ACOUSTIC MICROSCOPY BEYOND THE DIFFRACTION LIMIT: AN APPLICATION OF MICROFABRICATION

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Abstract: We have microfabricated the critical components of a scanning near-field acoustic microscope. A ZnO ultrasonic transducer is used to launch 175 MHz acoustic waves down a sharp silicon tip. Imaging can be done by raster scanning the tip over a sample while monitoring transmitted acoustic signal. Initial experiments indicate that the height sensitivity of the microscope is approximately 20 Å. One-dimensional scans show that the lateral resolution is approximately 800 Å. At present, the exact nature of the interaction of the tip and sample is not well understood but repeated scans over the same region of a sample do not result in noticeable sample damage. We intend to use this microscope in the future to image samples such as organic films and microfabricated structures.

Introduction

The scanning tunneling microscope (STM)[1] and the atomic force microscope (AFM)[2,3] introduced atomic resolution to microscopy. Their power immediately spurred new work on other scanning probe instruments which utilized other physical interactions such as heat transfer,[4] capacitance[5] and ionic conduction.[6] More recently, the focus has narrowed beyond just scanning probe microscopes to scanning probe microscopes which operate in the near-field regime of a given physical interaction.[7] Near-field microscopes include the STM, which can be considered a near-field electron microscope, the scanning near-field optical microscope[8], the tunneling acoustic microscope[9,10], and the near-field acoustic microscope.[11]

The near-field acoustic microscope consists of an acoustic transducer and tip assembly which acts as an acoustic source much smaller than the acoustic wavelength (Figure 1). A sample can be imaged by scanning the tip in a raster fashion while transmitting an acoustic signal. By feeding back on the intensity of the transmitted acoustic signal, the separation between the tip and the sample can be controlled. This technique has the potential to image both conducting and insulating samples using acoustic impedance and sample topography as contrast mechanisms. In addition, if the tip and sample are conductive, it may be possible to obtain simultaneous tunneling current images.

Instrument

The mechanical components and control electronics are identical to those typically used in STM and are described elsewhere.[12,13,14] Our implementation utilizes a tripod design[15] which allows control of separation between the tip and the sample as well as their relative tilt (Figure 2).

The essential feature of the microfabricated tip/transducer assembly is a sharp silicon tip. From several kinds of microfabricated tips available,[16,17] we chose to use a tetrahedral, single crystal silicon tip. The fabrication process for the tetrahedral tips is outlined in Figure 3. A silicon post is etched into a nitride covered (100) silicon wafer. The post is shaped so that a sharp corner points in the [110] direction of the wafer. Several thousand angstroms of oxide are then grown at low temperatures (950° C) so that the sidewalls of the post are protected by oxide whereas the top of the post is still capped by

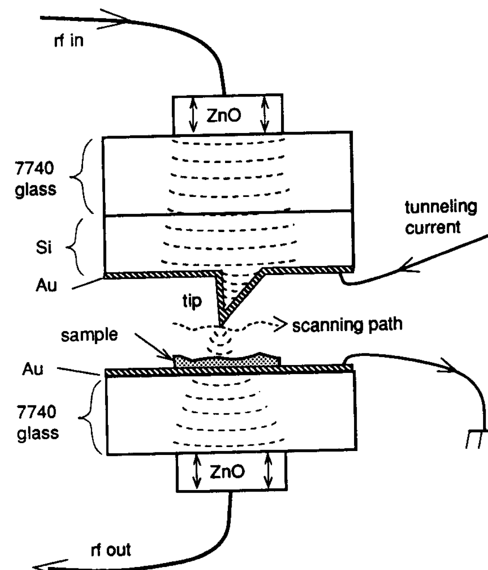

Figure 1. Schematic diagram of the tip and sample configuration.

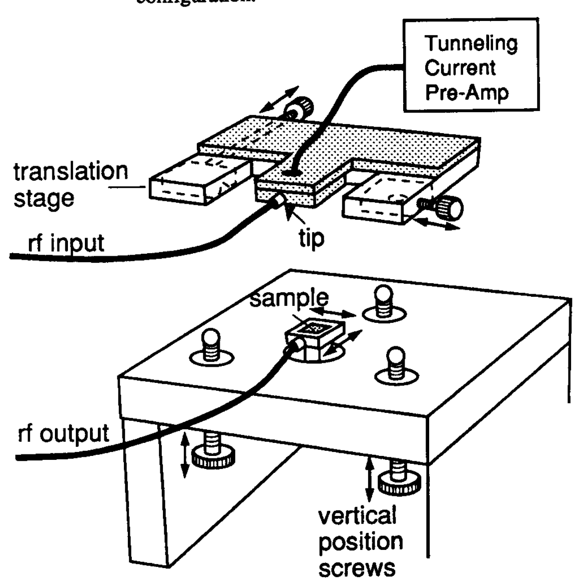

Figure 2. Near-field acoustic microscope based on a tripod configuration.

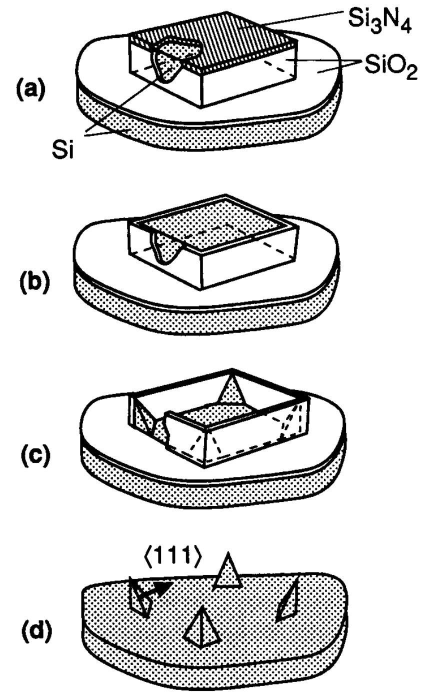

Figure 3. Process outline for tetrahedral silicon tips

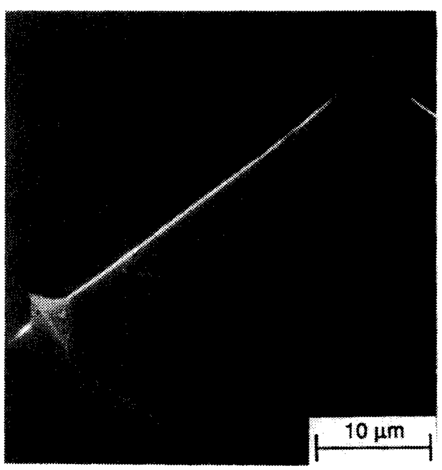

Figure 4. A tetrahedral silicon tip.

nitride (Figure 3a). The nitride cap is selectively removed using a reactive ion etch (Figure 3b). The exposed silicon in the center of the post is etched in an anisotropic silicon etchant such as EDP or KOH. Most of the post's interior is etched away during this step with the exception of small tetrahedral volumes in the corners of the post. These tetrahedral volumes are not etched since they are bounded on their sides by oxide and on one face by a (111) crystallographic plane (Figure 3c). To complete the process, the oxide sidewalls are selectively removed in an HF solution and the tip is fully exposed (Figure 3d). A finished tip is shown in Figure 4.

Tips made in this way have radii of curvature typically less than 500 Å and as low as 200 Å. Even though the original silicon post has corners whose sharpness is limited by the resolution of lithography, the final sharpness is determined by the sharpening effect of the low temperature oxidation.[17,18]

The ultrasonic transducer uses sputtered ZnO as a piezoelectric actuator. The ZnO film is sandwiched between Au and Ti/Au electrodes forming a 50 x 200 µm transducer that is resonant at a frequency of 175 MHz. The substrate for the transducer is Corning 7740 glass, chosen to be compatible with silicon during a subsequent anodic bonding step.

The tip and the transducer are aligned using a two-sided aligner, then heated to 325° C on a hot plate and anodically bonded by applying -1500 to -2500 V to the glass for 15 to 30 minutes. A special jig protects the tip at all times during alignment and bonding.

Experimental Procedure

The experiments are carried out by placing a sample on a bare ultrasonic receiver which is identical to the tip transducer except for the lack of a tip. As samples we have used 1000 Å evaporated gold films on Corning 7740 glass as well as a silicon grating anodically bonded to glass. The sample is mounted on a piezoelectric tube scanner commonly used in STM[19] which is capable of moving the sample in three dimensions. The tip transducer is mounted in the microscope head and is held firmly by a kinematic seating arrangement.

In order to align the transmitting tip transducer to the receiving sample transducer, water is first placed in the gap between the tip and sample. The water allows direct acoustic coupling of the tip and sample transducers across the entirety of their faces. A 175 MHz rf tone burst is applied to the tip transducer and the tip is moved in X and Y to maximize the transmitted signal. When the transmitted signal has been maximized, the water in the gap is removed and the tip is approached to the sample.

Typically, the transducer is excited with a 1 watt rf peak power. The transmitted signal is detected using a super heterodyne system. A signal averager is used to increase the signal to noise ratio. The total dynamic range of our system excluding the signal averager is 120 dB. Insertion loss of a transducer is typically 25 dB.

Two simple experiments have been conducted. The first was to measure the transmitted signal intensity versus gap spacing and the second was to scan the sample under the tip to try to obtain a topographic image of the sample surface. The first experiment was carried out by putting a modulation of approximately 1000 Å on the sample height. The sample was moved toward and away from the tip at 0.5 to 5 Hz while the transmitted signal was monitored. At large gap spacings, no signal was detected. Upon approaching the tip to the sample, the transmitted signal increased in correspondence to the tip position. Figure 5 shows a clear knee in the curve where the transmission begins and increases as the tip is brought closer to the sample. At these signal levels, we can detect a 20 Å excursion in the gap spacing at a unity signal to noise ratio. The hysteresis is most likely due to viscous contamination layer on the surface of the sample as well as hysteresis in the piezoelectric tube scanner. The lower curve was recorded with a -10 dB attenuator placed in series before the tip transducer to give scale to the non-linear vertical axis.

A one-dimensional topograph of the glass surface of the sample transducer was obtained by scanning the sample under the tip using height feedback to maintain constant transmitted signal intensity (Figure 6). The upper curve shows a 4000 Å scan of a region and the lower scan shows the same region scanning a range twice as small. Corresponding features can be identified on both scans. The deep valley appearing in the center of both traces indicates that the lateral resolution is approximately 800 Å. For a particular tip one-dimensional scans are reproducible and repeated scans over the same region show the topography is unchanged. There is significant variation from tip to tip however and to date, only 20% have been able to transmit acoustic signals to the receiver at detectable levels.

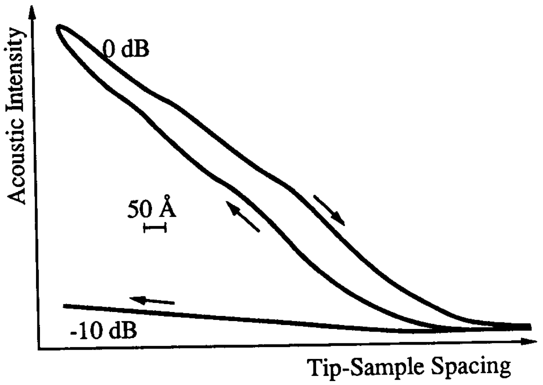

Figure 5. Transmitted acoustic signal intensity plotted versus tip/sample separation.

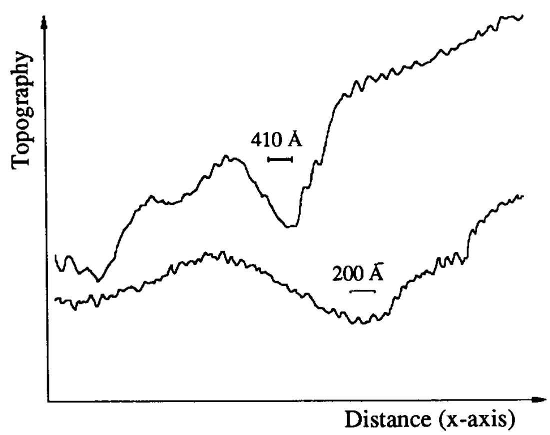

Figure 6. One-dimensional topography of a gold film on glass imaged using feedback to maintain constant transmitted signal intensity.

Discussion

The results of these experiments indicate that it is possible to transmit acoustic waves from one transducer to another through a point junction. Using an excitation of 175 MHz results in wavelengths on the order of 50 μm in silicon. Nonetheless we are transmitting this signal through a tip with radius of curvature of hundreds or perhaps a few thousand angstroms. This corresponds to imaging in the near-field with a resolution of λ/500.

A given tip can be approached to a sample over twenty times and the transmitted acoustic intensity versus distance curve (Figure 5) does not change significantly although variations in the curves are seen for different tips. We do not observe any changes in the distance at which acoustic coupling first occurs suggesting that the tip is not plastically deformed upon contacting the surface.

The one-dimensional scanning data is very interesting as it shows features with 800 Å lateral dimensions. While this data was being taken, several parameters such as scan size and frequency were varied to eliminate the possibility of scan artifacts.

Conclusion

We have microfabricated sharp silicon tips and integrated them with ZnO acoustic transducers. 175 MHz acoustic waves are launched into the tip from the ZnO transducer and transmitted down through the tip's apex to a receiving transducer. Using this configuration, we have transmitted energy with a 50 micron wavelength through a junction of a few thousand angstroms or less.

Initial experiments where the transmitted signal levels were monitored while modulating the gap separation indicate that a 20 Å variation in the tip sample separation can be detected. A one-dimensional scan has resolved 800 Å features in a gold film on a glass surface. Since the acoustic wavelength is approximately 50 μm, we believe that the acoustic transmission we are observing is a near-field effect.

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