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Electroluminescence from One-dimensionally Self-Aligned Si-based Quantum Dots with High Areal Dot Density

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1. Introduction

The application of nanometer-sized Si structures to light emitting diodes (LEDs) has been stimulated considerable interest as a potential approach to build an infrastructure for evolution of Si-based microelectronics to optoelectronics [1-3]. Because of the difficulty in achieving a good balance between charge injections and confinement in Si nanostructures, the improvement of the light emission efficiency and stability are major technological concerns. So far, we reported visible light emission from multiple-stacked Si-quantum dots (Si-QDs) embedded in a SiO2 matrix which was prepared by repeating the process cycle consisting of Si-QDs formation by low-pressure chemical vapor deposition (LPCVD), surface oxidation and subsequent surface modification by remote plasmas [4]. 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 growth of Ge on pre-grown Si-QDs by LPCVD, in-situ oxidation, thermal desorption of Ge oxide and subsequent deposition of Si-QDs, and demonstrated that the self-align formation of Si-QDs is quite effective to increase electron-hole recombination efficiency in electroluminescence (EL) [5].

In this work, we extended our research work to ultrahigh-density Si-based QDs with an areal density as high as ~10^{13}cm^{-2} and evaluated impact of dot density on their EL characteristics.

2. Experimental

After conventional wet-chemical cleaning steps, ~4.0nm-thick SiO_2 was grown on n-Si(100) by dry O_2 oxidation at 1000 °C. The SiO_2 surface was shortly dipped into a 0.1% HF solution just to obtain uniform surface termination with OH bonds. Subsequently, the OH-terminated SiO_2 surface was first exposed to 10% GeH_4 diluted with He in the total gas pressure of 100 Torr and for 10 min at room temperature and followed by Si dots formation from the thermal decomposition of 10% Si_2H_6 diluted with He at 400°C under a pressure of 0.2 Torr [6]. To minimize undesirable gas mixing of GeH_4 and Si_2H_6, the CVD chamber was purged with dry N_2 and evacuated down to ~10^{-7} Torr after the GeH_4 exposure. After that, Ge was deposited selectively on the pre-grown Si-QDs at 410 °C using 5% GeH_4 diluted with He [7] and followed by dry O_2 oxidation at 600 °C. To remove Ge-oxide, the sample was heated up to 1000 °C after the process chamber was evacuated down to ~10^{-7} Torr. Subsequently, the SiH_4-LPCVD was carried out at 580 °C under a pressure of 20 mTorr. For LEDs, after surface oxidation of dots at 850 °C, semitransparent Au (~10nm in thickness) top electrodes and the Al back contact to n-Si(100) were formed by thermal evaporation.

3. Results and Discussion

AFM images confirm that the areal dot density (~1.0×10^{13}cm^{-2}) remains unchanged after Ge deposition on the first Si-QDs while the dot height increases by ~1 nm (Fig. 1(a)). It should be noted that dome-shaped surface morphology was smeared out after 600 °C oxidation (Fig. 1(b)). This suggests that the surface oxidation of the pre-grown Si-QDs especially in the side of the dots being barely covered with Ge proceeds with the oxidation of the Ge clad and results the filling-in of gaps in-between the neighboring dots with the Si-oxide. In fact, no significant change in the topographic image was confirmed after thermal desorption of Ge-oxide from the dots at 1000 ˚C. As a result of the Ge-oxide removal from the dot surface the top portion of the Si-QDs emerges without surface oxide. By subsequent SiH_4-LPCVD, one-dimensional self-aligned Si-based QDs structure was formed successfully.

For the LEDs with self-aligned dots fabricated on n-Si(100), current-voltage (I-V) characteristics show clear rectification properties reflecting work function difference between the Au top gate and n-Si(100) substrate. Under the forward bias conditions, EL becomes observable in the near-infrared region even at room temperature, as shown in Fig. 2. In this case, the threshold voltage for EL was ~1.2V. Notice that no EL was detected under reverse gate bias conditions. From the spectral analysis using a Gaussian curve fitting method, it is revealed that the observed EL spectra can be deconvoluted into mainly two components peaked at ~1130nm and ~1030nm. With an

increase in the applied biases over threshold voltage, EL spectra became asymmetric shape with a tail toward the shorter wavelength side because of a remarkably increase in the ~1130nm component peak. It is likely that these two components are associated with radiative recombination in 1st and 2nd dots although the detailed study to identify the origin is needed. Figure 3 summarizes the integrated EL intensities as a function of current density. For the aligned dots with an areal density as high as $10^{13}cm^{-2}$, integrated EL intensities are over two orders of magnitude higher than that of $10^{11}cm^{-2}$ [5] under the same current density. This result can be interpreted in terms of not only an increase in radiative recombination sites with increasing dot density but also an improvement of radiative recombination efficiency due to enhanced carries injection into the aligned dots.

4. Conclusions

We have demonstrated that stable EL in the near infrared region from semitransparent-Au-gate LEDs with the one-dimensionally aligned Si-based QDs with an areal density as high as $10^{13}cm^{-2}$ under forward bias conditions over a threshold bias as low as +1.2V. With an increase in areal dot density from 10^{11} to $10^{13}cm^{-2}$, the EL intensity was enhanced by a factor of 425 at a current density of ~0.15A/cm^2, which is a clear evidence that the high density formation is of great importance for an increase in the carrier injection rate into the dots and recombination efficiency in EL.

Acknowledgements

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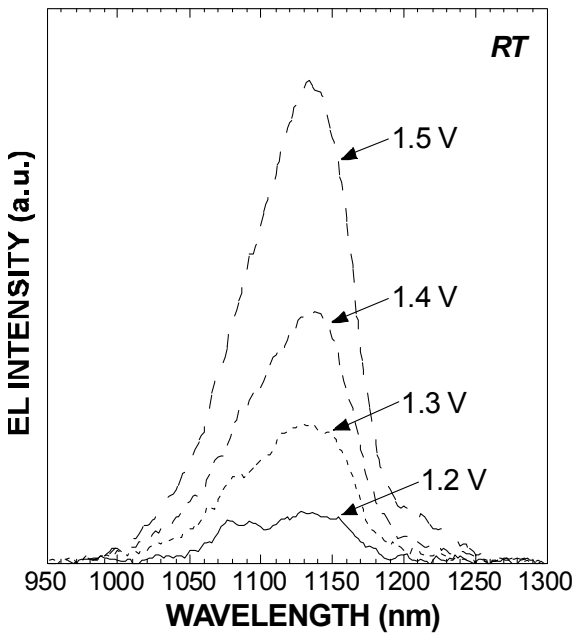

Fig. 2 EL spectra from a Au/self- aligned Si-QDs/n-Si(100) diode, which were taken at different forward biases at 297 K.

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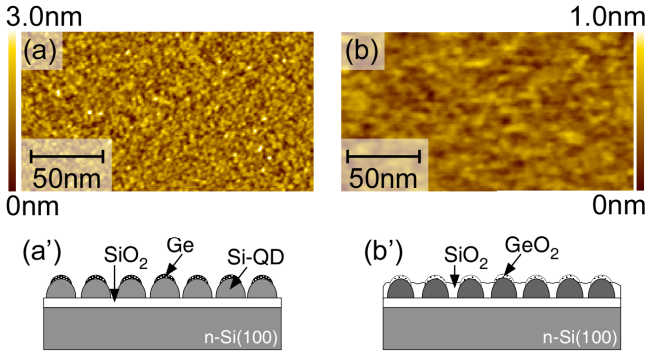

Fig. 1 AFM images taken after Ge deposition onto pre-grown Si-QDs (a) and after oxidation at 600˚C (b) and corresponding schematical illustrations ((a') and (b')).

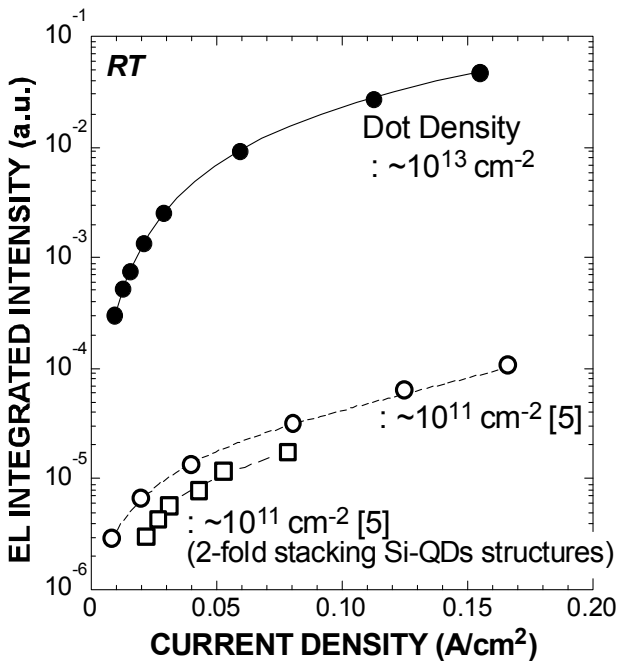

Fig. 3 EL integrated intensities of Au/self-aligned Si-QDs/n-Si(100) diodes with dot densities of ~10^{13} and ~10^{11} cm^{-2} [5] as functions of the current density.