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Characterization of Electron Field Emission from Si Quantum Dots with Ge Core/ Si Quantum Dots Hybrid Stacked Structures

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Abstract

We have fabricated multiply-stacked structures consisting of Si Quantum Dots (Si-QDs) with Ge core and Si-QDs (hybrid dots stack), and studied their electron field emission properties. Electron emission was observed from the hybrid dots stack by the application of a forward bias of 8V, which was lower than that for a pure Si-QDs stack. This result is attributed to electric field concentration on upper Si-QDs layers beneath the layers of Si-QDs with Ge core in the hybrid dots stack due to the introduction of Ge core which was positively charged reflecting deep potential well for holes. The results lead to the development of planar-type electron emission devices with a low voltage operation.

1. Introduction

Electron emission from Si nanocrystals has been intensively studied because electron emission devices are expected to be suitable for various applications such as electron microscope, electron lithography and field emission display [1-3]. In our previous work, we succeeded in the fabrication of multiple-stacked Si-quantum-dots (Si-QDs) emmbeded in SiO_2 by repeating low-pressure chemical vapor deposition (LPCVD) using pure SiH_4 and dry O_2 oxidation [4]. Recently, we also demonstrated electron emission from the multiple-stacked Si-QDs structures with ultrathin Au top electrodes when the negative biases of 6 V and over were applied to a bottom electrode with respect to the grounded Au top electrode, in which electric field concentrated on the upper dot layers as evaluated by hard X-ray photoelectron spectroscopy [5]. The electric field cocentartion is likely to increase the efficiency of the electron emission. To further enhance electric field concentration on the upper dot layers, based on our recent studies, we fabricated a multiply-stacked structure consisting of Si-QDs with Ge core and Si-QDs, and their electron emission characteristics were evaluated.

2. Experimental

After conventional wet-chemical cleaning steps, n-type Si(100) wafers with a resistivity of 8–10 Ωcm were oxidized at 800 °C in dry O_2 to form ~2.0 nm-thick SiO_2. After that, Si-QDs were formed on the SiO_2 by LPCVD using pure SiH_4, followed by thermal oxidation to cover the dot surface with ~2.0 nm-thick SiO_2. By repeating such a process sequence, 11-fold stacked Si-QDs layers embedded in SiO_2 network were formed. From the atomic force microscopy (AFM) measurement performed after SiH_4-LPCVD, the formation of Si-QDs with an areal dot density as high as ~4.5×10^{11} cm^{-2} and an average dot size of ~3.0 nm was confirmed. After that, twofold stacked layers of Si-QDs with Ge core were formed by GeH_4-LPCVD and subsequent SiH_4-LPCVD for the selective growth of Ge core and Si cap on pre-grown Si-QDs, respectively, where an areal density and an average height were ~4.5×10^{11} cm^{-2} and ~8.3 nm including ~2.3nm high Ge core, respectively. For the formation of the two-fold stacked Si-QDs with Ge core, surface oxide with a thickness of ~1.8 nm was grown by wet chemical oxidation. After the formation of the multiply-stacked structure consisting of Si-QDs with Ge core and Si-QDs, ~10 nm-thick Au for top electrodes and Al for bottom electrodes were formed by thermal evaporation. We also fabricated 13-fold stacked Si-QDs embedded in SiO_2 network as a reference.

Sample current (I_s) and electron field emission current (I_e) were measured simultaneously by sample bias application to the bottom electrode with respect to the grounded top electrode in a vacuum of ~10^{-2} Pa. To detect the I_e, a porous Au sheet fabricated by anodic oxidation was placed ~10 mm away from the sample surface as a collector electrode, to which acceleration voltage or retardation voltage was applied with respect to the top electrode.

3. Results and Discussion

Current-voltage characteristics of the diodes consisting of QDs show rectifying behavior (not shown). When the forward bias ($|V_s|$) exceeds a threshold value of ~8.0 V, the hybrid dots stack begin to emit electrons, and the I_e was exponentially increased with an increase in the $|V_s|$ (Fig. 1). No electron emission was observed in the reverse bias condition. Notice that, for the pure Si-QDs stacks, the electron emission current was detected at $|V_s|$ =14 V and over. These results can be interpreted in terms of the more electric field concentration on the upper Si-QDs layers beneath the layers of Si-QDs with Ge core caused by the introduction of Ge core reflecting deep potential well for holes (Fig. 2). To evaluate kinetic energy distributions of electrons emitted from the hybrid and pure Si-QDs stacks, the I_e was measured as a function of the retardation voltage applied to the collector electrode and was differentiated with respect to the retardation voltage (Fig. 3). The electron flux density has its maximum value at a kinetic of 2.0 eV for the pure Si-QDs stack biased at $|V_s|$ =12 V. With an increase in the $|V_s|$ from 12 to 14 V, peak kinetic energy was slightly shifted toward the higher kinetic energy side. It is interesting to note that, for the hybrid dots stack, the peak kinetic energies were larger than that for the pure Si-QDs stack under the same bias conditions. In addition, the peak kinetic energy for the hybrid dots stack more strongly depended on V_s than that for the pure Si-QDs stack (Fig. 4). These results can be explained by the reduction of electron scattering in the upper dot layers of the hybrid dots stack due to the higher kinetic energy of electrons. Change in potential distribution in the QD stack caused by holes stored in the Si-QDs with Ge core should be responsible for the generation of the higher kinetic energy electrons as expected from the energy band diagrams in Fig. 2. It is hoped that the above findings which resulted from the introduction of the Ge core into the Si-QDs will help to realize electron emission devices at low-voltage operation with no high external electric field.

4. Conclusions

We have demonstrated the stable electron emission from the hybrid dots stack structure consisting of two-fold stacked Si-QDs with Ge core formed on the 11-fold stacked Si-QDs at forward biases of 8 V and over, which was lower than that for the pure Si-QDs stack. The formation of Si-QDs with Ge core on pure Si-QDs stack is helpful in realizing high-efficiency planar-type electron emission devices.

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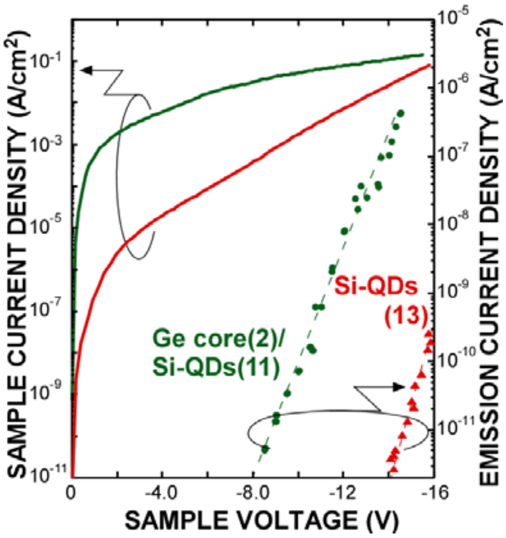

Fig. 1 Sample current-, and electron emission current-sample voltage characteristics of multiple stacked Si-QDs with and without Ge core at an acceleration voltage of 40V.

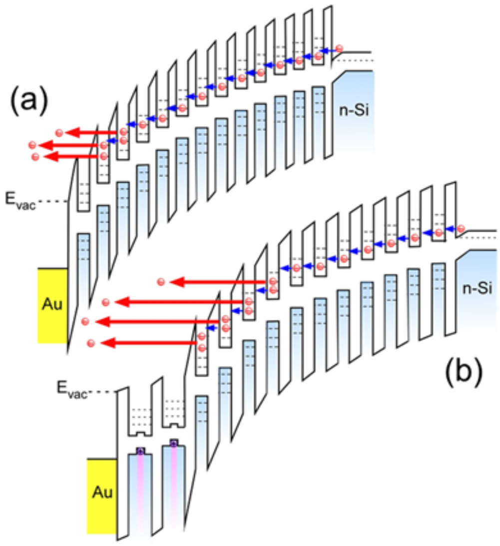

Fig. 2 Energy band diagrams of the pure Si-QDs stack (a) and the hybrid dots stack (b) at an applied bias of -14 V.

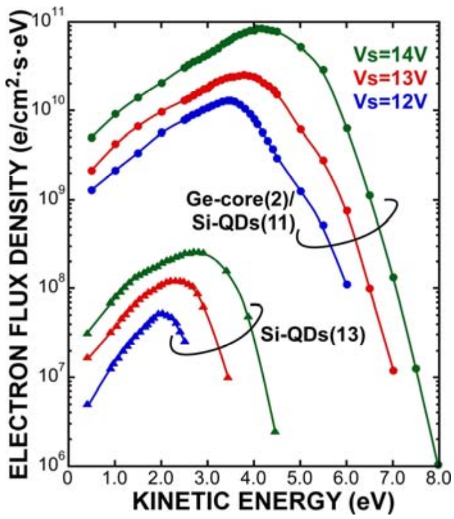

Fig. 3 Kinetic energy distributions of electrons emitted from the multiple stacked Si-QDs with and without Ge core Si-QDs at different sample voltages.

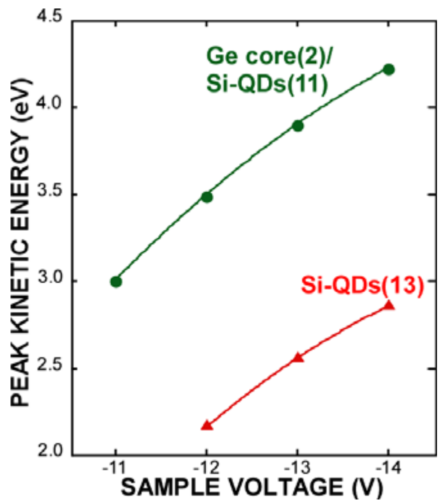

Fig. 4 Sample voltage dependences of peak kinetic energies in kinetic energy distributions of electrons emitted from the samples shown in Fig. 3.