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Transient Characteristics of Electroluminescence from Self-aligned Si-based Quantum Dots

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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 carrier injection and confinement in Si nanostructures, improvements in light emission efficiency and its stability are major technological concerns. So far, we reported visible light emission from multiple-stacked Si-quantum dots (Si-QDs) which were embedded in a SiO_2 matrix and 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 $\sim10^{11}cm^{-2}$ 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 that the self-align formation of Si-QDs is quite effective to increase electron-hole recombination efficiency for electroluminescence (EL) [5].

In this work, we extended our research work to ultrahigh-density Si-based QDs with an areal density as high as $\sim10^{13}cm^{-2}$ and evaluated their EL decay 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 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 1.3×10^4 Pa at room temperature for 10 min 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 27Pa [6]. 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 $\sim10^{-5}$ Pa. Subsequently, the SiH_4-LPCVD was carried out at 580 °C at a pressure as low as 2.7Pa. In the fabrication of LED structures, after surface oxidation of dots at 850 °C, semitransparent Au top electrodes and the Al back contact to the n-Si(100) were formed by thermal evaporation.

3. Results and Discussion

For LEDs with the self-aligned dots fabricated on the n-Si(100), current-voltage (I-V) characteristics show clear rectification properties inherently reflecting the work function difference between the Au top electrode and n-Si(100) substrate. Under forward bias conditions, EL becomes observable in the near-infrared region even at room temperature (Fig. 1). In the diode using the n-Si(100) substrate, electron injection from n-Si(100) and hole injection from, that is valence electron emission to, the Au electrode occur at forward bias conditions in which a positive bias is applied to the Au top electrode. In this case, the threshold voltage for EL was ~1.2V. Notice that no EL was detected under reverse 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 ~1140 and ~1100nm. With an increase in the applied biases over the threshold voltage, EL spectra became asymmetric shape with a tail toward the shorter wavelength side because of a remarkable increase in the component peaked at ~1140nm. It is likely that these two components are associated with radiative recombination in the lower- and upper-dots. Under the excitation of semiconductor laser (690nm, 6.5mW), a stable PL was also detected even at room temperature (Fig. 2). It should be noted that, for the PL, another component peaked at ~1070nm emarges in addition to the former two components seen in the EL. The result is attributable to the fact that photoexcitation can generate hole-electron pairs in high energy states more effectively than tunneling injections of carriers

We also measured the transient EL intensities at ~1140nm were measured under continuous pulse bias application (V_H: 5V, V_L: 0 V) with a width of 1.25 sec (Fig. 3). When the pulse bias with the duty ratio of 50% was applied to the Au electrode, EL intensities were reached to maximum value and then decreased down to zero level continuously. To characterize EL decay properties, the time resolved EL intensity peaked at ~1140nm was measured by application of pulse biases at room temperature (Fig. 4). Obviously, the EL for the LEDs shows non-exponential decay curves which reach to zero emission intensity within at most ~10 msec after pulse bias. From the curve fitting method by a stretched exponential function, the EL decay time can be roughly determined to be ~5 ms in the case of applied pulse bias at 5 and 0 V in the V_H and V_L, respectively. Note that, with an increase in the negative V_L level, namely reverse bias, from 0 to -4 V, the decay time was decreased down to ~4.6 msec. These results can be interpreted in terms of the accelerated extraction of electrons, which are injected from the n-Si(100) by forward bias application, from the conduction band of the lower-dots under reverse bias application and recombination of holes, which were generated by valence electrons extraction from the upper-dots to Au electrode, with electrons injected from the Au electrode to the upper-dots under reverse bias condition.

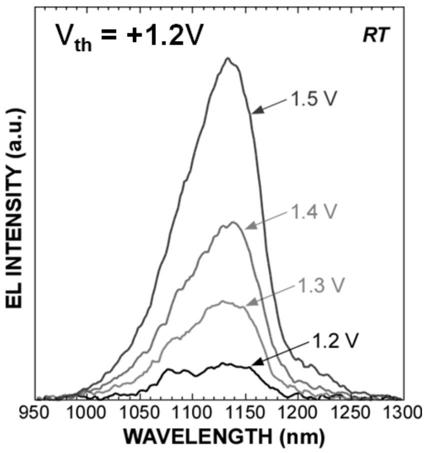

Fig. 1 EL spectra from a Au/self-aligned Si-QDs/n-Si(100) diode with areal dot density of ~10^{13} cm^{-2}, which were taken by applying different forward biases at room temperature.

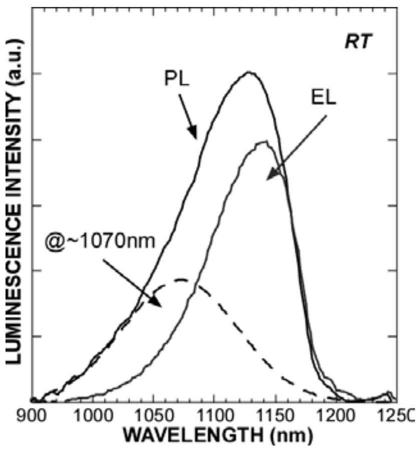

Fig. 2 Room temperature PL spectrum from a Au/self- aligned Si-QDs/ n-Si(100) diode which were taken under 690nm-light excitation and deconvoluted spectra. The EL spectrum at 5 V is also shown as a reference.

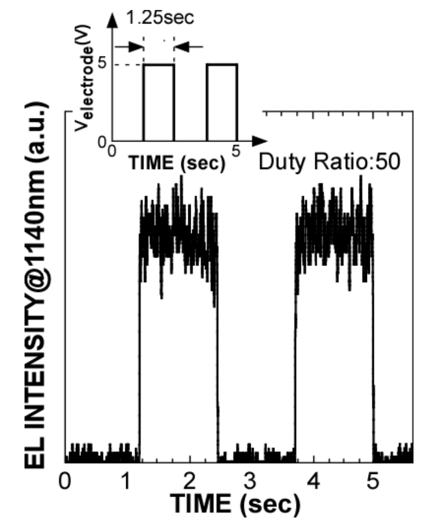

Fig. 3 EL response of the Au-electrode LEDs with aligned dots fabricated on n-Si(100) measured by switching applied voltage as represented in the inset.

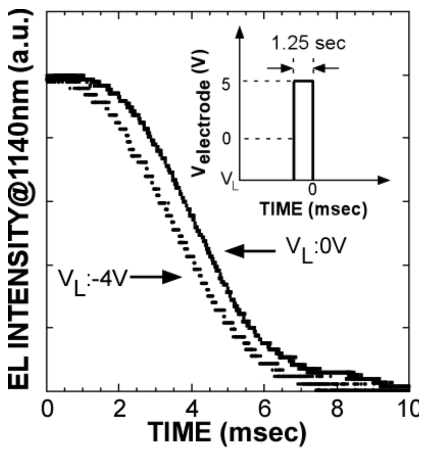

Fig. 4 EL decay characteristics of a LED with self-aligned Si-based QDs, which was measured at 1140nm in the wavelength.

4. Conclusions

We have demonstrated self-assembling formation of one-dimensionally aligned Si-QDs with an areal density as high as ~$10^{13}$$cm^{-2}$, and applied them to an active layer of light emitting diodes with a semitransparent Au electrode. Under forward bias conditions over a threshold bias for LEDs on n-Si(100) substrate, a stable EL was observed in the near-infrared region at room temperature. A broader PL spectrum compared with EL was observed at room temperature caused by radiative recombination between higher quantized states in aligned-dots. We have demonstrated that superimposed forward bias pulse on a revise bias condition is effective for the promotion of EL decay without deterioration in EL set-on characteristics.

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