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Characterization of Electroluminescence from One-dimensionally Self-Aligned Si-based Quantum Dots

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1. Introduction

Nanometer-scale Silicon structures show unique physical properties originating from carrier confinement effect and Coulomb blockade and their application to single electron transistor, floating gate memory and light emitting diode (LED) has been studied intensively [1-3]. In particular, light emission from Si nanostructures has stimulated considerable interest and research activity to develop Si-based LEDs. Despite many efforts, the improvement of the efficiency in electroluminescence (EL) and its stability are still major challenges. So far, we reported visible light emission from multiple-stacked Si-quantum dots (Si-QDs) embedded in a SiO_2 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 in the formation of one-dimensionally aligned Si-QDs 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 [5] and demonstrated stable EL in the near-infrared region from semitransparent Au-gate LEDs with one-dimensionally aligned Si-based QDs with an areal density as high as 10^{13} cm^{-2} formed on ~1nm-thick SiO_2/n-Si(100) under forward bias conditions over a threshold bias as low as 1.2 V [6].

In this work, to gain a better understanding of light emission mechanism, we extended our research work to comparative study on the EL properties of one-dimensionally aligned Si based QDs on n-Si(100) and on p-Si(100).

2. Experimental

After conventional wet-chemical cleaning steps, ~4.0nm-thick SiO_2 was grown on p- and 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 $1.3x10^4$ Pa 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 27 Pa [7]. 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^{-5} Pa 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 [8] and followed by dry O_2 oxidation at 600 ˚C. To remove Ge-oxide, the sample was heated up to 1000 ˚C in the same process chamber evacuated down to ~10^{-5} Pa. Subsequently, the SiH_4-LPCVD was carried out at 580 ˚C under a pressure of 2.7 Pa. For LEDs, after surface oxidation of dots at 850 ˚C, semitransparent Au (~10nm in thickness) top electrodes and the Al back contact to p- and n-Si(100) were formed by thermal evaporation.

3. Results and Discussion

The I-V characteristics of LEDs on p-Si(100) show a clear rectification property reflecting the work function difference between the Au top gate and the p-Si(100) substrate (not shown). Under the forward bias conditions, namely, in the application of negative bias with respect to the Au top electrode, EL becomes observable even at room temperature in the near-infrared region over a threshold voltage of ~2.0 V as shown in Fig. 1. It is interesting to note that the EL spectra can be deconvoluted into mainly two components peaked at ~1140 and ~1080 nm from the spectral analysis using a Gaussian curve fitting method as schematically illustrated inset in Fig. 1 (dashed lines). Considering that the energy bandgap of the lower dots is expected to be smaller than that of the upper dots because of the intermixing of lower Si-QDs and Ge during the thermal desorption of the Ge-oxide from the dots, which was confirmed by high resolution X-ray photoelectron spectroscopy analysis, the EL component peaked at ~1080 and ~1140 nm are attributable to upper and lower dots, respectively. With an increase in the applied gate biases, EL intensity was increased and EL spectra became asymmetric shape with a tail toward the shorter wavelength side because of a remarkably increase in the long-wavelength component peak. This result can be interpreted in terms of the difference in the potential well structure for carrier confinement between upper and lower dots as discussed later. Notice that the EL spectra show almost the same components as the EL spectra obtained from the aligned dots formed on n-Si(100) as reported in Ref.

6. This suggests that the recombination mechanism for EL is almost the same for the aligned dots on p- and n-Si(100). It should be noted that the threshold voltage of EL from self-aligned Si-QDs on p-Si(100) is higher than that on n-Si(100) under the same measurements conditions which is attributed to difference in the Fermi levels of the substrates. We summarized integrated intensities for two components peaked at ~1140 and ~1080 nm as functions of applied bias and power as shown in Fig. 2. Obviously, both spectrum intensities show power-law correlations between EL intensities and applied bias and input power. This implies that the emission originates from the electron-hole recombination in self-aligned dots rather than from the hot electron mechanism. The slope of the component peaked at ~1140 nm for lower dots is larger than that at ~1080 nm for upper dots in both cases. This result indicates that holes were stably stored in the lower dots due to deep potential well which facilitates recombination of injected electrons and stored holes as schematically illustrated in the inset of Fig. 2. In fact, by AC bias application as low as ~6.4 V (DC~2V) where electrons and holes were injected from the n-Si(100) substrate alternately, the EL spectra showing a single component peaked at ~1150 nm was clearly observable implying electron-hole recombination in the lower dots.

4. Conclusions

We have demonstrated stable EL in the near-infrared region from semitransparent Au-gate LEDs with one-dimensionally aligned Si-based QDs with an areal density as high as ~10^{13} cm^{-2} formed on ~1.0 nm-thick SiO_2/p-Si(100) under forward bias conditions over a threshold bias as low as +2.0 V. The EL spectra consist of two component peaks originating from upper and lower dots and these spectrum intensities show power-law correlations between EL intensities and applied bias and input power implying the electron-hole recombination in self-aligned nanodots. These results indicate that aligned structure facilitates recombination of injected electrons and holes under a relatively low electric field and in the carrier injection efficiency to the QD.

Acknowledgements

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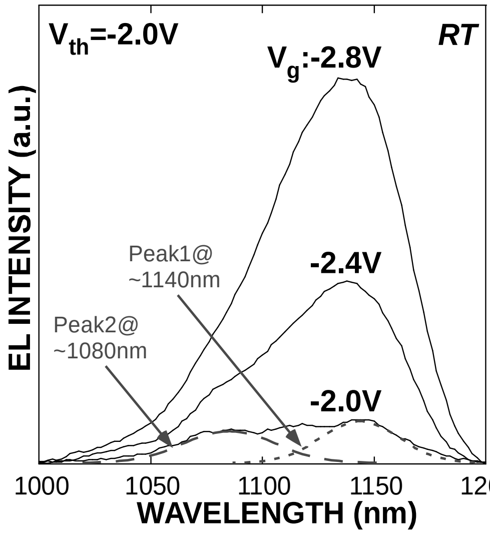

Fig.1 EL spectra of Au/self-aligned Si-based QDs/p-Si(100) diodes

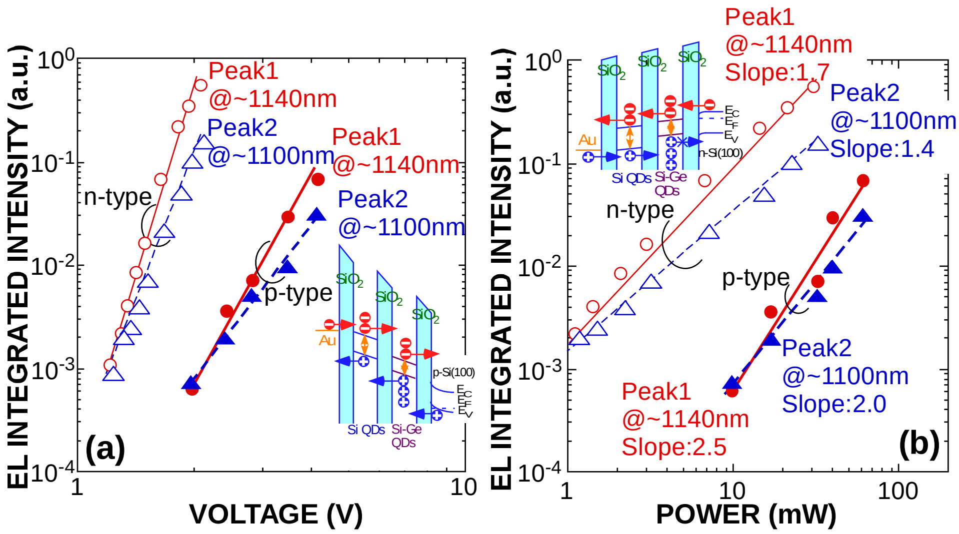

Fig.2 Integrated EL intensities of two comportments peaked at ~1140nm (Peak1) and ~1080nm (Peak2) from the diodes on n- and p-Si(100) as functions of applied gate voltage (a) and power (b), respectively.