2D Slab Silicon Photonic Crystal for Enhancement of Light Emission in Visible Wavelengths

Yonghao Cui, and Jeong-Bong Lee
Dept. of Electrical Engineering, University of Texas at Dallas, Richardson, TX 75083, U.S.A.
TEL:1-972-883-6549, e-mail: yxc046000@utdallas.edu

Keywords : Photonic Crystal, Insulator, Visible, LED, Silicon

Abstract

We present 2D slab silicon-based photonic crystal optical insulator to enhance light emission efficiency of light-emitting diode (LED). A 2D slab silicon photonic crystal is designed in such a way that light emitting diode die can be placed in the middle of the silicon photonic crystal. The device creates light propagation forbidden region in horizontal plane for Transverse Electric (TE) light with the wavelength range of 450 nm to 600 nm.

1. Introduction

Photonic crystal (PC) with photonic band gap [1-6] has been widely investigated since it has great potential to control and manipulate the flow of lights in various wavelengths. Properly designed photonic crystal which is artificially made by periodical patterning of dielectrics in 1D, 2D or 3D can function as a photonic insulator for designated polarization and wavelength range of light.

This characteristic of photonic crystal can be applied in LED design. Light emitted from LED has a tendency to propagate in any direction which will cause inefficiency of light emission. To enhance light intensity in a certain direction (typically, normal to the surface direction), photonic crystal-based light insulator is a good candidate to guide the light. Light propagation in horizontal direction can be reflected and re-guided in vertical direction using properly designed photonic crystal. There have been several investigations to enhance light extraction of LED using photonic crystal [7-8]. In order to increase light extraction efficiency and achieve fabrication simplicity, photonic crystal was directly fabricated on III-Nitride LED [9-10].

In this work, we designed a silicon-based photonic crystal which can be independently fabricated in silicon utilizing well established silicon-based technology and LED die regardless of material can be placed in the Si photonic crystal to enhance the light extraction efficiency.

2. Design

The device was designed to have square shape trenches inside the 2D silicon slab triangular lattice photonic crystal with the thickness of 1 μm. It is designed with in mind of silicon-on-insulator in such a manner that silicon slab sits on top of a thick SiO_2 layer. Refractive indices chosen for silicon, air, and buried oxide are 3.46, 1.0 and 1.5 respectively. In order to design the device so that it effectively blocks visible light spectrum in the range of 400 nm to 700 nm, plane wave expansion method (PWEM) was utilized to properly design the band structures. Several normalized radii (r/a) in the range of 0 to 0.5 were tested to find out the largest band gap which effectively block the propagation of the light in the visible light spectrum (r stands for air-hole radius and a stands for lattice constant). At normalized radius of 0.45, large band gap was generated by PWEM in TE polarization and it is wide enough to design a photonic crystal based light insulator to cover nearly entire visible light spectrum. Figure 1 shows the dispersion diagram generated by PWEM with normalized radius of 0.45. The band gap lies in the normalized frequency (a/λ) range around 0.3 to 0.47. In order to let the nearly whole visible light wavelength range lies in inside the band gap, we chose the triangular lattice constant to be 200 nm. Consequently, air-hole diameter was chosen to be 180 nm.

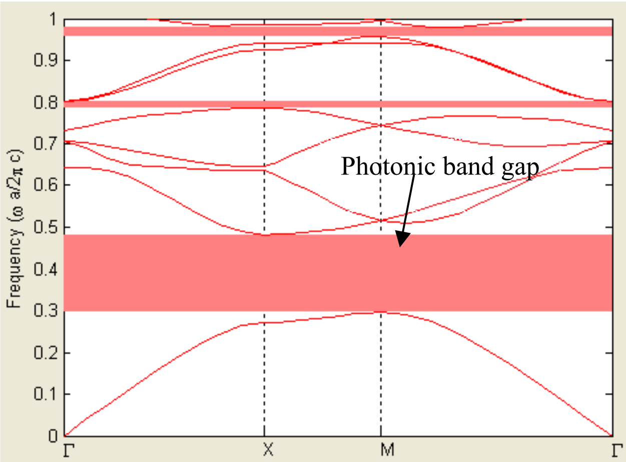

Fig. 1. Dispersion diagram for the 2D slab Si photonic crystal for visible wavelength LED application.

Figure 2 shows 3D view of the photonic crystal structure. Silicon slab with arrays of air-hole is sitting on top of buried oxide. LED lies in the center of the square trench in silicon slab and the light coming out of the LED should be guided to emit in perpendicular direction. Photonic crystal structure functions as light insulator in horizontal direction.

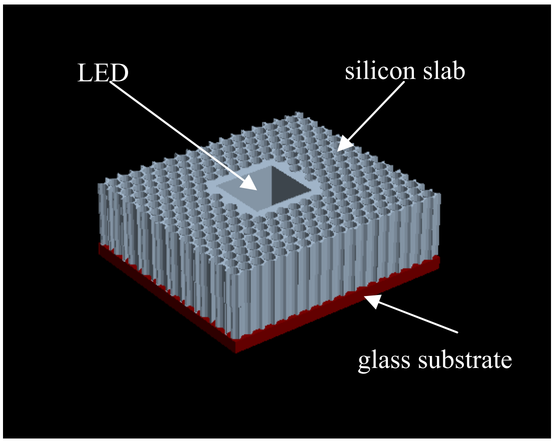

Fig. 2. 3D schematic of the photonic insulator

3. Simulation

Based on the design parameter extracted by PWEM, 2D and 3D finite difference time domain method was used to verify the design. EMPLab by EM Photonics (Delaware, USA) was used to carry out the FDTD simulation. In 2D FDTD simulation, light source with the wavelength of 400 nm, 450 nm, 500 nm, 550 nm, 600 nm and 650 nm were placed in the center square trench.

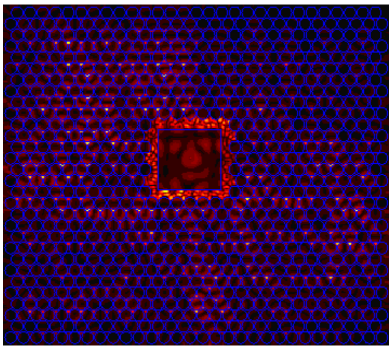

Fig. 3. 2D FDTD simulation result for wavelength 400 nm

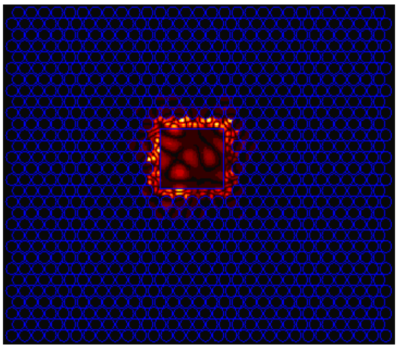

Fig. 4. 2D FDTD simulation result for wavelength 450 nm

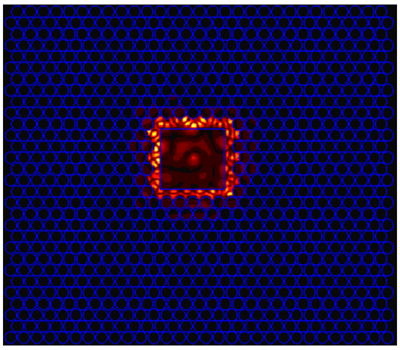

Fig. 5. 2D FDTD simulation results for wavelength 500 nm

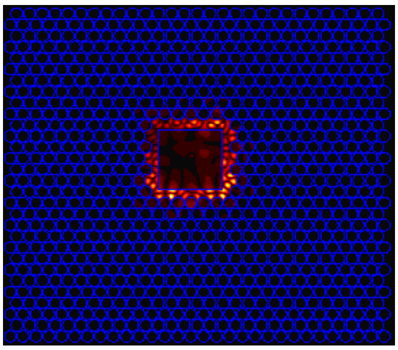

Fig. 6. 2D FDTD simulation result for wavelength 550 nm

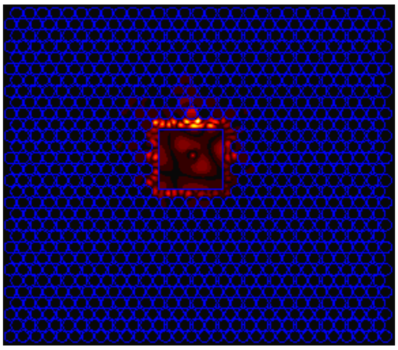

Fig. 7. 2D FDTD simulation result for wavelength 600 nm

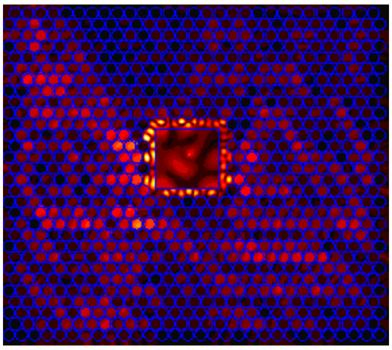

Fig. 8. 2D FDTD simulation results for wavelength 650 nm

In order to quantitatively measure the transmission characteristics of the designed photonic crystal light insulator, four detectors were placed as shown in Fig. 9. Fig. 10 shows the transmittance as a function of wavelength for the four detectors.

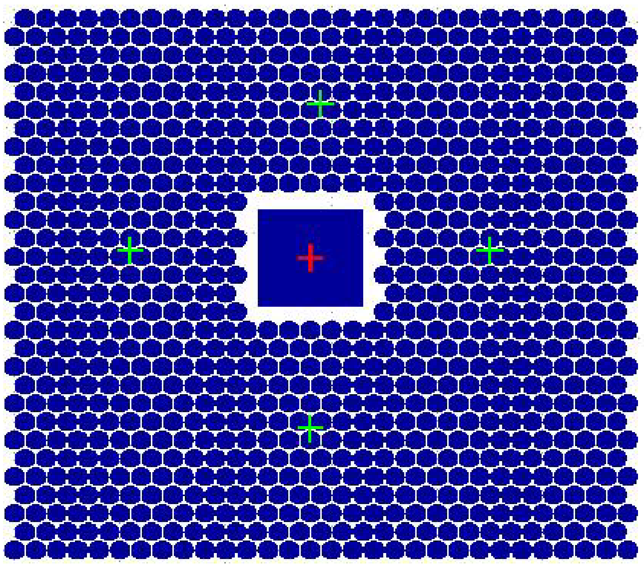

Fig. 9. Four detectors placed in the 2D slab photonic crystal.

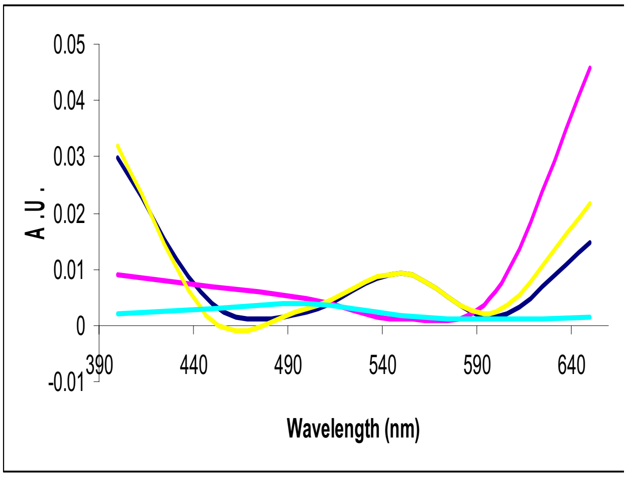

Fig. 10. Light transmittance vs. wavelength

In Figure 3, there is some portion of light leakage in horizontal direction with 400 nm wavelength, but as the wavelength increases, like shown in Figure 4 to 7 (450 nm ~ 600 nm), the visible light propagation are nearly completely confined in the square shape 2D silicon trench. 2D FDTD simulation clearly shows designed photonic crystal functions as a light insulator in wavelength range 450 nm to 600 nm in horizontal direction. When the wavelength increased to 650 nm (Figure 8), however, light is started to leak again. To verify 2D FDTD simulation results, 3D FDTD simulation was also carried out. Figure 11 shows 3D FDTD simulation in the wavelength of 500 nm. This result matches with 2D FDTD simulation result for 500 nm (Fig. 5).

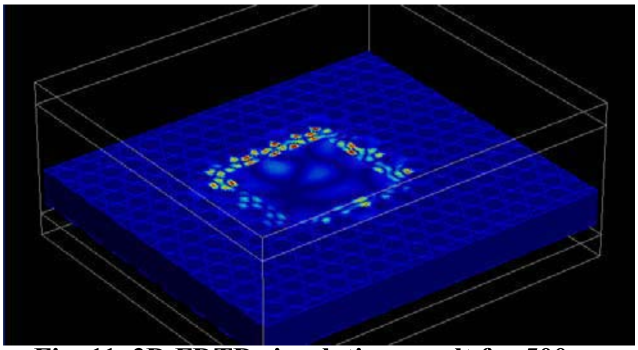

Fig. 11. 3D FDTD simulation result for 500 nm wavelength

4. Conclusions

Simple assembly of LED die (regardless of material used) into a properly designed 2D slab silicon photonic crystal will be beneficial to enhancement of light emission efficiency of LED. With the aid of photonic crystal technology, light propagation in certain directions is prohibited and light emission efficiency in desired direction will be significantly increased. Such a mix-and-match concept will streamline the manufacturing process of the LED and still being able to utilize photonic crystal-based light insulator for high light extraction efficiency.

Acknowledgment

This work was supported in part by the National Science Foundation grant BES-0608934.

5. References

1. E. Yablonovitch, *J. Opt. Soc. Am. B*, Vol. 10, No. 2, February, (1993).
2. R. D. Meade, A. M. Rappe, K. D. Brommer, and J. D. Joannopoulos, *Physical Review B*, Vol. 48, No. 11, September 15, (1993).
3. J. D. Joannopoulos, P. R. Villeneuve, and S. Fan, *Nature* (London) 386, 143-149, March 13, (1997).
4. V. N. Astratov, D. M. Whittaker, I. S. Culshaw, R. M. Stevenson, M. S. Skolnick, T. F. Krauss, and R. M. La Rue, *Physical Review B*, Vol. 60, No. 24, December 15, (1999).
5. J. S. Foresi, P. R. Villeneuve, J. Ferrera, E. R. Thoen, G. Steinmeyer, S. Fan, J. D. Joannopoulos, L. C. Kimerling, Henry I. Smith, and E. P. Ippen, *Nature*, Vol. 390, p 143, November 11, (1997).
6. S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and E. F. Schubert, *Physical Review Letters*, Vol. 78, No. 17, April 28,(1997).
7. W. Du, X. Xu, Z. Sun, L. Lu, J. Gao, Z. Zhao, C. Wang, and H. Chen, *Pan Tao Ti Hsueh Pao/Chinese Journal of Semiconductors*, Vol. 27, No. 5, p 921-925, May, (2006).
8. W. Claude, *International Nano-Optelectronics Workshop*, p 4-5, (2007).
9. J.J. Wierer, M. R, Krames, J.E. Epler, N.F. Gardner, J.R. Wendt, M. M. Siqalas, S.R.J. Brueck, D. Li, and M. Shaqam, *Progress in Biomedical Optics and Imaging - Proceedings of SPIE*, Vol. 5739, p 102-107, (2005).
10. D.H. Kim, J. Kim, H. Jeon, S.P. Yoon, J. Cho, S.I. Jin, C. Sone, and Y. Park, *Proceedings of SPIE, the International Society for Optical Engineering*, Vol. 5941, p 59410M.1-59410M.7, (2005).