Scanning thermal microscopy probe capable of simultaneous electrical imaging and the addition of a diamond tip

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Abstract. Scanning Thermal Microscopy (SThM) is a scanning probe technique that allows the mapping of the thermal properties and/or temperature of a substrate. Developments in this scanning probe technique are of great importance to further the study of thermal transport at the micron and at the nano scale, for instance to better the understanding of heat transport in nano-electronic devices or energy transfer in biological systems. Here we describe: 1) the scanning technique developed to acquire simultaneous images of the topography, the thermal and electrical properties of the substrate using a commercially available Veeco SThM probe; 2) how the SThM probe was modified by mounting a micron-sized diamond pyramid on its tip in order to improve the probe’s lateral resolution and the topography resolution tests on the performance of the modified probe.

1. The Veeco Thermal Probe

The Veeco thermal probe [1] (see Fig. 1) is made of a Wollaston wire: a 75 μm diameter wire made of Silver (Ag) with a 5 μm diameter core made of 90% Platinum and 10% Rhodium alloy (Pt90/Rh10). At the tip of the probe the Ag casing is removed and the Pt/Rh core is exposed, this tip is used as a resistive heater. The probe is one of the legs of a Wheatstone bridge (see Fig. 1). A feedback loop adjusts the voltage applied to the bridge in order to keep the probe at a constant temperature (by keeping it at a constant resistance). The total amount of heat lost by the self heating thermal probe (Q) is measured by monitoring the voltage needed to balance the bridge (V_{out}) using the equation:

\[ Q = \frac{R_p}{(R_1 - R_p)^2} V_{out}^2 \]  

(1)

where \( R_1 = 20 \Omega \) and \( R_p \) is the probe’s resistance defined as:

\[ R_p = R_o [(T - T_o) \alpha + 1] \]  

(2)

where \( R_o \) is the probe’s resistance at temperature \( T_0 \) and \( \alpha \) is the temperature coefficient of resistance for Pt90/Rh10 which is 0.00165 K^{-1}.

The operating temperature of the thermal probe is set by regulating the resistance \( R_C \) in the Wheatstone bridge according to the equation below (\( R_l \) is the leads’ resistance):

\[ T = \frac{1}{\alpha} \left[ (R_C - R_l)/5R_o - 1 \right] + T_o \]  

(3)
2. Experimental Set-up

The Veeco thermal probe was mounted on a modified Veeco Explorer AFM [2,3]; the experimental set-up is shown in Fig. 2; an AC current is applied between the thermal probe and the substrate and the voltage is measured using a lock-in amplifier. In this way the electrical and thermal properties of the substrate can be monitored simultaneously during the scan.

The substrate used for the scans was made out of a ~30 nm thick gold layer on glass, the structures were cut using a focused ion beam (FIB). These materials were chosen in order to produce a high contrast for the electrical and thermal scans. Two devices were made: a bar structure and a meander (see Fig. 3).
3. Results
In Fig. 4 are shown the simultaneous electrical, thermal and topography scans obtained on the bar structure shown in Fig. 3. The scans were taken at room temperature and pressure.

A high voltage in the thermal scan implies a large thermal conductance (proportional to the square of the voltage output $V_{\text{out}}$ – see equation (1)). In the electrical scan a high voltage implies a large electrical resistance.

In Fig. 5 are shown the electrical, thermal and topography scans obtained on the meander structure. The actual meander is visible in the topography only, this is most probably due to damage to the contacts between the meander and the electrodes during FIB cutting. The contrast observed in the thermal scan is due to the change in contact area between the tip and the substrate as the probe scans over the edge of meander. The electrical and thermal resistance values of two different regions of the substrate are calculated from the voltage readouts in the scans.

Figure 4. Simultaneous thermal, electrical and topography scans.

Figure 5. Simultaneous thermal, electrical and topography scans on the meander structure (taken at room temperature and pressure).
4. The addition of a diamond tip

In order to improve the lateral resolution of the thermal probe, a diamond pyramid was added to its Platinum-Rhodium tip. Diamond was chosen because of its high thermal conductivity and its hardness.

Micron-sized diamond crystals were taken from a diamond paste and cut with an FIB and the diamond pyramid was welded onto the Pt/Rh wire of the Veeco thermal probe using tungsten FIB deposition. A scanning electron microscope (SEM) image of the diamond pyramid welded onto the thermal probe is shown in Fig. 6.

Topography tests were done using the thermal probe with the diamond pyramid on a 3 μm and a 1 μm pitch calibration standard but there was no marked improvement in the resolution (see Fig. 7).

![Figure 6. SEM images of the diamond pyramid mounted on the tip of the Veeco thermal probe.](image)

![Figure 7. Testing the resolution of the diamond tip: 20 μm contact mode scans on a 3 μm grid.](image)

5. Conclusion

The scanning technique developed to acquire simultaneous images of the topography, the thermal and electrical properties of the substrate was tested on bespoke gold on glass structures. This technique was shown to work successfully and has great potential even though its resolution is at present limited to micron-sized features.

A pyramid diamond tip was successfully welded on the Platinum-Rhodium wire of the thermal probe and no damage to the tip or the welding was observed after prolonged scanning. However, topography tests on the resolution of the modified probe revealed no obvious improvement. This is most probably due to the high stiffness of the thermal probe (the nominal value of its spring constant is 5 N/m), which causes the Pt-Rh wire to bend when the diamond pyramid comes in contact with the substrate. Therefore further modifications to the thermal probe will be needed to extend the capability of simultaneous electrical, thermal and topography imaging to the nanometer scale. These will be aimed at nanofabrication of a thermocouple or resistance thermometer on an AFM tip (see e.g. [4,5]).
6. References

[1] Veeco Thermal probe details may be found at http://www.veeco.com/products/details_options.php?cat=1&sub=1&oid=66.
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