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Effects of tunneling barrier width on the electrical characteristic in Si-QD LEDs

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1. Introduction

While the bulk crystalline silicon exhibits very weak luminescence due to its indirect band-gap, silicon nanostructures having a quantum confinement effect (QCE) provide efficient luminescence at room temperature, thanks to the enhanced recombinative radiation of electron-hole pairs[1-5]. Silicon quantum dot (Si-QD) is a typical such nanostructure[6-7]. Few studies, however, exist on the electronic characteristics of Si-QD used in electronic luminescence devices, in contrast to those on Si-QD-based electronic devices such as single electron transistors, switching devices, and memory devices. Moreover, previous studies have mostly used high temperature annealing to crystallize the silicon dots, which remains as a challenge. In this situation, we have succeeded, by using plasma-enhanced chemical vapor deposition (PECVD), in *in-situ* formation of Si-QDs during growth of a Si-nitride matrix film[9-10]. No additional high temperature annealing is necessary, and still, well-organized Si-QDs can be obtained. In order for Si-QD-based LEDs to have high external quantum efficiencies, however, formation of well-organized Si-QDs is not enough, but precise control over their locations within the matrix film is also critical because this determines the effective injection of carriers into the Si-QDs.

In this work, we investigated the impacts of nitride source on the electrical properties of the Si-QD LEDs. Two nitrogen sources, nitrogen (N_2) and ammonia (NH_3), have been compared for the PECVD growth of the silicon nitride film, while silane (SiH_4) has been commonly used as the silicon source.

2. Experiment and Results

The Si-QDs were prepared by PECVD, in which argon-diluted 10% SiH_4 plus either N_2 or NH_3 were used. Flow rates of 12 and 1500 sccm were used for the SiH_4 and N_2 flows, while 50 and 10 sccm were used for the SiH_4 and NH_3 flows. The Si-QDs are formed *in-situ* during the film growth, and no post-annealing process was applied. To confirm the electrical properties of the Si-QD devices, we further deposited an *n*-type amorphous SiC film (~300 nm) and an indium tin oxide (ITO; ~100 nm) layer. The latter is to spread the current, thereby enhancing the current injection efficiency into the Si-QD. The *n*-type amorphous SiC layer was prepared by PECVD, in which argon-diluted 10% SiH_4 and CH_4 was used. Tri-methyl-phosphite metalorganic source was used as the doping source. Finally, Ni/Au (30/150 nm) film was deposited for the top and the back side contacts by a thermal evaporation. *I-V* characteristics of the Si-QD devices were measured using a semiconductor parameter analyzer (HP 4155A). Both p-type and p+-type Si substrates were tested in order to confirm the hole tunneling.

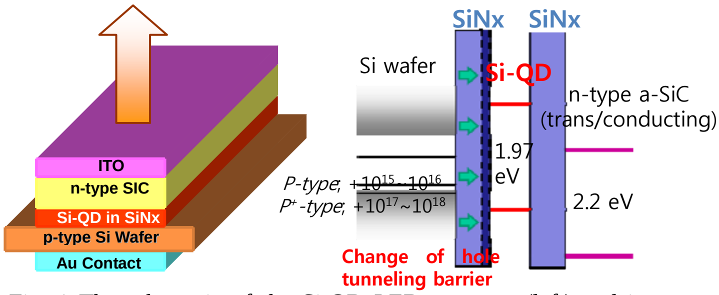

Fig. 1 The schematic of the Si-QD LED structure (left) and its band diagram (right).

Figure 1 describes the schematic of the Si-QD LED structure (left) and its band structure (right). Since the average distance of the Si-QDs from the SiN_x/Si boundary defines the tunneling barrier width, the location of the Si-QDs in the active region should be critical. To be specific, since the hole mobility in Si is by a factor of three smaller than that of electrons, the Si-QDs need to be located in the vicinity of the boundary between the Si nitride/*p*-type Si substrate to realize a practically high injection efficiency.

Fig. 2 Cross-sectional HRTEM images grown by SiH_4+NH_3

This idea is realized by using NH_3 for the nitrogen source, as can be confirmed by the HRTEM images shown in Fig. 2. The Si-QDs formed in this growth method are located at the Si-Nx/Si boundary. For N_2-grown Si-QDs, however, no such localization of Si-QDs at the boundary can be seen [9-10].

Figure 3 summarizes the current-voltage (I-V) curves of the Si-QD LEDs. The inset shows optical microscope images of the light emission of the Si-QD LED operating at a forward current of 70 mA. As can be seen, the operating voltages for the Si-QD LED grown by SiH_4+ NH_3 gas (circles) are significantly smaller than that grown by SiH_4+N_2 gas (squares) for all the current range. This cannot be attributed to difference in the series resistance of the silicon nitride matrix grown by the two growth methods because the difference in the shape and the threshold voltage of the I-V curves are too large [8]. Actually, if the series resistance is responsible for the different I-V characteristics, the chemical composition of the nitride should also be different, which is however not the case as indicated by the similar FTIR pattern shown in Fig. 4(b).

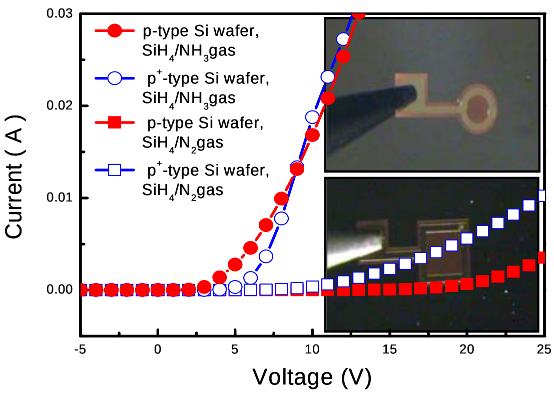

Fig. 3 Typical current-voltage (I-V) curves and a photograph of Si-QD LEDs using the Si-QD grown by SiH_4+NH_3 gas and grown by SiH_4+N_2 gas on the p-type and p^+-type Si substrate.

The different I-V behaviors should then come from either difference in the band gap of the Si-QDs or difference in the tunneling barrier width. To see which is the case, we obtained photoluminescence (PL) spectra from the two devices. If the I-V difference comes from the difference in the band gap of the Si-QD, we should see different PL emission spectra and different colors in the light emission. In the PL spectra shown in figure 4(a), however, we see no drastic changes. No color changes can also be seen in the emission color in the inset of figure 3. The larger current observed in the NH3-grown Si-QD LEDs, therefore, is concluded to come from the smaller tunneling barrier width between the Si substrate and the Si-QDs.

Another support to this understanding is given by a comparison between p- and p+-Si substrates. For these two Si substrates, the I-V curve in figure 3 shows a difference only in the N2-grown Si-QD LEDs. No difference can be seen in the I-V curves for the NH_3-grown Si-QD LEDs. This latter observation is understood to be caused by enhanced tunneling probabilities caused by the decreased tunneling width for holes.

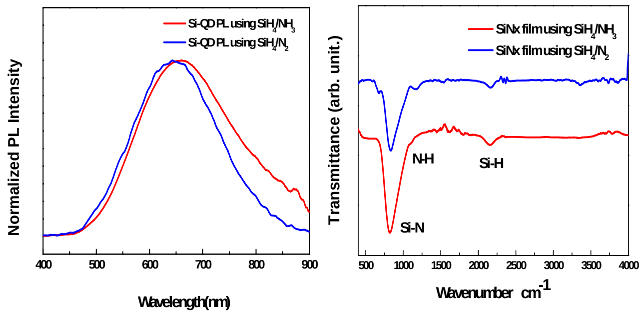

Fig. 4 Comparison of Photoluminescence (PL) spectra and FTIR of Si-QDs embedded in silicon nitride film grown by SiH_4+NH_3 and by SiH_4+N_2 gas.

3. Conclusions

We have studied the electrical properties of the Si-QD LEDs, especially in its dependence on the nitrogen source used in the PECVD for the Si-Nx matrix growth. The HRTEM analyses and the I-V measurement show that NH_3-grown Si-QDs are located at the interface between the Si-Nx matrix and the Si substrate. This is related to the observed increase in the forward current by considering a decrease in the tunneling barrier width between the Si substrate and the Si-QDs.

Acknowledgements

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