Extended Abstracts of the 1994 International Conference on Solid State Devices and Materials, Yokohama, 1994, pp. 40–42

S-I-3-4

Evaluation of Thin SiO_2 Layers by Beam Assisted Scanning Tunneling Microscope

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The band gap of thin thermal silicon dioxide layers are evaluated by beam assisted scanning tunneling microscope(BASTM). The insulator sample is exposed with an electron beam, which excites elctron-hole pairs and makes the sample conductive. A 10 nm thick and 100 nm wide line and space patterned silicon dioxide layer is observed by STM with electron beam exposure. Current-voltage curves are measured for SiO_2 layers with thicknesses between 1.8 to 4.5 nm. The results indicate that the band gap values have no dependence on the layer thichnesses.

1. INTRODUCTION

Scanning tunneling microscope $(STM)^{1)}$ is a powerful tool for imaging the surfaces of conducting materials with atomic resolution, but it is impossible to observe insulators. Atomic force microscope $(AFM)^{2)}$ enables one to image insulator surfaces, however, it is impossible to evaluate the electronic structure, as can be characterized by tunneling spectroscopy with STM. Beam assisted STM (BASTM) $^{3)}$ enables one to observe the surface structure and to evaluate the electronic structure of insulator layers. This paper demonstrates the possibility of evaluating the surface structure and the band gap of thin thermal oxide (SiO_2) layers which are indispensable for the nano scale devices.

2. EXPERIMENTAL

The observation mechanism of BASTM is schematically shown in Fig.1, where the insulator sample is irradiated with a high energy excitation beam such as electron, photon or ion beam. If the beam has high enough energy compared with the band gap of insulators, electrons are excited from the valence band to the conduction band inducing electron-hole pairs, which contribute to the conduction in insulators and enable STM observation. A high vacuum STM (HITACHI V-3000) installed in a scanning electron microscope (SEM: HITACHI-2700) was used in this experiment. This system permits us to observe the sample by SEM and STM simultaneously. During the SEM observation the sample is exposed with an electron beam, with an acceleration energy of 20 keV, a beam current of 30 pA and a scanning rate of 25Hz. The STM observation conditions are tunneling current of 1nA and tip bias voltage of 500mV.

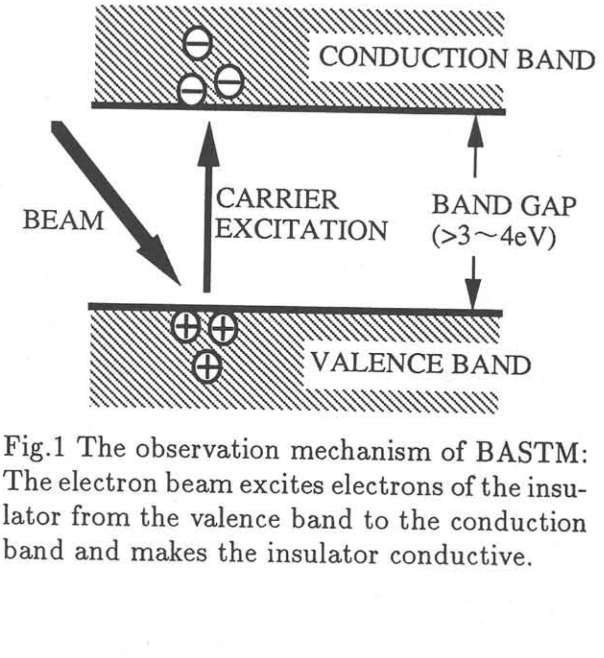

Fig.1 The observation mechanism of BASTM: The electron beam excites electrons of the insulator from the valence band to the conduction band and makes the insulator conductive.

The SEM beam current has no influence on the STM observation, because the current is about two orders of magnitude smaller than the tunneling current. A 10 nm thick silicon dioxide layer was thermally grown on a p-type,10 Ωcm, (100) oriented silicon wafer, followed by electron beam lithography and dry etching to form 100 nm wide line and space patterns. The sample structure is schematically shown in Fig.2.

3. RESULTS AND DISCUSSION

Figure 3 compares SEM and BASTM micrographs of the sample. In Fig.3(b) the bright regions correspond to higher area and the dark regions to lower area. The BASTM image was taken over 1μm × 1μm area and 200 nm pitch and 10 nm deep line and space patterns were observed, but the groove width is slightly narrower than that observed by SEM. This phemnomenon is due to the tip apex effect, which is reported elsewhere.[4] Except for this narrowing of grooves, the BASTM image almost perfectly corresponds to the sample structure observed by SEM.

Current-voltage(I-V) and dI/dV-V curves measured for the SiO_2 layer are depicted in Fig.4, which indicate a band gap of around 5 eV. Though this value is quite smaller than the theoretical value of 8eV[5], the discrepancy should be attributed to the thin SiO_2 thickness. The conductance curve corresponds to the band structure of insulator. These results demonstrate the possibility of evaluating the electronic structures of SiO_2 layers by BASTM.

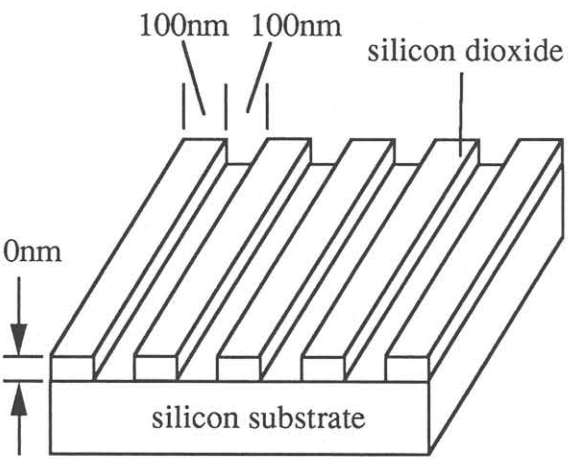

Fig.2 Schematic drawing of sample structure. A 10 nm thick, 100 nm wide line and space patterned silicon dioxide layer is formed on a silicon substrate.

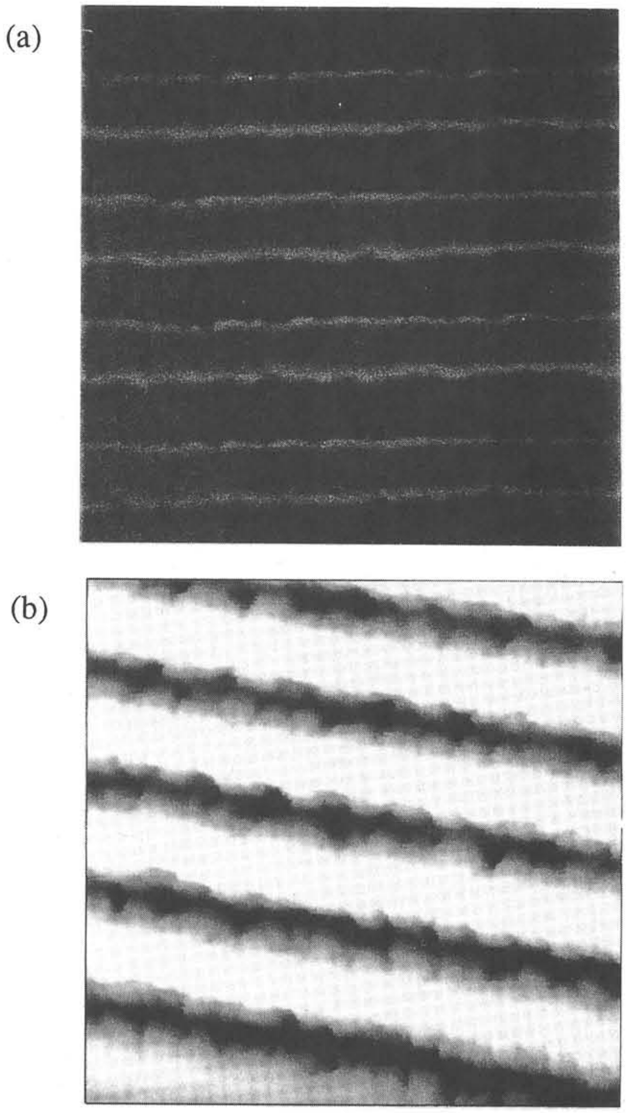

Fig.3 (a)SEM and (b)BASTM images of the sample shown in Fig.2.

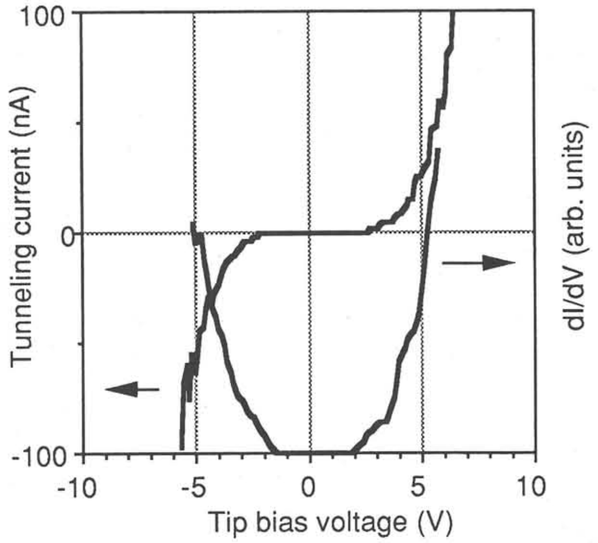

Fig.4 I-V and dI/dV-V curves measured on a 10nm thick SiO_2 layer.

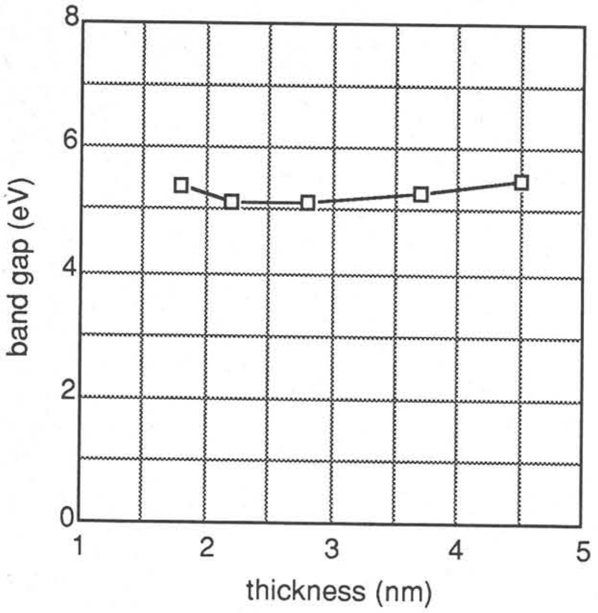

Fig.5 Thickness dependence of band gaps and berrier heights of thin SiO_2 layers with thicknesses of 1.8, 2.2, 2.8, 3.7 and 4.5nm.

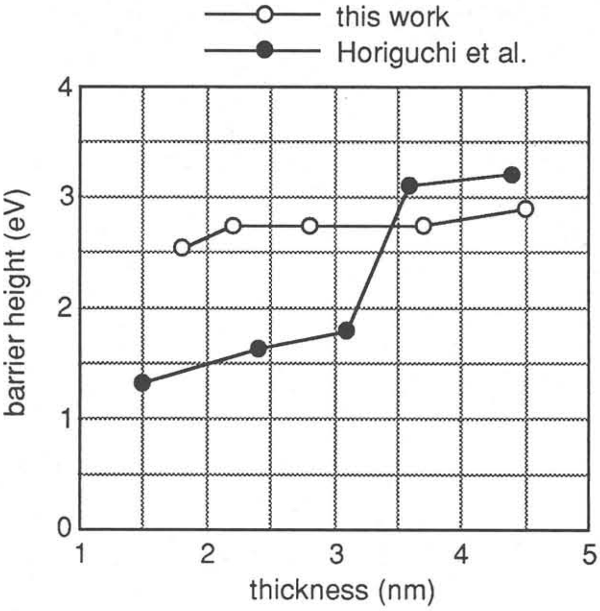

Fig.6 Thickness dependence of berrier heights of thin SiO_2 layers measured by BASTM and conductance measurement.

The band gaps of thermal SiO_2 layers with thicknesses between 1.8 to 4.5 nm were measured and the results are shown in Fig.5. These results indicate that the band gap has no dependence on insulator thicknesses. To the best of our knowledge, these results shown in Fig.5 are the first evaluation data of band gaps of thin oxide layers. Horiguchi et al. reported that the barrier height of SiO_2 reduces below the thickness of 3.5 nm derived from the conductance measurement $^{6)}$ as plotted by solid circles in Fig.6. This causes extreme increase of leakage current through thin oxide layers and makes it inpossible to use in advanced large scale integrated circuit(LSI). The barrier height represents the energy of the edge of conduction band measured from the Fermi level. The barrier heights measured in this work are also plotted by open circles in Fig.6, and no thickness dependence was detected. The discrepancies would originate from the experimental technique, and the present method should provide direct barrier height data. Since the barrier height values measured by BASTM do not reduce below 3.5 nm, it would be possible to realize highly reliable very thin gate oxide for nano scale devices.

4. CONCLUSION

A 10 nm thick and 100 nm wide line and space patterned silicon dioxide layer formed on a silicon wafer was observed by BASTM. The tunneling spectroscopy on the SiO_2 layers with thicknesses between 1.8 to 4.5 nm indicates that SiO_2 layer has a band gap of about 5 eV, which has no dependence on the layer thichness.

ACKNOWLEDGEMENTS

The authors would like to express thanks to Dr. Takashi Nishida, Dr. Fumio Murai and Dr. Tokuo Kure for valuable discussions on Si/SiO_2 structures.

REFERENCES

1) G. Binnig, H. Rohror, Ch. Gerger, and E. Weibel, Phys. Rev. Lett. 49(1982) 57 .
2) G. Binnig, C. F. Quate, and C. Gerger, Phys. Rev. Lett. 56(1986) 930.
3) S. Heike, Y. Wada, S. Kondo, M. Lutwyche, K. Murayama and H. Kuroda, Appl. Phys. Lett. 64(1994) 1100.
4) Y. Akama, E. Nishimura, A. Sakai, and H. Murakami, J. Vac. Sci. Technol. A8(1990) 429.
5) A. S. Grove, Physics and Technology of Semiconductor Devices (Wiley, New York, 1967).
6) S. Horiguchi, J. Appl. Phys. 58(1985) 1597.