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A new high-resolution profilometer has been demonstrated based upon a noncontacting near-field thermal probe. The thermal probe consists of a thermocouple sensor with dimensions approaching 100 nm. Profiling is achieved by scanning the heated sensor above but close to the surface of a solid. The conduction of heat between tip and sample via the air provides a means for maintaining the sample spacing constant during the lateral scan. The large difference in thermal properties between air and solids makes the profiling technique essentially independent of the material properties of the solid. Noncontact profiling of resist and metal films has shown a lateral resolution of 100 nm and a depth solution of 3 nm. The basic theory of the new probe is described and the results presented.

Over the past few years, several novel techniques for mapping surface topography with ultrahigh resolution have been proposed.[1–4] Perhaps the most notable of these is the scanning tunneling microscope[1] (STM), which is capable of directly mapping single atoms on the surface of a solid. The atomic force microscope[2] (AFM) overcomes a major limitation of the STM, in that it can profile both insulating and conducting surfaces. The AFM is based upon a measurement of the Van der Waal interaction between the atoms on the tip and the sample surface. As these forces exist over distances of a few tens of angstroms, the tip must be brought very close to the sample surface. The near-field scanning optical microscope[3,4] is a noncontacting instrument which can profile surfaces at a larger distance, but the signals are material dependent. In this letter, we present the scanning thermal profile (STP), a new technique for surface profiling based upon a near-field thermal interaction between a heated tip and surface. The approach is attractive because it provides a means for material-independent profiling of surfaces. Also, since the thermal interaction between tip and sample extends over a distance which is much larger than the STM or AFM interaction, imaging at intermediate resolutions on the order of 10–100 nm can be achieved without the need to fly the tip with sub-3-nm spacing.

The scanning thermal profiler is a noncontacting high-resolution surface characterization technique which has the potential for mapping surface topography with lateral resolution below 100 nm. The profiling is achieved by scanning a very small temperature sensor on the end of a heated tip 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 coupling between tip and solid. Since the thermal loading of the tip temperature varies rapidly as the gap between the tip and surface approaches zero, it provides a highly sensitive means for measuring and controlling this gap. In a servo system similar to that of the scanning tunneling microscope,[1] the detected ac temperature of 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. Because the conduction in any solid is so large relative to conduction through air, the solid surface temperature remains essentially unchanged during a scan and the thermal loading felt by the tip is dependent only on the tip to sample spacing. This permits the replication of the true surface topography while traversing structures which have substantially different thermal properties.

The key element of the STP is the ultrasmall thermal probe which provides the sensitivity and the spatial resolution necessary to achieve high-resolution profiling. The probe consists of a conical tip with a thermocouple sensor at its end. See Fig. 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 thermal coupling between tip and solid as the probe is scanned laterally across the solid surface. The thermal probe tips can be made to have dimensions on the order of 100 nm. The minimum detectable change in tip temperature is less than 0.1 millidegree.

To facilitate imaging, the thermal probe is mounted on a piezoelectric structure which provides up to 100 μm of travel in any of the three dimensions. To avoid the problems of dc drift in the thermal signal, the tip to sample spacing is modu-

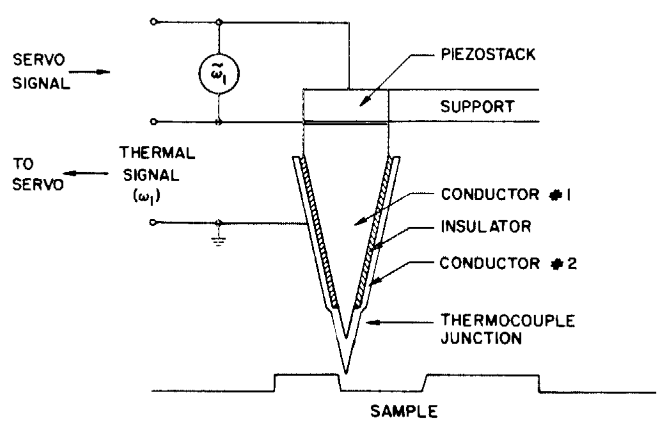

FIG. 1. Schematic diagram of the thermocouple probe supported on a piezoelectric element for modulation of tip to sample distance at frequency ω_1 as well as to provide average servo positioning. The ac thermal signal at ω_1 is detected, rectified, and sent to a servo loop, which supplies a voltage to the piezostack to maintain the average tip to sample spacing constant.

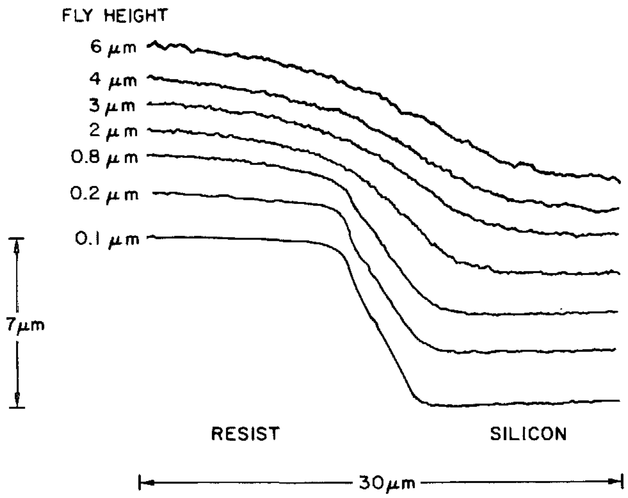

FIG. 2. Series of line scans across the edge of a 7-μm resist film on silicon as the average fly height is reduced.

lated at a frequency near 1 kHz, and the resultant ac thermal signal is detected and rectified before being sent to the servo loop. The proximity control is therefore provided by the gradient of the thermal loading versus tip to sample spacing, rather than the loading itself. Generally, the ac modulation of the spacing is small relative to the average spacing.

The thermal energy transfer between tip and sample is driven by a dc temperature difference between the thermal probe and sample. This temperature difference can be achieved in two ways. A constant current can be driven through the thermocouple sensor, providing Joule and Peltier heating and/or cooling at the tip. A demonstration of this approach has revealed, however, that the high current density at the tip creates excess $1/f$ noise in the temperature detection circuitry. A simpler approach is to heat the thermal probe holder itself. Because the thermal conductance between the tip and holder is large compared to the conductance between the tip and the air, the tip of the probe which extends beyond the holder assembly is essentially at the same temperature as the holder. When the thermal flux at the tip is increased by the near presence of a solid surface, however, the temperature at the tip is loaded, providing a means of sensing proximity to the surface.

Several structures were profiled to demonstrate the profiling capabilities of the scanning thermal profilometer. Figure 2 contains the profiling results on a 7-μm 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 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.

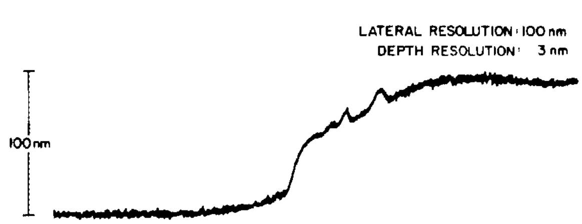

FIG. 3. Line scan of the edge of an aluminum film on silicon.

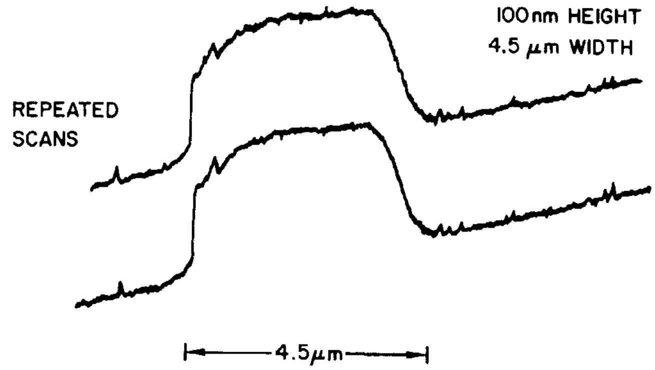

FIG. 4. Repeated line scans on an aluminum line on silicon.

The profile of the edge of a 100-nm-thick aluminum film on silicon is shown in Fig. 3. The data demonstrate a depth resolution of approximately 3 nm as determined by the noise seen in the trace, and a lateral resolution of approximately 100 nm as determined by the response of the profiler to the small defects on the aluminum film. The resolution seen is consistent with dimensions of the tip used to profile the structure. Figure 4 demonstrates the repeatability of the data on an 4.5-μm aluminum line. It is clear that most of the features are reproduced upon retrace. Figure 5 is a three-dimensional image of the same structure. It is composed of multiple line scans, each shifted by 200 nm in a direction normal to that of the line scan.

While the servo and scanning system of the STP are similar in concept to the scanning tunneling microscope, the two are very different for the following reasons. Firstly, the STP is based upon a thermal coupling between the tip and surface, while the STM is based on electron tunneling. The thermal interaction is one which can be used on any solid surface, whether metal, semiconductor, or insulator. Even liquid or semiliquid surfaces may be investigated. Secondly,

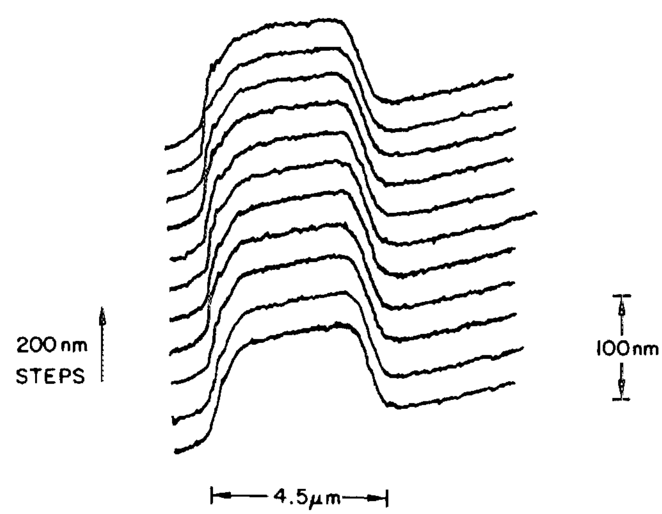

FIG. 5. Three-dimensional profile of an aluminum line on silicon.

conduction through air makes possible the profiling of surfaces without dependence upon material properties. This is the result of the large difference in thermal properties between air and any solid or liquid. Thirdly, the thermal interaction can be sensed over distances equal to the desired lateral resolution; i.e., it is not necessary to fly the tip at 1 nm when the desired lateral resolution is on the order of 10 or 100 nm. These properties make the STP look attractive for profiling applications. Such applications include microelectronic metrology, biological cell profiling, and the surface characterization of materials.

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