WA1 (Plenary)
09.15 – 10.00

High Efficiency Silicon Visible Light Emitter using Silicon Nanocrystals in Silicon Nitride Matrix and Transparent Doping Layer

Gun Yong Sung*, Nae-Man Park, Tae-Youb Kim, Kyung-Hyun Kim, Kwan Sik Cho, and Jae Heon Shin

Future Technology Research Division, ETRI
161 Gajeong-Dong, Yuseong-Gu, Daejeon 305-350, Korea

Abstract

Semiconductor electronics is strongly dominated by silicon technology. However silicon technology does not allow easy integration with optical component since silicon is a poor light emitter. The unique properties of Si nanocrystals (nc-Si) can be exploited to fabricate Si-based light source. We will introduce a quantum confinement effect in the nc-Si embedded in a silicon nitride formed by PECVD. The band gap of the nc-Si could be controlled from 1.38 to 3.02 eV by decreasing the nanocrystal size. In addition, we will demonstrate a silicon light emitter with a transparent doping layer on nc-Si embedded in silicon nitride active layer by using ITO and n-type wide bandgap semiconducting layer. This light emitter has high external quantum efficiency of 1.6%, which is the highest value ever reported in Si-based visible light emitters.

1. Introduction

The enormous growth of the communication industry has increased the demand for new photonic functionality at a low cost. For this purpose, it would be highly desirable to have light source, waveguides, amplifiers, and detectors that are monolithically fabricated on Si with CMOS technology. The materials used in current CMOS integrated circuit technology technologies are chosen to optimize electronic performance. The unique properties of nc-Si can be exploited to fabricate Si-based light source. There has been much effort to solve the inability of silicon to act as a light emitting source such as porous silicon, erbium doped silicon, and nc-Si[1]. Among these, nc-Si dispersed in SiO_2 matrix has attracted a great interest because their band gap is enlarged in comparison with bulk silicon due to quantum confinement effects. However, it is reported that due to silicon-oxygen double bonds, nc-Si in SiO_2 matrix have localized levels in the band gap and emit light only in the near-infrared range of 700~900nm even when the size of nc-Si was controlled to below 2nm[2]. Previously, we reported that red to blue PL were observed from amorphous and nanocrystalline silicon quantum dots and in silicon nitride matrix.[3,4] Therefore nc-Si in silicon nitride matrix supplies the possibility of Si-based full-color emitters.

2. Full-color photoluminescence from nc-Si

Silicon nanocrystals were *in situ* grown in a silicon nitride film by plasma-enhanced chemical vapor deposition. The size and structure of nc-Si were confirmed by high-resolution transmission electron microscopy as shown in Fig. 1.

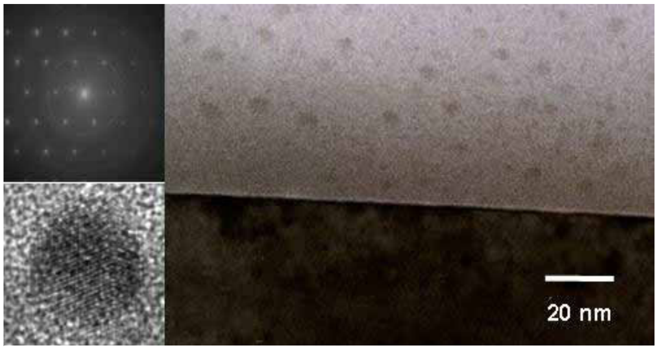

Fig. 1. Cross-sectional high-resolution transmission electron microscopic (HRTEM) images of nc-Si embedded in a silicon nitride film. The average size and the dot density of nc-Si was 4.6 nm and 6.0 x $10^{11}/cm^2$, respectively. The insets are the crystal image and the transmission electron diffraction pattern, showing silicon dot is crystalline.

---

*Electronic mail: gysung@etri.re.kr

Depending on the size, the photoluminescence of nc-Si can be tuned from the near infrared (1.38 eV) to the ultraviolet (3.02 eV). The fitted photoluminescence peak energy as $E(eV) = 1.16 + 11.8/d^2$ is an evidence for the quantum confinement effect in nc-Si. Fig. 2 shows a room-temperature photoluminescence spectrum obtained from various sized nc-Si, where the tuning of the photoluminescence emission from 410 to 900 nm is possible by controlling the size of the nc-Si and, as a result, the emission color can be changed by controlling the size of the nanocrystal. The results demonstrate that the band gap of nc-Si embedded in silicon nitride matrix was more effectively controlled for a wide range of luminescent wavelengths.

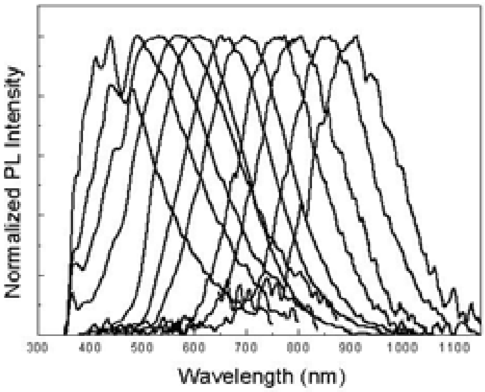

Fig. 2. Room-temperature photoluminescence spectra of silicon nanocrystals. The peak position can be controlled by appropriate adjustment of the nanocrystal size.

Recently, it is reported that the PL intensity of nc-Si grown by ammonia in stead of nitrogen can be increased to double due to the hydrogen passivation of the nonradiative defects in silicon nitride matrix.[5,6]

3. High efficiency visible EL from Silicon QD

We have fabricated light emitting diode with a transparent doping layer on nc-Si embedded in silicon nitride matrix formed by plasma-enhanced chemical vapor deposition. The device structure and its fabrication process have been described elsewhere, in detail[7]. Fig. 3 shows the J-V characteristics of EL device and the inset shows the schematic of the device structure.

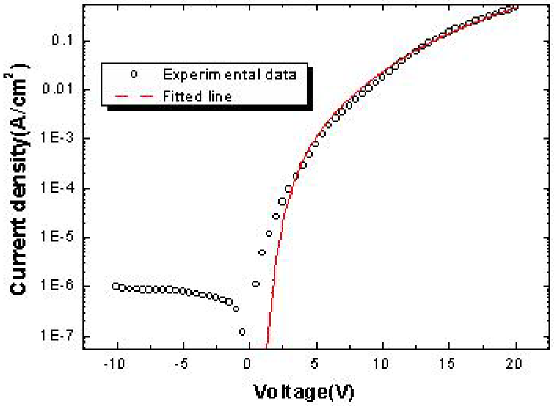

Fig. 3. Current density vs. applied voltage. Open circles and solid line denote the experimental data and the fitted data, respectively. The experimental data are best fitted by $J \sim V^2 \exp(-bV)$ which is known to be the expression for Flower-Nordheim tunneling process.

As indicated in the J-V curves, our device exhibits a current rectification of 2 ~ 4 orders of magnitude. To identify the charge transport mechanism, we fitted the experimental data. Open circles and dashed line in Fig. 3 denote experimental data and fitted data, respectively. The experimental data are the best fitted by $J \sim V^2 \exp(-b/V)$ which is known to be the expression for Flower-Nordheim tunneling process[8]. Therefore, these data confirm that Fowler-Nordheim tunneling of carrier is the dominant carrier transport mechanism in our device. Under forward biased condition, orange electroluminescence (EL) with its peak wavelength at about 600nm was observed at room-temperature. The peak position of the EL is very similar to that of the photoluminescence (PL) and the emitted EL intensity is proportional to the current density passing through the device. We suggest that the observed EL is originated from electron-hole pair recombination in nc-Si. By using ITO and n-type wide bandgap semiconducting layer combination as a transparent doping layer, we obtained high external quantum efficiency of 1.6%, which is the highest value ever reported in Si-based visible light emitters as shown in Fig. 4.

4. Summary

We have introduced the quantum confinement effect of the nc-Si embedded in silicon nitride matrix and demonstrated that the device with nc-Si embedded in silicon nitride matrix is an efficient light emitter at room temperature and the estimated external quantum efficiency of the device amounts to 1.6%. We suggest that excitation occur by the tunneling of electrically inject carriers into nc-Si and the subsequent radiative recombination of electron-hole pairs. These results are promising towards the applications of nc-Si as light emitting sources integrated within a silicon-based system.

Fig. 4 Silicon-based visible light emitter showing the electroluminescence from a nc-Si active layer(lower ETRI Logo), which has high external quantum efficiency of 1.6%.

Acknowledgement

This work was supported by the Ministry of Information and Communication in Korea and the Adventure Research Programs in ETRI.

References

[1] *Silicon Photonics*, eds. L. Pavesi, D. J. Lockwood (Berlin, Springer), 2004.
[2] M. V. Wolkin, J. Jorne, P. M. Fauchet, G. Allan, and C. Delerue, Phys. Rev. Lett. **82**, 197 (1999).
[3] Nae-Man Park, Chel-Jong Choi, Tae-Yeon Seong, and Seong-Ju Park, Phys. Rev. Lett. **86**, 1355 (2001).
[4] Tae-Youb Kim, Nae-Man Park, Kyung-Hyun Kim, Gun Yong Sung, Young-Woo Ok, Tae-Yeon Seong, and Cheol-Jong Choi , Appl. Phys. Lett. **85**, 5355 (2004).
[5] Baek-Hyun Kim, Chang-Hee Cho, Tae-Wook Kim, Nae-Man Park, Gun Yong Sung, and Seong-Ju Park, Appl. Phys. Lett. **86**, 091908 (2005).
[6] Chang-Hee Cho, Baek-Hyun Kim, Tae-Wook Kim, Seong-Ju Park, Nae-Man Park, Gun Yong Sung, Appl. Phys. Lett. **86**, 143107 (2005).
[7] Kwam Sik Cho, Nae-Man Park, Tae-Youb Kim, Kyung-Hyun Kim, Gun Yong Sung, and Jung H. Shin, Appl. Phys. Lett. **86**, 071909 (2005).
[8] S. M. Sze, *Physics of Semiconductor Devices*, 2nd edition. (Wiley, New York, 1981), Chap. 7.