophthalmology and The Neural Computation Center, The Hebrew University of Jerusalem
Sophia Kokotov, Galina Fish, Yefim Shambrot, and Klony Lieberman
Nanonics Imaging Limited, Jerusalem, Israel

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A double-wire cantilevered glass probe has been produced for scanned probe microthermal, resistivity, and topographic measurements. The structure has many potentially unique properties for scanned probe microscopy and other nanotechnological measurements. In this letter, a double Pt wire probe was fused at the tip and applied to thermal resistive measurements. The probe operation is based on the linear dependence of Pt resistance on temperature. Most microscopic structures are composed of a variety of materials. In the present study, the features of a static random access memory chip are investigated. Such memory chips are composed of materials such as dielectrics, metals, and semiconductors. We demonstrate that these samples, which are prepared using a chemical–mechanical polishing procedure and have essentially no surface topography, can be inspected using the thermal conductivity, resistivity, and topographic sensitivity of these probes.

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Thermocouple and resistance thermometries have been traditionally used for thermal gradient measurements. The first combination of such measurements with scanning probe microscopy was reported in 1986. This probe was based on the use of scanning tunneling microscopy. Specifically, the tunneling current that was measured was altered as a result of the use of scanning tunneling microscopy. The concept of Harootunian technology was initially used in scanned probe microscopy since it was first introduced by Harootunian et al. To adapt this approach for such thermal conductivity measurements we use a theta capillary in which metal wires are inserted into each of the channels of the capillary. Subsequently, the pulling technology of Harootunian et al. is used to taper simultaneously the glass/metal wire combination. The isolated wires in the glass channels are exposed by an etching procedure and fused together by heating. The resulting structure was bent using glass cantilevering technologies that were introduced by Shalom et al.

A probe produced by such a procedure has several ad-

4Electronic mail: lewisu@vms.huji.ac.il
vantages. The sensitive, resistive element of this probe is a platinum wire, which is tapered with the glass. The wire extends out of the glass for a dimension of only 3–10 μm and the wires can then be fused for the measurements reported in this letter. The surrounding glass protects the wires from external influences such as alterations in the ambient environment. Only the small protruding tip acts as a thermal sensor, and thus these structures provide for very stable measurement conditions. The wire fusion technique produces a structure that is more stable under scanning conditions than the probes produced by thin-film deposition techniques, and this significantly extends the lifetime of such probes. The pure platinum used for these probes has a linear dependence on temperature, and such pure platinum is used for precision macrothermometers. Since the diameters of the protruding wires are about 100 nm, high image resolution can be obtained. As has been demonstrated previously, such glass cantilevering technology can be amended to produce a variety of force constants and resonance frequencies with such frequencies being as high as 500 kHz. Thus, they are ideal for all the standard methodologies of AFM that are in use today. The high resonance frequencies of these probes allow intermittent contact modes to be employed for the investigation of soft samples. All these properties make this probe a very sensitive, stable, and precision element for AFM and nanothermal measurements.

For such double-wire probe fabrication, borosilicate theta capillaries with an outer diameter of 1 mm were used (Hilgenberg GmbH, Germany). Platinum wires 25 μm in diameter (GoodFellow Cambridge Ltd., Cambridge, U.K.) were inserted into each of the two channels of the capillary, and the combination was pulled in a Sutter P-2000 pipette puller (Sutter Instruments, Inc., Novato, CA) to a small tip with a diameter of about 100 nm. The process of pulling includes three steps: the glass tube pulling, the fusion of wires into glass, and the pulling of the fused glass/wires together.

In order to produce a sensitive element, the glass on the tip was removed by etching in HF, so that the two thin Pt wires with a diameter of about 100 nm were exposed out of the tip to a length of about 3–10 μm. The distance between the wires is 200–1000 nm. The process of pulling includes three steps: the glass tube pulling, the fusion of wires into glass, and the pulling of the fused glass/wires together.

In order to produce a high refractive surface for the feedback control the cantilever of the probe was coated with gold. The cantilevered probe was then mounted on a special tip mount

![FIG. 1. Overview of the fabrication of a double-wire thermal resistive probe.](image1)

![FIG. 2. (Color) (a) Chemically mechanically polished SRAM AFM topographic image. (b) Simultaneously obtained thermal conductivity image. (c) Near-field scanning optical microscope image of a similar region of the SRAM as in (a) and (b).](image2)

![FIG. 3. (Color) (a) Resistivity image of a region of the SRAM. (b) Thermal conductivity image simultaneously with the image in (a). (c) Topographic image simultaneously obtained with the images in (a) and (b).](image3)
for placement in a Nanonics NSOM/AFM 100 confocal system (Nanonics Imaging, Ltd., Jerusalem, Israel) scanned probe microscope.

Such probes with a resistance of 30 Ω and a wire diameter of about 150 nm were used in our experiments. In this probe a variation of 1 °C in temperature corresponded to a variation of the probe resistance by 0.1 Ω. For the scanned probe microscopy (SPM) measurements, a homebuilt signal amplifier was connected to an RHK control system (SPM 1000, RHK Technology, Inc., Rochester, MI). The thermoresistor was then placed as one of the legs in the bridge. The time response of the amplifier was 0.4 ms.

A constant current of about 4 mA was passed through the probe and this heated the sensitive resistive wire at the tip. The probe was brought into contact with the test sample and the heat flow passed into the sample surface. During scanning across the surface, the probe cooled faster in a region with higher thermal conductivity. The resistance of the probe was changed by this cooling and these variations were detected by the control system.

The goal of our experiments was to show the tip operation on a polished sample surface in order to avoid any artifacts that corresponded to a variation of contact area as a result of scanning a sample that was not essentially flat. A static random access memory (SRAM) chip polished by the chemical–mechanical polishing (CMP) method provided an ideal and interesting example of the capability of our probe. The SRAM in question was produced with 0.18 μ design rules and contained areas of Al and W metallic regions, polysilicon, and silicon-oxide materials. All these materials have a different thermal conductivity. The thermal conductivity of Al is 237 W/m/K, the thermal conductivity of W is 177 W/m/K, and the thermal conductivity of SiO2 is 1.4 W/m/K.

The results of our measurements are shown in Fig. 2. These thermal and topographic images of a 40×40 μm scan area were recorded with 10 ms integration per point. Because of the CMP process this contact AFM topographic image is very flat without any features, even though the thermal image exposes underlying features of the chip with different thermal conductivity. These results prove that this thermal image is independent of contact area variations and demonstrate that the probe has mapped the thermal conductivity variation only. For comparison, a reflection near-field scanning optical microscope (NSOM) image obtained with the same instrument is displayed in Fig. 2(c). The NSOM image corresponds to the underlying titanium silicide (TiSi) region of the SRAM in which TiSi is sitting on tungsten plugs. The round structures in the NSOM image correspond to the bright regions in the thermal conductivity image. The surrounding dark region in the conductivity image corresponds to silicon oxide.

The same measurements were done on different regions of the polished chip. The structures varied because the polishing of the chip is done at an angle relative to the chip surface. Hence, by placing the tip accurately at different points in the polished surface, different layers of the chip were detected. This was readily accomplished since the SPM we were using can be placed on the stage of a standard upright microscope where the far-field image and the tip can be simultaneously viewed. We found that not all regions of the chip were polished as flat as the region imaged in Fig. 2(a).

In order to get complimentary information on the chip structure and the connection between the layers, resistivity images were simultaneously recorded with the thermal and topographic images. For the resistivity signal, a lock-in amplifier was applied to the probe and to the chip. The magnitude of the ac signal was 2.5 V and the frequency was 80 kHz. The ac current passed perpendicularly through the chip surface. Hence, structures connected with the layers were detected. Figure 3 shows the results of this investigation.

The thermal image demonstrates features with different thermal conductivity. Brighter regions have a higher thermal conductivity. To guide the reader, a cross has been inserted in a location that is approximately equivalent in each of the images. The resistivity image indicates those regions of the surface that are connected to other parallel layers in the circuit. The topographic image shows regions of the surface where the underlying features are protruding. Interestingly, a rather flat region in the topographic image correlates with a relatively high region of resistivity. The same region in the thermal image is brighter than the immediate surroundings, which have a very low thermal conductivity and, therefore, appear black.

In conclusion, these advanced thermal probes allow us to obtain comparative information about the functional structure of a sample like the memory chips investigated in this letter. In addition, this technique provides complimentary information where the AFM topography indicates little or no topography. In addition, in terms of scanned probe microscopy, these double-wire force-sensing structures offer many opportunities for interesting probes including stable thermocouple structures with, for example, Au–Pt double-wire elements. We have been able to produce such thermocouples and future work will test the characteristics of such thermal elements. In general, these results indicate the flexibility of glass pulling technologies to produce a variety of interesting structures for scanned probe microscopy.

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