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Resonant Tunneling through SiO_2/Si Quantum Dot/SiO_2 Double Barrier Structures

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Crystalline Si quantum dots have been spontaneously fabricated on SiO_2 by controlling the kinetics of low-pressure chemical vapor deposition from pure silane. The current-voltage characteristics for Au/SiO_2/a single Si quantum dot/SiO_2/n^+Si(100) double barrier structures have exhibited the clear current bump or negative conductance at 300K. A peak current to valley ratio as high as10 has been obtained and explained by the resonant tunneling through the dot. Also, the oscillatory current with a voltage period of ~17mV has been observed around the resonance voltage and a possible reason for this is discussed.

1. INTRODUCTION

The resonant tunneling devices consisting of Si/SiO_2 double barrier structures will be integrated on a silicon chip in future to add a new function to the system. Detailed knowledge on tunnel current through ultrathin SiO_2 grown on Si and precise size control of a Si quantum well or dot will enable us to observe the resonant tunneling current through the double barrier structure at 300K. To date, the carrier transport through the double barrier systems consisting of ultrathin SiO_2 barriers and a well layer made of polycrystalline Si[1], microcrystalline Si[2,3], single crystalline Si[4] or amorphous Si[5] has been studied, and the conductance change associated with the resonant tunneling has been reported. However, a clear current bump due to resonant tunneling at 300K through a Si quantum well or dot has not been confirmed yet. Recently, Si quantum dots with diameters of 5~20nm and heights of 2~10nm have been prepared by low-pressure chemical vapor deposition (LPCVD) from SiH_4 and the quantum size effect has been observed as a blue shift of the optical absorption edge[6].

In this paper, the early stages of Si LPCVD have been systematically studied for developing a self-assembling or spontaneous process to form nanometer-size Si dots on SiO_2. Also, the resonant tunneling through a single Si quantum dot has been confirmed at 300K as a clear current bump or negative conductance.

2. EXPERIMENTAL

A 3nm-thick oxide layer was first grown at 900°C in dry O_2 on an n^+Si(100) substrate. The hemispherical Si quantum dots were grown on the SiO_2 layer by LPCVD using pure silane. The gas pressure was maintained at 0.2Torr and the substrate temperature was varied from 550 to 600°C. For fabricating an SiO_2/Si-dot/SiO_2 double barrier structure, the SiO_2 was etched-back to 1nm in thickness by 0.1%HF with an etch rate of 0.35nm/min. The etch uniformity for the SiO_2 layer was confirmed by atomic force microscopy (AFM) and FT-IR-ATR (Attenuated Total Reflection)[7]. After Si dot formation by LPCVD, 1nm-thick SiO_2 was grown at room temperature or 800°C. Thus the tunnel current through a gold-coated AFM conducting probe/SiO_2/Si-dot/SiO_2/n^+Si(100) double barrier was measured.

3. RESULTS AND DISCUSSION

The AFM image of Si dots formed at 600°C on a 3nm-thick, as-grown SiO_2 is shown in Fig.1, where the average dot diameter is ~15nm and the height ~5nm. The high-resolution transmission electron microscopy (TEM) image indicates that the dot is crystallized as shown in Fig.2. The average diameter and height of Si dots can be controlled by the growth temperature as demonstrated in Fig.3. The activation energy for dot height E_H=2.2eV is consistent with a Si cohesive energy of 2.45eV[8] or 2.14eV[9]. On the other hand the activation energy for dot diameter E_D=0.82eV is in good agreement with the SiH_4 decomposition energy on Si surfaces[10], implying that the decomposition process of SiH_4 molecules adsorbed on the Si nucleation sites controls the dot diameter. Significant decrease in dot size and corresponding increase in dot density have been achieved by treating the SiO_2 surface in a 0.1%HF solution before the LPCVD. This is because the HF treatment creates reactive sites such as Si-OH bonds on the SiO_2 surface. Enhancement of the SiH_4 decomposition reaction rate at such sites results in the increase of initial Si nucleus density and decrease of dot size.

A typical current-voltage characteristic for an AFM Au probe/1nm-thick SiO_2/Si-dot (2.5nm in height)/1nm

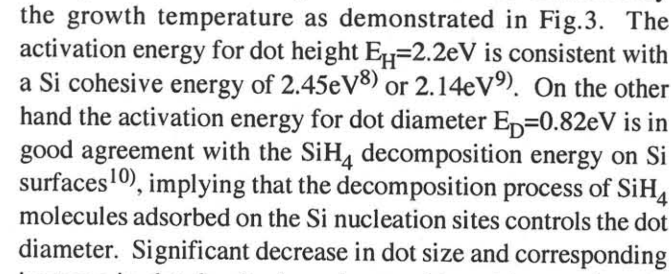

Fig.1. AFM image of Si dots formed on an as-grown SiO_2 surface.

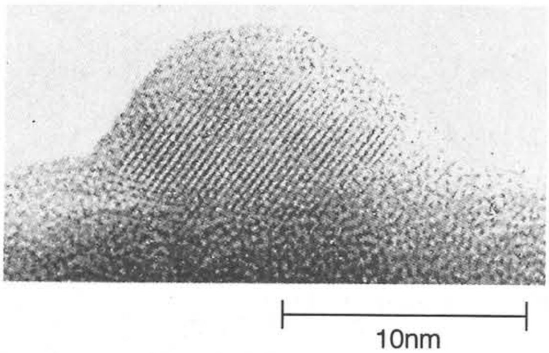

Fig.2. High resolution TEM image of a Si-dot formed on an as-grown SiO_2 surface.

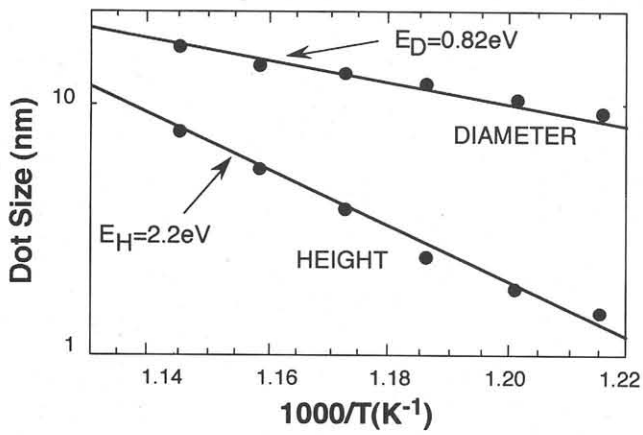

Fig.3. Temperature dependence of Si dot size. The deposition time was 60sec.

$SiO_2/n^+Si(100)$ double barrier structure is shown in Fig.4, where electrons are injected from an n^+Si substrate. The current bump and the negative conductance are clearly observable around 0.6V. The peak current to valley ratio is as high as 10 although the second peak expected to appear at 1.55V is not clearly visible. Also, in Fig.5 the current bump and negative conductance are observable at both 0.75 and 1.55V for a similar size of Si dot. The dashed curve in the figure corresponds to the calculated characteristic for the SiO_2 barrier thickness of 1nm and the tunneling effective mass of $0.3m_0$(m_0; the free electron mass)[11]. The arrows indicated in Figs. 4 and 5 refer to the calculated resonant tunneling voltages. For fitting the calculated I-V curve to the measured one a flat-band voltage shift due to the work function difference as well as the oxide charge is taken into account. The voltages at which the resonant tunneling current peaks or shoulders are observed and the voltage difference between the 1st and 2nd peak for the same device structure are summarized in Fig.6. The calculated resonant tunneling voltages as a function of dot height which primarily determines the resonance voltage are shown in Fig.7, where the open circles correspond to the experimentally determined values.

It is interesting to note that the distinct current oscillation with a voltage period of ~17mV is observed at the first resonance current peak in Fig.4 as clearly seen in Fig.8.

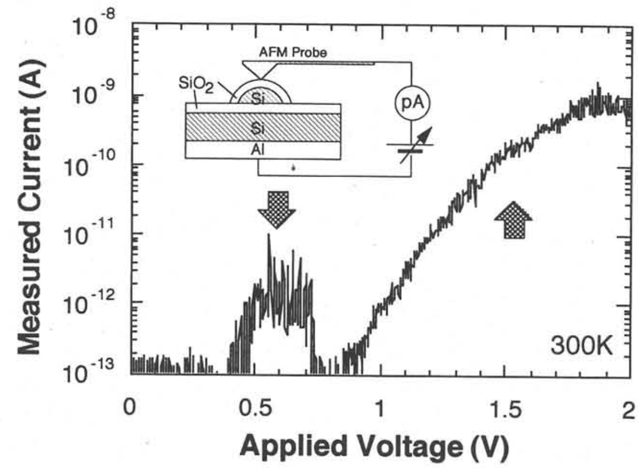

Fig.4. Measured I-V characteristic for an SiO_2/Si-dot(2.5nm in height)/SiO_2 double barrier structure. The inset illustrates the I-V measurement system. The arrows indicate calculated resonant tunneling voltages. Voltage was swept with a step of 2mV for every 0.1sec.

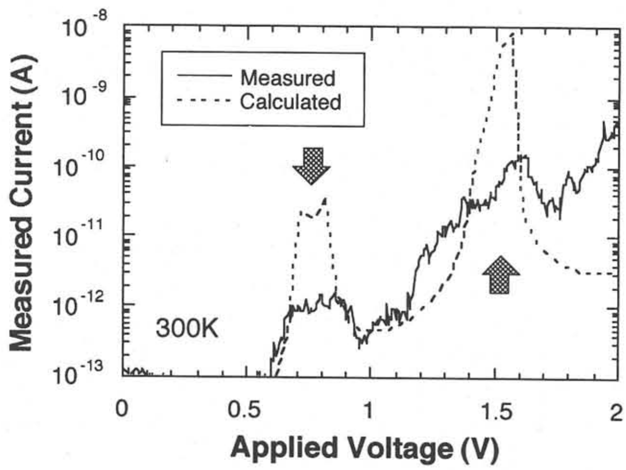

Fig.5. Measured and calculated I-V characteristics for an SiO_2/Si-dot(2.7nm in height)/SiO_2 double barrier structure. Voltage sweep with a 5mV step for every 0.1sec was used.

The origin of this periodic current could be associated with electron phonon interaction in the quantum dot because the transverse acoustic (TA) phonon energy in crystalline Si at the edge of phonon brillouin zone is 16meV. In the off-resonance region at the same current level, such periodic oscillation is not observable. This implies that TA phonon plays an important role for the energy and momentum conservation in resonant tunneling.

4. CONCLUSIONS

It is shown that the average size and density of Si quantum dots spontaneously grown on SiO_2 can be controlled by deposition temperature during LPCVD from SiH_4. The clear current bump with a peak to valley ratio of 10 and the corresponding negative conductance in the SiO_2/

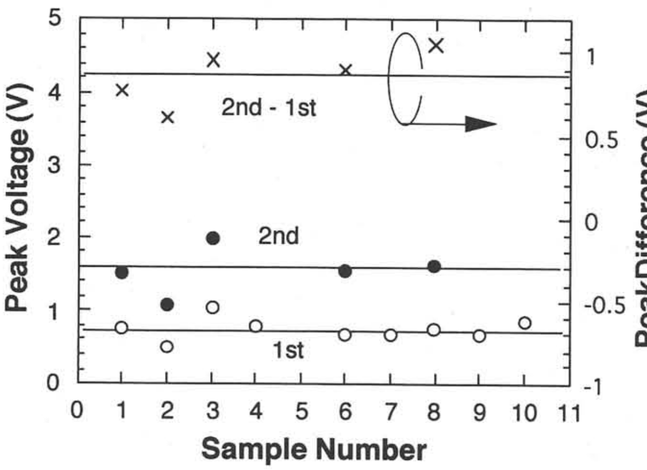

Fig.6. Measured voltages corresponding to 1st and 2nd current peaks and the voltage difference between 2nd and 1st peak for double barriers with dot heights of 2.1~3.1nm including the results of Figs. 4(sample number 6) and 5(sample number 1).

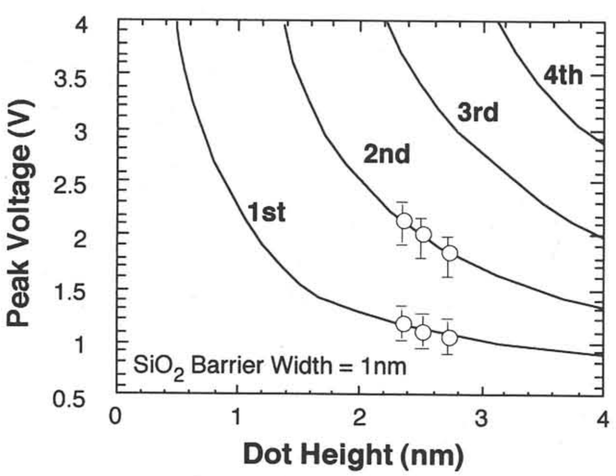

Fig.7. Calculated (solid lines) and measured (open circles) resonant tunneling peak voltages for SiO_2/Si-dot/SiO_2 double barrier structures.

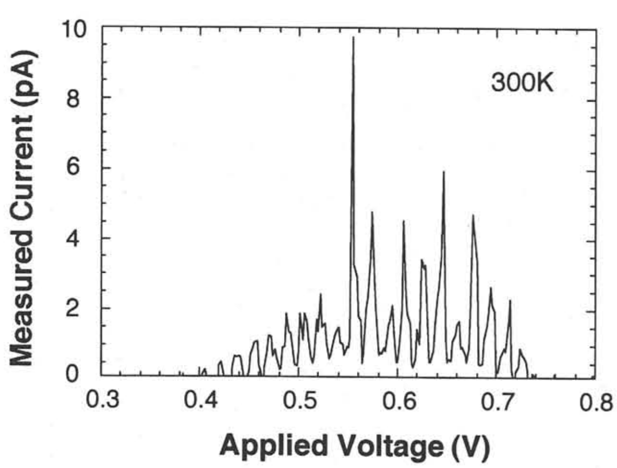

Fig.8. Magnified I-V curve around the 1st resonance voltage in Fig.4.

Si-dot/SiO_2 double barrier structures have been observed at 300K, indicating that the resonant tunneling occurs through a single Si quantum dot. Spatial control of Si nucleation sites on SiO_2 will be the next challenge for device application.

Acknowledgments

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