Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 827-829

Direct Observation of Working Vacuum Tunnel Junctions Using a Transmission Electron Microscope

Mark LUTWYCHE and Yasuo WADA

Advanced Research Laboratory, Hitachi, Ltd.,
Hatoyama, Saitama 350-03 Japan

This paper reports the transmission electron microscope (TEM) observation of a vacuum tunnel gap using a micromachined tunneling microscope (μ-STM). A chip containing a μ-STM that fits into a TEM holder has been fabricated. 1D μ-STMs work reliably during observation, allowing the tunnel gap to be observed. 2D μ-STMs that can scan the tip have been shown to be functional. A 3D μ-STM in which the sample is external to the chip is also being tested.

1. Introduction

This paper describes the use of micromachined tunneling microscopes to observe the tunneling gap in a transmission electron microscope (TEM) while the tip is in tunneling range. This should lead to a thorough understanding of the imaging mechanism and the mechanism of atomic manipulation by STM.

During the last decade the scanning tunneling microscope (STM) has become a very useful technique for imaging surfaces with atomic resolution[1]. The basic mechanism and some of the details of the image formation are becoming better understood[2]. The STM is also capable of atom manipulation[3][4][5]. Several experiments have been carried out and mechanisms proposed for this process, but it is difficult to say for certain which theories are valid in different experimental conditions[6][7][8].

There are considerable experimental difficulties with the observation of the tunnel gap but these have been solved by using a μ-STM[9]. Drives that can move in 1, 2 and 3 dimensions have been made. The μ-STMs are small and rigid, having lowest resonant frequencies in the range of 10 kHz, which makes them very resistant to vibration. State of the art VLSI techniques were used to fabricate the structure with a minimum dimension of 0.4 μm and alignment accuracy of 0.1 μm. Each μ-STM is placed on a chip 2.5 mm square and 0.5 mm thick.

2. Observation of a tunnel junction

The 1D μ-STMs shown in figure 1 have been used for observation of the tunnel junctions. They are very reliable when operated with less than 3-4 V bias. The tip can be withdrawn and re-engaged reliably and continuous operation produces no obvious change in performance with time. Bias voltages higher than about 4 V make the machine unstable because the Coulomb force between the tip and sample exceeds the maximum force generated by the comb actuator of the μ-STM. During TEM observation the electron beam of the TEM produces an offset in the tunnel current of up to 0.2 nA but does not affect the stability of the junction so long as the contamination in the TEM is low. The offset is caused by secondary electrons, since whenever the TEM beam strikes part of the sample near the tip, an offset is produced. The effects of vibration on the μ-STM are small since moving the TEM sample stage, which is driven by stepper motors, does not affect the operation of the μ-STM.

The STM current is found to be independent of voltage bias. The actuator voltage, however, is very sensitive to tip-sample bias voltage, this being caused by the change in Coulomb force between the tip and sample.

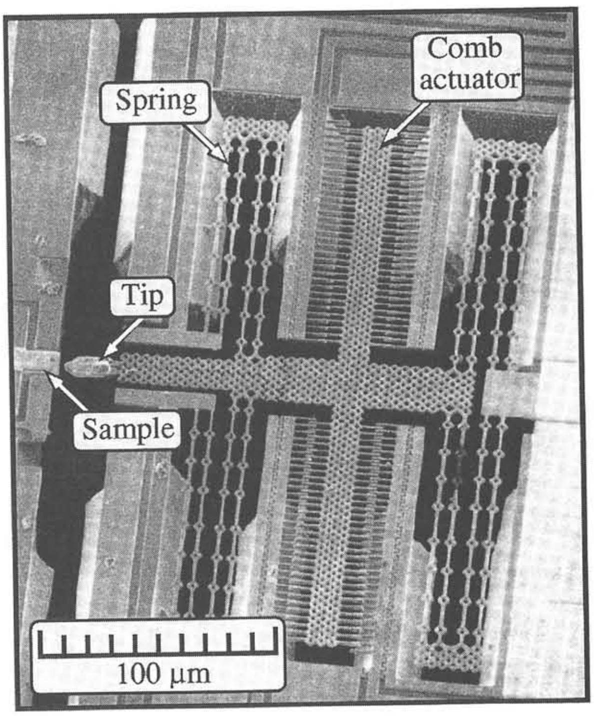

Figure 1. SEM micrograph of a 1D μ-STM

The μ-STM is operated in constant current mode, and as expected, the actuator voltage fluctuates continuously to control the current. The tip moves about 0.5 nm to control the current. The reason for the motion of the tip is thought to be contamination by adsorbed molecules since the pressure was about 10^{-5} Pa during this observation[10].

A gap of about 1 nm between the tip and sample is predicted for tunneling[11]. When a micromachine is first approached in the TEM, the tunnel gap is usually obscured. This is because the edge of tip and sample are irregular and much thicker than the width of the tunnel gap so the TEM beam is obstructed. The gold layers on the tip and the sample can be manipulated to see the junction. This is achieved by applying high voltages of up to 10 V and causing tip sample collisions to clean the tip and sample, and to form micro tips[12]. Figure 2 shows such a junction that was formed between a micro tip formed on the sample and the tip. The (200) gold lattice can be seen in micro tip. The observed gap is approximately 1 nm, about the value expected. However, the gap widens with time, this being not continuous but irregular, changing suddenly about every 5 seconds. This observation is also thought to be due to molecules depositing in the gap. If quantitative data is to be taken using this technique it will be necessary to produce near UHV conditions in the TEM specimen chamber.

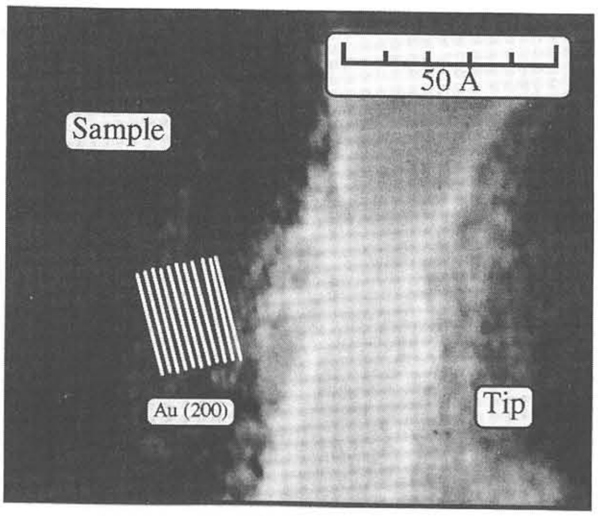

Figure 2. TEM micrograph of the tunnel gap with 1.4 V and 4 nA made from averages of 16 consecutive frames of video

The results of such studies will lead to a better understanding of the imaging mechanism of the scanning tunneling microscope and the mechanism of atomic manipulation by STM. This work also establishes a new method for observing the dynamic properties of materials with atomic resolution, the μ-STM being used to manipulate small particles and fabricate structures during observation in the TEM. Using this technique fields such as electron migration and the study of nano-particles might be better understood.

3. Demonstration of 2D and 3D μ-STMs

The 2D μ-STM shown in the SEM micrograph of fig. 3 has also been fabricated for observation in the TEM using the same process as for the 1D type. Three actuators are used, one to approach the sample and two to allow the tip to be scanned along the sample. Experiments with these machines have been in air, so reliable tunneling has not been seen yet because of contamination, but the tip can be approached and scanned up to 8 μm along the sample. The ability to scan the tip makes the observation of junction easier, since it is possible to move to the optimum position on the sample. It allows new experiments to be carried out as well. For example it is possible to compare the line scan of the μ-STM with the TEM profile of the sample It also makes it possible to use the μ-STM to observe the mechanism of sliding of atoms across the sample surface, the technique used to make quantum corrals[13].

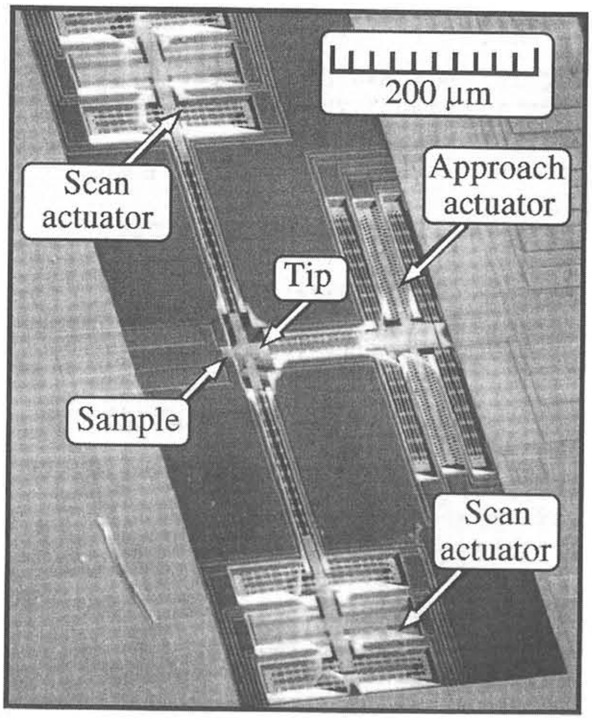

Figure 3. SEM micrograph of a 2D μ-STM machine

3D machines have also been made as shown in fig. 4. The motivation for making these machines is quite different. In these machines the sample is not incorporated on the chip but must be approached separately. For this reason the tip is made to overhang the edge of the sample. The approach and scan in the plane of the wafer are the same as for the 2D version, however the motion normal to the plane is carried out using a large electrode that pulls towards the substrate.

The motion of these 3D versions has been tested, and they can move more than 2 μm in all directions. Such machines are designed to replace existing piezo STM system with a "disposable STM" since if mass produced they could be relatively cheap, so that when the tip is damaged the whole STM is replaced. The μ-STM also has the advantage of using low voltages to drive it, less than 40V. Thus the control system can be smaller and might even be integrated onto the μ-STM chip.

These μ-STMs although small and delicate are resistant to vibration, can withstand low and high temperatures, corrosive environments and operate at all pressures. Current STM machines for these purposes are specialized and expensive. The disposable STM would allow much more daring experiments.

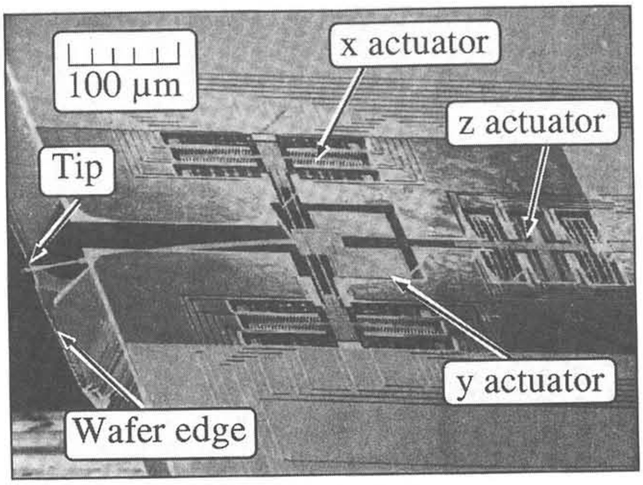

Figure 4. SEM micrograph of a 2D μ-STM machine

3. Conclusion

This paper reported the TEM observation of the vacuum tunnel gap between two conductors using a μ-STM. A 2.5 mm square chip containing a μ-STM was fabricated with a minimum feature size of 0.4 μm. The chip fitted into a modified side-entry TEM holder. 1D μ-STMs worked reliably during observation of the tip apex in a TEM, and allowed the voltage and current to be changed while the tunnel gap is observed. 2D μ-STMs that can scan the tip have also been tested and shown to be functional. A 3D μ-STM in which the sample is external to the chip has also been tested demonstrating the possibility of the "disposable STM".

Acknowledgments

The authors would like to express their sincere gratitude to Dr. Shojiro Asai, Dr. Michiharu Nakamura and Dr. Akira Tonomura for continual advice and encouragement. They are grateful to the ULSI Research Department as well as the Electron Device Research Department, both at Hitachi Central Research Laboratory, for valuable discussions and the fabrication of the μ-STM chips. Mr. Shigeo Kubota, Mr. Shokichi Matsunami and Mr. Mamoru Moriya are acknowledged for the fabrication of the TEM sample holder.

References

1) G. Binning, H. Roher, Ch. Gerber and E. Weibel, Appl. Phys. Lett., **40**(2) 178.

2) S. Watanabe M. Aono and M. Tsukada, J. of Vac. Sci. Technol. B **12**(3) (1994) 2167.

3) Ph. Ebert, M.G. Lagally and K. Urban, Phys. Rev. Lett. , **70**(10) (1993) 1437.

4) D.M. Eigler and E.K. Scweizer,, Nature **344** (1990) 524.

5) S. Hosoki, S.Hosaka and T. Hasegawa, Applied Surface Science, **60/61** (1992) 643 .

6) A. Kobayashi, F. Grey, R.S. Williams and M. Aono, Science, **259** (1993) 1724.

7) N.M Miskovsky and Tien T. Tsong, Physical Review B, **46** (1992) 26.

8) S. Kondo, M.I. Lutwyche and Y. Wada, Applied Surface Science, **75** (1994) 39.

9) M. I. Lutwyche and Y. Wada, , Sensors and Actuators A, **48**(2) (1995).

10) M.I. Lutwyche and Y. Wada , Appl. Phys. Lett., **66**(21) (1994) 2807.

11) R.S. Becker, J.A. Golovchenko, and B.S. Swartzentruber, Phys. Rev. Lett. **55** (1985) 987.

12) J.I. Pascual, J. Méndez, J. Gómez-Herreo, A.M. Baró and N. García, Phys. Rev. Lett., **71**(12) (1994) 1852.

13) M.F. Crommie, C.P. Lutz and D.M. Eigler, Science, **262** (1993) 219.