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Strong vertical light output from thin silicon rich oxide/SiO₂ multilayers via in-plane modulation of photonic crystal patterns

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Three-dimensional-confined structures with triangular-lattice air-hole photonic crystal patterns were fabricated to enhance the light output from silicon rich oxide/SiO₂ multilayer stack. The intensity and profile of spontaneous emission were found to be efficiently modulated by controlling the optical modes of the periodic arrays via varying their structural parameters. With lattice constant/radius of 700 nm/280 nm, the photoluminescence intensity was found to be enhanced by nearly nine times in the vertical direction. The mechanisms for different enhancement features have been theoretically analyzed based on coherent scattering and quantum electrodynamic effects, well supporting the experimental observation. © 2008 American Institute of Physics. [DOI: 10.1063/1.2976330]

In the light of promise for many potential applications in integrated photonic circuits and light emitting diodes, the subject of light emission from Si-based nanostructures has attracted a lot of attention.^{1–7} Among the materials studied, silicon rich oxide (SRO) embedded in a SiO₂ matrix has been extensively investigated. The known issue is the insufficient brightness due to the low radiative rate in the indirect-band-gap material system. As an alternative approach to improve the light output efficiency, photonic crystal (PC) patterns can be employed to increase the external quantum efficiency,^{8–13} thus to compensate for its internal low level brightness.

In this study, we have designed and fabricated three-dimensional (3D)-confined structures with two-dimensional (2D) air-hole PC arrays for the spontaneous emission from SRO/SiO₂ multiple quantum well (MQW). The patterns were penetrated into the active region, which shall be more capable of manipulating the light compared with the typical setup^{11,12} with separated active and extraction regions. The significant light-output enhancement has been observed, and the mechanisms therein are theoretically discussed.

Figure 1(a) shows the schematic of the 3D-confined structure investigated in this study. The upper and lower claddings are Si₃N₄ and SiO₂ with thicknesses of 50 and 150 nm, respectively. A ten-period thin SRO/SiO₂ multilayer stack acts as the light emitting source with vertical quantum confinement in SRO well layers. These multilayers were deposited sequentially on silicon substrate (100) by plasma-enhanced chemical vapor deposition system using SiH₄ and N₂O as the source gases. Figure 1(b) shows the cross-sectional transmission electron microscopy (X-TEM) image of the SRO (~12.9 nm)/SiO₂ (~13.1 nm) MQW layers. As shown in Fig. 1(c), the top-view image of scanning electron microscope (SEM) exhibits the exact regular 2D triangular-lattice air-hole PC geometry, which was fabricated by dry etching of the upper cladding down through the entire active region with the etching depth of $h=300$ nm. The lattice constant and the radius are labeled as a and r , and thus the duty

cycle of air holes (the percent coverage of air holes over the surface) is described as $2\pi\rho^2/\sqrt{3}$, here $\rho=r/a$. Five different PC patterns A–E with various lattice constants and duty cycles have been fabricated in this work, as listed in Table I. Patterns A and B (or C, D, and E) have the same lattice constant but with increasing duty cycle. Patterns A and D (or B and E) have the same duty cycle but with different lattice constant. All fabricated samples were annealed at 900 °C for 30 min in N₂ ambient to enhance the internal light emission efficiency.

The photoluminescence (PL) spectra were collected at room temperature using a Renishaw micro-PL system with the excitation source of He–Cd laser (325 nm) and the incident power of ~1 mW. The light emissions were recorded for a wavelength of 400–900 nm by the liquid-N₂ cooled charge coupled device CCD system in the vertical direction through the microscope. Figure 2(a) shows the PL emissions from the patterned regions A–E and from an unpatterned region as reference. To illustrate the enhancement features, the PL intensities were normalized to the effective area of the active material ($1-2\pi\rho^2/\sqrt{3}$) for each pattern, as plotted in Fig. 2(b). The light emission around 620 nm dominated the spectrum of the unpatterned region and also appeared in the

FIG. 1. (a) Schematic of the 3D-confined structure. (b) X-TEM image of the active region composed of ten periods of SRO/SiO₂ MQW. (c) SEM top view of a 2D triangular-lattice air-hole PC geometry.

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TABLE I. Structural parameters of patterns A–E.

Pattern ID	Lattice constant (a) (nm)	Ratio of radius to lattice constant ($\rho=r/a$)
A	400	0.35
B	400	0.40
C	700	0.25
D	700	0.35
E	700	0.40

patterned areas without discernible shift, which originated from the vertical quantum confinement effect in the MQW layers. The significant enhancements of light emissions were observed around 720 nm from all the patterned regions, but the enhancement magnitudes and peak positions were strongly dependent on the lattice constants and duty cycles. Especially, for pattern E with $a=700$ nm and $\rho=0.40$, the spectral integrated PL intensity in the vertical direction was boosted up to ninefolds, indicating that such 2D PC arrays had a large impact on the output of the spontaneous emission. The exact origin of such enhancement features could be well explained theoretically based on the band structure modulation of 2D PC slabs.

In this work, a nonlinear equation method based on plane-wave expansion was used to calculate the band structures of PC patterns.¹⁴ Here, only the results of patterns A ($a=400$ nm, $\rho=0.35$) and E ($a=700$ nm, $\rho=0.40$) are shown in Figs. 3(a) and 3(b) for different lattice constant and duty cycle. The diagram consists of a light cone (shaded region) above the light line of air (black solid line), the transverse-electric (TE)-like modes (red solid line with circle), the transverse-magnetic (TM)-like modes (blue solid line), and a photonic band gap (PBG). Modes in the light cone are inherent leaky or radiation modes, which are extended infinitely in the free space outside the slab. Modes below the light line are guided modes, which are the genuine eigenmodes of the PC slab. They are allowed to propagate in the horizontal plane, but will exponentially decay into the free space, analogous to the total internal reflection. The PBG is created as a result of multiple Bragg scattering of photons by lattices of periodically varying refractive indices. Propagation of modes in the PBG region (the portion below the light line) is forbidden in the PC slab.^{15,16}

FIG. 2. (Color online) (a) PL spectra recorded in the vertical direction at room temperature for patterns A–E and an unpatterned region. (b) PL spectra normalized to the area of the active material.

FIG. 3. (Color online) The photonic band diagrams for PC slabs with (a) pattern A ($a=400$ nm, $\rho=0.35$) and (b) pattern E ($a=700$ nm, $\rho=0.40$).

As shown in Fig. 2, the PL intensities from patterns with $a=700$ nm (C, D, and E) are much stronger than those from patterns with $a=400$ nm (A and B), which indicates that the enhancement factor of emission is primarily influenced by the variation of lattice constant rather than the duty cycle in the tested range. In the case of pattern E ($a=700$ nm, $\rho=0.40$), the PL peak around 694 nm corresponds to the normalized frequency $a/\lambda \approx 1.0$, near the Γ point of the TE-like leaky conduction band (indicated by arrow) in Fig. 3(b). The light generated thus strongly couples with the high- Q (quality factor) leaky modes⁸ and eventually escapes into free space from the slab in the vertical direction.^{13,15} Based on the same mechanism, PL intensities of the regions with patterns C ($a=700$ nm, $\rho=0.25$) and D ($a=700$ nm, $\rho=0.35$) are also greatly improved. As for patterns A ($a=400$ nm, $\rho=0.35$) and B ($a=400$ nm, $\rho=0.40$), the PL intensities exhibit about two to three times enhancement over the reference, mainly within the range of 550–800 nm. The corresponding optical modes of the PC slab move to the lower normalized frequencies from about 0.5 to 0.73 due to the smaller constant lattice compared with C, D, and E, which overlap with the PBG region and the TM-like resonant radiation band [refer to the blue line marked with arrow in Fig. 3(a)]. We therefore speculate that the enhancement in this case is mainly due to two possible mechanisms. First of all, since the lateral propagation of guided modes in the PBG region is prohibited in the slab, light generated can only radiate in the vertical direction, which is described as the redistribution of saved energy by PBG effect.¹⁷ Second, the light emission corresponding to TM-like guided modes is folded to high- Q resonant radiation modes at the Brillouin zone boundaries by phase compensation from a reciprocal lattice vector, thus leading to higher external quantum efficiencies.¹⁰ The relatively small enhancement factor observed is partially due to the inhibition of recombination of excited carriers in the in-plane direction by PBG effect.¹³

With the radius of air hole being increased from C, D, to E, the significant PL peak exhibits blue shift from 750 to 694 nm. Similar phenomena also occur in the cases of patterns A and B. That is because the effective refractive index of the PC slab decreases with the increase in the duty cycle while maintaining the lattice constant and slab depth, which consequently results in the blueshift of photonic band structures.¹⁵ When the value of ρ is reduced down to 0.25 in pattern C the states around K point lying in the conduction

FIG. 4. (Color online) The normalized (a) electric field intensity distribution and (b) magnetic field intensity distribution of excitation incidence (325 nm) in the plane of $h/2$ for the sample with pattern E.

band will fall outside the light cone and become guided modes, which might be responsible for the smaller enhancement compared with D and E.

Although the active material was partially removed by the dry etching process, spontaneous emission can also be compensated through two beneficial ways dominated by quantum electrodynamic effects. The first is the so-called Purcell spontaneous emission rate enhancement occurring in the wavelength-size cavities of PC due to the high quality factor and small mode volume.¹⁶ The second is the redistribution of pump energy in the active region. As an example, we calculated the electromagnetic (EM) field distribution of pump light (325 nm) in the plane of $h/2$ for the sample with pattern E, based on the rigorous coupled wave analysis method.¹⁸ The normalized electric and magnetic field distributions are depicted in Figs. 4(a) and 4(b), respectively. It can be seen clearly that most of the energy is concentrated in the dielectric material region outside the air holes, thus providing magnified pump power intensities for spontaneous emission.

In summary, 2D perfect PC formation is built in SRO/SiO₂ MQW layers to improve the light output at room

temperature. Vertical output enhancement and in-plane modulation of spontaneous emission are realized in the patterned regions with various structural parameters. The possible mechanisms for enhancement are discussed and attributed to (i) coherent scattering of the internal trapped light (PBG effect, or strong coupling to the high- Q leaky or resonant radiation modes) and (ii) quantum electrodynamic effects (Purcell enhancement of spontaneous emission and the concentration of EM fields in the active material).

¹L. T. Canham, *Appl. Phys. Lett.* **57**, 1046 (1990).

²A. Polman, *Nat. Mater.* **1**, 10 (2002).

³R. J. Walters, G. I. Bourianoff, and H. A. Atwater, *Nat. Mater.* **4**, 143 (2005).

⁴I. Bineva, D. Nesheva, Z. Aneva, and Z. Levi, *J. Lumin.* **126**, 497 (2007).

⁵W. K. Tan, M. B. Yu, Q. Chen, J. D. Ye, G. Q. Lo, and D. L. Kwong, *Appl. Phys. Lett.* **90**, 221103 (2007).

⁶A. Morales-Sánchez, J. Barreto, C. Domínguez-Horna, M. Aceves-Mijares, and J. A. Luna-López, *Sens. Actuators, A* **142**, 12 (2008).

⁷M. H. Wang, D. R. Yang, D. S. Li, Z. Z. Yuan, and D. L. Que, *J. Appl. Phys.* **101**, 103504 (2007).

⁸M. Boroditsky, T. F. Krauss, R. Coccioli, R. Vrijen, R. Bhat, and E. Yablonovitch, *Appl. Phys. Lett.* **75**, 1036 (1999).

⁹S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and E. F. Schubert, *Phys. Rev. Lett.* **78**, 3294 (1997).

¹⁰A. A. Erchak, D. J. Ripin, S. Fan, P. Rakich, J. D. Joannopoulos, E. P. Ippen, G. S. Petrich, and L. A. Kolodziejski, *Appl. Phys. Lett.* **78**, 563 (2001).

¹¹J. Y. Kim, M. K. Kwon, K. S. Lee, S. J. Park, S. H. Kim, and K. D. Lee, *Appl. Phys. Lett.* **91**, 181109 (2007).

¹²S. H. Kim, K. D. Lee, J. Y. Kim, M. K. Kwon, and S. J. Park, *Nanotechnology* **18**, 055306 (2007).

¹³H. Y. Ryu, Y. H. Lee, R. L. Sellin, and D. Bimberg, *Appl. Phys. Lett.* **79**, 3573 (2001).

¹⁴D. S. Gao and Z. P. Zhou, *Appl. Phys. Lett.* **88**, 163105 (2006).

¹⁵S. G. Johnson, S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and L. A. Kolodziejski, *Phys. Rev. B* **60**, 5751 (1999).

¹⁶M. Boroditsky, R. Vrijen, T. F. Krauss, R. Coccioli, R. Bhat, and E. Yablonovitch, *J. Lightwave Technol.* **17**, 2096 (1999).

¹⁷S. Noda, M. Fujita, and T. Asano, *Nat. Photonics* **1**, 449 (2007).

¹⁸E. Noponen and J. Turunen, *J. Opt. Soc. Am. A* **11**, 2494 (1994).