Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 106-107

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Electroluminescence from Multiple-Stacked Structures of Impurity Doped Si Quantum Dots

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1. Introduction

Nanometer-scale silicon structures have great potential to introduce new generation Si-based devices because they show unique physical properties associated with carrier confinement effect and Coulomb blockade [1, 2]. Recently, light emission from Si nano-structure has stimulated considerable interest in developing silicon based light emitting diodes (LEDs) in order to leverage the infrastructure of microelectronics technology for the fabrication of optoelectronic devices [3]. In addition, the improvement of the efficiency and stability are still major challenges. More recently, we have reported visible light emission from multiple-stacked Si-QDs embedded into SiO_2 matrix, where Si dot formation by low-pressure chemical vapor deposition (LPCVD) using pure SiH_4 are combined sequentially with surface oxidation and subsequent surface modification by remote plasmas [4]. We also demonstrated that, by impurity δ-doping to Si-QDs, electroluminescence (EL) was enhanced for LEDs with 6 fold staking structures [5].

In this work, we extended our research to a two-tiered structure consisting of P-doped Si-QDs and B-doped Si-QDs being similar to PN junction, and current-voltage and light emission characteristics were evaluated in comparison to those of both P- and B-doped Si-QDs stacked structures.

2. Experimental

After conventional wet-chemical cleaning steps of p- and n- Si(100) wafers, the wafer surfaces were oxidized at 1000ºC in dry O_2 to form ~3.5nm-thick SiO_2. The SiO_2 surface was exposed to remote plasmas of pure Ar and subsequently H_2 at 560ºC for 1min in each steps. Subsequently, Si-QDs were formed from the thermal decomposition of pure SiH_4 under 0.5Torr at 560ºC [4] and followed by radical oxidation of 1%O_2 diluted with He under 0.1Torr at 560ºC to cover the dot surface conformally with ~2.0nm thick SiO_2. To generate remote plasmas, a 60 MHz power source was used. In phosphorus or boron δ-doping to Si-QDs, 1% PH_3 or B_2H_6 diluted with He was injected in a short pulse during the Si-QDs formation [6]. By repeating such a process sequence consisting of the surface oxidation and modification by remote plasma treatments and the impurity doped Si-QDs formation by LPCVD, 3 fold stacking of B-doped Si-QDs over 3 fold stacking of P-doped Si-QDs structure embedded in the SiO_2 network was formed. For a light emitting diode structure, after N_2 annealed at 1000ºC to stabilize the stack structure and to reduce non-radiative recombination centers, semitransparent Au (~10nm in thickness) and Al were formed as front and back electrodes, respectively, by thermal evaporation.

3. Results and Discussion

Current-voltage (I-V) characteristics of light emitting diodes with P-doped and B-doped Si-QDs stacking structures fabricated on p- and n-Si(100) show clear rectification properties as shown in Fig. 1. Obvisouly, in the diode fabricated on p-Si(100), electron injection from the Au gate and hole injection from p-Si(100) occur at negative gate voltages. On the other hand, in the diode on n-Si(100), electron injection from the n-Si(100) and hole injection from the Au gate occur when the positive gate bias is applied, namely at the forward bias condition. Under the forward bias conditions, EL becomes observable in the range from near-infrared to visible region even at room temperature as shown in Fig. 2. No EL was detected under reverse gate bias conditions. It should be noted that

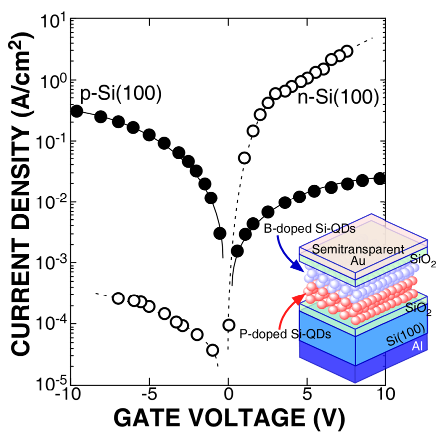

Fig. 1. Current-Voltage characteristics of 6 fold stacking structures of P- and B-doped Si-QDs formed on p- and n-Si(100) substrate. The device structure was schematically illustrated in the inset.

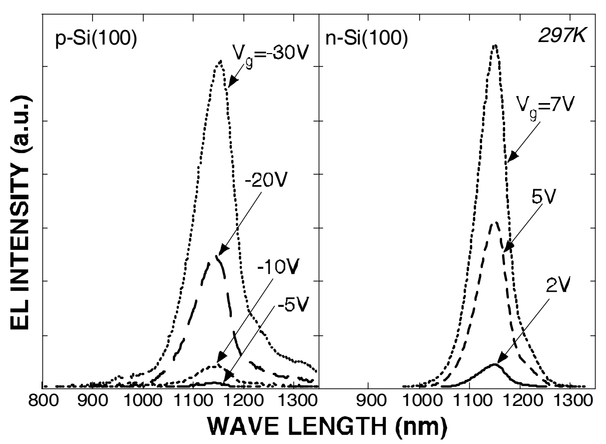

Fig. 2. Electroluminescence (EL) spectra of 6 fold stacking structures of δ-doped Si-QDs formed on p- and n-Si(100) substrates, which were taken at different gate biases at 297K.

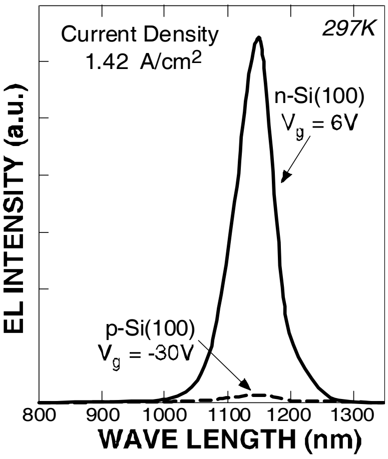

Fig. 3. Electroluminescence spectra of 6 fold stacking structures of P- and B-doped Si-QDs formed on p- and n-Si(100) substrates at 297K. The EL spectra of Si-QDs stacking structures were taken at a current density of 1.42A/cm^2.

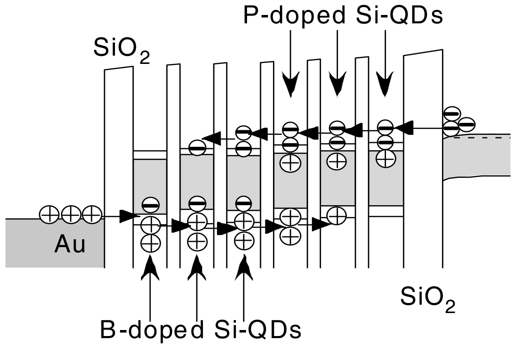

Fig. 4. Energy band diagram for 6 fold stacking structures of P- and B-doped Si-QDs formed on n-Si(100).

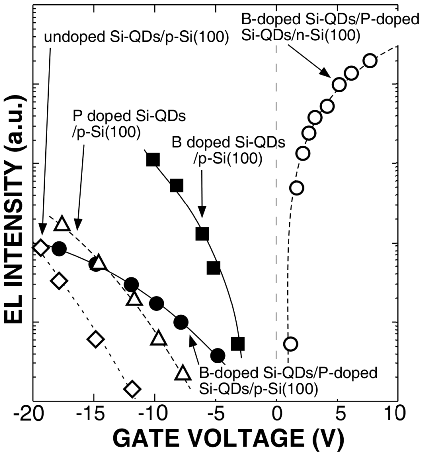

Fig. 5. Bias dependence of EL intensity for 6 fold stacking structures of Si-QDs with and without impurity doping.

the P- and B-doped Si-QDs staking structure formed on n-Si(100) enhance the emission intensity by a factor of 50 under the same current density compared with the same stacking structure fabricated on p-Si(100) substrate (Fig. 3). Considering the average electric field in the diode on p-Si(100) is higher by a factor of 5 than that in diode on n-Si(100), carriers transport with insufficient energy relaxation to band edges in QDs for the diode on p-Si(100). In contrast, for the diode on n-Si(100), electrons and holes are smoothly injected to P-doped dots and B-doped dots, respectively, and injected carriers facilitate to recombine under a relatively low electric field as schematically illustrated in Fig. 4.

The EL intensities as a function of applied gate bias are summarized as shown in Fig. 5. The EL intensities for 6 fold stacking structure of undoped and impurity doped Si-QDs [5], which were measured under the same condition, are also shown as for comparison references. The emission intensity of P- and B-doped Si-QDs stacking structure on p-Si(100) and n-Si(100) increase with the current over the threshold bias of -4V and +1V, respectively. We summarize EL intensities at a current density of 1 A/cm^2, which were normalized by an EL from the 6 fold stacking structure of undoped Si-QDs/p-Si(100), and threshold voltage for EL in Table 1. P- and B-doped Si-QDs stacked structure enhance the emission intensity by a factor of 12 when it was formed on p-Si(100), and 560 on n-Si(100) compared with the undoped Si-QDs stacked structure. This result indicates that two-tiered δ-doped Si-QDs structure can contribute to an increase of charge injection rate in EL.

Table 1. EL intensity, which were normalized by the 6 fold undoped Si-QDs stacking structure, and threshold voltage for EL.

Structure	EL Intensity (Current Density=1A/cm^2)	V_{th}
6 fold undoped Si-QDs /p-Si(100)	1	~ -12V
6 fold P-doped Si-QDs /p-Si(100)	~1.9	~ -8.0V
6 fold B-doped Si-QDs /p-Si(100)	~0.9	~ -3.0V
3 fold B-doped Si-QDs/3 fold P-doped Si-QDs/p-Si(100)	~12	~ -4.0V
3 fold B-doped Si-QDs/3 fold P-doped Si-QDs/n-Si(100)	~560	~ +1.0V

Summary

We fabricated multiple-stacked structures consisting of P- and B-doped Si quantum dots and ultrathin SiO_2 interlayers by repeating a process sequence of Si dot formation by LPCVD and in-situ surface oxidation with remote O_2 plasma and applied them to an active layer of light emitting diodes with a semitransparent Au gate. Under forward bias conditions over a threshold bias as low as +1V for LEDs with P-doped and B-doped dot stack formed on n-Si(100) substrate, stable EL was obtained in the visible to near infrared region and increases with current injection at room temperature and EL was enhanced by a factor of 560 for LEDs with 6 fold undoped dot stack presumably because of an improvement of carrier injection rate.

Acknowledgement

This work was supported in part by Grant-in Aids for Scientific Research (A) No. 18206035 and for Scientific Research on Priority Area (458) No. 18063017 of MEXT, Japan.

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