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Electroluminescence of Super-atom-like Si-Ge based Quantum Dots Floating Gate

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Abstract

We have fabricated high density super-atom like Si-Ge based quantum dots (Si-QDs with Ge core) floating gate (FG) and studied their luminescence properties. From characteristics of electroluminescence (EL) from FG with a 3-fold stack Si-QDs with Ge core under pulsed bias application with visible light illumination, it is confirmed that stable EL originates from radiative recombination between quantized states in the Ge core with deep potential well for hole caused by alternate electron/hole injection from the p-Si substrate.

1. Introduction

Si-based quantum dots (QDs) have attracted much attention as active elements in various optical and electronic application including solid-state quantum computation. In particular, light emission from Si-based nanostructures including Si- and Ge-QDs has stimulated considerable interest in the field of silicon-based photonics because of its potential to combine photonic processing with electronic processing on a single chip [1, 2]. To improve light emission efficiency and stability, a lot of efforts have been devoted with deliberate approaches which include not only the confinement of injected carriers but also the use of strained structures and impurity doping. So far, we have reported the formation of Si-QDs with Ge core on ultrathin SiO_2 by controlling the thermal decomposition of SiH_4 and GeH_4 alternately, and reported unique charge storage characteristics of an individual Si-QD with a Ge core, and confirmed type II energy band alignment between Si clad and Ge core being regarded as super-atom [3]. More recently, we also demonstrated light emission from the Si-QDs with Ge core [4]. The observed PL spectra can be deconvoluted into mainly four components originating from radiative recombination of photo-generated carriers through quantized states of Ge core. In this work, we extended our research work to the development of a light emitting device containing a Si-QDs with Ge core as a floating gate in MOS structure, and their electroluminescence characteristics were evaluated at room temperature.

2. Sample Preparation and Experimental Procedure

After conventional wet-chemical cleaning steps, ~2.0nm-thick SiO_2 was grown on p-Si(100) by dry O_2 oxidation at 1000 ˚C. The SiO_2 layers so prepared were slightly etched back in a 0.1% HF solution to form Si-OH bonds on the SiO_2 surface. After that, Si-QDs with an areal density as high as $\sim 1\times 10^{11}$cm^{-2} were formed on the thermally-grown SiO_2/c-Si(100) by controlling the early stages of LPCVD using pure SiH_4 at 560˚C and subsequently highly selective depositions for Ge core and Si cap on pre-grown Si-QDs were carried out by thermal decomposition of 10% GeH_4 diluted with H_2 and of pure SiH_4, respectively. Subsequently, radical oxidation using 40% O_2 diluted with Ar under 13.3 Pa at 500˚C was carried out to cover the dot surface conformally with ~2.0-nm-thick SiO_2. By repeating such a process sequence 3 cycles, 3-fold stacking of the Si-QDs with Ge core embedded in the SiO_2 network were formed. After that, a ~7.0-nm-thick SiO_2 was grown as a control oxide by inductively-coupled remote plasma CVD with SiH_4 and excited O_2/Ar at a substrate temperature of 500°C. Finally, Al/Au gate and back side electrodes were fabricated by thermal evaporation. The structure of a fabricated floating gate type-light emitting diode is schematically illustrated in Fig. 1.

3. Results and Discussion

Formation of high density Si-QDs with Ge core, of which the average height was ~7nm including a Ge core with a height of ~2.0nm, was confirmed by atomic force microscopy measurements taken at each process steps. Under the excitation with semiconductor laser (976nm, 139mW/cm^2), a stable PL signal in the energy region from 0.68 to 0.88eV was detected at room temperature (Fig. 2). From the spectral analysis using a Gaussian curve fitting method, it is revealed that the observed PL spectrum can be deconvoluted into mainly four components peaked at ~0.71 (Comp. 1), 0.75 (Comp. 2), 0.79 (Comp. 3) and 0.83eV (Comp. 4). Although, in the type II energy band alignment, the Si clad acts as a shallow potential well for electrons, electron wave function in the Si clad can penetrate into the Ge core. Therefore, it is likely that the Comp. 1 is attributed to the radiative recombination caused by coupling between the electron quantized state in Si clad and the hole quantized state in Ge core as discussed in ref. 4. The Comp. 2 is attributable to recombination through the 1st quantized states in the conduction and valence bands of the Ge core. And the radiative transitions between the higher order quantized states in the conduction and valence bands of Ge core are likely to be responsible for the higher energy Comps. 3 and 4. With application of continuous square-wave pulsed bias at ±1.0V and over with the duty ratio of 50% at 500 kHz, EL signal was observed from the backside through the c-Si substrate even at room temperature, where, during the EL measurements, cold light in the region from 400-800nm through a fiber-optics equipped with an infrared filter from a 100W halogen lamp was illuminated (Fig. 3). The observed

EL can be explained by radiative recombination through quantized states of the Si-QDs with Ge core caused by alternate electron/hole injection from the p-Si(100) because under the cold light illumination, photo-generated electrons in the peripheral region of the area masked with Al/Au gate flow into the inversion region formed underneath the gate oxide and respond to the pulsed gate bias even at high frequencies. Namely, the peripheral region with the light illumination virtually works as a source of carriers [5]. Obviously, with an increase in the applied bias, EL peak and integrated EL intensities lineally increased (Inset in Fig. 3). Notice that, the observed EL spectra can also be deconvoluted into four components whose peak energies and FWHM values are almost the same with those of the corresponding components in the PL signal (Fig. 4). From the deconvolution of the EL signals, integrated peak intensities of the each component as a function of applied bias were summarized as shown in Fig. 5. With an increase in the applied bias, the integrated peak intensities monotonously increased except Comp. 1, which shows plateau in the range of ±2.0 to ±3.0 V. Notice that, at the applied bias below ±3.0V, Comp. 4 was hardly detected. At an applied bias of ±2.0V, the recombination through the lowest quantized levels, namely electron quantized state in the Si clad and the hole quantized state in Ge core (Comp. 1) is dominant rather than recombination through the 1st and 2nd quantized states in the conduction and valence bands of the Ge core (Comps. 2 and 3). At ±3.0V and over, the Comp. 4 corresponding to the radiative transition between the higher order quantized states of Ge core appeared, implying that photo-generated electrons and holes are injected to higher order quantized states.

4. Conclusions

We have demonstrated stable EL in the near-infrared region from floating gate light emitting diodes having 3-fold Si-QDs with Ge core with an areal density of ~10^{11} cm^{-2} under pulsed bias conditions. The formation of Si-QDs with Ge core is effective to realize high efficient EL. These results imply that super-atom-like Si-Ge based-QDs floating gate is greatly promising for their optoelectronic device applications.

Acknowledgements

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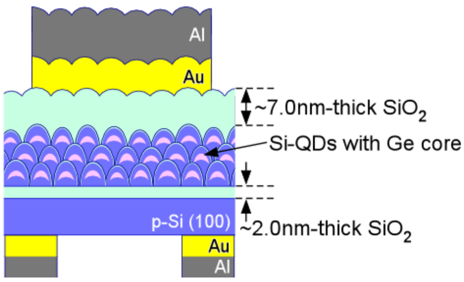

Fig. 1 Schematic cross-sectional view of a MOS-LED with a 3-fold Si-QDs with Ge core FG.

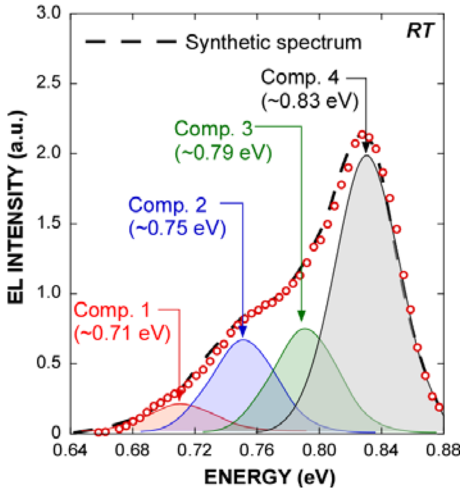

Fig. 2 Room temperature PL spectrum of 3-fold Si-QDs with Ge core and its deconvoluted spectra.

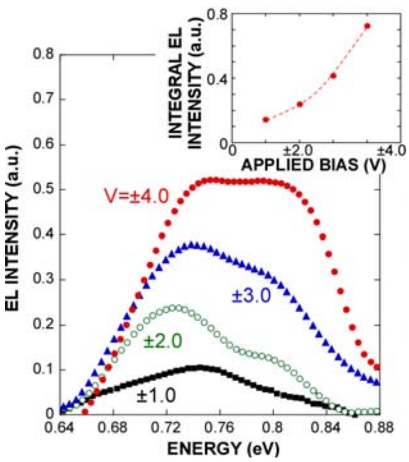

Fig. 3 EL spectra from a MOS-LED with a Si-QDs with Ge core FG, which were taken at different biases at room temperature. Integrated EL intensity as a function of applied bias is also shown in inset.

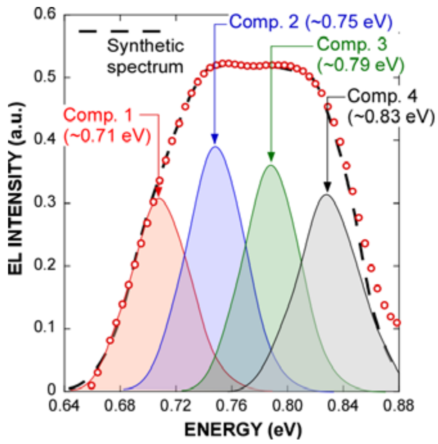

Fig. 4 Room temperature EL spectrum of a MOS-LED with a 3-fold Si-QDs with Ge core FG and its deconvoluted spectra.

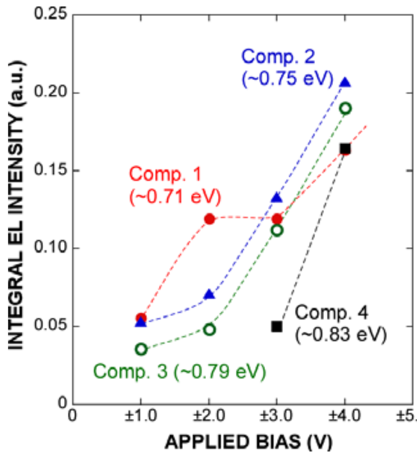

Fig. 5 Applied bias dependence of the integrated EL intensity of each decomvoluted component.