Strong Visible Light Emission from Silicon Nanocrystals Embedded into a Silicon Carbide Film

Chul Huh, Tae-Youb Kim, Chang-Geun Ahn, and Bong-Kyu Kim
IT Convergence Technology Research Laboratory, Electronics and Telecommunications Research Institute (ETRI), Daejeon 305-700, Republic of Korea
E-mail: chuh@etri.re.kr

***Abstract*—We report the strong visible light emission from silicon (Si) nanocrystals (NCs) embedded in a Si carbide (SiC) film. Compared to Si NC light-emitting diode (LED) by employing the Si nitride (SiN_x) film as a surrounding matrix, the turn-on voltage of the Si NC LED with the SiC film was significantly decreased by 4 V. This was attributed to a smaller barrier height for injecting the electrons into the Si NCs due to a smaller band gap of SiC film than a SiN_x film. The electroluminescence spectra increase with the forward voltage, indicating that the electrons are efficiently injected into the Si NCs in the SiC film. The power efficiency of the Si NC LED with the SiC film was 1.56 times larger than that of the Si NC LED with the SiN_x film. The Si NCs in a SiC film show unique advantages, and are a promising candidate for application in optical devices.**

Keywords-silicon nanocrystals, Silicon carbide, Light-emitting diode, Electroluminescence

I. INTRODUCTION

Recently, since the optical band gap of Si NCs can be easily tuned by changing the size of NCs due to a quantum confinement effect, Si NCs are of particular interest as a light-emitting diode (LED) covering whole visible wavelength range [1][2]. Si-rich oxide (SRO) film has been generally used as the surrounding matrix to synthesize the Si NCs [3][4]. The SRO film, however, has disadvantages in the formation of Si NCs as the surrounding matrix due to the trapping of the electrons in localized levels in the band gap of Si NC, a relatively high annealing temperature (> 1000 °C), and the high operating voltage (> a few tens of V) caused by a large band gap of SRO film (> 9 eV). In our previous result [5], well-organized Si NCs in the silicon nitride (SiN_x) film grown by a plasma enhanced chemical vapor deposition (PECVD) at a low temperature (250 °C) showed a clear quantum confinement effect depending on the size of Si NC, resulting that the band gap of Si NCs could be tuned from the near infrared (1.38 eV) to the ultraviolet (3.02 eV) range. In addition, we fabricated the mesa-type Si NC LED by applying an amorphous silicon carbide (SiC) film as an electron injection layer [6][7]. Because SRO and SiN_x films, however, have a relatively high band gap (approximately 9 eV for SRO and 5.3 eV for SiN_x, respectively), the tunneling probability between Si NCs decreases due to a high barrier height, resulting that the high operating voltage is required to inject the current into Si NCs. In the previous result [7], we have *in-situ* grown the well-organized Si NCs in a SiC matrix by using a PECVD. It was found that Si NCs in a SiC film showed a quantum confinement effect depending on the size of the Si NCs. In this work, we report the strong visible light emission from the LEDs by employing the Si NCs in a SiC film. The turn-on voltage of the Si NC LED was approximately 5 V and also decreased by 4 V compared to that of the Si NC LED by using Si NCs in SiN_x film. In addition, the wall-plug efficiency (WPE) was increased by 56 % compared to the Si NC LED with a SiN_x film.

II. EXPERIMENTAL

Si NCs in a SiC film with a thickness of 50 nm were *in-situ* grown at 250 ºC by conventional plasma enhanced chemical vapor deposition (PECVD). Ar-diluted 10 % SiH_4 and CH_4 were used as the reactant gases. The plasma power, chamber pressure, and substrate temperature for the growth were fixed at 5 W, 500 mTorr, and 250 °C, respectively. The flow rates of SiH_4 and CH_4 gases were 60 and 10 sccm, respectively. An amorphous SiC layer (~ 10 nm) doped with phosphorous, which was used to inject the electrons into the Si NCs, was deposited onto Si NC layer at 300 ºC by using a PECVD. ITO layer (100 nm) used as a transparent current spreading layer was deposited onto n-SiC layer at 150 ºC by using a pulsed laser deposition method. The size of Si NC LED fabricated was 300 um×300 um. The Si NC LED with Si NCs in a SiN_x matrix was also fabricated to compare the performance. The structure of Si NC LED investigated here was ITO (100 nm)/n-SiC (10 nm)/Si NCs in SiC (50 nm)/p^+-Si, as shown in Figure 1(a).

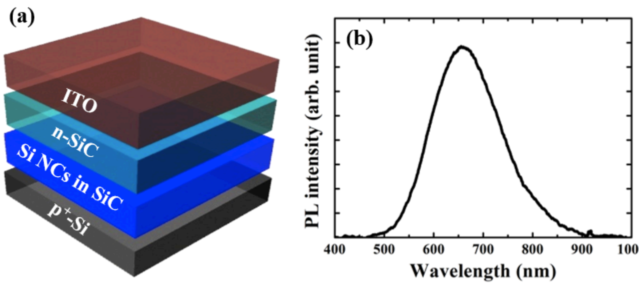

Figure 1. (a) A schematic diagram of the LED structure. (b) A RT PL spectrum taken from the Si NCs in a SiC film.

III. RESULTS AND DISCUSSION

A RT photoluminescence (PL) spectrum taken from the Si NCs in a SiC film is shown in Figure 1(b), which is centered at ~ 650 nm. The average size of Si NCs into the SiC film was ~ 9 nm, which was confirmed by a HRTEM [8].

The *I-V* characteristics of Si NC LEDs with SiC and SiN_x films measured at RT are shown in Figure 2(a), respectively. The turn-on voltage of Si NC LED with the SiC matrix was decreased by around 4 V compared to that of Si NC LED with the SiN_x matrix.

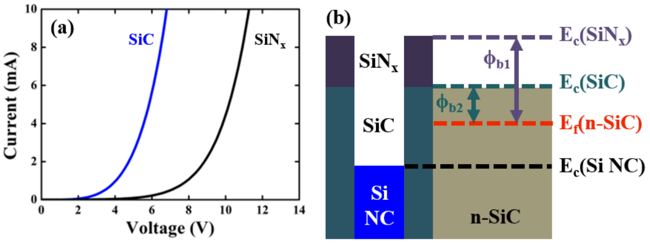

Figure 2. (a) *I-V* characteristics of Si NC LEDs with SiC and SiN_x films measured at RT, respectively. (b) A schematic band gap diagram of the Si NC LED structure with SiN_x and SiC films. ϕ_{b1} and ϕ_{b2} are the barrier height for the SiN_x film and the SiC film, respectively.

The schematic band gap diagram of the Si NC LED structure with SiN_x and SiC films is shown in Figure 2(b). As can be clearly seen in Figure 2(b), the barrier height (ϕ_{b2}) for the SiC film is lower than that (ϕ_{b1}) for the SiN_x film. The barrier height is very crucial to inject the electrons into the Si NCs from the transparent current spreading layer. The smaller the barrier height, the better the electron injection into the Si NCs. As the barrier height decreases, the electrons injected into the Si NCs for an external applied voltage to the LED can be increased. The electron transport between the Si NCs can be, therefore, significantly increased, resulting that the electrical performance of Si NC LED can be greatly improved. Therefore, lowering the turn-on voltage of Si NC LED with a SiC film was attributed to a lower barrier height for injecting the electrons into the Si NCs from the transparent current spreading layer caused by a lower band gap of SiC film (~ 2.5 eV) compared to SiN_x film (~ 5.3 eV).

The electroluminescence (EL) spectra of the Si NC LED as a function of forward voltage measured at RT are shown in Figure 3(a). We found that both PL (shown in Figure 1(b)) and EL showed a similar peak centered at 650 nm. This indicates that the PL and EL processes could be related to the same origin. Even though the center of EL peak was around 650 nm, overall EL peak showed the broad spectrum in the range of 500 ~ 850 nm. EL intensity was increased with the the forward voltage, as shown in Figure 3(a).

The light output power of Si NC LED with a SiC film as a function of the forward voltage is shown in Figure 3(b). With increasing the forward voltage, the light output power was linearly increased, indicating that the light emission was increased as more electrons and holes were injected into the Si NCs into a SiC film. The WPE, which means the power efficiency (output power/input power), is very important in LED applications. Based on the *I-V* data and light output power, the WPE of Si NC LED with a SiC film at 20 mA (~ 8 V) was estimated to be 1.94×10^{-9} %. The WPE was increased by 56 % compared to the Si NC LED with a SiN_x film. Inset shows the optical microscope image of light emission from the Si NC LED measured at a forward voltage of 12 V. As shown in the inset of Figure 3(b), the uniformity of light emission was quite good.

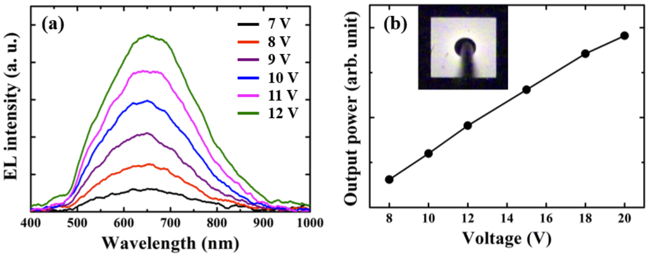

Figure 3. (a) EL spectra of the Si NC LED as a function of forward voltage measured at RT. (b) Light output power of Si NC LED with a SiC film as a function of the forward voltage. Inset shows the optical microscope image of light emission from the Si NC LED with a SiC film measured at a forward voltage of 12 V.

IV. CONCLUSION

A strong visible electroluminescence from Si NCs embedded into a SiC film was demonstrated. Compared to the Si NC LED by employing the SiN_x film, the electrical characteristics of the Si NC LED with the SiC film were significantly improved. This was originated from a smaller barrier height for injecting the electrons into the Si NCs due to a smaller band gap of the SiC film than the SiN_x film. Moreover, WPE of the Si NC LED with the SiC film was enhanced by 56 % compared to that of the Si NC LED with the SiN_x film. The light emission originated from the Si NCs in the SiC film was quite uniform.

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