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Electroluminescence from Multiply-Stack of Doped Si Quantum Dots

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Abstract

We have fabricated two-tiered hetero-structures consisting of B δ-doped and P δ-doped Si-QDs embedded in SiO_2 on n-Si(100) by repeating Si-QDs formation by LPCVD using pure SiH_4 and subsequent surface oxidation and modification by remote plasma, and characterized their electroluminescence (EL) in near-infrared region under DC and AC bias applications through semitransparent Au top-electrodes. The observed EL spectra can be deconvoluted into mainly two components peaked at ~1155 and ~1120 nm, which involve recombination processes through impurity levels. The input power dependence of EL intensities shows that two-tiered stacking of P-doped and B-doped Si-QDs is effective to improve EL efficiency while a simple stacking of B-doped Si-QDs is better suited to low power operation. The frequency dependence of EL intensities suggests that electron injection from n-Si(100) to P-doped Si-QDs is rate-limiting factor on EL from the two-tiered stack structure..

1. Introduction

Nanometer-size Si structures have attracted considerable interest due to their potential as light sources for integrated silicon photonics [1, 2]. However, improvement of the efficiency and stability are still major concerns because of the difficulty in achieving a good balance between charge injections and confinement in the Si nanostructures. Previously, we have reported light emission from multiple-stacked Si-quantum dots (Si-QDs) embedded into Si-QDs matrix [3]. We also demonstrated that, by B δ-doping to Si-QDs, electroluminescence (EL) was enhanced for light emitting diodes (LEDs) with 6 fold stacking structure [4].

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

2. Experimental

After conventional wet-chemical cleaning steps, ~3.5nm-thick SiO_2 was grown on n-Si(100) by dry O_2 oxidation at 1000 ˚C. The SiO_2 surface was exposed to remote Ar plasma and then to remote H_2 plasma for the termination with OH bonds, where a 60-MHz power source was used to generate these remote plasmas [5]. Subsequently, Si-QDs with an areal dot density of ~10^{11}cm^{-2} were formed from the thermal decomposition of pure SiH_4 under 66.7 Pa at 560˚C and followed by radical oxidation of 1% O_2 diluted with He under 13.3 Pa at 560˚C to cover the dot surface conformally with ~2.0-nm-thick SiO_2. In phosphorus or boron doping to Si-QDs, 1% PH_3 and B_2H_6 diluted with He were injected in a short pulse during the Si-QDs formation [6]. By repeating such a process sequence 6 cycles, two-tiered hetero-structures with 3-fold stacking of B-doped Si-QDs above 3-fold stacking of P-doped Si-QDs embedded in the SiO_2 network were formed. For a LED structure, semitransparent Au (~10nm in thickness) and Al were formed as top and back side electrodes, respectively, by thermal evaporation.

3. Result and Discussion

Current-voltage characteristics of the two-tiered Si-QDs hetero-structures show rectification properties (rectification ratio of 1000 at +/-2V) which is similar to PN junction. Indeed, the incorporation of phosphorous or boron atoms into Si-QDs were confirmed by X-ray photoemission measurements. Under forward bias conditions over ~2V, EL was observed in a near-infrared region. To avoid EL reduction with thermal effect, the EL properties under AC bias application were measured as shown in Fig. 1. By applying AC biases over ± 2.3V, EL being almost the same spectrum as that obtained by DC bias application was observed. The result indicates that the observed EL can be explain by electron-hole recombination caused by electron injection from the n-Si(100) and hole injection from the Au-electrode, as a result of efficient electron emission from the Si valence band of B-doped Si-QDs as well as ionized acceptors to Au electrode. The spectral analysis using a Gaussian curve fitting method confirms that the observed EL spectra are deconvoluted into mainly two components peaked at ~1155 and ~1120 nm. Considering the fact that ~1120nm EL is observed from undoped Si-QDs, ~1155 nm EL is attributable to radiative recombination process involving impurity levels. With increasing the applied biases, the EL intensity was increased with no significant change in the spectral shape. This implies that the emission originated from the electron-hole recombination in the PN junction-like Si-QDs stack rather than from the hot electron mechanism. It is interesting noted that the integrated EL intensity of PN stacked Si-QDs is enhanced by a factor of ~3 in comparison to the that of B-doped Si-QDs stack under the same bias condition in AC voltage. In Fig. 2, integrated EL intensities of the PN junction-like Si-QDs stack are summarized as a function of input power and compared with the result of B-doped Si-QDs stack. Obviously, both spectrum intensities show power-law correlations between EL intensities and input power. In the input power below ~1.0 W, B-doped Si-QDs stack was dominant. However, slope for the PN junction-like Si-QDs stack was increased by a factor of ~2 compared with that for the B-doped Si-QDs stack. It is likely that, in the case of PN junction-like Si-QDs stack, both electron injection from the n-Si(100) to P-doped Si-QDs and hole transfer among B-doped Si-QDs are major rate-limiting factors, and also energy relaxation in charge transfer among Si-QDs plays a role on recombination of injected electrons and holes as schematically illustrated in Fig. 3.

To get an insight into the effect of AC bias application on EL efficiency, EL integrated intensities were summarized as a function of frequency, as shown in Fig. 4. By increasing the frequency in the range from 5 to 400 Hz, significant no change in the EL intensity was observable. Further increase in the frequency over 400 Hz, the EL intensity was decreased rapidly irrespective of bias amplitude while, for the B-doped Si-QDs stack, a EL reduction was detected at frequencies of 1000 Hz. The observed degradation in the EL intensities for the PN junction-like Si-QDs stack is thought to be mainly due to suppression of electron injection from n-Si(100) to P-doped Si-QDs and partly due to electron transfer from P-doped Si-QDs to B-doped Si-QDs.

4. Conclusion

We have demonstrated stable EL in the near-infrared region from semitransparent Au-gate diodes with two-tiered hetero-structure consisting of P-doped Si-QDs and B-doped Si-QDs with an areal density of 10^{11} cm^{-2} under forward DC bias and AC bias conditions. The formation of PN junction-like Si-QDs stack is effective to realize high efficient EL while B-doped Si-QDs stack is a potential for low power EL operation below ~1.0 W. These results imply that multiple stacking of doped Si-QDs is great promising for their optoelectronic device applications.

Acknowledgements

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References

[1] G.F. Grom et al., Nature 407 (2000) 358.

[2] R.J. Walters et al., Nature Mat. 4 (2005) 143.

[3] K. Makihara et al., Trans. of MRS-J, 31 (2006) 133.

[4] T. Yamada et al., Proc. of The 8th Int. Conf. Silicon epitaxy and Heterostructures /6th Int. Symp. on Control of Semiconductor Interfaces (2013, Fukuoka), P1-31.

[5] K. Makihara et al., Appl. Surf. Sci., 244 (2005) 75.

[6] K. Makihara et al., Jpn. J. Appl. Phys., 49 (2010) 065002.

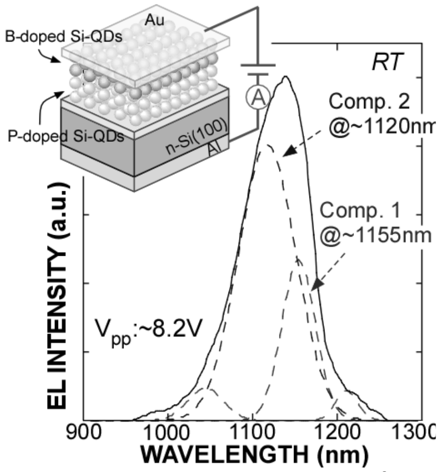

Fig. 1 EL and deconvoluetd spectra from LEDs with PN stacked Si-QDs. The schematically illustration of PN stacked Si-QDs structure is also shown in the inset.

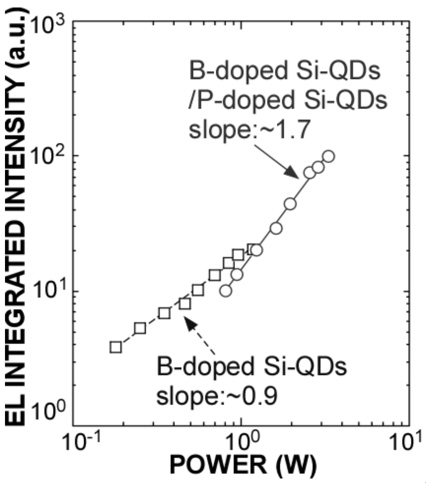

Fig. 2 Input power dependence of integrated EL intensities of PN stacked Si-QDs. B-doped Si-QDs stack is also shown as a reference.

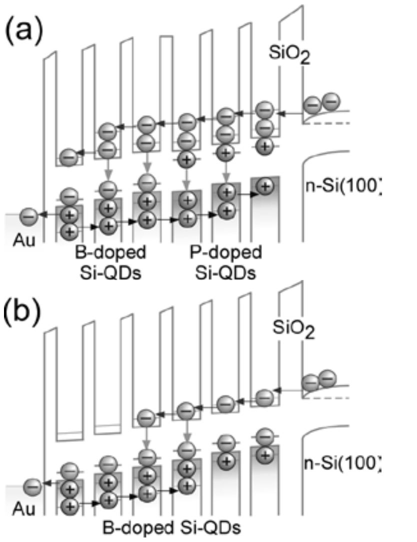

Fig. 3 Energy band diagram of PN stacked Si-QDs (a) and B-doped Si-QDs (b).

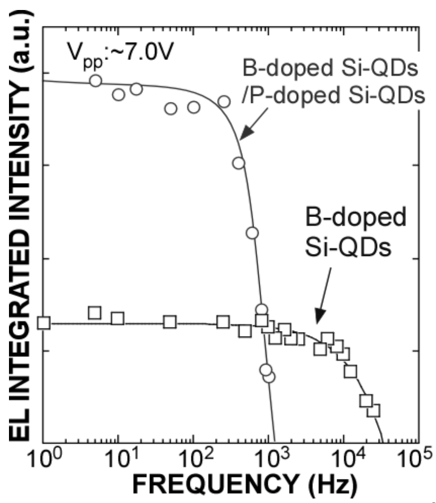

Fig. 4 Frequency dependence of integrated EL intensities of PN stacked Si-QDs and B-doped Si-QDs.