High Resolution Thermal Microscopy

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Abstract

A new high resolution thermal microscope has been demonstrated capable of imaging thermal fields with sub 1000 angstom resolution. It is based upon a non-contacting near field thermal probe. The thermal probe consists of a thermocouple sensor on the end of a tip with sub 1000 angstrom dimensions. The probe tip is scanned in close proximity to a solid or liquid surface and the local temperature is mapped with a resolution determined by the size of the tip. Material independent surface profiling has also been demonstrated with the thermal probe, providing a lateral resolution of approximately 300 angstroms. Temperature mapping and surface profiling results are presented on both electronic and biological materials.

Over the past few years , there has been considerable activity in the field of photoacoustic and photothermal microscopy. These activities have primarily concentrated on mapping the thermal properties of samples (such as the heat diffusivity and conductivity[1]) and imaging sub-surface features[2,3]. A typical scheme employed in these imaging systems is to use a focused and modulated laser beam to heat the sample and some sort of focused probe such as a laser[4-8] an infra-red detector[9] , or an acoustic lens[10], to detect directly or indirectly,the temperature fluctuation induced in the sample. An image is formed by scanning the sample in a raster fashion and recording the probe signal as a function of lateral position in a scan synchronised computer display.

In order to achieve a high spatial resolution in these systems, it is necessary to either work with a focused probe, a focused detector, or both. To date, the resolution[11] of these approaches is limited either by the probe size, (which at best is around one micron; for most cases limited by the optical wavelength) or by the source size which in the case of optical probes will again be limited to around one micron. One might expect to do somewhat better with an electron source; however,in most practical situations the effective source size with electron heating is limited by electron diffusion in the sample to around one micron. This paper is concerned with a new thermal microscope which has increased this spatial resolution by an order of magnitude.

In the following sections, we present the principle of operation of the new thermal microscope and describe it's experimental demonstration. Results on conducting, insulating and biological materials are then reported and finally a brief summary is made.

Principle of Operation

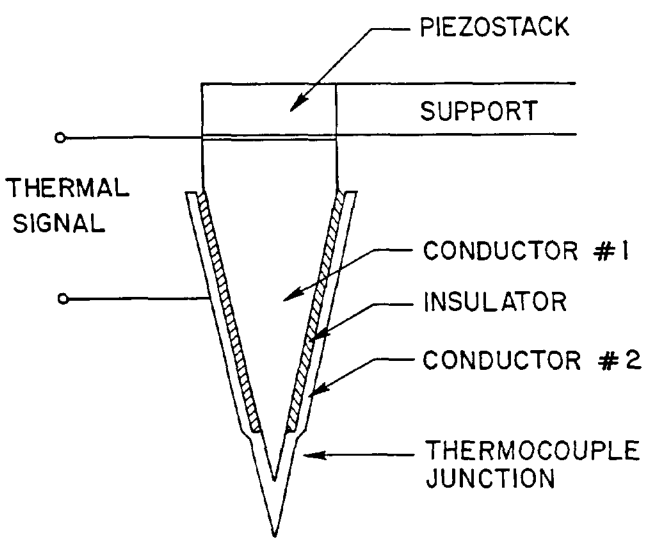
The results of the Scanning Tunneling Microscope (STM)[12] have vividly demonstrated that extremely high spatial resolution can be achieved by a scanned imaging system composed of a very fine tip which interacts with a surface through some physical process. Under this condition, a resolution can be achieved which is limited only by the size of the tip used. This principle is the basis for the work presented here. The thermal interaction between an ultra small thermal sensor and a surface provide the means for the independent mapping of both the surface temperature and the surface topography, with a lateral resolution determined by the tip size.

The mapping of surface temperature can be simply achieved by scanning the ultra small temperature sensor across the surface to be imaged. The spatial resolution of the temperature map is limited by the greater of either the tip size or the gap between tip and surface. If the tip size and the gap are below 1000 angstroms, the surface temperature can be mapped with sub 1000 angstrom resolution.

The thermal microscope can also be used to map surface topography. In this mode, the thermal probe is heated above the ambient temperature. As the tip is brought close to a surface, the tip temperature is reduced due to the increased thermal conduction between tip and sample. Since the tip temperature changes rapidly as the tip is brought close to the surface, it provides a sensitive means for controling the tip to sample spacing. Because the thermal conductance of air is small compared to that of any solid, a solid surface acts as a thermal ground, and the thermal signal depends only upon the distance between tip and sample. Therefore, a true topographical profile can be achieved on a sample which has strong variations in it's thermal properties. As the probe is scanned across the sample surface, the resultant variations in tip temperature are used to control the vertical height of the tip, so as to maintain constant the gap between tip and surface. Under this condition, the vertical drive signal replicates the topography as the tip is scanned across the sample.

Experimental Description

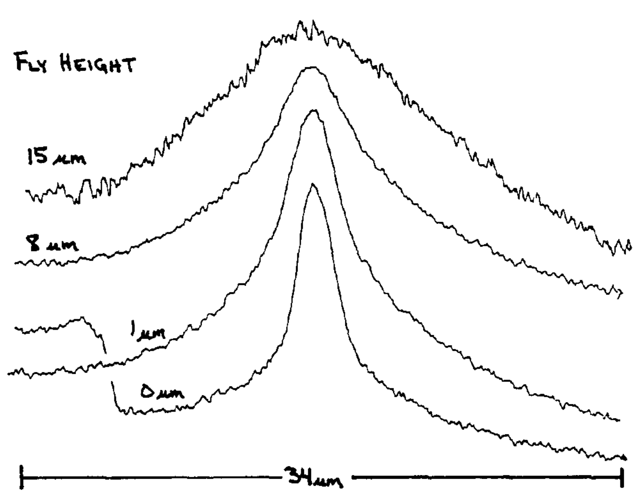
The key element of the thermal microscope is the ultra small thermal probe which provides the sensitivity and the spatial resolution necessary to achieve high resolution temperature mapping and profiling. The probe consists of a conical tip with a thermocouple sensor at its end. See Figure 1. As shown schematically in the figure, a thermocouple sensor is produced at the tip by the junction of the dissimilar inner and outer conductors. An insulator separates these conductors in all areas remote from the tip. The thermocouple junction produces a temperature dependent voltage which can be sensed at the other end of the probe across the two conductors. This voltage provides the means for remotely sensing the local temperature as the tip is scanned laterally across the solid surface for temperature mapping. The thermal probe tips can be made to have dimensions below 1000 angstroms. The minimum detectible change in tip temperature is less than 1 millidegree in a 100 Hz bandwidth.



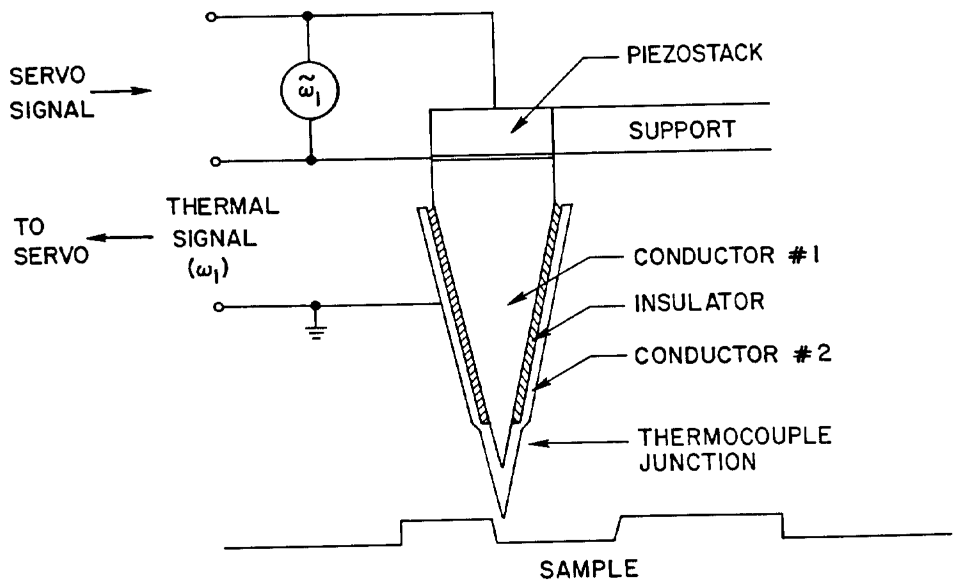
[1] Schematic diagram of the thermocouple probe.

The temperature mapping capabilities of the probe were demonstrated in the following experiment. A dc current is driven through an aluminum line on silicon while the probe is scanned across the line above the substrate surface. The line has a 4.5 micrometer width and a 1000 angstrom thickness. The temperature is measured and recorded as a function of lateral probe position at several tip to sample spacings. As can be seen in Figure 2, the spatial resolution and signal to noise are improved as the tip approaches the surface. At the smallest gap, the tip actually has run into the sample due to a slight sample tilt, illustrating the need for control of the gap between tip and surface.

Figure 3 contains a description of the thermal probe configuration for high resolution surface profiling. The surface profiler has been called Scanning Thermal Profiler (STP)[13]. It is based upon the scanning of a heated thermal probe above the surface of a solid. When the heated tip is in close proximity to the solid, the tip temperature is reduced by the thermal conduction between tip and surface. As the tip is scanned laterally across the surface, changes in the tip temperature are used to control the vertical height of the tip, so as to maintain a constant gap between tip and sample. To avoid the problems with dc drift in the thermal signal, the tip to sample spacing is modulated at a frequency near 1 kilohertz. The modulation of the spacing is generally small relative to the average spacing. The resultant ac signal is detected and rectified, providing a means for controling the tip to sample spacing without sensitivity to fluctuations in the ambient temperature. In a servo system similar to that of the STM, the rectified ac thermal signal from the tip is fed into a servo control loop which adjusts the average vertical height of the tip, via a piezoelectric element, to maintain constant the ac thermal coupling as the tip is scanned laterally over the surface. To facilitate imaging, the thermal probe is mounted on a piezoelectric scanner which provides up to 100 micrometers of travel in any of the three dimensions. The scanner resonance frequency limits the data aquisition to a 200 Hz bandwidth. The thermal energy transfer between tip and sample is driven by a dc temperature difference between the thermal



[2] Thermal signal as the probe is scanned across a current heated aluminum line at various heights. The aluminum linewidth is 4.5 micrometers, 1000 angstrom thickness and 0.5 millimeter length.



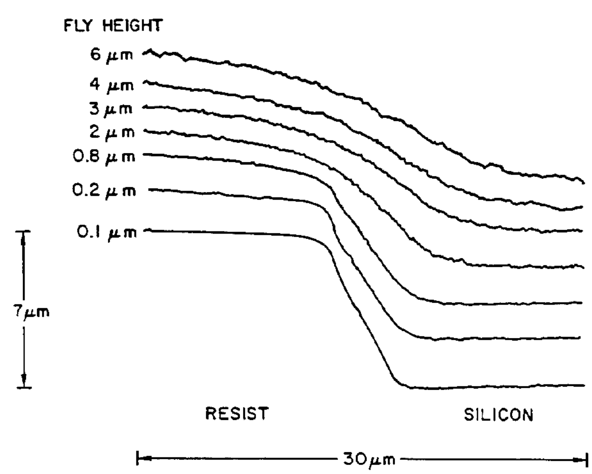
[3] Schematic diagram of the thermocouple probe supported on a piezoelectric element for modulation of tip to sample distance at frequency ω_1 as well as to provide average servo positioning. The AC thermal signal at ω_1 is detected, rectified and sent to a servo loop, which supplies a voltage to the piezostack to maintain the average tip to sample spacing constant.

probe and sample. This temperature difference can be achieved by driving current through the thermocouple sensor, providing Joule and Peltier heating and/or cooling at the tip.

The profiling capability of the STP is very useful in the measurement of surface temperature. Since high resolution temperature mapping can only be achieved if the tip is in close proximity to the surface, the combination of profiler and thermal microscope provide an ideal means for the measurement of high resolution surface temperature in a non-destructive and non-contacting way. If the profiler feedback loop is locked to the gap modulation frequency f_1, and the sample temperature is modulated at a frequency f_2, then a constant gap between tip and sample can be achieved without interference from the sample temperature variations if f_2 is sufficiently outside the bandwidth of the profiler servo loop.

Results

Surface profiling was demonstrated by scanning the heated thermal probe over several different structures. Figure 4 contains the profiling results on a seven micron photoresist film on a silicon substrate. Two interesting features are contained in these line scans. The first is that as the fly height of the probe over the resist edge is reduced, a considerable improvement in lateral resolution is



[4] A series of line scans across the edge of a 7 micrometer resist film on silicon as the average fly height is reduced.

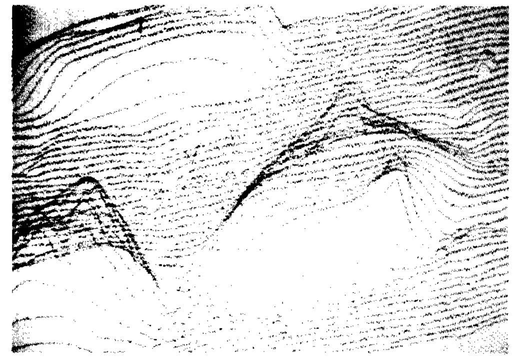
achieved. Secondly, the signal to noise ratio is also improved as the tip approaches the surface. The slight differences in the line scans can be attributed to a lateral drift in the scanning system. The sequential scans do not exactly retrace the same surface area.

The profile of the edge of a 1000 angstrom thick aluminum film on silicon is shown in Figure 5. The imaged surface structure on the aluminum line demonstate a lateral resolution on the order of 300 angstroms. The vertical resolution was measured to be less than 10 angstroms. The resolution seen here is consistent with dimensions of the tip used to profile the structure.

Since the thermal profiler may have applications to the imaging of biological structures, a surface profile was made of some fixed red blood cells on a glass surface. This is shown in Figure 6.

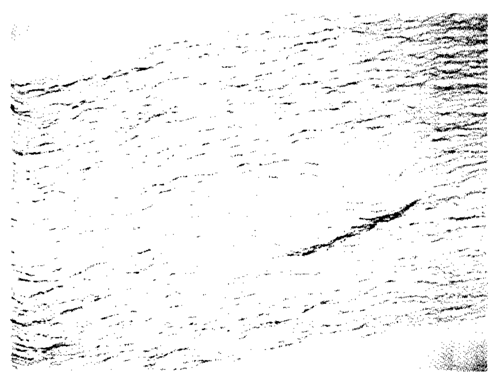
Finally, a temperature map was made on a heated aluminum surface, with the profiler feedback loop closed. This allowed a temperature measurement across the surface while maintaining a constant gap between tip and surface. The profile of a 1 micrometer square area of an aluminum film seen in 7a indicates that a sub micrometer particle with a thickness of 300 angstroms is attached to the aluminum surface. The heating of the aluminum film is generated by a 4 kHz current driven through the aluminum. The resultant temperature variation at 8 kHz is detected via a lock-in amplifier, while the profiler feedback maintains a constant gap between tip and surface. A slight drift between 7a and 7b accounts for the imperfect correspondence between the surface profile and the temperature map. The temperature change due to the presence of the particle is less than 1 millidegree centigrade. The lateral resolution in the temperature map appears to be less than 1000 angstroms.

[5] A line scan of the edge of a 1000 angstrom thick aluminum film on silicon. The scan area is 8000 by 8000 angstroms.



[6] Surface profile of several fixed red blood cells on a glass substrate. The image area is 15 by 15 micrometers.

a)



b)

[7] a)Surface profile of a one micrometer square area of an aluminum film upon which a sub micrometer particle is found, with a 300 angstrom height. b)Temperature map of the same area. The presence of the particle is seen in the temperature map. The measured variation in thermal signal due to the particle was measured to be below 1 millidegree.

Summary

The principles of near field imaging have been demonstrated in a new high resolution thermal microscope. The thermal interaction between an ultra small thermal sensor and a solid has been used to map the temperature distribution of surfaces with sub 1000 angstrom lateral resolution and sub 1 millidegree temperature resolution. Surface profiling has been demonstrated with approximately 300 angstrom lateral resoltuion. The temperature mapping and surface profiling has been applied to both electronic and biological materials.

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