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Direct Observation of a Scanning Tunneling Microscope Tip Apex Using a Transmission Electron Microscope

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A micromachined scanning tunneling microscope was designed and fabricated to study the interaction between the tip and sample. It fits into the side entry sample holder of a Hitachi HF-2000 transmission electron microscope. State of the art ULSI technology was used to make a 2.5 mm square chip with a minimum dimension of 0.4 μm and alignment accuracy of 0.1 μm. The chip uses a balanced drive to produce a force great enough to overcome the forces between the tip and sample. A novel process was required to produce the micromachine because of the need to make a thin transmission electron microscope sample. The tip apex of the scanning tunneling microscope has been successfully observered, which should enable the direct observation of the tunnel gap and atomic motion at the tip apex.

1. Introduction

The scanning tunneling microscope (STM) was invented more than 10 years ago but there has been no direct measurement of the tunnel gap with voltage and current, or observation of the motion of atoms at the tip sample interface. At present the study of atomic manipulation by STM is difficult because the tip must be used both to modify the surface and then to observe it. It is thus not simple to tell whether the tip or sample was modified, or what the source and destination of the manipulated atoms is. What is required is a second method for observing the tip and sample during STM operation. The only instrument that can directly see things on the atomic scale is a transmission electron microscope (TEM). One successful attempt has been made to install an STM into a TEM, and the results revealed how inaccurate the STM images are, but the TEM measurements were at the nanometre scale rather than atomic scale[1]. There are several problems to be solved to obtain high resolution from the TEM.

1]. The objective lens pole piece width of the TEM must be small, which limits the width of the STM mechanism to about 2 mm.
2]. The other dimensions of the STM are limited by entry into the TEM to about 6 mm.
3]. The 200 keV electrons must be able to penetrate the tip apex and the sample to obtain a good image. This means the edges of the tip and sample need to be less than 0.5 μm.
4]. If the STM is to work it must be mechanically isolated from the environment, but if the TEM is to have atomic resolution then the STM must be firmly attached to the pole piece of the objective lens, so the STM mechanism must be very rigid to avoid disruption by vibrations.

The aim of this project is to view the tip and sample of an STM while in operation using a TEM. To solve the problems associated with installing an STM into a TEM it was decided to micromachine a single chip STM that could fit into a modified TEM holder. Such STM chips can then be viewed by the TEM, using the high resolution objective lens pole piece while in operation. The thin film technology used to fabricate the STM means that the entire STM is naturally thin, making it a good TEM specimen.

2. Design and Fabrication

1, 2 and 3 dimensional scan units for use in the TEM and as a normal STM head have been constructed. The micromachines designed are small and rigid, having resonant frequencies between 10 kHz and 1 MHz. Each is placed on a chip 2.5 mm square and 0.5 mm thick. Their small size means they can easily be placed into a standard Hitachi HF-2000 side entry sample holder. In order to make electrical contact with the chips a modified holder was built which allows for 8 press contacts. A simple and portable STM controller was also built to control the STM chip.

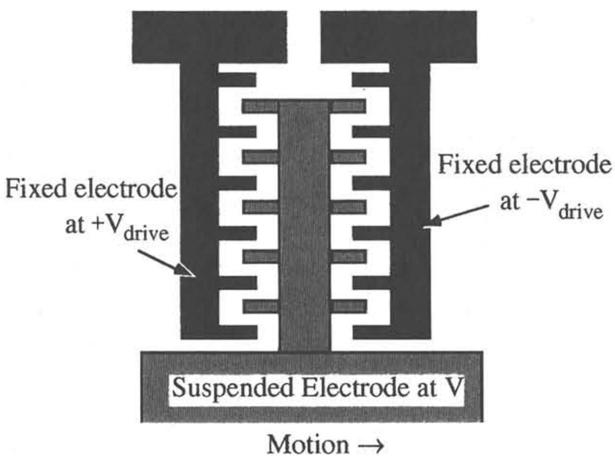
The structures are similar in style to previously made lateral STM chips [2] [3]. However the chips were designed to give the following improvements:-

1]. The force between the tip and sample can be surprisingly large and 100 nN is possible. In order to overcome these tip sample interaction forces, the comb actuators were designed to give maximum force for the size.
2]. The design uses a balanced attractor system which means force is not only linear with displacement, but also with voltage, perhaps the first time this structure has been possible in such

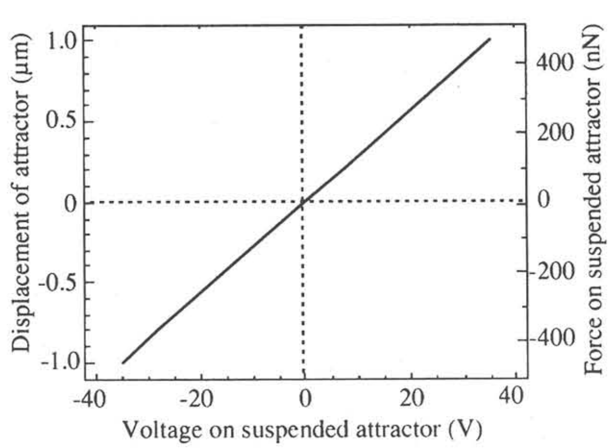
a micromachine. The arrangement is shown in fig. 1 along with a calculation of the force and displacement of the attractor with applied voltage. This makes the feedback loop for the STM easier to build.

3]. The suspended structure is not a single conducting piece but has several areas of insulator and conductor, and is suspended by removal of the silicon substrate.

4]. The comb electrodes are coated by an insulating layer, which prevents shorting and sticking. Since the conductors in the comb electrodes are always separated by insulator, the force they provide is also limited. This prevents them snapping together.



(a). Attractor layout



(b). Relationship between voltage, force and displacement for 85 μm long attractors.

Fig. 1. Layout of attractors and the relationship between voltage, force and displacement.

To produce these structures without stress a complex process was required. The micromachines were fabricated using state of the art ULSI fabrication techniques with a minimum dimension of 0.4 μm and alignment accuracy of 0.1 μm. Figure 2 shows the layout for one of the chips. The STM can be seen in the centre, with the eight bond pads across the top. The layout was very careful to prevent stray currents leaking across the chip which could easily be misinterpreted as tunneling current. Most of the chip surface is grounded conductor to prevent charging in the TEM and screen the electron beam from the voltages used to drive the actuators.

Only three mask layers were required but seven layers of material were deposited and etched to produce the final structure. A cross-section of this structure is shown in fig. 3.

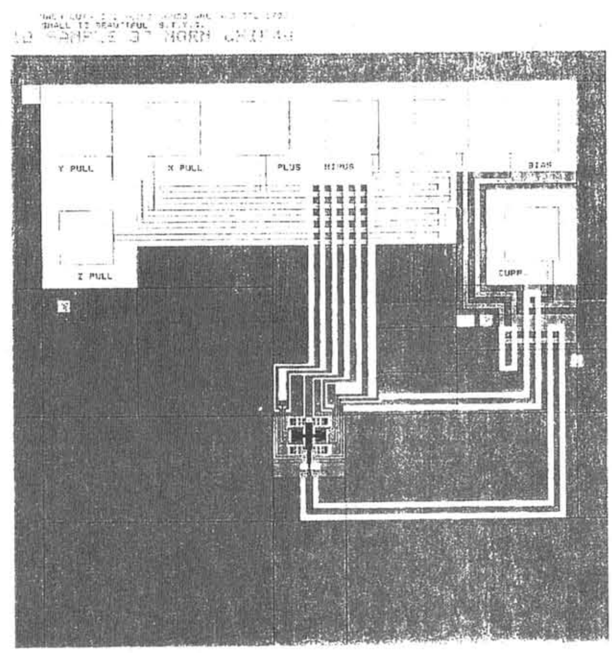
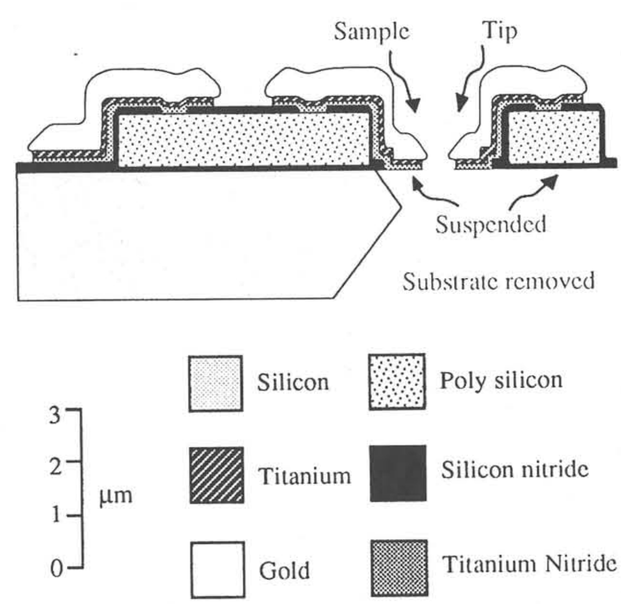


Fig. 2. Layout for 1 dimensional STM.



Scale and colour code

Fig. 3. Cross-section of the final structure.

A KOH etch was used to suspend the structures by removing the silicon substrate. As a result the polysilicon conductors are completely surrounded by silicon nitride insulator to protect them, and gold was used for the tip sample and bond pads. Buffer layers of titanium and titanium nitride were included between the polysilicon and gold. Both these materials are also reasonably resistant to the KOH etch.

A hole was etched though the centre of the chip from the back side of the chip, also using a KOH etch, so the STM can be viewed as a thin TEM sample. Figure 4 shows an SEM micrograph of a completed 2 dimensional STM. Three actuators can be seen with their springs and comb attractors. These push and pull the tip around via the three sets of bars leading to the tip. The voltages for the tip and actuator reach the suspended parts via the springs, different springs carrying different signals.

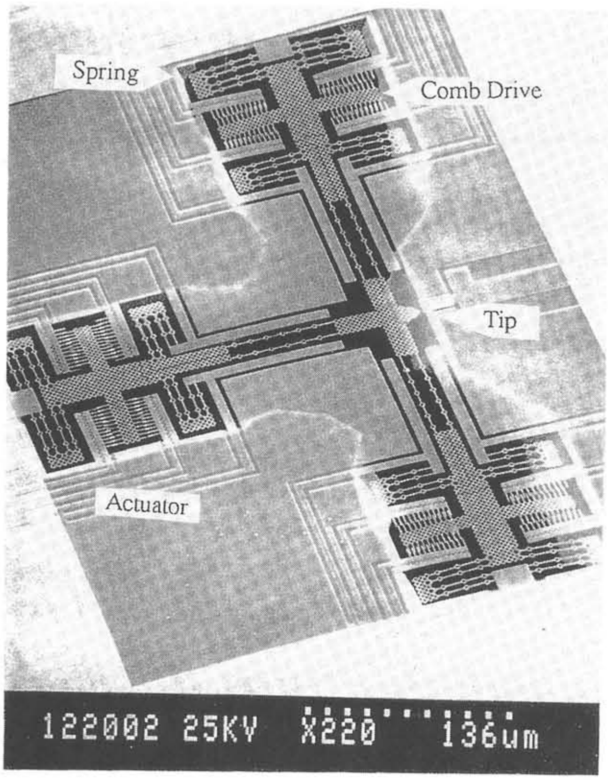


Fig. 4. SEM of 2 dimensional STM chip.

3. Observation by TEM and Optical microscope

Several sizes of actuator were built and tested using an optical microscope. These experiments indicate that actuators at least 200 μm long were needed to provide the required force. This was in agreement with calculations.

Figure 5 shows a micrograph of the tip apex and sample as viewed in the TEM. The apex and the sample can be seen to have been modified during contact where a contamination layer was removed. To the best of our knowledge this is the first TEM micrograph of its kind.

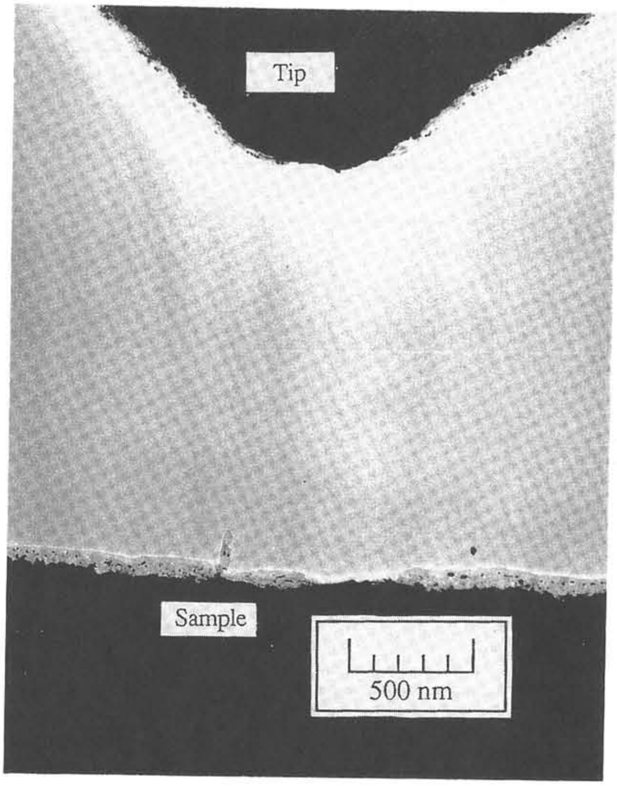


Fig. 5. TEM image of tip and sample.

4. Conclusions

A micromachined STM was designed and fabricated, small enough to fit into the side entry sample holder of the Hitachi HF 2000 TEM. State of the art ULSI technology made possible a 2.5 mm square chip with a minimum dimension of 0.4 μm and alignment accuracy of 0.1 μm. The tip apex of the STM has been successfully observered, which should enable direct observation of the tunnel gap and the motion of atoms at the tip apex.

Acknowledgement

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