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**A SCANNING TUNNELING MICROSCOPE FOR SURFACE MODIFICATION**

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ABSTRACT

With the recent success for the scanning tunneling microscope (STM) has come the question of whether the instrument might be used for material modifications and lithography. We embarked on the design of an STM with this application in mind. Its features include a wide x-y piezoelectric scan range of 10 or more microns, plus coarse mechanical motion in the x direction to a new region on the sample while in vacuum. Coarse motion in the z direction is accomplished with a micrometer drive, while fine movement is done with a piezoelectric transducer. Both the sample and the tip can be quickly changed. Finally, the instrument is mounted on the stage of a scanning electron microscope which allows real-time observation while it is operating.

Using this instrument we were able to pattern sub-micron gold lines on silicon substrates by sputter etching through a contamination resist pattern laid down by the tunneling electrons polymerizing organic molecules present on the target. We were also able to expose lines using a Langmuir-Blodgett film, which consists of several molecular monolayers of a material known to act as an electron beam resist deposited individually on the surface of the substrate.

INTRODUCTION

The scanning tunneling microscope (STM) has shown itself to be a remarkable instrument capable of imaging individual atoms on conducting surfaces [1]. However, the possibilities of the instrument for modifying surfaces rather than just looking at them are only beginning to be explored. In previous work we have shown that when operated in the field emission mode it can generate an intense submicron beam of low energy electrons [2]. In the theoretical study we modelled the emitter tip as a sphere and studied the beam diameter which resulted from different geometries. It turned out that for any given voltage there is an optimum tip diameter which results in a minimum beam diameter (Figure 1).

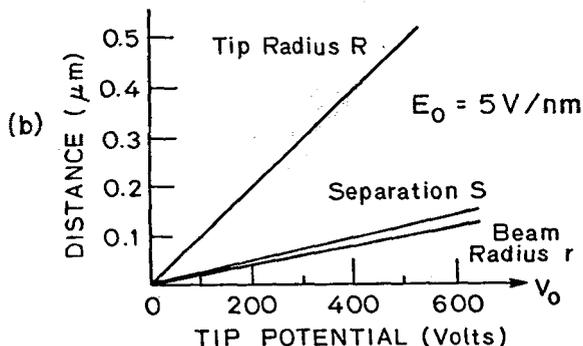


Figure 1. Minimum beam radius for a field emission tip in close proximity to a target plane.

Because of absence of space charge and lens aberrations, the STM can produce submicron beams of a few hundred volts or less with currents much higher than are possible using more conventional technologies. We felt that beams of at least a few eV would be needed in order to effect various chemical and physical changes on the surface of a sample, although recent work indicates that 0.1 volts is capable of some effect [3].

The requirements for an STM intended mainly for surface modification are quite different from those required of an instrument capable of imaging atoms. Most important is a large scan field. Fields less than several microns on a side are extremely difficult to locate with a microscope (optical or electron) once the sample has been removed from the STM. The other requirement is the ability to vary the beam voltage and current over several orders of magnitude.

Since the instrument isn't necessarily required to resolve atoms, the design can be much simpler in several ways. Much higher noise levels can be tolerated, and an ultra-high vacuum is not required. Since this instrument was intended mainly for use at higher voltages and thus a larger gap between the tip and sample, a much higher vibration level can be tolerated.

#### SCANNER DESIGN

A piezoelectric scanner similar to those in other STMs, was chosen as the most practical way of achieving three-dimensional, electronically-controllable motion on a nanometer scale. In order to provide a large scan area, one design shown in Fig. 2a used orthogonal one inch PZT tubes driven with a 900 volt scan signal, sufficient to provide a 10x10 micron scan range.

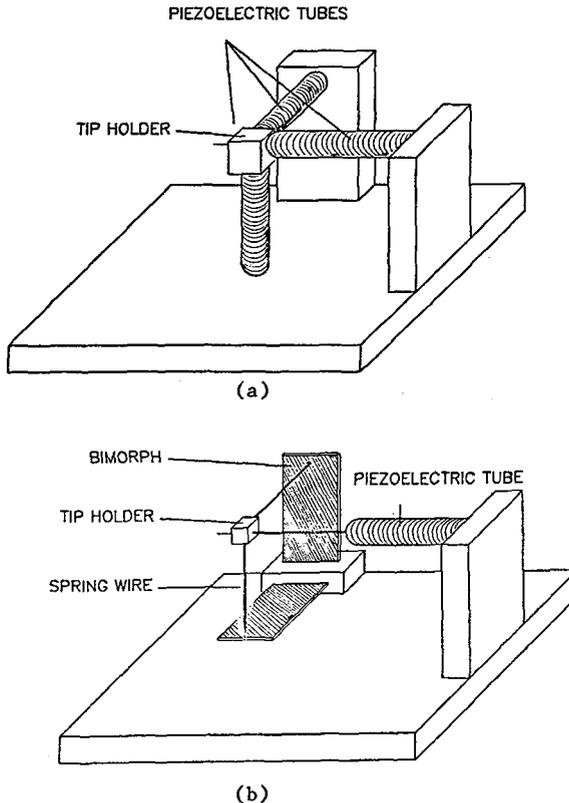


Figure 2. a) Piezoelectric tube scanner, b) piezoelectric bimorph scanner.

Tubes provide good mechanical stiffness as well as light weight. An alternate design using piezoelectric bimorphs is shown in Fig. 2b. Bimorphs are made from two strips of oppositely poled piezoelectric material joined such that one side contracts while the other expands when an electric field is applied, with the result that the strip bends relatively large distances. Using this design a compact scanner could be built with a range of hundreds of microns. Our design used .5 inch strips and gave a 30 micron range for a 150 volt scan signal. A PZT tube continues to provide motion in the z direction. An earlier version used a bimorph in the z as well as the x and y directions. This design suffered from severe mechanical resonance at a frequency of 1.2 kilohertz. The scanner could be made usable by adding damping consisting of a thick film of vacuum grease, but its performance was still inferior to the other designs. Emitter tips were made by electrochemically etching tungsten wire to a sharp point with a radius of curvature of several hundred to several thousand angstroms. Tips were mounted on these scanners using a small metal block with a set screw, holding them securely while allowing them to be quickly changed, useful since the tips are easily destroyed.

#### SAMPLE MOUNT

The sample mount shown in Fig. 3 is a spring loaded steel strip connected to a micrometer drive. This provides a coarse motion in the z direction that allows the sample to be brought within the range of the z piezoelectric transducer. This design is much simpler than the "louse" or "walker" used in other STMs although it makes it difficult to provide vibration isolation inside the vacuum chamber. The sample is held on the sample mount by spring clips which also provide electrical contact to the front surface of the sample. This allows for simple and quick sample changes. The sample mount also provides coarse motion in the x direction by means of a line connected between a second micrometer drive and the end of the steel strip, which pivots at the other end. This allows several different exposures to be made on a sample without having to bring the system up to atmospheric pressure between each exposure.

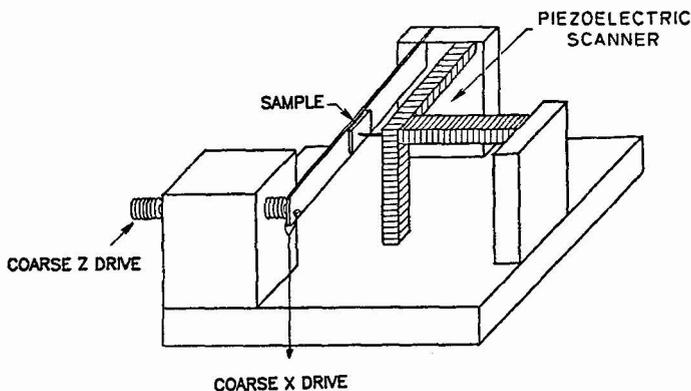


Figure 3. STM configuration.

#### SYSTEM DESIGN

Since noise and surface cleanliness were not severe constraints, an ultra-high vacuum was not required and it appeared that a vacuum of a few times  $10E-5$  torr should be sufficient [4]. Thus the system was designed to be placed on the stage of a scanning electron microscope. This not only satisfied the vacuum requirements, but also allowed in situ examination of the tip and the sample, and

enabled us to watch as the sample was brought up to the tip using the coarse z motion. The SEM also provides a single stage of vibration isolation which proved to be adequate for voltages down to 1 volt and less. Figure 4 shows the control circuitry. The beam voltage,  $V_B$ , is set with a regulated variable DC supply. The current is sensed across a resistor in series with the tip and compared with a reference signal to produce an error signal. The error signal is filtered to remove frequencies around the resonance of the scanner. The error signal and its integral are then fed through variable gain amplifiers to the z piezoelectric transducer, forming a PI controller that keeps the beam current constant and thus sets the tip a constant height above the sample.

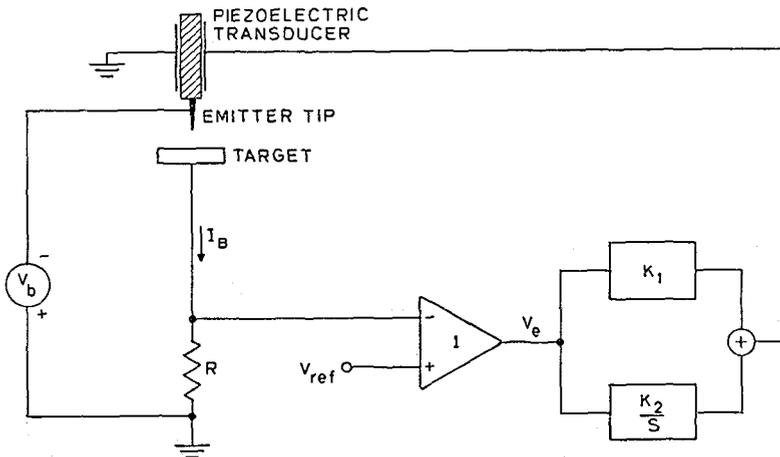


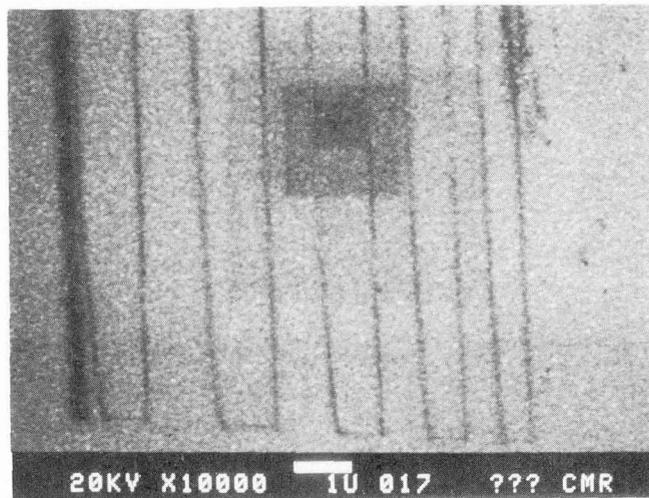
Figure 4. STM control circuitry.

### PRELIMINARY RESULTS

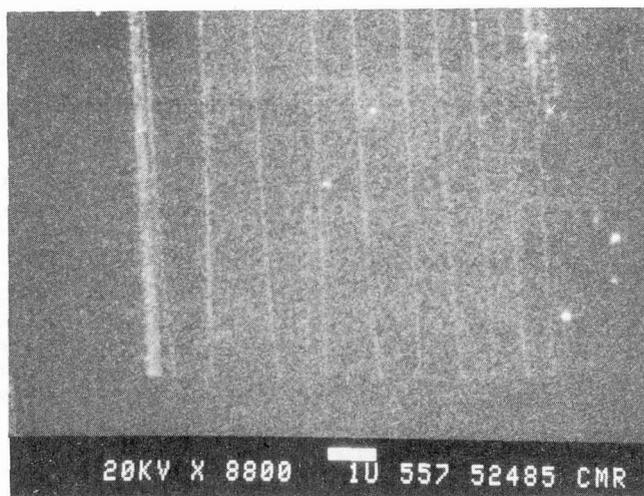
Beam voltages from 1 to 200 volts at currents from 1 to several thousand nA have been produced. Careful setting of the gain parameters  $k_1$  and  $k_2$  is important, since too little gain limits the response time and thus the maximum scan speed and also increases noise, while too much gain causes oscillations. At beam voltages above 20 volts the current was noisy and unstable, possibly due to sputter etching of the tip. As the voltage was reduced below 20 volts the current became much less noisy, presumably due not only to a reduction in the energy of sputtering ions but also to a transition from the field emission regime to the MVM tunneling regime.

The first attempt at lithography used contamination resist where hydrocarbons present in the vacuum are polymerized on the surface of the sample by the beam [5]. Figure 5a shows a micrograph of lines of contamination on a 100 nm gold [1] film on silicon. The exposure was done with a 10 volt, 60 nA beam and a scan speed of .25 microns/second. The sample was then sputter etched to remove the gold revealing lines of gold shown in Fig. 5b. Lines were also made by exposing a Langmuir-Blodgett film of docosenoic acid [6]. This is a film sensitive to an electron beam deposited a single monolayer at a time. The film was 10 nm thick on top of 100 nm of aluminum on silicon. It was exposed with a 25 volt 15 nA beam at a scan speed of .5 microns/second, developed in alcohol and the aluminum wet etched away. The result was coarse aluminum lines shown in Fig. 6.

[1] These results were presented at the 29<sup>th</sup> International Conference on Electron, Ion, and Photon Beams.



(a)



(b)

Figure 5. a) Lines of contamination on gold. Dark squares are additional contamination caused by the SEM taking the micrograph, b) after sputter etching the gold.

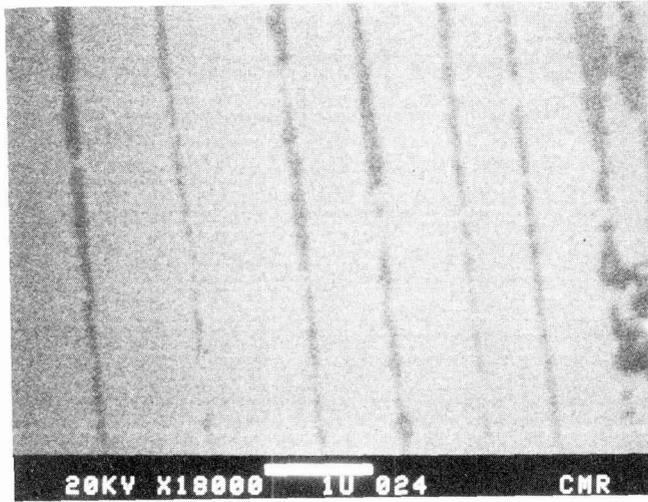


Figure 6. Lines of aluminum on silicon formed by exposure of a Langmuir-Blodgett film.

#### DISCUSSION

We have demonstrated tenth-micron lithography using the STM described above. Other possible uses for the instrument include localized heating or melting for microfabrication or extremely dense mass storage. Another interesting possibility would be to reverse the applied voltage and operate as a liquid or gaseous ion source. One serious problem that an ion source would need to overcome would be field emission of electrons from the sample back to the source.

Future plans include moving the STM to an ultra-high vacuum system to lower noise, reduce undesired contamination, and to allow stable operation at higher voltages. Experiments will include attempts to expose novel resist systems including metal halides as well as more ordinary polymeric resists.

Before this could ever become a commercial system, a great deal of engineering is needed to allow reasonable writing speeds. Both the bandwidth of the feedback loop and surface flatness must be greatly improved in order for the tip to follow surface topography at higher speeds. However, modern disc mass storage technology employing head fly heights of a few thousand angstroms or less offers hope that this might not be an unrealistic goal.

#### ACKNOWLEDGMENTS

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