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Characterization of Electron Transport Through Ultra High Density Array of One-dimensionally Self-Aligned Si-based Quantum Dots

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1. Introduction

Si-quantum dots (Si-QDs) have attracted much attention due to the interest in future application to novel functional devices such as single electron transistor [1], floating gate memory [2] and resonance tunneling devices [3]. In these devices, the electronic transport through the dots is sensitively affected by Coulomb interaction among charged states of neighboring dots. In a two-dimensional Si-QDs array, it has been reported that charging and discharging of the dot adjacent to the percolation current path will give rise to a discrete switching of the current with time [4-6], which may lead to novel functionality. Considering that the Coulomb interaction between the percolation path and the adjacent charged dot is dependent on dot size and distance between the dots, one of crucial issues to control electrical transport properties is the formation of well-defined high-density Si-QDs. Recently, we have succeeded the formation of one-dimensionally aligned Si-QDs with an areal density of ~10^{11} cm^{-2} by process sequence consisting of selective Ge growth on pre-grown Si-QDs by LPCVD, in-situ oxidation, thermal desorption of Ge oxide and subsequent Si-QDs formation and demonstrated a clear current bump and negative differential conductance at room temperature by means of atomic force microscopy with a conductive cantilever [7].

In this work, we extended our research work to characterize electron transport through aligned-dots, which are closely packed with ~10^{13} cm^{-2}, in a MIS tunnel diode structure at room temperature to gain a better understanding on electronic coupling between neighboring dots.

2. Experimental

After a conventional wet-chemical cleaning step, Si(100) was oxidized at 1000 ˚C for 10 min in dry O_2 to form a ~4.0 nm thick SiO_2 layer. To obtain OH-terminated SiO_2 surface which enables us to enhance the dot density and improve the dot size uniformity, the oxidized surface was shortly dipped in a 0.1 % HF solution for 1 min. After exposing the OH-terminated surface to 10% GeH_4 diluted with He at room temperature, hemispherical Si-QDs were first grown with an areal density of ~10^{13} cm^{-2} on the SiO_2 surfaces at 580 ˚C from the thermal decomposition of pure Si_2H_6 at a pressure of 26.6 Pa [8]. Subsequently, Ge was selectively deposited on the pre-grown Si-QDs at 380 ˚C using 5 % GeH_4 diluted with He [9] and followed by dry O_2 oxidation at 600 ˚C. To remove the Ge-oxide and residual surface OH-bonds acting as nucleation sites in the next LPCVD, the sample was heated to 1000 ˚C after the process chamber was evacuated down to ~1.3×10^{-5} Pa. After that, the SiH_4-LPCVD was carried out at 580 ˚C under a pressure of 4.0 Pa for self-aligned selective formation of the 2nd Si-QDs on the 1st grown dots. After surface oxidation of dots at 850 ˚C, Au top electrodes and the Al back contact to n-Si(100) were formed by thermal evaporation.

3. Results and Discussion

Current–voltage (I-V) characteristics of MIS diodes with aligned-dots show rectification properties originating from the work function difference between Au top electrode and n-Si(100) substrate and hysteresis properties due to charge trapping (not shown). Notice that, in the reverse bias region between 0 and 2.0 V, characteristic fluctuation in the current level were observed clearly at room temperature as shown in Fig. 1 (a). There seems to be distinct transitions in current levels at random in time at each constant applied bias, implying Random telegraph signals (RTS), which imply charging and discharging of aligned-dots adjacent to the percolation current path in the dots array. In fact, from the histograms of the current levels obtained by a 100 ms sampling as shown Fig. 1(b), we found the transition between two current states. At -0.5 V, the low current state was dominant although that was drastically decreased with an increase in the applied bias up to -1.4 V. The low current state can be interpreted in terms that a percolation current path was interrupted by a potential increase of a Si-QD near the path due to electron trapping. Figure 2 shows the ratio of total time in the high current state to that in the low current state as a function of applied bias. With an increase in the applied bias, the time ratio shown in Fig. 2 is increased exponentially, reflecting a promotion of carrier transfer by tunneling. On the other hand, the difference in current level between two distinct states was decreased with increasing applied bias presumably because of limitation in the high current level under reveres bias conditions. It is likely that the electron emission of the adjacent dot depends strongly on applied bias in comparison to hole injection from the substrate. Considering the fact that the current ratio of the low state to the high state is almost constant at 99 % independently of

applied bias, it is likely that ~1 % of current passes is closed by charging of the trap site with a specific energy level at random times. It is interesting noted that the three level became observable by white light irradiation in the wavelength region of 400-800 nm through a fiber-optics equipped with an infrared filter from a 100 W halogen lamp (Fig. 3). The result suggests that two-dimensional distribution of photo-generated electrons and holes in aligned-dots array play a role on an increase in the potential fluctuation throughout the dots array.

4. Conclusions

We fabricated one-dimensionally aligned Si-based quantum dots with an areal density as high as ~10^{13} cm^{-2} on ~1.0 nm-thick SiO_2 and characterized electron transport through the aligned-dots in MIS tunnel diodes. Random telegraph signals were clearly observed at constant applied bias conditions in dark condition and under light irradiation at room temperature. The result indicates the charging and discharging of a dot adjacent to the percolation current path in the dots array.

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References

[1] L.P. Rokhinson, L.J. Guo, S.Y. Chou and D.C. Tsui, Appl. Phys. Letts., **76** (2000) 1591.

[2] S. Tiwari, F. Rana, H. Hanafi, H. Hartstein, E.F. Crabbe and K. Chan, Appl. Phys. Lett., **68** (1996) 1379.

[3] M. Fukuda, K. Nakagawa, S. Miyazaki and M. Hirose, Appl. Phys. Lett., **70** (1997) 2291.

[4] R. Nuryadi, Y. Ishikawa and M.Tabe, Physical Review B, **73** (2006) 045310.

[5] K.K. Likharev, N.S. Bahhvalov, G.S. Kazacha and S.I. Serdyukova, IEEE Trans. Magn., **25** (1989) 1436.

[6] C. Dumas, J. Grisolia, G. BenAssayag, C. Bonafos, S. Schamm, A. Claverie, A. Arbouet, M. Carrada, V. Paillard and M. Shalchian, Physica E, **38** (2007) 80.

[7] K. Makihara, M. Ikeda and S. Miyazaki, J. Appl. Phys., **112** (2012) 104301.

[8] K. Makihara, A. Kawanami, M. Ikeda, S. Higashi and S. Miyazaki, ESC Trans., **16** (2008) 255.

[9] Y. Darma, R. Takaoka, H. Murakami and S. Miyazaki, Nanotechnology, **14** (2003) 413.

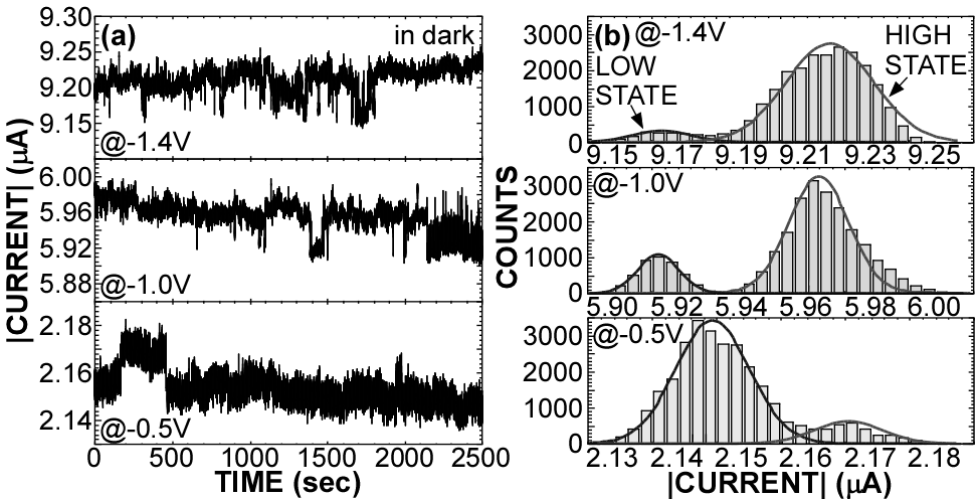

Fig. 1 Currents for 2500 sec observed in one-dimensionally self-aligned dots/SiO_2 /n-Si(100) at constant applied biases of -1.4, -1.0 and -0.5 V (a) and histograms in time domain obtained by a 100 ms sampling (b).

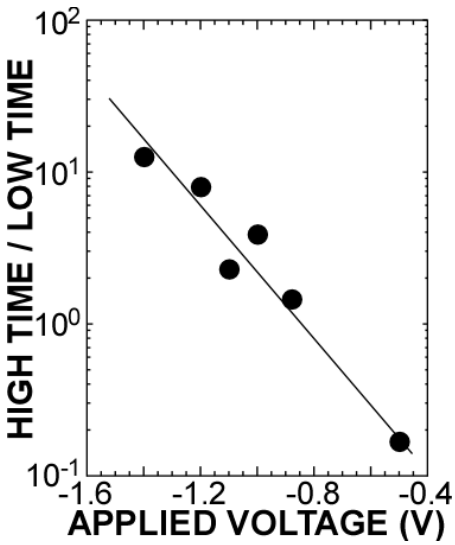

Fig. 2 Total time ratio of high current state to low current state as a function of applied bias evaluated from histograms as shown in Fig. 1 (b).

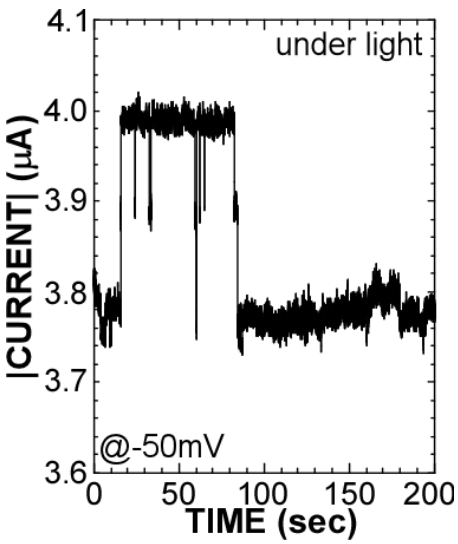

Fig. 3 Current for 200 sec measured in self-aligned dots array at a constant applied bias of -50 mV under white light irradiation.